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VOLUME 6, NO. 2 (OCTOBER 2025)

TABLE OF CONTENTS

RESEARCH ARTICLES

REVIEW ARTICLE

SEED LONGEVITY AND MEDICINAL PROPERTIES OF *BRUCEA ANTIDYSENTERICA* J.F. MILL. IN ETHIOPIA

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ABSTRACT: Medicinal plants comprise a diverse group of species used traditionally for the alleviating and treatment of human diseases, and they have played an essential role in healthcare systems for thousands of years worldwide. *Brucea antidysenterica* is a well-known medicinal plant in Ethiopia, widely used to treat dysentery and other ailments. However, overexploitation of medicinal plants threatens their long-term survival, highlighting the urgent need for effective conservation strategies. Therefore, this study aimed to evaluate the effects of two storage temperatures (+4 °C and −10 °C) under different storage durations on the seed viability of *B.antidysenterica*. Germination tests were conducted at regular intervals to assess seed longevity during storage. Multivariate analysis indicated no statistically significant reduction in germination percentage ($P < 0.05$) over the storage period. Seeds maintained high viability, with germination percentages exceeding 80% after nine months of storage, including under sub-zero conditions. In parallel, a comprehensive examination of prior findings was conducted to document the medicinal value of the species, using scientific databases such as PubMed, Science Direct, and Google Scholar, with emphasis on studies from Ethiopia published from 2006 -2024. The synthesis of scientific evidence revealed that various parts of the plant are extensively used to treat dysentery, diarrhea, malaria, skin diseases, and other ailments, indicating the importance of conserving the species. The experimental results indicated that *B.antidysenterica* seeds exhibit orthodox storage behavior. However, further studies are recommended to determine the optimal combination of seed moisture content and storage temperature for long-term conservation with certainty.

Key Words: Germination percentage, Germination tests, Orthodox seeds, Storage, Viability

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INTRODUCTION

Medicinal plants are defined as those capable of alleviating or curing diseases due to the various molecules and compounds they contain. They have a traditional use as a remedy in a population or community. Such plants have been used for thousands of years in traditional medicine in many countries around the world. The empirical knowledge about their beneficial effects was transmitted over Centuries within human communities (Khan, 2014). These plants used for thousands of years in traditional medicine in many countries around the world (Marrelli, 2021).

It is estimated that approximately 50,000 plant species worldwide are used in traditional medicinal systems (Chen et al., 2016). In many developing countries, including Ethiopia, traditional medicine remains the primary source of healthcare for nearly 80% of the population (Ekor, 2014; Hamilton, 2004). Moreover, 90% of livestock population in Ethiopia depends on utilization of medicinal plants for primary health care (Kassaye et al., 2007; Yeshiwas et al., 2019).

Teklehaymanot et al. (2006) reported that there are around 800 plant species used in traditional medicine to treat roughly 300 mental and physical disorders. In a study of antiviral properties of Ethiopian plants, Fekadu et al., (2023) identified 387 species, about 6% of Ethiopia's known flora, for which records of use by local communities and traditional herbalists have been documented for the treatment of viral diseases.

The medicinal plants may even be considered as the origin of modern medicine. Medicinal plants are accessible, affordable and culturally appropriate sources of primary health care. Plant-derived compounds have long been and continue to be a major source of molecules for drugs (Salmerón-Manzano et al., 2020). According to Chaachouay and Zidane (2024), in addition to its employment as folk herbal medicines to treat various disorders, their different natural products have inspired the design, discovery, and development of new drugs. Over 25% of prescribed medicines in developed countries are derived from wild plant species (Hamilton, 2004).

The continued increasing demand of medicinal plants is causing their overexploitation that, subsequently, would result in the extinction of many valuable plants, risking the future benefits and knowledge of human beings. Today, many medicinal plant species are disappearing at a high speed and have reached the fate of extinction or severe genetic loss (Chen et al., 2016). The major threats to medicinal plants include habitat destruction, urbanization, agricultural expansion, investment, road construction, and deforestation (Lulekal et al., 2013). Kloos (2023) also emphasized that overharvesting of medicinal plants and habitat destruction are the major threats to medicinal plant sustainability. In addition to *in-situ* conservation efforts, reproductive materials of medicinal plants should be stored in seed banks for future replanting (Hamilton, 2004). Thus, there is an urgent need to develop and implement conservation strategies of *ex situ* conservation through collection and preservation of seeds.

One of the most basic tools for forest conservation is *ex situ* conservation of seeds in a temperature-controlled environment. Forest tree seeds can be stored in optimum conditions for a long time for later use. Storage of seeds using *ex situ* conservation requires an understanding of the lifespan or longevity of a seed, which is the time period over which it can remain viable. However, not all seeds can be safely stored without a proportional loss of viability. Therefore, investigation if specific storage requirements are needed and for how long seeds can be stored before they lose significant viability is prerequisite for seed handling to obtain preliminary information for their storage. It is imperative to examine the desiccation responses of seeds of unknown storage behavior.

Understanding, documenting and developing conservation strategies are key issues that need to be urgently addressed. *B. antidysenterica*, is one of the most important medicinal plant species. According to Youmbi et al. (2023), *B. antidysenterica* is an African medicinal plant traditionally used to treat cancer, dysentery, malaria, diarrhea, stomach aches, helminthic infections, fever, and asthma. The species is a widely used medicinal indigenous plant in Ethiopia, traditionally employed to treat a variety of ailments. With this background, the current study aims to investigate the impact of storage duration and storage temperature on the viability of seeds of *B. antidysenterica* and its implication for *ex-situ* conservation. In addition, different articles have been reviewed to document the medicinal values and applications of the species. The main objective of this study was to investigate the impact of storage duration and storage environment on the viability of seeds of *B.antidysenterica* and to document medicinal values of the species for the treatments of different ailments and parts used for treatment. The selection of study species was based on the interest in conservation of medicinal plant species.

MATERIALS AND METHODS

Description and geographic distribution of the study species

B. antidysenterica is a plant in the family Simaroubaceae named in honor of a Scottish traveler, James Bruce (1730-1794), who stayed in Ethiopia from 1768 to 1773 and also for its value in traditional medicine for the treatment of dysentery (Jansen, 1981). *B. antidysenterica* is a shrub or smal1 tree to 10(-15) m, often found in regrowth of deforested areas or at forest edges in Montane Forest, evergreen forest, forest margins and montane grass- land at 1650-2800 m (Stannard, B. 1989).

Flowering and fruiting of *B.antidysenterica* continue throughout the year, even during in the dry season (Schmelzer and Gurib-Fakim, 2008; Dagnachew et al., 2023). Jansen, (1981) also reported the plant flowers or fruits all the year round and it is not usually eaten by cattle, sheep or goats, despite the fact that it bears fresh-looking green leaves clustered at the ends of younger branches even throughout the dry season. The plant is traditionally used to treat various diseases in different parts of Ethiopia. It is widely used for treating a number of disorders, including diarrhoea, skin problems and leprosy (Stannard, 1989). The distribution of the plants in Africa and across the flora area of Ethiopia is provided in Table 1.

Seed collection site

Seed collection was conducted in the Choke Mountain Range, near Digotsion town, at the edge of farmland. Collection sites were selected based on the availability of mature seeds at the time of the study. Detailed information on the species, collection altitude, and geographical coordinates is provided in Table 1. All seeds were collected for research purposes under the standard protocols of the Ethiopian Biodiversity Institute (EBI), a government-recognized institution responsible for national biodiversity conservation. Moreover, the seed samples were collected solely for research purposes and not for storage or further utilization.

Seed collection and processing

Ripe fleshy fruits, characterized by red color, were collected from several individuals immediately after natural abscission. The seeds were collected for research purposes under Ethiopian Biodiversity Institute (EBI)'s institutional mandate. The mature fruits were hand-picked before they had fallen to the ground to avoid the risk of contamination and to collect fruits with healthy seeds. The collected fruits were thoroughly mixed to create a composite sample (ISTA, 2022). The sample was then transported to the EBI, Addis Ababa, on a vehicle in an ambient condition within two days of collection. During transportation, the fleshy fruits were kept in small quantity of small Cotton bags to be well ventilated to avoid seed suffocation and decay following Hong and Ellis, (1996). The cleaning of fruits was conducted upon arrival at EBI. All experiments were subsequently conducted at the Institute. During cleaning, the fleshy fruits were soaked in water to facilitate softening of the pulp. Seeds that float to the top were typically considered non-viable and discarded. The fleshy pulp was removed by rubbing between hands and continuously washing with water (Rao, et al., 2006). The moist seeds were air dried under shade immediately after extraction.

Seed drying, moisture content determination and seed storage

In the laboratory, cleaned and air-dried seeds were placed in a drying room set at 15^{o}C and 15% relative humidity for three weeks. The moisture content of seeds was determined gravimetrically with 5 g of three replications using the low-constant-temperature oven method (103 ± 2^{o}C for 17

± 1h) following the method recommended by Rao et al (2006). Seed moisture content expressed as the wet-weight (wb) computed using the following equation:

$MC\% = \frac{W2-W3}{W2-W1)} X100$; Where, MC moisture content, W1= weight of container; W2 = weight of container and seed sample before drying; and W3 the weight of the container with seed sample after oven drying.

After seed moisture content reduced to desired moisture content level (Table 1), seeds of *B. antidysenterica* were tested for initial germination. The remaining seeds were stored in two cold rooms set at 4^{o}C and -10^{o}C temperatures with sealed aluminum foil bags for consequent germination tests. The seeds were stored for 3, 6 and 9 months.

Germination Tests

After each storage interval, germination tests were conducted in a laboratory at room temperature maintained at 15 to 21^{o}C with 12 h day and 12 h night cycle. Four replicates of 25 seeds per treatment (a total of 100 seeds) were allowed to germinate before the storage of seeds and after each storage interval to determine longevity of seeds at different storage durations. The seeds were periodically tested for their germination percentage at three-month interval for 9 months as recommended by (Hong and Ellis (996), as applied in previous studies by Dagnachew et al. (2023) and Mewded et al. (2022).

Germination of seeds was conducted on plastic boxes of 6 x 18 x 26 cm with 13 randomly equidistant holes at the bottom. The holes are used for air circulation on sand medium moistened with 20 ml of water for 1 kg of sand. The sand was sterilized and the plastic boxes were half filled in which the seeds were covered with the sand as recommended by Rao et al. (2006). The samples were watered during the whole germination period to maintain the moisture of the sand.

Germination assessments were made on weekly basis. Germination was defined as the emergence of a 2 mm radicle based on visual observation, indicating the potential for the seed to develop into a normal seedling. Germinated seeds were evaluated, counted and removed from the trays in each count. Tested seeds were incubated for up to 60 days in which all experiments continued until no seed germinated for two weeks. The number of germinated seeds was converted to germination percentages.

Medicinal value documentation

Data regarding the medicinal properties and utilized parts of *B. antidysenterica* were summarized from peer-reviewed articles, ethnobotanical surveys, and pharmacological studies published between 2006 and 2024. To document these data, a comprehensive literature search was performed across scientific databases, including PubMed, ScienceDirect, and Google Scholar. The search strategy utilized combinations of keywords such as “medicinal plants of Ethiopia”", “traditional medicine”, and “pharmacological properties of *B. antidysenterica”* with an emphasis on studies undertaken in Ethiopia. The medicinal uses of the *B.antidysenterica* presented in a tabular form (Table 2).

Table 1. Species description, geographical distribution, altitude and geographical coordinates of seed collection **sites**

AR = Arsi, BA = Bale, EW - Eritrea West above 1000m contour TH, GD = Gonder, GJ = Gojjam, HA = Harerge, IL = Illubabor, KF = Keffa, SD = Sidamo, SU = Shewa Upland, TU = Tigray Upland. (Stannard, 1989).

Local Name	Growth Habit	Species Altitudinal Range and Brief Botanical Description	Geographical Distribution Throughout Ethiopia	Geographical Distribution in Africa	Altitude and (Geographical Coordinates) of Seed Collection site	Seed Moisture Content (%) during Storage
Abalo (Amharic)	Shrub or small tree to 10(-15) m.	Montane forest, evergreen forest, forest margins, secondary growth in deforested areas, montane grass-land;1,650-2,800 m.	EW, TU, GD, GJ, WG, SU, AR, IL, KF, SD, BA HA;	Angola, Burundi, Cameroon, Central Afncan Republic, Congo, Ethiopia Kenya, Malawi, Mozambique, Nigeria Ruanda, Sudan	Alt 2732 (10° 53' 03.4''N, 37° 43'49.2'' E.)	3.1

Table 2. Summary of Traditional Medicinal Uses of *Brucea antidysenterica*

Study (Plant Material collection area)	Medicinal Uses	Parts Used	Mode of preparation and application	Source(s)
(Lummamie District) east Gojjam zone of Amhara Region	antimalarial effects	Leaves and seeds	extracts of the seed and leaf of *Brucea antidysenterica* and *Ocimum lamiifolium* (Plant parts air-dried at room temperature under shade, without exposure to sun light, and ground into powder)	Kefe et al., 2016
Zegie and Lake Tana monasteries in Northwest Ethiopia Amhara regional state	Dysentery ('Kuruba')	Leaf	Juice of leaf is taken orally in the morning	Amuamuta et al., 2015
	Hemorrhoids,	Leaf or fruit	Fruit or leaf powder mixed with milk is taken orally for three days	
	Weight loss, fever, itching, and diarrhea	Leaf	Leaf/fruit powder mixed with honey and fermented for seven days is taken orally until cure	
Guduru District of Oromia Regional state	Used to treat Ascaris	Not mentioned	Ethnobotanical data	Tadesse et al., 2018
Atawi, Wara Jarso woreda, Semen Shoa Zone, Oromia Regional state	wound healing and antibacterial activities	Powder of fresh leaves	Methanol (80%) leaf extract of *Brucea antidysenterica* was fractionated using three solvents; water, n-butanol and chloroform. An ointment containing 2% and 4% of each fraction was formulated and applied to wounds inflicted on rats	Wolde et al., 2022
Bahir Dar rural Kebeles Amhara regional state	To treat Wound	Leaf	The leaf of *Brucea antidysenterica* is pounded, squeezed and then creamed on wounded part until getting recovered	Mazengia et al., 2019

Nensebo District West Arsi Zone of Oromia regional state	Ear infection Hair fungus	Not mentioned	Ethnobotanical data	Abdela et al.,2022
Dega Damot district West Gojjam Amhara regional state	used for the treatment of cutaneous leishmaniasis	extract of seeds	The crude (80% methanol) extract of *Brucea antidysenterica* seeds and its fractions were evaluated for their anti-leishmanial activities against mammalian cells.	Ketema et al., 2023
Wayu Tuka District East Welega Zone Oromia regional state	To treat Ascaris	Fresh leaves	Fresh leaves crushed and mixed with Leaves of Bersema abyssinica Fresen. and cooked With porridge and given for a person in need	Megersa *et al*., 2013
Kembatta Tembaro (SNNPR) of the Southern Ethiopia.	To treat diarrhea	Leaves/Seeds	Buds used to treat Snake bite and leaves and seed used to treat Diarrhea/	Maryo et al., 2015
Gudaya Bila district, East Wollega Zone, Oromia Regional State	Active against all bacterial species	powdered leaves of the plant	The extracts obtained as such were subjected to phytochemical screen-ing and the results of the screening revealed the presence of diverse phytochemicals about the extracting solvents	Guluma et al., 2020
Debre Libanos monastery (9 ∘ 72’ N, 38 ° 87’ E)	Kusil (wound) healing		Oral uses water paste beaked –‘Venereal Diseases’ Powder butter paste dressing to treat wound -‘Ekeke’ Nasal Inhaling of Smoke of mixed powder to treat-‘Evil Eye’	Teklehaymanot et al., 2006
Zegie and Lake Tana	wound healing	leaf extracts of	leaf extract aqueous solutions of *Croton marcostachyus*	Mekonnen et al., 2019

	potential	*Croton marcostachyus* and *Brucea antidysenterica*	and *Brucea antidysenterica* were prepared and applied to wound of mice	
Debre LibanosWoreda Central part of Ethiopia	Wound and Skin itching	Leaves	Leaves crushed and mixed with butter to cover the wound	Getaneh and Girma, 2014
Jawi district, located in Northwestern Ethiopia,	To treat Gastritis	Bark and root	Dried stem bark and root part pounded, mixed with water and administered orally	Derso et al., 2024
'Lumame' District east Gojjam zone of Amhara region	Anti-diarrhoeal and antibacterial activities	Roots	The dried crude extract extracted by maceration technique using 80% methanol	Zewdie et al., 2020
published research findings on Ethiopian traditional medicinal plants	for the management of rabies	Fruit Leaf Root	Squeezed and baked with teff flour and given for 3 days [together with *Croton macrostachyus* and *Rumex nervosus*].	Meresa et al., 2017
West region of Cameroon (5° 03′ 60.00" N / 10° 27′ 59.99"E)	antiproliferative activity against cancer cell lines.	Stem and leaves	Phytochemicals isolated from the leaves and stem crude extracts and compounds	Youmbi et al., 2023
Bakouok (Bamenda)	against the	Root and bark	its extract might be considered an	Makong et al., 2019

Germination data analysis

Germination results were analyzed using Microsoft Office Excel (Version 2010). Bar graphs with standard error were used to analyze results of germination under different storage duration and storage environment. The percentage data from the different germination tests were first arcsine transformed to meet the requirement of normality (Zar, 2010). A two-way ANOVA was performed to examine the main effects of storage temperature and storage duration, as well as their interaction, on germination percentage. The effects of storage temperatures and durations on the germination of seeds were evaluated separately using a generalized linear model (GLM) for multiple comparisons between treatments. Adjusted p-values < 0.05, obtained using the Bonferroni–Holm method, were considered statistically significant. Tukey's Honestly Significant Difference (HST) test was used for pairwise comparisons, and significant differences between treatment means.

RESULTS AND DISCUSSION

Storage trial-based germination test

In the initial test, which has been conducted after drying before the storage of seeds, the germination percentage was 97%. For seeds stored at 4°C, the germination percentage decreased steadily over storage periods up to six months compared with seeds stored at -10^{o}C (Fig. 1 and Fig. 2). The germination percentage decreased steadily over storage periods up to six months for seeds stored at 4^{o}C. However, after nine months of storage, seeds maintained a relatively high germination percentage (80%), representing only a slight reduction from the initial value (Figure1). After six months, the germination percentage showed a noticeable reduction in germination percentage, compared to. initial germination percentage but sustained acceptable viability percentage. In contrast, seeds stored at −10 °C showed a noticeable reduction in germination percentage after three months of storage. However, beyond this initial decline, germination percentage remained relatively stable and was not significantly affected by further increases in storage duration up to nine months (Figure 2).

In general, no significant reduction in germination percentage was observed in *B. antidysenterica* seeds after nine months of storage under either 4 °C or −10 °C storage environment. A two-way ANOVA indicated that there was no statistically significant reduction in germination during storage time for seeds stored at both 4 °C and −10 °C ($F(3, 24) = 1.525$, $p = 0.233$).

Comparing the two storage environments, seeds stored at −10 °C exhibited a relatively higher germination percentage. This higher germination and greater stability of viability with increasing storage duration are characteristic of orthodox seeds. According to (Hong and Ellis, 1996), if no loss in viability is evident during subsequent storage, then the species probably shows orthodox seed storage behavior. The current result revealed that *B.antidysenterica* can be grouped in the orthodox seed storage category. Roberts, (1973) explained that orthodox seeds have enhanced seed longevity at lower temperatures and lower moisture contents, which enhances viability and germination.

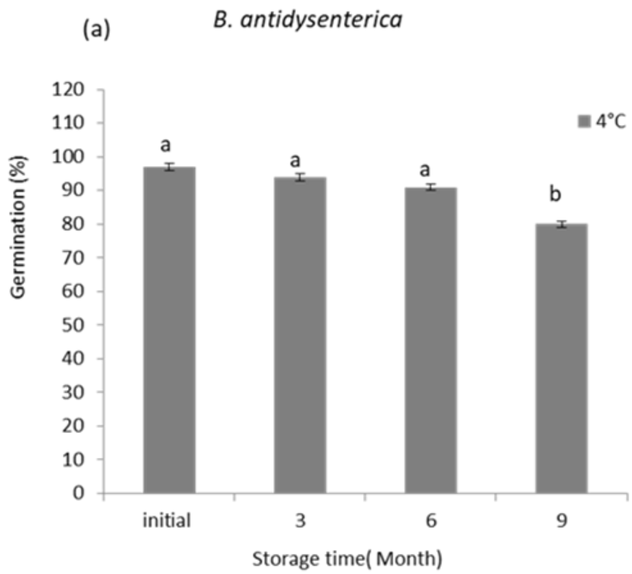

Figure 1. Germination of *B. antidysenterica* stored at 4°C moisture content and over a period of 9 months. Bars with different letters show statistically significant differences.

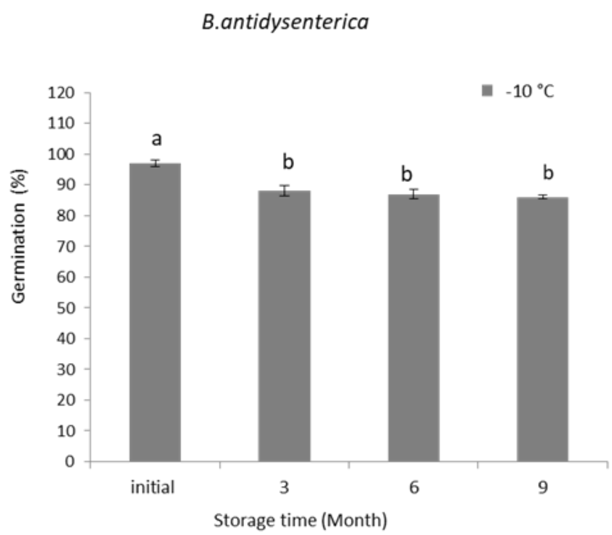

Figure 2. Germination of *B. antidysenterica* stored at -10°C moisture content over a period of 9 months. Bars with different letters show statistically significant differences.

Findings from different researchers also support the principle that lower storage temperatures enhance seed longevity by preserving germination capacity and viability compared with warmer storage conditions. Several studies (Nyo *et al.*, 2019; Hong and Ellis, 1996) have shown that maintaining seeds at low temperatures and low moisture content effectively slows physiological and biochemical deterioration processes, thereby sustaining seed viability over extended storage periods. This pattern has been observed in various species and is well documented in studies such as Mewded et al. (2022) and Dagnachew et al. (2023). Although laboratory conditions differ from those found under field conditions, assessing the effects of storage on germination provides valuable information for ecological restoration and germplasm conservation. Although the storage duration of the present experiment was relatively short (nine months), the findings provide useful guidance for long-term storage of *B. antidysenterica* seeds in a conventional seed bank.

Medicinal values and parts used

The medicinal value of *B. antidysenterica* in Ethiopia is extensive in traditional folk medicine. As its name suggests, it is widely used to treat dysentery and diarrhea, but the species demonstrates a wide range of medicinal properties and has been extensively used in traditional medicine for treating several ailments across several regions of Ethiopia (Yirgu, 2019; Zewdie et al., 2020; Table 2). Numerous researchers indicated that various parts of the plant (roots, leaves, bark and seeds) are traditionally employed against ailments like malaria, leishmaniasis (including cutaneous leishmaniasis), helminthiasis (intestinal worms), wounds and skin complaints (such as scabies, leprosy, and eczema), fever, cancer, weight loss, stomach ache, and as an anti-inflammatory agent (Amuamuta, 2015; Makong, 2019; Wolde et al., 2022 and Ketema et al., 2023).

CONCLUSIONS AND RECOMMENDATIONS

The present study demonstrated that *B. antidysenterica* seeds maintained high germination percentages over nine months of storage at both 4 °C and −10 °C, indicating no rapid loss of viability during this period. These findings suggest that the seeds of this species can be classified as orthodox, capable of tolerating drying and low-temperature storage at conventional seed bank facilities. Moreover, a review of ethnobotanical literature confirmed that *B. antidysenterica* is widely used in traditional medicine in Ethiopia, particularly for the treatment of dysentery and diarrhea, as well as for malaria, leishmaniasis, intestinal worms, skin diseases, fever, stomach ache, and as an anti-inflammatory agent. The combination of traditional importance and demonstrated seed storage category urges the value of conserving this species both in situ and ex situ. Based on the current findings, further studies should include desiccation screening tests under different temperature regimes and moisture levels, together with longer storage durations, to determine optimal storage conditions for long-term conservation with greater certainty.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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EFFECT OF AGRO-ECOLOGICAL ZONES ON THE NUTRITIONAL CONTENT OF BARLEY (*HORDEUM VULGARE* L.) ACCESSIONS CONSERVED IN THE ETHIOPIAN GENE BANK

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ABSTRACT: Barley (*Hordeum vulgare*) is one of conserved crop under cold storage in the Ethiopian Gene Bank, as it grows across a wide range of agro-ecological zones. This study utilized 33 barley accessions for nutrient content analysis to determine and compare the nutritional values of barley grown in different agro-ecological zones. Sample preparation and nutritional analysis were conducted following standard procedures defined by the Association of Official Analytical Chemists (AOAC). Descriptive statistical analysis and paired t-tests were employed to analyze the data. The findings revealed significant mean differences in the percentage of crude protein, moisture, and total carbohydrates content between barley sourced from Ethiopia's highlands and midlands. The results showed that the highest average crude protein (11.96%) and total carbohydrates (76.1%) were found in barley from midland agro-ecologies. Conversely, midland barley exhibited the lowest average moisture content (7.68%) and average crude fat content (1.86%). Both zones yielded an equal average mineral ash content of 2.4%.The study concluded that as altitude increases, the nutritional values of barley significantly decreased for all nutritional values except moisture and crude fat content. Based on the finding that higher altitude correlates with lower protein and carbohydrates but higher moisture and crude fat, it is recommended to prioritize barley accessions from midland agro-ecologies for breeding and food security programs aimed at maximizing crude protein and total carbohydrate content.

Key Words: Carbohydrates, Crude fat, Crude protein, Highlands, Midland,

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INTRODUCTION

Ethiopia is recognized as a center of genetic diversity and origin for numerous cultivated and wild plants (Vavilov, 1951; Harlan, 1969). However, this diversity, particularly among landraces is under severe threat from genetic erosion induced by modern agricultural practices (Melaku and Hailu, 1993). To protect this decline, the Ethiopian Biodiversity Institute (EBI), formerly the Plant Genetic Resources Centre of Ethiopia (PGRC/E) was established in 1976. The EBI focuses on preserving genetic diversity of crops, their wild relatives, and native species crucial to Ethiopia's agriculture. It has successfully collected over 90,000 accessions from more than 120 plant species, among these; barley is one of the most conserved crops, with 16,685 accessions (Angassa and Tesfaye, 2019).

Barley (*Hordeum vulgare* L.) is an economically significant and ancient crop in Ethiopia, with a cultivation history spanning at least 5,000 years (Kemelew and Alemayehu, 2011; Girma, 2014). According to Hadado et al. (2010), landraces account for over 90% of cultivated barley diversity, reflecting a deep-rooted relationship between the crop and Ethiopian farmers. Barley ranks fifth in acreage and production among Ethiopian cereals, following teff, maize, wheat, and sorghum (Teklemariam et al., 2022). It is grown across all regions of the country, primarily at altitudes ranging from 1,500 to 3,400 meters above sea level (masl) with adequate moisture (Yaynu, 2006). The majority of barley production is concentrated between 2,000 and 3,400 masl in northern and central Ethiopia (Asfaw, 2000).

This resilient crop is primarily cultivated by smallholder farmers for subsistence, especially in regions where modern agricultural methods are less feasible (Lakew et al., 1997). Barley is grown during two main seasons: the major rainy season ('meher') and a shorter one ('belg'), contributing to 20% of Ethiopia’s total cereal production (Wosene et al., 2015).

Ethiopia's landscape includes three major agro-ecological zones: highlands (2,300–3,500 masl), midlands (1,500–2,300 masl), and lowlands (below 1,500 masl) (Dereje and Eshetu, 2011). While barley is predominantly a highland crop, it also adapts to certain midland regions (CSA, 2016). This cool-weather crop flourishes best between 2,000 and 3,500 masl (MoA, 1998). Notably, barley exhibits significant resilience, thriving in well-drained soils and tolerating higher salinity levels than most other crops (Bekele et al., 2005). "Food barley" is commonly cultivated in stressed areas where soil erosion, occasional drought, or frost limits the viability of other crops (Bekele et al., 2005). It serves as a reliable food source in the highlands, cultivated during both rainy seasons and under residual moisture conditions (Tilahun et al., 2015).

Barley types are generally categorized as food or malting barley based on their use; in Ethiopia, the vast majority of cultivation area is allocated to food barley. It is a staple in various traditional recipes and beverages, including Bread, Injera, Kolo, Genfo, Kitta, Kinche, Beso, Tella, and Borde. Additionally, barley straw is an essential component of animal feed, particularly during the dry seasons in the highlands (Getachew et al., 1996).

Nutritionally, barley possesses health-promoting functional properties (Cook, 2013; Idehen et al., 2017). Its primary components are carbohydrates, with low fat content, proteins, minerals, and vitamins (especially vitamin E). It is also rich in dietary fiber and antioxidants, predominantly polyphenols (Das et al., 2016).

Despite its importance, there remains a knowledge gap regarding how altitude, soil, and climate affect barley's nutritional content across different zones. While barley is vital for food security, existing research has not adequately compared the nutritional attributes of barley grown in distinct agro-ecological regions. This research gap presents an opportunity to investigate barley's nutritional profile across diverse zones, considering ecological, economic, and societal dimensions. Addressing these gaps could strengthen the understanding of barley’s role in enhancing food security and improving agricultural practices in regions dependent on this resilient crop.

This study aims to bridge that gap by analyzing 33 accessions of conserved barley (15 from the midlands and 18 from the highlands). Therefore, the objective of this study was to evaluate and compare the nutritional value of barley cultivated in highland and midland regions, assessing the impact of agro-ecological conditions on its nutritional composition. These findings will enhance our understanding of barley's nutritional profile, benefiting both domestic consumption and future research efforts.

MATERIALS AND METHODS

Sample Size and Sample Preparations

A total of 33 barley accessions were utilized, comprising 15 accessions from the midland and 18 accessions from the highland region. Each sample accession, weighing 30 g, was sourced from the EBI cold storage facility, accompanied by complete passport data collection specific to each agro-ecological zone. Seeds were hand-sorted to remove foreign materials. Raw seeds (with seed coats) were processed into flour using an electric grinder (Retsch, ISO9001) and passed through a 0.5 mm mesh sieve. Flour was stored in airtight polyethylene bags. Analysis was conducted in duplicate (n=2) at the EBI laboratory.

Nutritional Content Analysis

Nutritional values were determined according to the Association of Official Analytical Chemists (AOAC. 2000) methods.

Determination of Moisture Content

The moisture content of the barley samples was determined by the oven drying method (AOAC, 2000). A clean, empty aluminum dish and its lids were dried in a drying oven (Moment, Germany) at 100°C for 1hr, and cooled in a desiccator (with granular silica gel) for about 30 min, and weighed. For each accession were conducted in 2 replicates. The samples prepared for each accession were mixed thoroughly, and about 3.0 g of flour was weighed in duplicate. The dishes and the samples were placed in the drying oven and dried for 3hr at 105°C. After drying, the samples were cooled in a desiccator for 30 min and weighed. The percentage of moisture calculates as follow:

$$\% \, Moisture = \frac{(wt \, of \, empty \, dishes + sample) - (wt \, of \, dishes + dry \, sample)) * 100)}{wt \, of \, sample}$$

Determination of Crude Protein

The protein content of the barley flour samples was determined by the Kjeldahl method (AOAC, 2000). 1g of barley sample was used for this process, the experiment was passed three steps, such as digestion, Distillation, and titration was involved. All nitrogen is converted to ammonia by digestion with a mixture of concentrated sulfuric acid and Kjeldahl tablet containing copper sulfate and potassium sulfate as a catalyst by 420°C temperature. The ammonia released after alkalization with sodium hydroxide is steam distilled into boric acid and titrated with 0.1N hydrochloric acid. Then the result is calculated based on the conversion factor from Nitrogen to protein.

Protein content (% N × 5.83) was determined by the Kjeldahl method described by (AOAC, 2000).

$$\% \, total \, Protein = (\% \, N \, x \, 5.83)$$

Where, % N = Percentage of Nitrogen,

5.83 = barley conversion factor

Determination of Crude Fat Content

The crude fat content of barley flour samples was determined according to AOAC (2000) by Soxtec using Petroleum ether (b. pt 40-60°C) solvent. About 3.00 g of barley flour sample was added into the extraction thimbles and covered with fat-free cotton. The thimbles with the sample content were placed into soxtec extraction chamber and then switched on the heater. The cooling water was switched on, and 25 ml of Petroleum ether was added to the extraction can and attached to the corresponding thimbles in soxtec extraction chamber. Overall extraction processes were conducted for about 1hr including solvent recovery and evaporate. Then the extraction can with their content were removed from the extraction chamber and placed in the drying oven at 100°C for about 30 min, cooled to room temperature in the desiccator for about 30 min and weighed. The amount of fat was quantified gravimetrically and calculated from the difference in weight of the extraction can before and after extraction as a percentage.

Calculate the fat content as follows: $Crude\ fat = \frac{((weight\ of\ can + fat) - (weight\ of\ can))*100}{weight\ of\ sample}$

Determination of Total Ash Content

The total ash content of barley flour samples was determined by the dry ash method in a muffle furnace according to AOAC (2000). The crucible was placed in the muffle furnace (Carbolite CSF 1200) at 550°C overnight to ensure that impurities on the surface of the crucible are burned off and the crucible cooled in the desiccator for 30 min. Then the crucible was weighed. About 3.0 g of barley flour of each sample in duplicate was added into each crucible, then put into the muffle furnace and heated at 550°C overnight.

Finally, taken out of the crucible from the Muffle Furnace and immediately place in a desiccator till cooled to room temperature, and each crucible with ash was weighed. The weight of total ash was calculated by difference and expressed as a percentage of samples.

Calculate the percentage ash content (wet weight basis) as follows:

$$\%\ \text{ash (wet)} = \frac{((weight\ of\ crucible +\ ash) - (weight\ of\ crucible)) * 100}{weight\ of\ sample}$$

Calculation of ash content on a dry basis (when the moisture content is known) is as follows:

$$\% \; ASH\;(dry) = \frac{\% \; ash\;(wet) * 100}{(100 - \%\, moisture)}$$

Total Carbohydrate Content

Total Carbohydrate content was obtained by subtracting the sum of the combined percent of moisture, protein, ash, and fat from 100 described by (AOAC, 2000). The result was calculated as follows;

Total Carbohydrate content = 100 – {moisture (g %) + crude protein (g %) + total fat (g %) + total ash (g %)}

Where (g %) = grams per 100 grams.

Statistical analysis

Experiments were conducted at the Ethiopian Biodiversity Institute laboratory, with each analyzed in duplicate (n=2). Summary statistics, tables, and line graphs were utilized to present the research data effectively. A two-sample t-test was employed to evaluate the mean differences in nutritional value of Ethiopian barley across various agro-ecological zones, with a significance level set at 5%.

The independent samples t-test was used to compare the means of two independent groups, assessing statistical evidence for significant differences between the population means, assuming equal variance. This assumption was tested using Levene's Test for homogeneity of variances at a 10% significance level. If this assumption was not met, and sample sizes differed across agro-ecological zones, the reliability of the p-value could be compromised. The output of the independent samples t-test also provides an approximate t-statistic that does not rely on the assumption of equal population variances.

RESULTS

Agro-ecological Zones

The study was conducted, on the barley accessions that preserved in the Ethiopian gene bank, were collected from altitudes ranging from 1,910 to 3,490 masl. In total, 33 accessions (15 midland, 18 highland) were gathered between June 6 and June 25, 1980 (E.C). Collections included samples from Debub Wello (8 accessions from Dessie Zuria, 8 accessions from Were-Ilu) and North Shewa (15 accessions from Gerar Jarso, 1 accession from Yaya Gulele and 1 accession from Sululta) different part of Ethiopia, as illustrated in Figure 1.

Figure 1. Agro- ecological Zone of Barley Accession Conserved in Gene Bank of Ethiopia

The Nutritional Analysis of Barley

The nutritional analysis of barley accession that was conserved at Gene Bank of Ethiopia was conducted based on dry weight for all agro-ecological zone of Ethiopian in 2010 E.C. As indicated in the Table 1, the minimum percentage of crude protein (10.59%) was observed in the barley that sampled from highland area of Ethiopian whereas; maximum (13.25%) was obtained in midlands, highlighting the nutritional superiority of midland barley. On contrary, the highest (2.38%) percentage of crude fat was recorded from barley grown in the highland and minimum (1.61%) percentage of crude fat were obtained in the barley that collected from midland while; both maximum (3.04%) and minimum (2.11%) percentage of mineral ash was obtained at highland areas. On contrary, the maximum (80.26%) and minimum (73.55%) percentage of total carbohydrates content were obtained in the barley that collected from midland. And also, the highest (9.55%) and lowest (4.64%) percentage of moisture were measured from barley gotten in highland and midland areas respectively. These nutritional variations underline the importance of agro-ecological zones in influencing the quality of barley, which has implications for agricultural practices and nutritional profiling of barley cultivars in Ethiopia.

Table 1. Experimental Results of Nutritional Analysis of Barely Based on Dry Weight

S/N	Accession No.	Crude Protein (%)	Crude Fat (%)	Mineral ash (%)	Moisture (%)	Total Carbohydrate (%)	Altitude	Agro-ecological Zone
1	4918	10.86	1.84	2.40	4.64	80.26	2250	Midland
2	4919	10.77	2.09	2.49	4.74	79.91	2250	Midland
3	4923	12.17	1.70	2.69	6.30	77.14	2250	Midland
4	4926	11.95	1.73	2.53	6.65	77.14	2200	Midland
5	4927	11.77	1.63	3.04	8.03	75.53	2540	Highland
6	4930	11.09	1.80	2.35	6.23	78.53	1910	Midland
7	4934	11.50	1.89	2.43	7.41	76.77	2300	Midland
8	4935	11.91	2.05	2.44	9.44	74.16	3050	Highland
9	4938	11.00	1.86	2.72	9.54	74.88	3160	Highland

10	4939	11.97	1.86	2.58	9.08	74.51	3350	Highland
11	4943	11.11	1.79	2.66	9.55	74.89	3490	Highland
12	4945	10.77	1.86	2.34	9.40	75.63	3450	Highland
13	4946	11.01	2.00	2.24	9.54	75.21	3330	Highland
14	4947	11.11	2.04	2.23	9.41	75.21	3420	Highland
15	4949	11.13	1.86	2.34	9.45	75.22	3300	Highland
16	4952	11.14	1.86	2.41	9.43	75.16	1910	Midland
17	4954	11.36	1.88	2.36	9.24	75.16	2200	Midland
18	4955	12.09	1.87	2.24	9.42	74.38	2250	Midland
19	4958	12.34	1.90	2.31	9.38	74.07	2250	Midland
20	4961	12.18	2.26	2.11	9.37	74.08	2970	Highland
21	4962	11.81	2.14	2.12	9.31	74.62	3120	Highland
22	4963	11.04	1.85	2.35	9.23	75.53	3100	Highland
23	4965	11.14	1.81	2.51	9.44	75.10	3040	Highland
24	4966	11.12	1.83	2.41	9.51	75.13	3040	Highland
25	4969	10.59	1.94	2.36	9.42	75.69	2500	Highland
26	4971	11.42	1.78	2.30	9.33	75.17	3100	Highland
27	4973	11.12	2.38	2.34	9.30	74.86	3100	Highland
28	4975	12.49	2.04	2.23	8.47	74.77	3050	Highland
29	4976	12.68	1.81	2.36	8.28	74.87	2100	Midland
30	4978	12.73	2.18	2.34	7.63	75.12	2100	Midland
31	4979	13.25	1.82	2.79	7.21	74.93	2300	Midland
32	4984	13.05	1.85	2.18	9.37	73.55	2250	Midland
33	4995	12.35	1.61	2.34	9.30	74.40	2250	Midland

Variation in Nutritional Value of Barley across Agro-ecological Zone of Ethiopia

The percentage of crude protein content of Ethiopian barley conserved at Gene Bank of Ethiopia was varied across different agro-ecological locations. As it can be depicted in Figure 2, the percentage of crude protein for barley cultivated in the midland was higher but also only in a few accession it got less as compared to highland areas. In contrast, the highest percentages of crude fat were predominantly observed in barley grown in the highland areas, as shown in Figure 3. This trend indicates that highland environments contribute positively to the fat content of barley, highlighting potential regional advantages for producing barley with enhanced lipid profile.

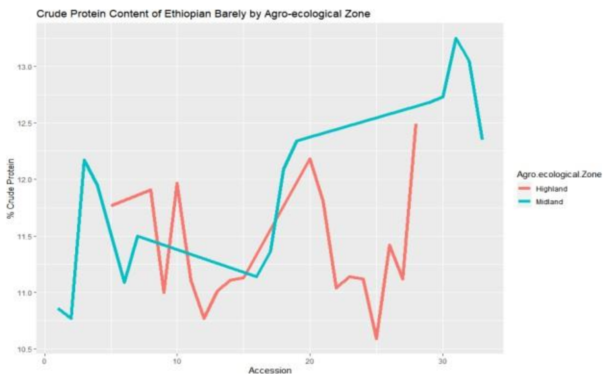

Figure 2. Crude Protein Content

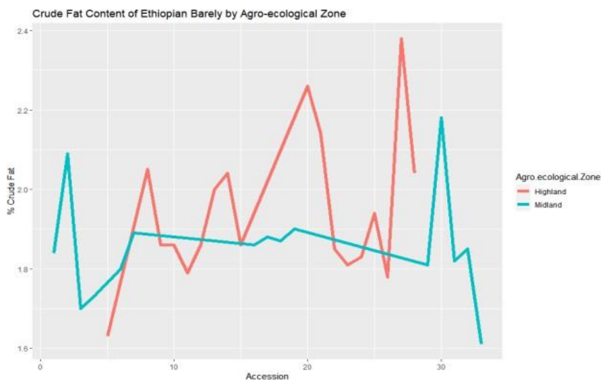

Figure 3. Crude Fat Content

The percentage content of mineral ash of barley for both highland and midland areas showed some sort of fluctuations across agro-ecological zone of Ethiopia (see Figure 4.) where; the highest moisture content was consistently observed in barleys from all highland agro-ecological zones, as shown in Figure 5. This trend suggests that highland environments may contribute favorable conditions for moisture retention in barley.

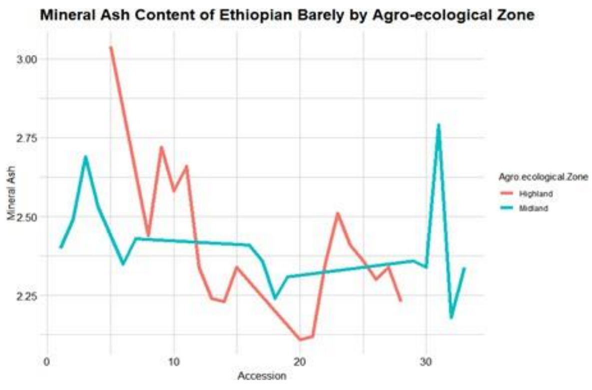

Figure 4. Mineral Ash Content

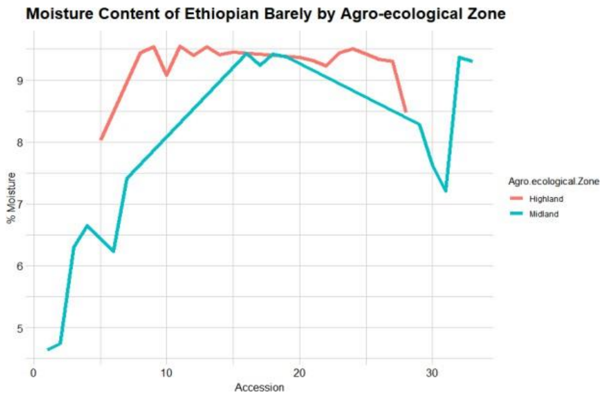

Figure 5. Moisture Content

The majority of the highest percentages of total carbohydrates were found in barley sourced from midland agro-ecologies. However, certain accessions from highland regions also exhibited elevated carbohydrate levels, as depicted in Figure 6. This finding highlights the potential for highland barley to possess competitive carbohydrate content, despite midland barley generally being superior in this regard.

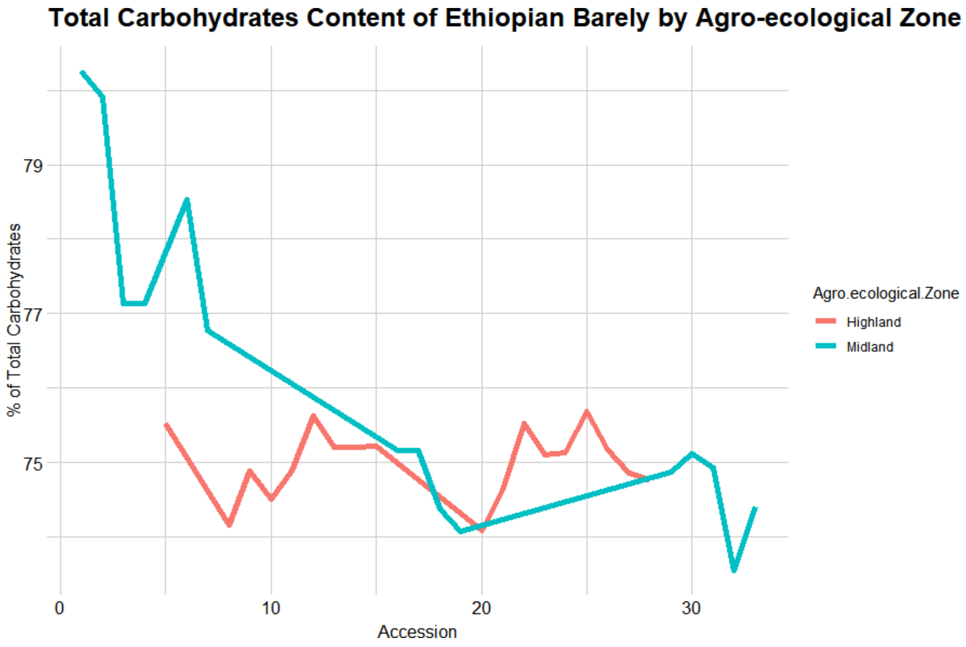

Figure 6. The Percentage of total carbohydrates Content of Barley

The Mean Difference of Nutritional Content of Barley across Agro-ecological Zone

To achieve the objectives of the current study, two independent t-tests were conducted under the assumption of homogeneity of variances, which posits that the variances of the percentage content for each nutritional component of barley are equal across agro-ecological zones.

Levene's Test for equality of variances was performed at a 10% significance level for all nutritional values, as detailed in Table 2. The test revealed significant homogeneity of variances for crude protein, moisture, and total carbohydrates, indicating comparable variance in these nutritional components of Ethiopian barley between midland and highland agro-ecological zones. Consequently, independent samples t-tests were conducted to assess the mean differences in these nutritional values of barley between the midland and highland regions. This analysis provides insights into the nutritional disparities that may exist due to environmental factors inherent to each region.

Table 2. Levene's Test for Homogeneity of Variances

Nutritional Components	Df	F-value
Crude Protein	1	3.32*
Crude Fat	1	0.98
Mineral Ash	1	0.8
Moisture	1	29.10*
Total Carbohydrates	1	9.37*
Total	31	

(*Significant at 10 % level)

Based on two independent samples t-test shown in the Table 3, a significant mean difference in the percentage content of crude protein, moisture and total carbohydrates was found between highland and midland agro-ecological locations of Ethiopian barley that conserved in the gene bank. As a result, the highest (11.96%) average percentage of crude protein was found in the barley that was taken from midland agro-ecology. Similarly, the highest (76.1%) mean percentage of total carbohydrates was obtained from barley gotten in the midland areas. In contrasts, the minimum (7.68%) average percentage of moisture was measured in the barley collected from midland agro-ecological zone.

Table 3. Independent t-test for Nutritional Contents of Barley across Agro-ecological Zone of Ethiopia

Nutritional Components	Agro-ecological Zone	Mean	SD	Df	T
Crude Protein	Highland	11.37	0.52	31	-2.52*
	Midland	11.96	0.80		
Crude Fat	Highland	1.94	0.18	31	1.52
	Midland	1.86	0.14		
Mineral Ash	Highland	2.41	0.23	31	-0.11
	Midland	2.41	0.16		
Moisture	Highland	9.27	0.40	31	3.84*

	Midland	7.68	1.70		
Total Carbohydrates	Highland	75	0.46	31	-2.12*
	Midland	**76.1**	2.11		

(*Significant at 5 % level)

DISCISSIONS

Barley is a crucial staple food crop and a cool-weather species predominantly grown in the highlands of Ethiopia, with an optimal altitude range of 2,000 to 3,500 meters above sea level. Understanding the impact of agro-ecological zones is vital for assessing the nutritional content of crops, as these values are heavily influenced by environmental factors (Dereje and Eshetu, 2011).

The highest crude protein percentage (11.96% ±0.80) was observed in barley from midland agro-ecologies, while the lower protein content (11.37% ±0.52) was recorded in highland areas. These findings align with previously reported values ranging from 7.50% to 12.12% (Jood and Kalra, 2001). Furthermore, it has been established that the protein content in barley is significantly influenced by the cultivar (Qi et al., 2006) and can vary based on growth conditions, particularly the rate and timing of nitrogen fertilization (Arendt and Zannini, 2013). This indicates that while midland barley tends to possess superior crude protein levels, there are exceptions that suggest adaptability and environmental influences on nutritional traits.

A statistically significant difference was also observed in the average crude fat content of barley. The highest crude fat percentage (1.94% ±0.18) was found in highland barley, while midland samples showed a slightly lower average (1.86% ±0.14). These results are consistent with the chemical composition reported by Makeri et al., (2013). This trend indicates that highland environments contribute positively to the fat content of barley, highlighting potential regional advantages for producing barley with enhanced lipid profile.

Additionally, the mineral ash content remained relatively uniform across all agro-ecological zones, although significant variations were noted in the moisture content of barley from different regions. Moisture percentages were recorded at 9.27% ±0.40 for highland barley and 7.68% ±1.70 for midland barley. Notably, moisture content increased with altitude, suggesting that it is influenced by both elevation and the hygroscopic capacity of the seed (Qi et al., 2006). This trend suggests that highland environments may contribute favorable conditions for moisture retention in barley.

The average difference in total carbohydrate content was found to be statistically significant as well. Midland barley exhibited the highest percentage of total carbohydrates (76.1%
±2.11), while highland barley showed a value of 75% ±0.46. This trend indicates that as altitude decreases, the percentage of total carbohydrates tends to increase, likely due to the reduction in certain nutritional values in the samples. Barley consistently demonstrates higher total carbohydrate levels compared to most other crops, as supported by various studies in the literature (Gashaw, 2021).

CONCLUSIONS AND RECOMMENDATIONS

This study established significant differences in the nutritional value of barley across Ethiopia's agro-ecological zones. As altitude increases, crude protein and total carbohydrates tend to decrease, while moisture content and crude fat increase. These variations can be attributed to factors such as temperature, soil composition, and annual rainfall, which differ across agro-ecological zones.

Recommendations:

- Focus on midland barley in agricultural practices for enhanced food security and dietary quality due to its higher nutritional values.

- Conduct further studies to investigate the mechanisms behind nutritional variations across agro-ecological zones and assess environmental impacts on barley quality.
- Policymakers should consider agro-ecological factors affecting barley production and nutrition when developing agricultural policies and food security initiatives.

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ECONOMIC VALUATION OF ECOSYSTEM SERVICES AND COMMUNITY SUPPORT FOR CONSERVATION IN THE YAYO COFFEE FOREST BIOSPHERE RESERVE, SOUTHWESTERN ETHIOPIA

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ABSTRACT: The Yayo Coffee Biosphere Reserve (YCBR) in southwestern Ethiopia, a UNESCO-recognized site, harbors globally significant wild Arabica coffee genetic resources, biodiversity, and vital ecosystem services. Despite its economic and ecological importance, the reserve faces pressures from deforestation, agricultural expansion, and limited conservation funding. This study quantified the economic value of YCBR's ecosystem services and assessed community willingness to pay (WTP) and willingness to work (WTW) for its conservation. A cross-sectional survey of 300 respondents across four kebeles employed the Contingent Valuation Method to elicit monetary and labor contributions. Provisioning services, notably freshwater (87%), medicinal plants (74%), and food resources (63%), were most recognized, alongside substantial awareness of regulating, cultural, and supporting services. The mean annual WTP was ETB 435 (USD 3.82), while 62% expressed WTW, with tree planting as the preferred volunteer activity. Logistic regression identified income, education, gender, awareness, and association membership as significant predictors of WTP, while WTW was more likely among men, residents closer to the reserve, and those with lower formal education. Policy recommendations emphasized stricter protection laws (72%), greater community involvement (65%), and ecotourism development (59%). Findings highlighted the potential for hybrid conservation strategies integrating modest financial contributions with structured, role-differentiated volunteer programs. Coupling community engagement with legal enforcement, participatory governance, and sustainable livelihood initiatives, particularly coffee-linked ecotourism can enhance both ecological integrity and local well-being. This integrated approach offers a practical pathway to securing the long-term conservation of YBR while fostering community ownership and socio-economic resilience.

Keywords/phrases: Contingent Valuation Method, Payment for Ecosystem Services, Rural livelihoods, Wild Arabica coffee

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INTRODUCTION

The Yayo Coffee Forest Biosphere Reserve (YBR), located in the Illubabor Zone of southwestern Ethiopia, is one of six UNESCO designated biosphere reserves in the country (UNESCO, 2017). Covering approximately 167,000 hectares, the reserve is globally recognized as a primary center of origin and genetic reservoir of wild Coffea arabica L., a species that supports the livelihoods of millions of people around the world and contributes significantly to Ethiopia's national economy through export earnings and employment (Aerts et al., 2016; Davis et al., 2019). Beyond its importance to the global coffee industry, YBR is home to a rich diversity of plant and animal species, making it a critical hotspot for biodiversity conservation at both regional and international levels (Senbeta et al., 2022). At the same time, the reserve plays a vital role in sustaining local livelihoods, particularly in rural communities where dependence on forest resources is high, creating a strong connection between ecological health and human wellbeing (Duguma et al., 2024).

The ecosystem services provided by YBR can be clearly understood through the four categories identified in the Millennium Ecosystem Assessment (MEA) (2005). Provisioning services such as freshwater, wild foods, timber, and medicinal plants directly support household subsistence and income generation. Regulating services, including carbon sequestration, climate regulation, erosion control, and water purification, help maintain environmental stability at both local and global scales (Fenta et al., 2023). Cultural services are reflected in ecotourism opportunities, spiritual values, and traditional practices such as Ethiopia's coffee ceremony, which highlight the deep cultural connections between communities and the forest landscape. Supporting services, including soil formation, pollination, and biodiversity maintenance, form the ecological foundation that sustains agricultural productivity and ensures long term ecosystem resilience. For communities that depend on coffee and other forest resources, these services are not only ecological in nature but also represent essential economic safety nets and opportunities for improving livelihoods.

Despite their wide-ranging benefits, many ecosystem services remain largely invisible in conventional economic systems because they are not traded in formal markets. As a result, they are often undervalued or overlooked in policy and decision-making processes. Economic valuation helps to address this challenge by assigning measurable value, whether monetary or non-monetary, to ecosystem services, making their contributions more visible and easier to compare with alternative land use options (Costanza et al., 1997; TEEB, 2010; Pascual et al., 2022). In this regard, the Contingent Valuation Method has become a widely used approach for estimating the value of non-market environmental goods. By presenting individuals with carefully designed hypothetical scenarios, this method allows researchers to capture how much people are willing to contribute toward the conservation or improvement of ecosystem services.

Within this framework, two closely related concepts are particularly important, Willingness to Pay and Willingness to Work. Willingness to Pay refers to the maximum amount of money individuals are willing to contribute for the conservation or improvement of ecosystem services, reflecting how they perceive and value these benefits in economic terms. However, in rural settings such as YBR, where household incomes are often limited, financial contributions alone may not fully reflect the extent of community support. This makes Willingness to Work, which represents the time and labor individuals are willing to contribute voluntarily, equally important. Volunteer labor can play a significant role in conservation through activities such as tree planting, forest monitoring, and soil conservation. In many cases, it provides a practical and culturally appropriate way for communities to participate in conservation efforts, especially when financial resources are constrained.

Considering both Willingness to Pay and Willingness to Work together offers a more complete picture of community support and opens up opportunities for designing hybrid conservation strategies that combine financial contributions with organized volunteer efforts. Such approaches are increasingly recognized as effective in resource constrained settings, where relying solely on external funding is often not sufficient to sustain conservation in the long term. By incorporating both monetary and labor-based contributions, policymakers can design conservation models that are more inclusive, flexible, and better aligned with local socio-economic conditions.

However, despite its ecological and economic importance, YBR is currently facing growing pressures that threaten its long-term sustainability. Rapid deforestation, agricultural expansion particularly the encroachment of coffee cultivation into core conservation zones, and population growth are contributing to habitat fragmentation and the degradation of ecosystem services (Tolessa et al., 2017; Duguma et al., 2024; Fenta et al., 2023). Although the reserve benefits from UNESCO recognition, the enforcement of conservation regulations remains weak, and financial resources for management are often limited and unreliable (Mekonnen et al., 2022; Abate et al., 2021). These challenges underline the urgent need for more sustainable financing mechanisms and stronger community engagement in conservation efforts.

In Ethiopia's rural context, successful conservation is closely linked to active community participation. Local households rely heavily on provisioning services such as water, forest foods, and medicinal plants, yet formal conservation budgets are not sufficient to ensure their protection over time (Bekele et al., 2020; Tadesse and Woldemariam, 2023). As a result, community contributions, both financial and labor based, become essential for bridging the gap between policy objectives and practical implementation (Gebreselassie et al., 2020; Alemayehu et al., 2022). While previous studies conducted in YBR and similar landscapes have examined land use change, biodiversity conservation, and general ecosystem service values for example Tolessa et al. (2017) and Senbeta et al. (2022), they have largely focused on biophysical assessments or general perceptions. There is still limited empirical evidence that quantifies the economic value of ecosystem services from the perspective of local communities while also examining both Willingness to Pay and Willingness to Work as complementary forms of conservation support.

This study seeks to address this important gap by applying the Contingent Valuation Method to estimate the economic value of ecosystem services in YBR, while at the same time assessing community willingness to contribute through both financial payments and voluntary labor. By integrating Willingness to Pay and Willingness to Work, the study provides a more comprehensive understanding of how communities value and support conservation. It also highlights the potential for developing hybrid financing mechanisms that reflect the socio-economic realities of the area.

Ultimately, the findings of this study are intended to inform the design of equitable and context specific conservation strategies that balance ecological sustainability with local livelihood needs. By explicitly linking ecosystem service valuation with Willingness to Pay and Willingness to Work, the study contributes to a deeper understanding of how community-based conservation can be effectively implemented in biosphere reserves such as YBR, where both ecological significance and economic constraints are strongly interconnected.

METHODOLOGY

Study Area

The Yayo Biosphere Reserve (YBR) is located in the Illubabor Zone of Oromia Regional State, southwestern Ethiopia, about 500 km from Addis Ababa. Geographically, it lies between about 8°10′ to 8°30′ N latitude and 35°30′ to 36°00′ E longitude. It covers approximately 167,000 hectares and is recognized by UNESCO-MAB program for its global ecological significance as a center of origin and genetic diversity for wild Arabica coffee (*Coffea arabica* L.). The reserve features a landscape mosaic of montane forests, semi-forest coffee systems, and agricultural lands, structured into core, buffer, and transition zones. Ecologically, it harbors high levels of biodiversity, including endemic plant and animal species, while socio-economically, it sustains rural communities that depend heavily on both forest products and agricultural livelihoods.

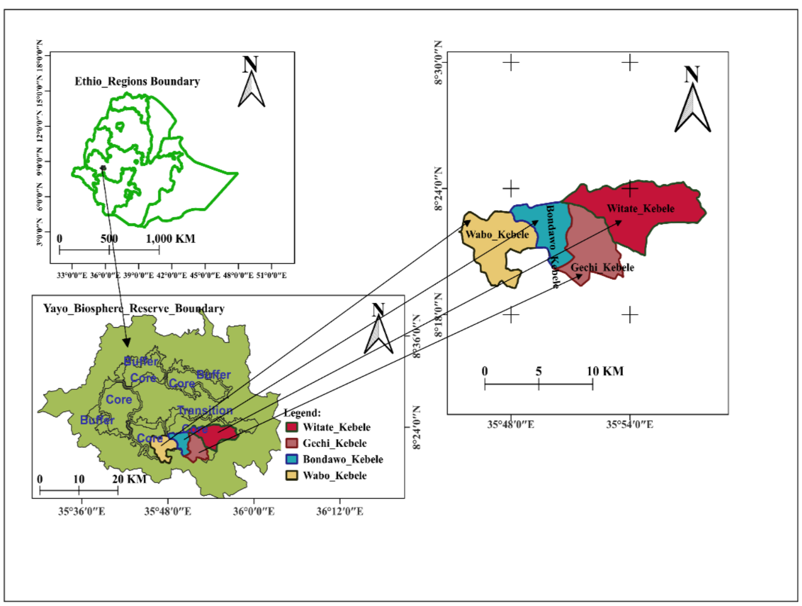

Figure 1. Map of Yayo Biosphere Reserve, Oromia, Southwestern Ethiopia

Research Design and Sampling Strategy

This study employed a cross-sectional survey design, which collects data at a single point in time to capture prevailing socio-economic conditions, community perceptions, and conservation attitudes. This design is suitable for valuation studies because it allows comparisons across groups while minimizing time and resource constraints.

The four kebeles Gechi, Wutete, Wabo, and Bondawo were purposively selected to represent variation in proximity to the Yayo Biosphere Reserve's core and buffer zones, dependence on forest ecosystem services, and exposure to conservation interventions. This purposive selection ensured that both communities living closer to the forest and those farther away were included, thereby capturing diverse perspectives.

Within each kebele, a stratified random sampling approach was employed to ensure proportional representation of key stakeholder categories. Strata were defined by livelihood type (e.g., farmers, small business owners, wage workers) and community roles (e.g., households, local leaders, government officials). From each stratum, respondents were randomly selected to minimize bias. A total of 75 respondents per kebele were included, giving a final sample of 300 respondents.

The sample size was determined using Cochran's (1977) formula for proportion estimates, with a 95% confidence level and a 5% margin of error. An initial sample size of 384 was obtained, which was then adjusted for the finite population of the study kebeles using the finite population correction (FPC), resulting in a final target of 300 respondents. This balance between statistical rigor and practical feasibility ensured that the sample was both representative and analytically robust.

Data Collection

Primary data were collected using a structured questionnaire administered through face-to-face interviews in the local language. This approach aimed to reduce literacy-related bias and ensure clear responses. The questionnaire included both socio-economic information and views on conservation, organized into six sections. The first section focused on the demographic and socio-economic details of respondents, including age, gender, education, and main sources of income. The second section evaluated awareness of the Yayo Biosphere Reserve (YBR). This assessment included familiarity with the reserve, its perceived importance, and knowledge of management rules. The third section looked at the economic benefits that households gain from the reserve, covering both market and non-market values. In the fourth section, respondents identified and evaluated ecosystem services based on the Millennium Ecosystem Assessment framework, which included provisioning, regulating, cultural, and supporting services. The fifth section measured Willingness to Pay (WTP) and Willingness to Work (WTW) for conservation through the Contingent Valuation Method (CVM). Participants were presented with a hypothetical conservation fund and volunteer program and asked to declare the maximum financial contribution or number of workdays they would be willing to commit each year. Finally, the sixth section asked respondents to suggest policy recommendations that could improve conservation outcomes in the YCBR.

Data Analysis

Survey data were coded and analyzed using Stata version 15, combining descriptive and inferential approaches. Descriptive statistics, including frequencies, percentages, means, and standard deviations, were used to summarize respondents' demographic and socio-economic characteristics, awareness of YBR, perceived benefits, and recognition of ecosystem services.

Qualitative responses on policy recommendations were analyzed thematically to capture recurring patterns, priorities, and suggestions for improving conservation governance.

To estimate the economic value of ecosystem services, the Contingent Valuation Method was applied using the open ended responses obtained from respondents. The mean Willingness to Pay was calculated as the average of the stated monetary contributions among respondents willing to pay. Aggregate Willingness to Pay was then estimated by multiplying the mean Willingness to Pay by the total number of households in the study area, providing an estimate of the overall monetary value of ecosystem services.

Similarly, Willingness to Work was analyzed by calculating the average number of labor days respondents were willing to contribute annually. This was further aggregated across households to estimate the total labor contribution, which represents a non-monetary value of ecosystem services and an important form of conservation support in resource constrained settings.

To examine the determinants of community support, binary logit regression models were employed for Willingness to Pay and Willingness to Work, coded as 1 for willing and 0 for not willing. Independent variables included demographic characteristics such as age, gender, education, and household size, socio economic factors such as income and livelihood type, and perception related variables including awareness of YBR, recognition of ecosystem services, and membership in local associations.

Model robustness was assessed using multicollinearity diagnostics through Variance Inflation Factor values, as well as goodness of fit measures including the Hosmer Lemeshow test, Pseudo R square, and chi square statistics. In addition, t tests and analysis of variance were used to compare group differences. This comprehensive approach ensured both statistical rigor and meaningful interpretation of the results.

Model Specification

The study employed a binary logit regression model to identify the socio-economic and perceptual factors influencing community support for conservation. The dependent variables were Willingness to Pay (WTP) and Willingness to Work (WTW), coded as 1 = willing and 0 = not willing. Independent variables included demographic factors (age, gender, household size, education), socio-economic factors (income, livelihood type), and perception-related variables (awareness of YBR, recognition of ecosystem services, membership in local associations). The model estimates the probability PiP_iPithat respondent iii is willing to contribute as:

$$\text{Logit}(P_i) = \ln\left(P_i / (1 - P_i)\right) = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki} + \varepsilon_i \text{----1}$$

Where $\beta_0$is the intercept, $\beta_1 ... \beta_k$ are coefficients for the explanatory variables $X_{1i} ... X_{ki}$, and ϵ_i is the error term.

RESULTS AND DISCUSSIONS

Demographic Characteristics of Respondents

Table 1 summarizes the demographic characteristics of the 300 respondents surveyed across four kebeles. The gender distribution was nearly balanced, with 54% male and 46% female participants. The age range indicated that most respondents (69%) were between 18 and 45 years old, which represents the working-age population relevant for volunteer-based conservation efforts. In terms of educational attainment, the largest share of respondents had completed secondary education (39%), which was higher than those who completed primary education (28%). A smaller proportion of respondents held a bachelor’s degree (18%), while 15% reported having no formal education. Overall, respondents with at least primary or secondary education constituted the majority of the sample, indicating a relatively moderate level of literacy in the study area. This variation in educational attainment provides an important basis for analyzing differences in awareness of ecosystem services, as well as willingness to pay and willingness to participate in

Table 1. Demographic profile of survey respondents (N = 300)

Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	162	54.0
	Female	138	46.0
Age group	Below 18 years	18	6.0
	18–30 years	108	36.0
	31–45 years	99	33.0
	46–60 years	60	20.0
	Above 60 years	15	5.0
Education level	No formal education	45	15.0
	Primary	84	28.0
	Secondary	117	39.0
	Bachelor’s degree	54	18.0

Source: Survey data, 2025

Awareness and Perceptions of the Yayo Biosphere Reserve

Table 2 summarizes the respondents’ awareness and perceptions of the Yayo Biosphere Reserve (YBR). Respondents demonstrated high levels of familiarity with YBR, with 68% reporting being “very familiar” and 22% “somewhat familiar,” while only 10% were not familiar. The primary perceived benefits included biodiversity conservation (85%), water source protection

(78%), and tourism/recreation potential (65%). Major threats identified were deforestation (72%), agricultural expansion (65%), and lack of funding (52%). These findings indicated strong community awareness of both the ecological value of the reserve and the challenges it faces, providing a solid foundation for conservation engagement strategies.

Table 2. Awareness levels and perceptions of benefits and threats related to YBR (N = 300)

Variable	Category	Frequency (n)	Percentage (%)
Familiarity with YBR	Very familiar	204	68
	Somewhat familiar	66	22
	Not familiar	30	10
Top perceived benefits	Biodiversity conservation	255	85
	Water source protection	234	78
	Tourism and recreation	195	65
Perceived threats	Deforestation	216	72
	Agricultural expansion	195	65
	Lack of funding	156	52

Source: Survey data, 2025

Recognition of Ecosystem Services

Recognition of ecosystem services means acknowledging the tangible benefits humans receive from nature, such as supporting, cultural, regulating and provisioning or clean air, water filtration, pollination, and climate regulation, and incorporating this value into policy and economic decisions(Fig.2).

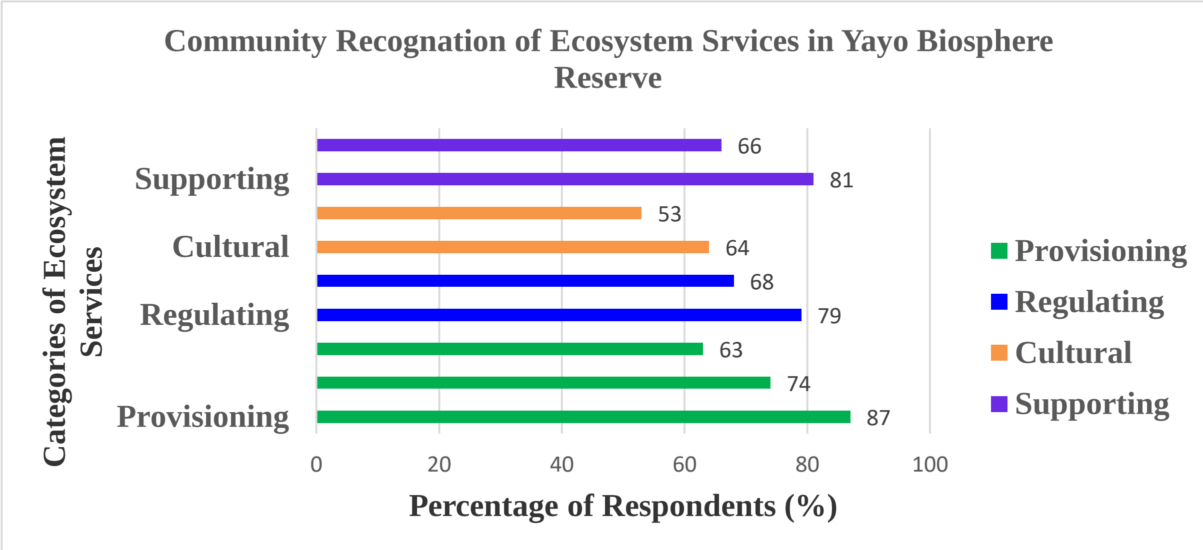

Figure 2. Community Recognition of Ecosystem Services in Yayo Coffee Biosphere Reserve
Source: Survey data, 2025

Table 3 presents respondents' recognition of ecosystem services provided by the Yayo Biosphere Reserve (YBR). Across all categories, provisioning services were the most widely recognized, with freshwater supply at 87% ranked highest overall. This makes sense since local households depend on rivers and springs in the YBR for domestic and agricultural use. Medicinal plants were acknowledged by 74% of respondents, reflecting ongoing reliance on traditional medicine in rural areas. Food resources, including wild fruits, honey, and occasional bushmeat, were recognized by 63%, further showing the reserve's contribution to food security.

In the regulating services category, 79% of respondents identified climate regulation, suggested a growing awareness of the forest's role in moderating local temperatures and rainfall patterns. Air and water purification, recognized by 68%, indicates that communities understand the connection between forest cover and environmental quality.

Cultural services received moderate recognition. Tourism and recreation were noted by 64%, ranking higher than cultural heritage at 53%. This may reflect the limited development of structured ecotourism programs, alongside a continued appreciation for local traditions, sacred sites, and cultural practices tied to the landscape.

Among supporting services, biodiversity and habitat provision scored very high at 81%, showed that communities value the YBR's role in maintaining wildlife and plant diversity. Pollination services, recognized by 66%, were especially notable in a coffee-growing region where both wild and managed pollinators are essential for production.

Overall, the results showed that while provisioning services dominate local recognition due to their direct benefits for livelihoods, there is significant awareness of regulating and supporting services. This understanding could help promote a more complete view of conservation benefits.

Table 3. Recognition of key ecosystem services in Yayo Coffee Forest Biosphere Reserve (N = 300)

Category	Ecosystem Service	Percentage (%)	Frequency (n)
Provisioning	Freshwater supply	87	261
	Medicinal plants	74	222
	Food resources (e.g., wild fruits, bush meat, honey)	63	189
Regulating	Climate regulation	79	237
	Air and water purification	68	204
Cultural	Tourism and recreation	64	192
	Cultural heritage (sacred sites, traditional practices)	53	159
Supporting	Biodiversity/habitat provision	81	243

Pollination (wild & agricultural crops)	66	198

Source: Survey data, 2025

Willingness to Pay (WTP) and Willingness to Work (WTW)

Table 4 summarizes respondents' willingness to pay (WTP) and willingness to work (WTW) for conservation of the Yayo Biosphere Reserve (YBR). The mean annual WTP was ETB 435 (USD 3.82), with a median of ETB 400, and 58% of respondents expressed willingness to contribute financially. When interpreted relative to the average monthly income (ETB 3,200), the mean WTP represents approximately 1.1% of annual household income, indicating a meaningful contribution within a low-income rural context. Although modest in absolute terms, this reflects a positive economic valuation of ecosystem services. In terms of non-monetary contributions, 62% of respondents were willing to participate in conservation activities through labor. The most preferred activities included tree planting (42%) and trail maintenance (32%), followed by awareness campaigns (29%). These findings highlight that labor contributions constitute an important component of ecosystem service valuation, rather than only complementing financial contributions. When aggregated across households, both WTP and WTW suggest the potential for a hybrid conservation financing mechanism, combining small financial contributions with structured volunteer programs.

Table 4. Willingness to Pay and Willingness to Work for YBR conservation (N = 300)

Variable	Category / Statistic	Value
WTP (annual)	Mean (ETB)	435
	Mean (USD*)	3.82
	Median (ETB)	400

WTW participation	Willing to volunteer	186 respondents (62%)
	Not willing to volunteer	114 respondents (38%)
Top volunteer activities	Tree planting	126 respondents (42%)
	Trail maintenance	96 respondents (32%)
	Awareness campaigns	87 respondents (29%)

Source: Survey data**,** 2025, *USD values calculated using the average exchange rate during the survey period.

Policy Recommendations from Respondents

Table 5 presents community-identified strategies to strengthen conservation of the YBR. Respondents emphasized stronger legal protection (72%), increased community participation in decision-making (65%), and the development of ecotourism (59%). These preferences are consistent with the valuation results, where both WTP and WTW indicate strong community support for conservation. The emphasis on participatory governance reflects the importance of institutional trust, while ecotourism reflects recognition of ecosystem services as income-generating assets. Overall, the responses indicate a preference for integrated conservation approaches, rather than isolated interventions.

Table 5. Community-recommended policy actions for YBR conservation (N = 300)

Policy Recommendation	Frequency (n)	Percentage (%)
Stricter protection laws	216	72
Greater community involvement in decision-making	195	65
Development of ecotourism	177	59

Source: Survey data, 2025

Summary of Descriptive Statistics

Table 6 summarizes the key socio-economic and perception variables used in the analysis. On average, respondents were willing to pay ETB 435/year (~USD 3.82/year) for YBR conservation, with a median of ETB 400. A majority (58%) expressed willingness to pay (WTP), and 62% indicated willingness to work (WTW) through volunteer activities. Mean monthly income was ETB 3,200, and the average education level was 7.4 years of schooling. Slightly over half of respondents were male (54%), with an average age of 35.6 years and household size of 5.3 members. The average distance to YBR was 8.7 km, with most respondents (90%) aware of YBR's conservation importance and two-thirds (66%) belonging to a local association. High awareness levels (90%) and strong association membership (66%) indicate favorable conditions for community-based conservation financing and participation.

Table 6. Descriptive statistics of variables used in WTP and WTW analysis

Variable	Mean	Std. Dev.	Min	Max	% / Notes
WTP (ETB/year)	435	118.4	150	800	Median = 400
WTP (USD/year)	3.82	1.04	1.32	7.02	Based on avg. exchange rate
WTP Binary (1 = Yes)	0.58	0.49	0	1	58% willing to pay
WTW Binary (1 = Yes)	0.62	0.49	0	1	62% willing to volunteer
Income (ETB/month)	3,200	1,050	900	6,800	—
Education (years of	7.4	3.2	0	16	—
Gender (1 = Male)	0.54	0.5	0	1	—
Age (years)	35.6	11.2	18	65	—
Household size	5.3	1.9	2	10	—
Distance to YBR (km)	8.7	4.3	0.5	18	—

Awareness (1 = Aware)	0.9	0.3	0	1	—
Membership in local association	0.66	0.47	0	1	—

Source: Survey data, 2025

Econometric Data Analysis Results

This section presents the results of binary logit regression models used to identify factors influencing households' willingness to pay (WTP) and willingness to work (WTW) for conservation of YBR. The WTP model demonstrates moderate explanatory power (Pseudo R^2 = 0.267), which is acceptable for cross-sectional household data. Statistical significance is reported using standard thresholds ($p < 0.05$, $p < 0.01$, $p < 0.001$), ensuring robustness and reliability of the estimates.

Determinants of Households' Willingness to Pay (WTP)

Table 7 highlights that income significantly affects households' willingness to pay for the conservation of the Yayo Biosphere Reserve (YBR). Specifically, each additional 1,000 ETB in monthly income increases the chance of willingness to pay (WTP) by 54%. This means that households with more financial resources are more likely to contribute money to conservation efforts. This positive relationship is consistent with neoclassical economic theory, where environmental goods are considered normal goods, meaning demand increases as income rises. The positive link between income and WTP also aligns with findings from other conservation studies, which indicate that households with more disposable income can allocate resources to environmental projects (Abdeta, 2023; Tadesse et al., 2022). Financial capacity emerges as an important factor for voluntary conservation support. It shows the need for payment plans that consider local income levels.

Education also significantly influences WTP. The findings revealed that each additional year of schooling raises the odds of WTP by 20%. This supports the concept of human capital theory, where education enhances individuals' knowledge and preferences toward public goods such as environmental conservation. Education improves understanding of ecosystem services and the value of biodiversity, which can boost motivation to provide financial support for conservation (Chala et al., 2021; Abdeta, 2023). This highlights the importance of environmental education programs as tools to promote community involvement and encourage sustainable behaviors.

Gender differences were noticeable, with men being 41% more likely than women to pay for conservation. This gap may reflect traditional household roles in rural Ethiopia, where men usually control finances and make decisions, while women's roles may be limited by less access to income (Abdeta, 2023; Gebremedhin & Swinton, 2021). This finding highlights the need for inclusive conservation programs that actively engage women, possibly through specific awareness campaigns or micro-conservation projects that lower financial barriers.

Household size had a negative impact on WTP, with each additional member reducing the odds by 12%. Larger households might face tighter budgets, prioritizing immediate needs over voluntary contributions to conservation (Tadesse et al., 2022). This finding emphasizes the importance of considering household economic pressures when creating payment-for-ecosystem-services schemes to ensure fairness and practicality.

The distance to YBR negatively affected WTP, with each additional kilometer from the reserve decreasing the likelihood of contributing by 18%. This suggests that households closer to the reserve see more direct benefits from conservation, such as access to forest products, water, or eco-tourism opportunities. In contrast, those farther away may see fewer tangible benefits (Chala et al., 2021). Thus, targeting conservation programs based on location may improve participation rates and the effectiveness of community contributions.

Awareness and social networks significantly boost WTP. Households that know about YBR and its ecological importance are more than twice as likely to pay (odds ratio = 2.21), and being part of local associations raises WTP by 72%. This shows that environmental knowledge and community involvement strengthen commitment to conservation. Educational campaigns, participatory planning, and utilizing local associations can be effective strategies to increase financial support for conservation initiatives (Abdeta, 2023; Gebremedhin & Swinton, 2021).

Finally, age had a minimal effect on WTP, indicating that willingness to support conservation is fairly consistent across age groups. This suggests that outreach efforts can broadly target households without needing to focus on specific age demographics.

Table 7. Logit Regression Results – Willingness to Pay (WTP)

Variable	B	Std. Error	z-value	p-value	Odds Ratio
Income (1000 ETB)	0.432	0.112	3.86	0.000***	1.54
Education (years)	0.186	0.065	2.86	0.004**	1.20
Gender (Male=1)	0.341	0.170	2.01	0.044*	1.41
Age (years)	0.011	0.014	0.78	0.435	1.01
Household size	-0.125	0.058	-2.16	0.031*	0.88
Distance to YBR (km)	-0.198	0.045	-4.40	0.000***	0.82
Awareness (1 = Aware)	0.792	0.276	2.87	0.004**	2.21
Membership in association	0.543	0.211	2.57	0.010**	1.72
Constant	-1.987	0.652	-3.05	0.002**	—

Model Fit: Log-likelihood = -162.4, Pseudo R^2 = 0.267, N = 300,Significance codes: ***p<0.001, **p<0.01, *p<0.05
Source: Authors' survey data analysis, 2025

Determinants of Households' Willingness to Work (WTW)

Table 8 presents the results of the logistic regression analysis for factors influencing willingness to work (WTW) for conservation in the Yayo Biosphere Reserve (YBR). The analysis of WTW shows that gender is the most important factor in determining whether someone is willing to volunteer for conservation activities in the Yayo Biosphere Reserve (YBR). The odds ratio for males is 1663.16, which is remarkably high. This indicates that men are much more likely to participate in manual labor than women. This trend reflects significant gender differences in labor roles in the study area, where men usually take on physically demanding tasks while women often focus on managing the household and caregiving responsibilities. Similar patterns have been seen in rural Ethiopia, where gender roles influence participation in community-based conservation programs (Gebremedhin & Swinton, 2021; Chala et al., 2021).

Education had a strong negative connection with WTW, with an odds ratio of 0.007. This suggests that higher education levels significantly lower the likelihood of volunteering for manual work. More educated individuals often prefer to contribute to conservation through financial support, organizational involvement, or advocacy rather than physical labor. Additionally, educated households may see higher opportunity costs in terms of time, leading them to emphasize income-generating activities over unpaid work (Abdeta, 2023). This indicates that education changes how people engage rather than their willingness to support conservation.

Distance from YBR had a minor negative effect on volunteering. Each additional kilometer slightly lowers the chance of participation. Households closer to the reserve likely see more direct benefits from its conservation, such as access to forest products, ecosystem services, or job opportunities. These benefits motivate their involvement (Tadesse et al., 2022). In contrast, households farther away may notice fewer tangible benefits, which reduces their incentive to engage in labor-intensive conservation efforts.

Awareness showed positive trends. Knowledge about the reserve and its ecological importance appears to encourage volunteering. Households that recognize the benefits of YBR are more likely to contribute their labor. This highlights the importance of environmental education and outreach programs in encouraging community participation (Chala et al., 2021).

Finally, income had little impact on WTW. This means that financial capacity does not greatly influence the decision to volunteer. Unlike willingness to pay (WTP), which is heavily affected by income, volunteering is mainly shaped by social, spatial, and gender factors. This finding emphasizes that contributions of manual labor depend less on economic ability and more on proximity, perceived benefits, and social norms related to gender and community roles.

Table 8. Logit Regression Results – Willingness to Work (WTW)

Variable	Odds Ratio
Income	~1.000
Education level	0.007
Male	1663.157
Distance (km)	0.984
Awareness	0.697
Constant	31,409

Source: Authors' survey data analysis, 2025

SUMMARY, CONCLUSION AND RECOMMENDATIONS

Summary

The study found that communities near the Yayo Coffee Forest Biosphere Reserve (YCBR) strongly recognize the reserve's various ecosystem services. These include provisioning, regulating, supporting, and cultural services. Freshwater resources and biodiversity are the most notable. Respondents expressed positive willingness to pay (WTP) in cash, though volunteer labor (WTW) emerged as the most scalable and immediate form of support. Logit regression analysis revealed that WTW is significantly influenced by gender, distance from YBR, awareness, and education, with men more likely to participate, a slight decline in participation with increased distance, a positive effect of environmental awareness, and differentiated contribution patterns by education level.

Conclusion

A hybrid conservation-finance strategy is most suitable for YBR's socio-ecological context. The analysis reveals distinct drivers for monetary and labor-based contributions among local communities. Willingness to pay (WTP) is most strongly influenced by income and awareness, followed by education and distance, reflecting the role of economic capacity and environmental knowledge in shaping financial support for conservation. In contrast, willingness to work (WTW) is dominated by gender, alongside education and proximity, indicating that labor participation is primarily shaped by social norms and opportunity costs rather than financial capability. This approach combines modest cash contributions where feasible with structured, role-differentiated volunteer programs that convert strong local stewardship into regular on-the-ground conservation work. Embedding these programs within stronger legal protections, participatory governance, and ecotourism-linked livelihood opportunities will enhance both durability and equity. By integrating financial incentives with meaningful volunteer roles, the reserve can leverage community engagement while sustaining ecosystem services and local livelihoods.

Recommendations

- Community-Based Conservation Contributions: Establish a Payment for Ecosystem Services (PES) scheme where households can contribute either small annual payments or labor days. This will provide flexibility for poorer families.

- Strengthen Awareness & Education Programs: Launch community-wide conservation education through schools' clubs, farmer cooperatives, and religious institutions to improve understanding of ecosystem benefits.

- Promote Coffee Certification and Eco-Labelling: Expand certification schemes such as shade-grown, organic, and fair-trade coffee to strengthen conservation-linked income opportunities for local communities. These certification programs can create market incentives for sustainable forest management while enhancing the value of coffee produced within the Yayo Coffee Forest Biosphere Reserve. Revenue generated through certified coffee markets should be partly reinvested in local development initiatives and ecosystem management activities, thereby supporting both forest conservation and community livelihoods.

- Adopt Gender-Sensitive Approaches: Offer flexible options for women, such as home-based nurseries and forest product businesses, to ensure fair participation in conservation.

- Rebuild Institutional Trust & Capacity: Strengthen local cooperatives and kebele administrations with transparent fund management and community participation in decision-making.

- Support Alternative Livelihoods: Promote income diversification (beekeeping, ecotourism, coffee value chain improvements) to reduce reliance on forest clearing.

- Establish a Conservation Endowment Fund: Create a multi-source financing mechanism combining household contributions, coffee premiums, and donor support for long-term ecosystem management.

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ASSESSMENT OF FARMERS' CHICKPEA (*CICER ARIETINUM* L.) SEED PROCESSING AND STORAGE PRACTICES IN CENTRAL ETHIOPIA

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ABSTRACT: Smallholder chickpea producers should implement effective and efficient post-harvest seed handling practices to guarantee that their seeds are high quality, competitive in domestic and international markets. However, there is limited information on current post-harvest handling practices applied by chickpea farmers in central Ethiopia. Therefore, this study assessed chickpea seed processing, storage, and management practices through a field survey across five major chickpea-growing districts, using multi-stage and purposive sampling to engage 203 farmers. Results revealed that core processing operations threshing, cleaning, drying, and moisture testing were entirely guided by traditional knowledge. The majority of farmers (79.3%) used fumigant chemical treatments to protect stored seed from insect pests and diseases. More than 90% stored seed in polypropylene or reused fertilizer bags, with or without inner plastic lining. Farmers identified key storage challenges as vulnerability to fluctuating weather conditions and both qualitative and quantitative seed losses caused by insect pests and rodents. Regarding management practices, 86.7% of farmers stored grain and seed separately after processing, while 74.4% cleaned storage facilities before loading newly produced seed. Nearly all farmers relied on visual observation for seed and storage inspection. These findings highlight that continued dependence on traditional practices is insufficient to address existing gaps in seed quality and quantity. Adopting improved, evidence based post-harvest handling methods is essential for smallholder chickpea producers to remain competitive in both domestic and international markets. Hence, farmers should adopt improved seed processing, storage technologies, and extension support to enhance chickpea seed quality and market competitiveness.

Keywords: Drying and trashing, farmers' survey, quality loss, seed cleaning, seed inspection

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INTRODUCTION

Chickpea (*Cicer arietinum* L.) is an important food legume globally, recognized as the third-largest pulse crop with a cultivated area of 14.14 million hectares and a production of 15.94 million tons (FAO, 2021). In Sub-Saharan African (SSA) countries, chickpeas have shown an increase in land area allocated and production since 1961 (Fikre *et al.*, 2020a). Specifically, the land area cultivated with chickpeas expanded from 188,000 hectares in 1961 to 380,395 hectares in 2018, while production increased remarkably from 123,600 tons to 637,681 tons during the same period (FAO, 2020). Chickpea has strategic relevance for the agricultural sector transformation and improving food and nutrition security, soil health, economic returns, and income stability for SSA (Gaur *et al*., 2018; Fikre *et al.*, 2020a). Additionally, chickpea is a vital protein and minerals source for millions in developing countries (Gaur et al., 2010). Hence, chickpea contributes to the improvement of the livelihoods of many farmers and food security (ICARDA, 2019; Haileyesus and Mekuriaw, 2021; Bishaw *et al*., 2022).

Chickpea cultivation spans over 50 countries (Jukanti *et al*., 2012), with Ethiopia being among the six largest producers globally and the leading producer, consumer, and exporter of chickpeas in Africa (FAO, 2021; Chichayebelu *et al*., 2021). Chickpea accounts for more than 14% of Ethiopia's legume production, with the production of 0.46 million tons on an estimated land area of 0.22 million hectares during the main cropping season (CSA, 2021). This demonstrates that chickpea is the third-largest food legume in volume of production and land area allocated in the country (CSA, 2021; Chichayebelu *et al.*,2021). In addition, chickpea has become the third-most important exported legume crop, generating about US$61 million annually (ICARDA, 2019). Moreover, chickpea is part of the integrated crop-livestock farming systems based on the experience and resources of the farmers (Mekuanint *et al.*,2018).

This shows that chickpea has become the source of livelihood for many farmers in the country (Ferede *et al.*,2018; ICARDA, 2019).

Although chickpea has substantial economic, nutritional, and agronomic benefits, the national chickpea productivity remains relatively low, with an average yield of about 2 t ha^{-1} (CSA, 2021), which is considerably lower than the potential grain yield of about 4 t ha^{-1} under improved management conditions (Eshete et al., 2015). Seed quality is recognized as one of the major constraints limiting chickpea production and productivity in Ethiopia (Fikre and Bekele, 2020b). Crop productivity can be substantially improved through the use of high-quality seed of improved varieties combined with appropriate agronomic practices (Abebaw et al., 2023). High-quality seed plays a critical role in ensuring better crop establishment, improved yield performance, and resilience to pests, diseases, and drought stresses (FAO and ICRISAT, 2015). However, farmers' seed processing, handling, and management practices often influence the quality of seed used for subsequent planting.

Seed processing operations and management practices are essential components of high-quality seed production (Delouche, 2021; Sinha *et al.*, 2023). However, seed processing is a technical operation that requires skilled, knowledgeable, and experienced personel, as well as appropriate equipment (FAO, 2018). As a result, farmers in developing countries could face a common challenge during seed processing operations and management practices (Delouche, 2021). Seed frequently deteriorates in the field during harvesting or drying, resulting in low-quality seed being stored (Saeed *et al.*, 2020). In developing countries, it is a common practice to heap threshed crops in the field for several days to allow adequate drying (Bam *et al.*, 2007). This may not provide a guarantee to attain optimum seed moisture, particularly during the rainy season.

In developing countries, smallholder farmers use traditional seed storage methods, which are often inefficient in protecting stored seeds from pests, moisture damage, and other storage-related losses during extended storage periods (Endashaw and Hiruy, 2021). Such inadequate storage practices may lead to deterioration in seed quality, reduced germination capacity, and significant post-harvest losses. However, there is limited information regarding chickpea farmers seed processing, storage and seed management practices in the central Ethiopia. Therefore, understanding the existing knowledge, experience, and practices of smallholder farmers regarding chickpea seed post-harvest and storage management practices is essential for improving seed quality and ensuring the availability of viable seed for planting. Hence, this study was undertaken to assess current chickpea seed processing, storage, and seed management practices among smallholder farmers in central Ethiopia.

MATERIALS AND METHODS

Description of the study areas

The chickpea on-farm storage study was conducted in five districts drawn from three administrative zones: Two districts from East Shewa Zone (Ada'a and Lume), two districts from West Shewa Zone (Dandi and Ejersa Lafo), and one district from North Shewa Zone (Minjar-Shenkora) (Figure 1). The study districts are geographically located between 7°53′21.84″N and 9°59′21.84″N latitude and 38°00′47.52″E and 39°31′38.64″E longitude, with altitudes ranging from 1,699 meters above sea level (m a.s.l.) in Minjar-Shenkora district to 2,263 m.a.s.l., 102 in Lume district. According to the agro-ecological zone (AEZ) classification developed by the Ministry of Agriculture and Rural Development (MoARD, 2005), Dandi and Ejersa Lafo districts fall within the tepid to cool moist mid-highland (M2) agro-ecological zone, while Ada'a and Lume districts are categorized under the tepid to cool sub-moist mid-highland (SM2) zone. In contrast, Minjar-Shenkora District is classified under the hot to warm sub-moist lowland (SM1) agro-ecological zone.

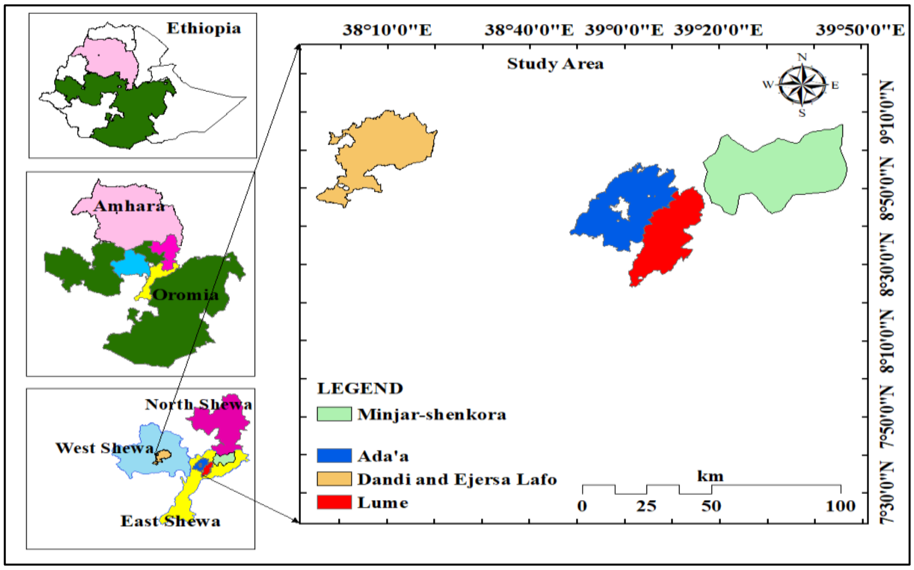

Figure 1.Map of Ethiopia showing the chickpea field survey zones and districts in 2021/2022 crop season

Sampling Procedures and Sample Size

A four-stage and purposive sampling techniques was employed, involving zones, districts, *kebeles*, and chickpea farmers as sampling units. In the first stage, major chickpea-producing zones in central Ethiopia were purposively identified based on their production potential and relevance to the study objectives. During the second and third stages, five districts from the three zones and four *kebeles* from each district were selected, respectively. The selection of districts and *kebeles* was carried out purposively in consultation with agricultural experts and local extension agents, based on their suitability for chickpea production. In the fourth stage, a total of 203 chickpea farmers were selected from 20 *kebeles* using a simple random sampling technique. Primary data was collected through face-to-face interviews using a carefully designed and pre-tested structured questionnaire. The enumerators and the researcher conducted interviews in the farmers' local languages (Afan Oromo and Amharic) to ensure understanding and accuracy. All responses were then recorded and translated into English for data processing and analysis.

Data collection

Primary and secondary data were collected. Primary data came from chickpea growers via household surveys. This data included information on household characteristics (gender, age, education, family size, oxen and land ownership, and chickpea farming experience), and socio-economic factors (labor source, off-farm income, access to credit and extension services, and farmer's Association membership). Additionally, the study examined chickpea farmers' knowledge and experience regarding current seed processing and storage practices in central Ethiopia.

Data Analysis

The survey data were carefully cleaned, coded, and checked for accuracy and completeness prior to analysis. The cleaned data were entered into the Statistical Package for the Social Sciences (SPSS), version 25 (IBM SPSS Statistics) for further analysis. Data coding and entry procedures were standardized to minimize errors and ensure data consistency. Both descriptive and inferential statistical methods were employed for data analysis. Descriptive statistics, including frequencies, percentages, and means, were used to summarize and describe the key characteristics of the sampled households and study variables. In addition, inferential statistical techniques were applied to examine differences among districts. Specifically, one-way analysis of variance (ANOVA) was used to test for statistically significant differences in continuous variables, while the Chi-square (χ^2) test was employed to assess differences among categorical variables across districts. All statistical tests were conducted at level of significance of $p \leq 0.05$.

RESULTS

Farmer Household Characteristics

A summary of descriptive statistics and results of statistical significance tests for both categorical and continuous variables are presented in Tables 1, 2, and 3. The results of the Chi-square (χ^2) test indicated that there was no statistically significant difference in the gender of household heads across districts ($\chi^2 = 8.15$; $p > 0.05$). However, the educational status of household heads varied significantly among districts ($\chi^2 = 39.98$; $p = 0.005$). Out of the 203 households (HHs) surveyed, male-headed households accounted for 93.6%, indicating a strong dominance of male household heads in the study areas (Table 1). Approximately one-quarter (24.9%) of the household heads were illiterate, while the majority (75.1%) were literate at different levels, including informal education (19.0%) and formal education (elementary school and above). This suggests a relatively moderate level of literacy among chickpea-producing households, which may influence the adoption of improved agricultural practices.

Table 1. Chickpea farmers' gender and educational levels

Variable		Sex of HH (%)		Education level of HH (%)					
District	N	MHH	FHH	Illite Rate	Inform Edu.	Elementary	Junior School	High School	College and above
Dandi	41	85.4	14.6	31.7	7.3	29.3	17.1	12.2	2.4
E. Lafo	43	95.4	4.7	20.9	11.6	30.2	25.6	7.0	4.7
Ada'a	35	91.4	8.6	14.7	20.6	26.5	14.7	23.5	0.0
Lume	43	95.4	4.7	25.6	18.6	39.5	4.7	11.6	0.0
M/Shenkora	41	100.0	0.0	31.7	36.6	24.4	0.0	4.9	2.4
Total	203	93.6	6.4	24.9	19.0	30.0	12.4	11.8	1.9
F/x^2- value		8.15^a (4) ^{ns}				39.98^a (20) **			

**, ns = values are significant at 1% and non-significant at 5% level of significance, respectively. [a] Chi-square value (X^2) is from two-way cross-tabulation (number in the parentheses are degree of freedom). Abbreviations: HH = Household (head); MHH = Male household head; FHH = Female household head.

The result of the analysis of variance (ANOVA) revealed that there are statistically significant age differences ($F_{(4, 198)} = 3.40$; $p = 0.01$) and active family size ($F_{(4, 198)} = 3.80$; $p = 0.005$) among the HHs across the districts (Table 2). However, there was no significant difference ($F_{(4, 198)} = 2.16$; $p = 0.075$) in the farmers' experiences in growing chickpea across the five districts (Table 1b). The ages of the household heads ranged from 24 to 78 years, with an average of 46.6±0.9 years, while the mean active family size was 4.7 ± 0.2 members, ranging from 3.6 ± 0.3 in Minjar-Shenkora to 5.4±0.4 members in Ejersa Lafo districts (Table 2). Moreover, the average household head experience in growing chickpea was around 24.0 ± 0.9 years (Table 2).

Table 2. Chickpea farmers' age, active family labor and experience in chickpea production

District	N	Age	Active family size	Experience of HH
Dandi	41	45.7±1.5	5.0±0.4	25.0±1.8
Ejersa Lafo	43	50.9±1.8	5.4±0.4	28.0±1.9
Ada'a	35	46.9±2.2	4.5±0.3	20.8±2.1
Lume	43	47.5±1.9	4.7±0.3	23.5±1.7
Minjar-Shenkora	41	41.7±1.8	3.6±0.3	22.0±2.0
Mean/Total	203	46.6±0.9	4.7±0.2	24.0±0.9
Df(error)		198	198	198
F. values		3.40**	3.80**	2.16^{ns}
P-values		p=0.01	p=0.005	p=0.075

Source: Our survey, 2022.

*, ** values are significant at 5% and 1%, respectively. ns = non-significant ($p > 0.05$); HH= household head. The variables mentioned in Table 2 were analyzed using one-way ANOVA.

The one-way ANOVA results further indicated statistically significant differences among districts in the number of oxen owned ($F (4, 198) = 11.50$; $p < 0.01$), land area allocated for chickpea production ($F (4, 198) = 2.86$; $p = 0.025$), and grain yield (kg ha^{-1}) during the 2021/2022 main cropping season ($F (4, 198) = 13.61$; $p < 0.01$) (Table 3). On average, households owned 3.1 ± 0.1 oxen, with the lowest ownership recorded in Minjar-Shenkora District (2.3 ± 0.2) and the highest in Ada'a District (4.4 ± 0.4). Similarly, the mean land area allocated to chickpea production was 0.66 ± 0.04 ha, varying from 0.49 ± 0.01 ha in Dandi and Minjar-Shenkora districts to 0.84 ± 0.1 ha in Ejersa Lafo District.

The average chickpea grain yield across the study districts was 1449.92 ± 94.00 kg ha^{-1}, which is lower than the national average yield of 2018 kg ha^{-1} (CSA, 2021). This indicates a yield gap in the study areas, potentially attributable to differences in management practices, input use, and agro-ecological conditions. Among the districts, Lume recorded the highest yield (2460.65 ± 154.60 kg ha^{-1}), whereas Minjar-Shenkora recorded the lowest yield (651.12 ± 87.50 kg ha^{-1}). Furthermore, the observed yields in the present study are lower than those reported by Ashu et al. (2023) for central and southern Ethiopia, suggesting potential constraints in productivity that warrant further investigation.

Table 3. Chickpea farmers' oxen ownership, land allocation, and grain yield in the study districts

Districts	N	Oxen (head)	Land area (ha)	Grain yield (kg/ha)
Dandi	41	2.4±0.2	0.49±0.1	1313.50±295.41
Ejersa Lafo	43	3.0±0.2	0.84±0.1	1115.14±171.12
Ada'a	35	4.4±0.4	0.76±0.2	1715.00±165.23
Lume	43	3.7±0.2	0.76±0.1	2460.65±154.60
Minjar-Shenkora	41	2.3±0.2	0.49±0.0	651.12±87.50
Total/mean	203	3.1±0.1	0.66±0.04	1449.92±94.00
Df (error)		198	198	198
F-values		11.50**	2.86*	13.61**

Source: Own survey data (2022). *, ** values are significant at 5 and 1% levels of significance, respectively.

The results of the chi-square tests (X^2-value ranged from 3.17 to 8.64; P = 0.05) showed that there were no significant differences ($p > 0.05$) among the HHs of the five districts in their responses to the categorical variables (Table 4). When considering farmers' involvement in off-farm and on-farm activities, about 44.3% of farmers engaged in off-farm activities, whereas 55.7% of them were engaged in on-farm activities (Table 4). Family members provided roughly 63.5% of the labor that chickpea farmers needed, while about 36.5% of HHs hired labor to support their families (Table 4). Considering credit service access, about 42.4% of HHs in the study areas accessed credit services from various micro-financial intuitions (Table 4). However**,** the majority (57.6%) of farmers in the study areas did not get access to credit services.

Table 4. Chickpea farmers' socio-economic characteristics by categorical variables in the studied districts

Variables	Districts							
	Dandi	Ejersa Lafo	Ada'a	Lume	M/Shenkora	Mean	X^2	Df
Source of labor	*n*=41	43	35	43	41	203	3.17ns	4
Family alone	61.0	55.8	60.0	72.1	68.3	63.5		
Family and hired	39.0	44.2	40.0	27.9	31.7	36.5		
Off-farm income	*n*=41	43	35	43	41	203	7.60ns	4
Yes	58.5	51.2	42.9	32.6	36.6	44.3		
No	41.5	48.8	57.1	67.4	63.4	55.7		
Credit service	*n*=41	43	35	43	41	203	8.64ns	4
Yes	43.9	46.5	51.4	23.3	48.8	42.4		
No	56.1	53.5	48.6	76.7	58.5	57.6		
Extension service	*n*=41	43	35	43	41	203	6.85ns	4
Yes	80.5	86.0	88.6	95.3	95.1	89.2		
No	19.5	14.0	11.4	4.7	4.9	10.8		
Membership (FA)	*n*=41	43	35	43	41	203	4.56ns	4
Yes	78.0	90.7	82.9	79.1	90.2	84.2		
No	22.0	9.3	17.1	20.9	9.8	15.8		

Source: Own survey data (2022). Note*:* ns= values are not significant at 5% by the Chi- square test. Abbreviation: FA = Farmers' Association.

3.2. Chickpea Seed Processing

3.2.1.Drying and threshing

The survey results indicated that smallholder farmers employed a range of traditional techniques for chickpea drying and threshing operations in central Ethiopia during the 2021/2022 cropping season (Table 5). More than one-quarter of the respondents applied combined sun-drying methods, including piling harvested crops in the field followed by spreading on the threshing floor, or piling near the threshing floor and subsequently spreading on the threshing floor (Figure 2). These results suggest that farmers rely on multiple sequential drying practices rather than a single method to ensure adequate drying prior to threshing. Similarly, the majority (87.2%) of smallholder chickpea farmers reported that threshing was carried out by trampling the harvested crop using draft animals, primarily oxen, while a smaller proportion (12.8%) used a combination of animal trampling and beating with sticks (Table 5). This indicates a heavy reliance on traditional threshing techniques, which may have implications for seed quality and post-harvest quantitative losses.

Figure 2. Chickpea drying by spreading on an unplastered threshing floor. Photograph taken during the field survey (Abebe Sori, 2022).

Table 5. Chickpea drying and threshing practices among farmers in the study districts

1.What technique(s) did you apply to dry chickpea before threshing?(n=203)	Frequency	%
Natural, (complete sun dry before harvesting)	1	0.5
Sundry by piling harvested crop in the field	6	3.0
Sundry by piling harvested crop near threshing floor	28	13.8
Sundry by spreading harvested crop on threshing floor	17	8.4
Natural, and sun drying by piling in the field	2	1.0

Sundry by piling in the field and near threshing floor	2	1.0
Sundry by piling in the field and spreading on threshing floor	52	25.6
Sundry by piling near threshing floor and spreading on threshing floor	53	26.1
Natural, sundry by piling in the field, and spreading on threshing floor	4	2.0
Sundry by piling in the field, near threshing floor and spreading on threshing floor	33	16.3
Natural, sundry by piling near threshing floor, and spreading on threshing floor	4	2.0
2. How did you thresh the chickpea after harvest (n=203)	Frequency	%
Trampling with animals (usually oxen)	177	87.2
Trampling with animal and biting with stick	26	12.8

Source: Own field survey (2022)

Note: Natural practice indicated where chickpea crop is allowed to sundry completely before harvesting.

Seed cleaning and moisture tests

In the study districts, about 56.2% of farmers cleaned seeds by winnowing under natural wind, followed by manual cleaning and handpicking of the inert materials in central Ethiopia. However, about 42.4% of farmers cleaned chickpea seeds using winnowing under natural wind and manual cleaning using sieves and other locally made tools (Table 6). Furthermore, farmers were asked if they measured seed moisture content before harvesting and storage. Accordingly, the majority (86.2%) of farmers assessed the seed moisture content before harvesting and storage using a combination of visual examination and teeth biting (53.7%), whereas about 36.0% of farmers assessed moisture content with visual examination alone.

Table 6. Chickpea seed cleaning and moisture assessment practices among farmers

1. How did you clean seed after threshing? (n=203)	Frequency	Percent
a. Winnowing under natural wind	3	1.5
b. Winnowing and manual cleaning	86	42.4
c. Winnowing, manual cleaning and hand-picking inert materials	114	56.2
2. Did you measure seed moisture content? (n=203)		
a. Yes	175	86.2
b. No	28	13.8

3. How did you know whether the seed is dry enough to store? (n=175)		
a. Biting with teeth	18	10.3
b. Visual observation	63	36.0
c. Both biting with teeth and visual observation	94	53.7
4. After cleaning, did you manage separately grain for Consumption and seed for planting? (n =203)		
a. Yes	176	86.7
b. No	27	13.3
5. Did you clean chickpea seed before storing? (n=176)		
a. Yes	146	83.0
b. No	30	17.0
6. How did you clean the seed? (n=146)		
a. Winnowing alone	4	2.7
b. Hand picking the inert matters alone	2	1.4
c. Winnowing, hand pick the inert matters and manual cleaning	98	67.1
d. Winnowing and manual cleaning	23	15.8
e. Hand picking the inert matters, and manual cleaning	19	13.0

Source: Own field survey (2022).

Note. In all cases, winnowing was performed under naturally blowing wind.

Seed Storage Practices and associated challenges

Chickpea seed storage practices

Table 7 presents the current on-farm chickpea seed storage practices among smallholder farmers in central Ethiopia during the 2021/2022 cropping season. The survey results indicate that farmers employ a range of traditional storage techniques, largely depending on the availability, accessibility, and perceived effectiveness of storage materials. The findings reveal that nearly all farmers rely on traditional storage containers, primarily polypropylene (PP) bags (57.1%), either used alone or in combination with re-used fertilizer bags with or without inner plastic linings. Only a negligible proportion of farmers (0.5%) reported using hermetic storage technologies such as Purdue Improved Crop Storage (PICS) bags, indicating extremely low adoption of improved storage technologies in the study areas (Table 7). This suggests a significant technological gap in post-harvest seed management practices.

Table 7. Current on-farm chickpea seed storage practices by farmers in the central high lands of Ethiopia during the 2021/2022 main cropping season

1. What type of storage containers do you employ? (n=203)	Frequency	Percent
a. Polypropylene bags (PP bags)	116	57.1
b. PP bag and fertilizer bag without inner plastic	25	12.3
c. Fertilizer bag without inner plastic	18	8.9
d. PP bag and re-used fertilizer bag with inner plastic	11	5.4
e. Fertilizer with inner plastic	8	3.9
f. PP bags, fertilizer bag and *dogogo*	4	2.0
g. PP, fertilizer bags w/out inner plastic, and ZeroFly® bag	20	9.9
h. Hermetic bags (e.g. PICS bag)	1	0.5
2. Do you currently utilize hermetic bags for chickpea seed storage? (n= 203)		
a. Yes	1	0.5
b. No	202	99.5
3. What was/ were you concerns with current seed storage(n=203)		
a. Insect pest and rodents	119	58.6
b. Insect pests, rodents and birds	57	28.1
i. Rodents	11	5.4
j. Insect pest	9	4.4
k. Insects, rodents and mold	3	1.5
l. No challenge	4	2.0

Source: Own field survey data (2022).

Challenges of on-farm chickpea seed storage

Seed quality and quantity losses

During the 2021/2022 field survey, farmers were asked to identify the major constraints associated with their current seed storage systems (Table 8). The results indicated that the primary challenges were storage insect pests and rodents, as reported by 58.6% of respondents. In addition, 28.1% of farmers identified a combination of insect pests, rodents, and birds as key storage problems, while a smaller proportion reported issues related to rodents alone (5.4%) or insect pests alone (4.4%). These findings highlight that biological seed storage agents are the dominant constraints affecting seed quality, quantity and storage performance.

Table 8. Farmers' challenges associated with current seed storage practices in central Ethiopia

What was/ were you concerns with current seed storage (n=203)	Frequency	Percent
m. Insect pest and rodents	119	58.6
n. Insect pests, rodents and birds	57	28.1
o. Rodents	11	5.4
p. Insect pest	9	4.4
q. Insects, rodents and mold	3	1.5
r. No challenge	4	2.0

Source: own field survey data (2022)

Capability to withstand fast changing weather condition

In this study, farmers were asked for their perceptions of the effectiveness of existing storage methods and their willingness to adopt improved technologies (Table 9). The results revealed that 78.3% of farmers believed that their current storage systems are not resilient to fluctuating environmental conditions, such as temperature and humidity variations. This perception reflects limitations in the protective capacity of traditional storage materials. Subsequently, farmers were asked about their demand for improved seed storage technologies. The findings show that an overwhelming majority (99.0%) expressed willingness to adopt improved storage methods, indicating a strong demand for technological interventions in seed storage. Further, farmers identified the specific reasons for preferring improved storage technologies, with the most frequently cited being protection against insect pests (30.0%), followed by combined benefits such as insect pest protection and seed longevity (22.2%), and insect pest protection and durability (17.7%). Other reasons included durability alone (16.3%) and durability combined with seed longevity (11.8%), while only a small proportion (2.0%) indicated seed longevity alone as the primary reason (Table 9). These results suggest that farmers prioritize protection against storage pests as the key driver for adopting improved storage technologies.

Table 9. Farmers' perceptions of current seed storage systems and demand for improved technologies during the 2021/2022 cropping season

1.Can your current seed storage methods withstand ever-changing weather conditions? (n=203)	Frequency	%
a. Yes	44	21.7
b. No	159	78.3
2. Do you need improvement of current seed storage systems? (n=203)		%
a. Yes	201	99.0
b. No	2.0	1.0
3. Why do you need improved seed storage? (n=203)		
a. Insect pest protection	61	30.0
b. Insect pest protection and seed longevity	45	22.2
c. Insect pest protection and durability	36	17.7
d. Durability alone	33	16.3
e. Durability and seed longevity	24	11.8
f. Seed longevity alone	4.0	2.0

Source: Own field survey data (2022).

Farmers' Seed and Storage Management Practices

Separate seed and grain storage

Farmers were asked to describe how they manage chickpea seed and grain after threshing and cleaning operations (Table 10). The results indicate that farmers differentiate seed from grain based on physical characteristics, whereby larger, denser, and well-filled seeds are selected for planting, while lighter, shriveled, and immature seeds often separated during winnowing are designated for consumption or sale. This traditional selection method reflects farmers' indigenous knowledge of seed quality attributes. Accordingly, the majority of farmers (80.3%) reported storing seed and grain separately after processing, while 19.7% did not practice such separation (Table 10). This suggests that most farmers recognize the importance of maintaining seed quality through segregation from consumable grain. Furthermore, farmers were asked to indicate the locations used for seed storage. The results show that chickpea seed was primarily stored indoors using various arrangements within the household (Appendix A).

The largest proportion of farmers (43.4%) stored seeds within the living house but in a separate room, often together with grain and seeds of other crops, while 37.9% used separate storage spaces that still contained both grain and seed of different crops (Table 10). This storage practices indicate a potential vulnerability in the farmers' seed management, which could influence seed quality.

Table 10. Chickpea farmers' seed management and storage location practices in central Ethiopia during the 2021/2022 cropping season

1. Do you store seed and grain separately? (n=203)	Frequency	Percent
a. No	40	19.7
b. Yes	163	80.3
2. Where do you store your seed? (n=203)		
a. In living room with grain and seed of other crops	31	15.3
b. In separate seed store with seed of other crops	7	3.4
c. In separate store but with grain and seed of other crops	77	37.9
d. In living house but in separate room with grain and seed of other crops	88	43.4

Source: Own field survey data (2022).

Seed inspection practices

Seed inspection was identified as one of the keys on-farm storage management practices among chickpea farmers. The results indicated that nearly all farmers (98.5%) reported inspecting their stored seed, demonstrating a high level of awareness regarding the importance of monitoring seed condition during storage (Table 11). Among those who practiced seed inspection, the frequency of inspection varied considerably. About 45.8% of farmers inspected their stored seed on a monthly basis, while 30.5% conducted inspections weekly, and 9.4% performed inspections every two weeks. Only a small proportion of farmers carried out inspections either daily or at longer intervals (beyond one month). This variation suggests differences in farmers' management intensity and perceived storage risks. In terms of inspection methods, farmers relied predominantly on indigenous techniques, including visual observation alone (26.6%) or in combination with manual methods such as inserting the hand into the storage container to assess seed condition (34.0%). Other sensory-based methods, such as listening to sound or smelling the seed, were used less frequently (Table 11). These findings indicate a reliance on experiential and sensory-based assessment methods rather than standardized or instrument-based stored seed inspection practices in the study areas.

Table 11. Chickpea seed storage inspection practices among the farmers in central Ethiopia

1. Do you inspect storage? (n=203)	Frequency	Percent
a. Yes	200	98.5
b. No	3	1.5
2. How often do you inspect your seed storage? (n=200)		
a. On daily basis	6	3.0
b. Weekly	62	30.5
c. Bi-weekly	19	9.4
d. Every three weeks	3	1.5
e. Monthly	93	45.8
f. Bi-monthly	11	5.4
g. Every 3 up to 5 months	4	3.0
3. How do you inspect your stored seed? (n=200)		
a. Visual observation alone	54	26.6
b. Insert hand and visual observation	69	34.0
c. All except smell methods	31	15.3
d. Listen to sound and visual observation	14	6.9
e. Smell and visual observation	4	2.0
f. All except listen the sound	2	1.0
g. Listen sound alone	7	3.4
h. All methods	22	10.8

Source: Own field survey data (2022)

Storage management practice

Farmers' seed storage management practices are presented in Table 12. The results showed that farmers employ several management strategies to maintain the quality of stored chickpea seed. Approximately 74.4% of respondents reported cleaning their storage facilities prior to loading newly harvested seed, which is a critical practice for reducing contamination and pest infestation risks. However, only 43.1% of farmers reported repairing or maintaining storage containers, while the majority (56.9%) did not practice storage repair and maintenance (Table

12). This may be attributed to the widespread use of single-use woven polypropylene (PP) bags, which are often difficult to repair once damaged. The limited practice of storage maintenance may contribute to increased vulnerability of stored seed to pest infestation and physical damage.

Table 12. Farmers' storage management practices in central Ethiopia

1.Do you clean the store before loading them with newly harvested seed?(n=203)	Freq.	%
a. Yes	151	74.4
b. No	52	25.6
2. Do you practice seed storage container repair and maintenance? (n=203**)**		
a. Yes	88	43.1
b. No	115	56.9

Source: Own survey results (2022).

DISCUSSION

Household characteristics

The characteristics of chickpea-growing households in five districts of central Ethiopia were assessed during the 2021/2022 main cropping season to understand production and seed management practices. The results revealed that gender composition and farming experience were relatively uniform across districts, whereas age, education level, and family size exhibited notable variation, suggesting heterogeneity in human capital among farming households. Regarding household headship, male-headed households dominated the sample (93.6%), which is consistent with previous findings in Ethiopia, where male-headed households accounted for approximately 93% of respondents (Haileyesus and Mekuriaw, 2021). This pattern reflects prevailing socio-cultural norms influencing land ownership, decision-making, and access to agricultural resources. In terms of education, about 25% of household heads were illiterate, while the remainder had either informal or formal education. This level of illiteracy is comparable to earlier studies in the central highlands of Ethiopia, which reported about 21% illiteracy among household heads (Mekuria et al., 2020). Educational status is a critical determinant of technology adoption, particularly for improved seed and storage practices. This need efforts to improve educational access to rural areas to reduce illiteracy rates over time.

The mean age of household heads (46.6 years) indicated that most farmers fall within the economically active age group, which is favorable for labor-intensive agricultural operations such as chickpea production. This finding aligns with Asfaw et al. (2012), who reported similar average ages (46–46.8 years) in major chickpea-growing areas. Likewise, the average farming experience of about 24 years suggests substantial accumulated indigenous knowledge, which can positively influence management decisions, although it may also reinforce reliance on traditional practices. The average active family size (five persons) implies adequate household labor availability, consistent with findings by Asfaw et al. (2010). Family labor constituted the primary workforce, supplemented by hired labor during peak agricultural periods, confirming earlier reports (Bishaw et al., 2010). Labor availability is particularly important for timely operations such as harvesting, threshing, and seed processing.

Regarding resource ownership, oxen were the primary source of draft power, with households owning an average of three oxen, underscoring their critical role in land preparation and overall crop production systems. The average land allocation for chickpea (0.66 ha) is consistent with findings by Mulat et al. (2023). However, the average grain yield (1449.9 kg ha^{-1}) was substantially lower than the national average (2018 kg ha^{-1}; CSA, 2021) and significantly lower than yields reported in other regions (Ashu et al., 2023). This yield gap suggests the presence of production and post-harvest constraints, including sub-optimal seed quality and storage practices, as identified in earlier sections of this study.

Chickpea seed processing practices

Seed processing plays a critical role in maintaining seed quality, encompassing operations such as drying, threshing, cleaning, treatment, and storage. Effective processing is essential to ensure physical, physiological, and sanitary seed quality, which directly influences germination, vigor, and field performance (van Gastel et al., 2007; Sudhakar et al., 2020). The findings of this study indicated that farmers rely predominantly on traditional, labor-intensive seed processing methods, which are often influenced by environmental conditions and resource availability. While these practices demonstrate adaptability, they may not consistently meet recommended standards for high-quality seed production, particularly under variable climatic conditions.

Drying and threshing practices

Farmers employed multiple traditional sun-drying methods, often in combination, to reduce seed moisture content to acceptable levels before storage. The absence of standardized drying techniques reflects dependence on ambient weather conditions, which can delay drying and expose seeds to risks such as re-wetting and fungal contamination. This variability increases the likelihood of pre-storage seed deterioration. Empirical evidence suggests that reducing seed moisture content to safe levels is essential for prolonging seed longevity (Vernooy et al., 2022). Failure to achieve optimal moisture levels prior to storage is a major factor contributing to seed quality decline, particularly in tropical environments.

Threshing practices were predominantly based on animal trampling, consistent with findings from other regions (Tinsley, 2014). However, this method has several limitations, including, mechanical damage to seed, contamination with soil, inert matter, and other crop seeds and increased exposure to pests and pathogens**.** Additionally, threshing on unplastered or poorly prepared surfaces further exacerbates contamination risks. Delayed threshing due to labor or weather constraints also contributes to quality deterioration. These findings are consistent with Sudhakar et al. (2020), who reported that inappropriate threshing practices lead to increased seed damage and reduced quality.

Seed cleaning practices

Shortly after the threshing was finished, chickpea farmers carried out traditional seed-cleaning operations. To maximize the physical seed quality, inert matter (such as plant parts, damaged seed, dust, soil, stone particles, etc.) must be removed from the threshed seed, along with other crop seeds, weed seeds, immature seeds, etc. Our study results showed that most farmers applied seed-cleaning operations that involved different stages using traditional homemade tools. Initially, winnowing under natural wind is carried out to remove major impurities (dust, lightweight straws, other light materials, etc.) using traditional tools like *menshe/Manshi/Qorbi*, *layeda/lameda/Darba* (Appendix B). Further seed cleaning is accomplished, which includes hand-picking larger-sized inert matter and manual cleaning using traditional tools such as *wonfit/gingilcha* (sieve), *safed/Safedi/Gundo* (Appendix B) to remove small-sized inert matter, immature/shriveled, damaged/broken seed, etc. In addition, seed cleaning may be applied before planting if the physical condition of the seed is believed to be unsatisfactory. Similarly, Bishaw *et al*. (2010) investigated that wheat seed cleaning involved two-stage operations, in which the threshed wheat grain is separated from the rough straw first and followed by further seed cleaning from fine straw, inert materials, shriveled and broken seeds using homemade tools. Chichayebelu (2014) reported that farmers' only method of cleaning chickpea grain was winnowing under the naturally blowing wind. This could mean that for chickpea seed and grain, farmers use different management practices.

According to Gaur *et al.* (2010) and Sudhakar *et al.* (2020), the threshed seeds must be cleaned to remove contaminants such as plant parts, soil particles, stones, weed seeds, other crop seeds, and shriveled, broken/damaged seeds. Thus, a maximum percentage of other varieties or crop seeds, weed seeds, and other inert matters present in the seed lot need to be considered as vital components of physical seed quality. This study confirms that chickpea farmers employ traditional and time-consuming practices for chickpea seed cleaning using locally made inefficient tools. Reliance on manual and traditional tools could limits the ability to meet formal seed quality standards, particularly regarding removal of inert matter, elimination of diseased or damaged seeds, and uniformity of seed size and weight. Consequently, achieving certified seed quality under such systems remains challenging.

Seed moisture tests

Seed moisture content is a critical determinant of seed storability and longevity. The findings reveal that farmers rely on traditional methods such as visual inspection and teeth-biting to estimate seed moisture content, consistent with earlier studies (Chichayebelu, 2014). While these indigenous methods are accessible and cost-effective, they lack precision, potentially resulting in storage of seeds at unsafe moisture levels. This limitation is primarily due to the lack of access to affordable moisture measurement technologies, as also noted by Akter *et al.* (2018). Improving access to simple moisture testing tools could significantly enhance seed storability.

Chickpea seed storage practices

Chickpea farmers in the central part of Ethiopia could employ on-farm seed storage facilities that evolved in terms of size, form, holding capacity, and the material from which they were fabricated. In our present study, practically all chickpea farmers currently use traditional seed storage containers, including polypropylene bags (PP), fertilizer bags with and without inner plastic, or a combination of these, depending on which bags are easily accessible and secured. PP bags and re-used fertilizer bags were the most widely used storage facilities in Ethiopia (Dessalegn *et al.*,2017). Similarly, several authors also revealed that PP bags were the most common seed storage method in the central highlands of Ethiopia (Hengsdijk and de Boer, 2017; Getaneh *et al*.,2021; Name *et al.*,2021; Hunduma *et al.*,2021).

The reason for this is that these bags could be accessible in the local markets and affordably priced. Name *et al.* (2021) also reported that PP bags were the most popular storage container types in Ethiopia because they are inexpensive and easily accessible in the local markets. Unfortunately, because of mold and insect pests' inadequate protection and unstable storage conditions, the PP bags now in use cannot guarantee the preservation of quality seeds for a longer time. Therefore, spending resources on seed processing operations alone is insufficient to preserve and supply the required quantity and quality of seed. Appropriate seed storage method should be regarded as an integral component of a high-quality seed supply.

In our present study, it was indicated that nearly no respondents use improved storage methods like hermetic bags for chickpea seed storage. This finding agrees with the recent studies by Getaneh *et al*. (2021), Alemu *et al*. (2021), and Hunduma et al. (2021), who indicated that nearly no respondents in the districts under study used improved storage practices. A few farmers in the surveyed areas have already experienced the advantages of hermetic bags. However, chickpea farmers were unable to use the hermetic bags, mainly because they were not aware of the potential benefits of the bags. In general, hermetic bags are relatively new storage technologies for smallholder chickpea farmers in central Ethiopia, so there is a need to test and validate the technology as well as create awareness (Jones and Walsh, 2014). For effective seed production and distribution, storage must preserve quality seed until it reaches end users. Therefore, hermetic bags should be widely promoted and made accessible locally to increase adoption (Kaske *et al.*,2019).

Seed and Storage Management Practice

Seed quality losses can also result from improperly implemented seed and storage management practices (Bishaw *et al.,* 2010). In the study districts, most farmers employed separate seed and grain storage practices. It is impressive to note that most chickpea farmers separate chickpea seed from grain while it is still on the threshing floor. Farmers would categorize a chickpea as a seed if it appeared larger and heavier in weight, whereas the lighter, shriveled, and immature chickpeas that are removed by the wind in the far front area of the threshing floor are considered grain for consumption and/or sale in the market. Alemu *et al*. (2023) and Abebaw *et al*. (2023) reported that about 42.6% of bread wheat farmers separated the seeds soon after threshing and stored the cleaned seeds separately for the forthcoming cropping season. In addition, all farmers used the indoor storage method (their living houses) to minimize the risk of the thief and other uncertainties. It would be safer to preserve seeds inside the house to prevent theft and similar dangers (Thijssen *et al*. 2008). However, chickpea households rarely ever use a separate seed storage house, mostly due to a lack of resources to construct separate seed and grain storage. Only a limited number of chickpea farmers had separate seed storage houses that were entirely owned by the local seed producer unions and cooperatives.

It is vital practice to assess the condition of the seed and storage facilities for timely management of storage insect pests and rodents (WCDI, 2020). Thus, most of the farmers employed seed and storage inspection practices at least once a month, using their traditional experiences. Similarly, most wheat farmers inspect their stored products at least once a month (Chichayebelu, 2014). This result is consistent with the observation of Befikadu (2014), who stated that inspection needs to be done at least once a month during the colder season and every two weeks during the warmer ones. The chickpea farmers commonly preferred a visual observation technique. This finding is in line with the investigation by Chichayebelu (2014), and Tesfaye (2020), who reported that visual inspection was the primary traditional knowledge employed by farmers for inspecting stored products from time immemorial.

Farmers used several seed and storage management practices to ensure that their stored seed lasted for the intended period. Our results indicated that most farmers employed storage containers cleaning activities before loading them with newly produced chickpea seed.

It is important to clean the storage container and the surroundings before loading the new season's harvested seed into storage to prevent early pest infestations in the storage area (Befikadu, 2014). Otherwise, even a small number of moldy seeds and insect-infested seeds from the previous season could contaminate the seed that has just been stored (Haile, 2006). In addition to cleaning storage containers, repairing damaged seed storage containers is also an essential management practice when impairment occurs before storage or at any time during storage. Similarly, according to Kshetri (2010), the majority of farmers repair on-farm seed store management practices. However, most farmers did not regularly repair seed storage containers in central Ethiopia. This is because the majority of chickpea growers store their seeds in one-time-use woven PP bags that cannot be repaired.

CONCLUSION AND RECOMMENDATION

This study demonstrates that chickpea farmers in central Ethiopia predominantly rely on traditional knowledge and practices for seed processing, storage, and storage management. While these practices are locally adapted and resource-efficient, they are insufficient to maintain seed quality under prevailing environmental and production conditions. The widespread use of polypropylene and reused fertilizer bags reflects their accessibility and affordability; however, these storage systems provide inadequate protection against biological agents such as insect pests and rodents, as well as physical factors including temperature and humidity fluctuations. Consequently, significant losses in seed quality and quantity occur during storage. The findings further indicate that inefficiencies across post-harvest operations, including drying, threshing, cleaning, moisture assessment, and storage practices. Although traditional practices remain integral to smallholder farming systems, their continued dominance limits the effectiveness of improved crop varieties, as genetic potential cannot be fully realized without adequate post-harvest management. Therefore, improving productivity in chickpea systems requires a more integrated approach that combines varietal improvement with enhanced seed handling and storage technologies. To address these challenges, the study recommends the promotion of affordable and context-appropriate improved storage technologies, such as hermetic storage systems, alongside strengthened extension services to enhance farmer awareness and technical capacity. Capacity-building interventions should focus on improved seed processing practices and the introduction of simple, low-cost moisture assessment tools. In addition, integrating post-harvest management into existing agricultural development programs and supporting community-based storage solutions could substantially reduce losses. Policy support and institutional collaboration are also essential to facilitate dissemination and adoption of improved or/and new technology. Future research should prioritize evaluating the impacts of improved storage technologies on seed quality and quantity, as well as identifying location-specific constraints and adoption barriers to ensure sustainable interventions.

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Supplementary Materials

Appendix A. Different indoor chickpea seed storage mechanisms in central Ethiopia

A. Seed stored in living room with grain and seed of other crops

B. Seed stored in a separate store together with other crops seed

C. Seed stored in a separate store together with grains and seed of other crops

D. Seed stored in separate room together with grain and seed of other cops

These pictures represent different on-farm chickpea seed storage mechanisms practices in central Ethiopia during the 2021/2022 storage season. Source: Photo by Abebe Sori (March 2022)

Appendix B. Different chickpea seed cleaning homemade traditional tools

E. *Mensh/Manshii*/*Qorbi*

F. *Layeda/Lameda/Darba*

G. *Wenfit*/*Gingilcha* (sieve)

H. *Safed/Gundo*

These pictures represent different traditional homemade tools used for chickpea seed cleaning at different stages in the central Ethiopia during the 2021/2022 cropping season.

Source: These Photos are captured by Abebe Sori (March 2022).

SOIL SEED BANK COMPOSITION AND ITS IMPLICATIONS FOR DRY WOODLAND RESTORATION IN ARGO FOREST, BENA-TSEMAY DISTRICT, SOUTHERN ETHIOPIA

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ABSTRACT: Soil seed banks are critical for the natural regeneration of degraded dryland forests. This study provides the first comprehensive assessment of the soil seed bank in the Argo Forest, Bena-Tsemay District, Southern Ethiopia. The study quantified the composition, density, and vertical distribution of the soil seed bank and evaluated its potential for spontaneous vegetation recovery across four land-use types (grassland, woodland, bushland, and bare land) and three soil depths (0–3 cm, 3–6 cm, and 6–9 cm). A total of 84 composite soil samples were collected and subjected to an eight-month greenhouse germination assay. The total seed bank density was 8,232 seedlings m^{-2}. The outcome showed a distinct vertical gradient: species richness and seedling density peaked in the top layer (0–3 cm) and sharply declined with depth. Using Jaccard's and Sørensen's indices, floral similarity was lowest between woodland and bare land (0.16) and highest between grassland and bushland (0.48). Importantly, Analysis of variance, ANOVA revealed a significant difference ($p < 0.001$) between the species composition of the established above-ground flora and the soil seed bank. This stark difference suggests that the in-situ seed bank's ability to support the restoration of the original woody ecosystem is severely limited. As a result, it concludes that passive restoration relying solely on the soil seed bank is unlikely to be sufficient. Active interventions, specifically enrichment planting of native woody species and the implementation of stringent controlled grazing regimes, are essential to accelerate ecological restoration in this dry Afromontane forest.

Keywords/Phrases: Density, Ecological restoration, herbaceous dominance, Seedlings, Vertical seed distribution,

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INTRODUCTION

Dryland ecosystems, encompassing arid, semi-arid, and dry sub-humid regions, represent one of the planet's most expansive and fragile biomes, covering over 40% of the global terrestrial surface (Cherlet et al., 2018). These ecosystems are vital for biodiversity, carbon storage, and the livelihoods of over two billion people globally. Nonetheless, they are increasingly being recognized as centers for desertification and land degradation because of the combined effects of unsustainable human activity and climate change (IPBES, 2018). Ethiopia's drylands, which are undergoing rapid ecological change that threatens both environmental stability and socioeconomic resilience, are a notable instance in this global setting.

The vast dryland areas of Ethiopia are particularly susceptible to increasing climate variability, which can show up as frequent droughts, unpredictable rainfall patterns, and rising temperatures (Conway and Schipper, 2011). The rich mosaic of native flora and fauna that communities rely on is being undermined, rain-fed agriculture is becoming unstable, and water supplies are being depleted as a result of these climate shocks (Sintayehu, 2018; Gezie, 2019; Bogale and Erena, 2022). Anthropogenic stresses, especially unsustainable livestock populations and related overgrazing, exacerbate this climate stress throughout the nation's vast pastoral and agro-pastoral systems (Angassa and Oba, 2008). Large tracts of formerly productive rangelands have been reduced to bare, compacted soil by the ensuing feedback loop, seriously impairing plant communities' natural recruitment, survival, and population dynamics (Zerga et al., 2018). This degradation challenges not only ecological integrity but also the very foundation of pastoral livelihoods, triggering a cycle of poverty and resource depletion (Desta and Coppock, 2004).

Notably, the visible aboveground vegetation is only one aspect of the adaptability and survival of a plant community. The soil seed bank (SSB), a mysterious but essential basement legacy, runs parallel to this. A key element of ecosystem memory, this store of viable, dormant propagules retains the genetic capacity for future recovery while capturing the imprint of previous vegetation (Baskin & Baskin, 2000). By allowing populations to endure adverse times, promoting secondary succession following disturbance, and preserving genetic variety within the landscape, the SSB serves as a defensive buffer against environmental fluctuation (Davy, 2008; de Medeiros-Sarmento et al., 2021). As a result, it is essential to ecological resilience and a crucial factor in determining a system's inherent capacity to recover after degradation (Walck et al., 2011).

The Argo Natural Forest in the Bena-Tsemay district of southern Ethiopia is a prime instance of the ecological significance of the SSB. This environment, which is an array of dry woodland and savanna, is an essential socio-ecological refuge. For the local populations, it offers vital resources such fuel wood, fodder, non-timber forest products, and traditional remedies (Lemenih and Kassa, 2014). However, multiple anthropogenic pressures continuous and frequently uncontrolled grazing, shifting fire regimes, and land conversion for other uses are posing an increasing threat to this lifeline. By reducing seed output, raising seed predation, and changing the soil microenvironment required for seed survival, these disruptions directly endanger the SSB (Wang et al., 2009). Consequently, the depletion of this belowground reservoir directly constrains the ecosystem's innate capacity for natural regeneration. It needs active treatments like planting or seeding because it lacks target species and is dominated by weeds (Bossuyt and Honnay, 2008). However, a diverse native SSB increases climate resilience and speeds up recovery (Warrier and Kunhikannan, 2022).

This research was therefore designed to establish the foundational scientific sympathetic of the soil seed bank (SSB) within the drought-vulnerable Argo Forest, where no prior representation exists. The study addresses this critical gap through three integrated objectives: first, to quantify the floristic composition, density, and vertical distribution of the SSB across the ecosystem's dominant land-use types; grassland, woodland, bushland, and bare land. Second, to assess the degree of floristic similarity between the SSB and the standing aboveground vegetation, a key determinant of regeneration potential. Finally, by synthesizing these empirical findings, the study formulates evidence-based recommendations that critically evaluate the feasibility of passive natural regeneration versus the necessity for active, targeted restoration interventions. This work provides the essential data required to guide effective biodiversity conservation and sustainable forest management strategies for this imperiled dryland ecosystem.

MATERIALS AND METHODS

Study Area

The Argo Forest is located in the Bena-Tsemay District of Ethiopia's Southern Nations, Nationalities, and Peoples' Region, between 05°31′30″–05°37′00″ N and 36°40′30″–36°50′30″ E. Over 80% of the district is characterized by a dry, semi-arid agro-ecology, with the town of Keye Afer experiencing mean annual temperatures ranging from 16°C to 40°C and highly erratic rainfall between 260 and 570 mm. The broader landscape is rugged and undulating, with district elevations varying from 560 to 2300 m above sea level, though the forest is situated primarily between 1400 and 2000 m. This topographical diversity has adopted a variety of soil types, predominantly brown (60%), followed by black (30%) and reddish (10%) soils, which collectively underpin the forest's ecological dynamics (Figure1).

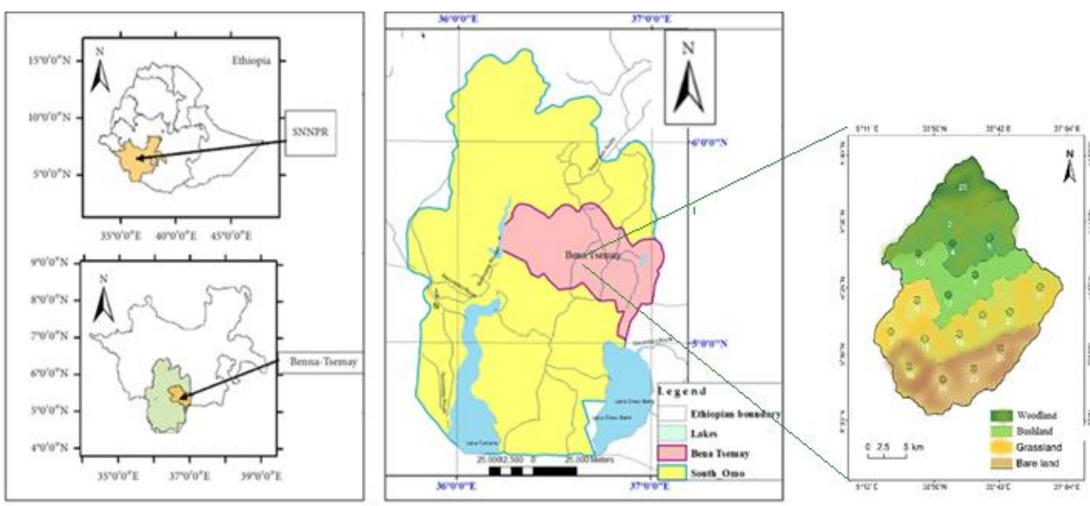

Figure 1. Map of the study area

Design and Methods of Data Collection

This research employed a stratified random sampling design to evaluate the soil seed bank (SSB) across the dominant land-use mosaic of the Argo Forest. The study area is characterized by a vegetation assemblage of grassland, woodland, bushland, and bare land, influenced by anthropogenic activity and grazing. Dominant woody vegetation includes *Combretum-Terminalia* and *Acacia-Commiphora* woodland types, with semi-desert scrubland at lower altitudes. To systematically capture spatial heterogeneity driven by vegetation structure and disturbance regimes, the landscape was classified into four distinct land-use strata based on established definitions: Grassland (herbaceous, grazed), Woodland (scattered trees/shrubs over a grassy understory), Bushland (dense shrubs and small trees with limited ground cover), and Bare land (erosion-prone, sparse or no vegetative cover).

Within each of these four strata, seven main sampling plots were systematically established, totaling 28 plots, each measuring 20 m × 20 m. At each main plot, soil sampling was conducted at five predetermined sub-points: four at the plot corners and one at the center. To assess the vertical distribution of soil seed bank (SSB), samples were systematically collected from a total of 140 points (28 plots × 5) using a sharp knife and spoon across three successive depth intervals: 0–3 cm, 3–6 cm, and 6–9 cm. Following standardized protocols, the five samples from each identical depth layer within a single main plot were thoroughly homogenized to form a single composite sample per depth per plot. This compositing procedure resulted in a final analytical dataset of 84 composite soil samples (28 plots × 3 depths), which were then processed for seed germination trials to determine species composition, density, and viability across the defined land-use and depth gradients (Figure 2)

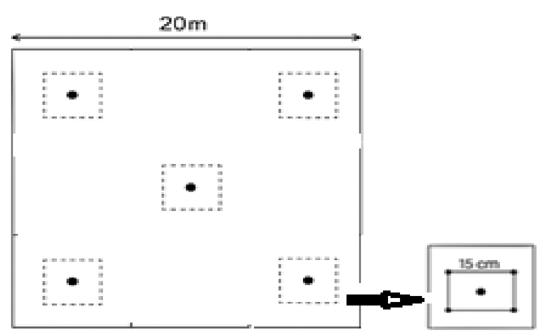

Figure 2. Design of the soil seed bank sampling

Following collection, each composite soil sample was transported to a controlled greenhouse facility at Addis Ababa University for processing. Samples were first sieved through a 2 mm mesh to remove coarse debris, with any seeds retained on the sieve subsequently reintroduced to the fine soil fraction. The seed germination analysis was conducted using the direct germination method, wherein each prepared sample was spread evenly in a labeled plastic tray. Trays were maintained under greenhouse conditions with daily watering. The germination trial was monitored continuously for a period of eight months to ensure maximal seedling emergence, aligning with established protocols for capturing both immediate and dormant seed populations. To prevent competition and shading, all clearly identifiable seedlings were systematically recorded, identified to species level where possible, counted, and then removed from the trays following the methodology used by Dollery (2017). Furthermore, the seedlings that could not be identified in the greenhouse were examined at the Ethiopian National Herbarium (Addis Ababa University) through comparison with authenticated specimens. This meticulous protocol allowed for the accurate quantification of viable seed density and floristic composition within the soil seed bank (Figure 3).

Figure 3. Soil seed bank samples and greenhouse germination

Data Analysis

The data generated from the eight-month seedling emergence trial were subjected to comprehensive statistical analysis to characterize the soil seed bank's composition, structure, and relationship with standing vegetation. The analysis focused on core ecological metrics; species richness, seedling density (reported as seeds m^{-2} for both cumulative and depth-specific values), and diversity. To determine significant differences in soil seed bank attributes among four land-use types (grassland, woodland, bushland, and bare land) and across three soil depths (0–3 cm, 3–6 cm, and 6–9 cm), a one-way analysis of variance (ANOVA) was performed using SPSS software (Version 20). This tested the main effects of land-use type and soil depth, as well as their interaction. Where significant effects were detected, post-hoc comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test at a 95% confidence level ($p < 0.05$). Floristic similarity was assessed using two established coefficients; the Jaccard similarity index was employed to quantify compositional overlap between different land-use types and soil layers:

$$\mathbf{Sj} = \frac{\mathbf{a}}{\mathbf{a + b + c}}$$

Where Sj = Jaccard similarity coefficient

a = Number of species common to both land use types/ soil layers

b = Number of species unique to land use type b / soil layer b.

c = Number of species unique to land use type c/ soil layer c. The coefficient has a value from 0 to 1, where 1 indicates complete similarity and 0 shows a complete dissimilarity.

While the Sørensen similarity index was used to evaluate the degree of floristic similarity between the soil seed bank and the standing aboveground vegetation based on (Levassor *et al*., 1990) by using Sorenson index (SI) by the formula:

$$\mathbf{Ss} = \frac{\mathbf{2C}}{(\mathbf{2C + a + b})}$$

Where Ss= Sørensen Coefficient of similarity, C= the number of species found in both the soil seed bank and the standing vegetation, a is the number of species in the soil seed bank and b is the number of species in the standing vegetation. The coefficient may be 0 to 1 which stands for no similarity or full similarity respectively (Peco et al., 1998).

The vertical distribution of seeds was explicitly analyzed to describe stratification patterns, detailing shifts in density and species composition with increasing soil depth. This multi-faceted analytical approach provided a robust quantitative foundation for evaluating natural regeneration potential and informing management recommendations.

RESULTS

Soil seed bank composition and density

From the soil seed bank of the Argo forest, 62 species, belonging to 48 genera and 29 plant families, were recorded. The Poaceae family was the most prevalent in the soil seed bank, comprising roughly 22% of all species recovered. Asteraceae (17%), Fabaceae (10%), and Solanaceae (5%) were the next most abundant families, ranking second to fourth, respectively. As a result, about 54% of the species recovered from the soil seed bank in the area comprised these four most prevalent plant families. Herbs were the dominant life form, accounting for 76% of species, followed by shrubs (19%), trees (2.6%), and climbers (2.4%) respectively (Figure 4).

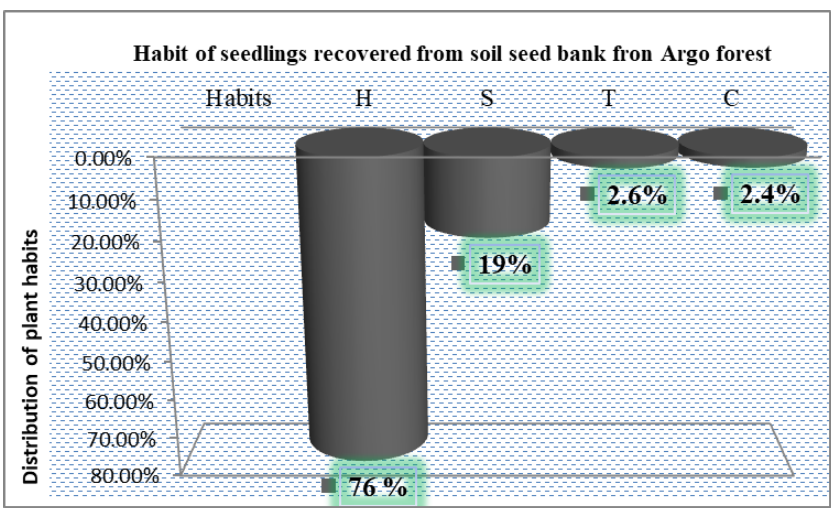

Figure 4. Habits of plant species recovered from soil seed bank in Argo forest.

The ten most dominant species recorded in the study area were *Hyparrhenia pilgeriana* (11%), *Pennisetum petiolare* (9%), *Eleusine floccifolia* (8.7%), *Senna occidentalis* (8%), *Senna petersiana* (7.4%), *Alchemilla abyssinica* (7.1%), *Digitaria ternata* (6.6%), *Cynoglossum lanceolatum* (6.3%), *Oxalis procumbens* (5%), and *Pennisetum thunbergii* (4.8%). Together, these species accounted for approximately 74% of the total frequency in the area, indicating their ecological dominance in the soil seed bank.

Woody species recovered from the soil seed bank included *Acacia seyal*, *Indigofera articulata*, *Calpurnia aurea*, *Olea europaea* subsp. cuspidata, *Rhus natalensis*, *Solanum incanum*, *Dodonaea angustifolia*, *Senna petersiana*, *Croton macrostachyus*, and *Solanum marginatum*.

Species composition varied across land-use types. Grassland exhibited the highest species richness (49 species), followed by bushland (42 species); bare land had the lowest richness (33 species). Seedling density showed a similar pattern: grassland supports the highest density (3316 m^{-2}), followed by woodland (2251 m^{-2}) and bushland (1869 m^{-2}), with bare land showing the lowest density (796 m^{-2}).

Vertical distribution of the soil seed bank revealed that the uppermost soil layer consistently contained the highest seedling density across all land-use types. The uppermost soil layer contributed the largest proportion of seedlings, whereas the deepest layer contained the fewest (Figure 5).

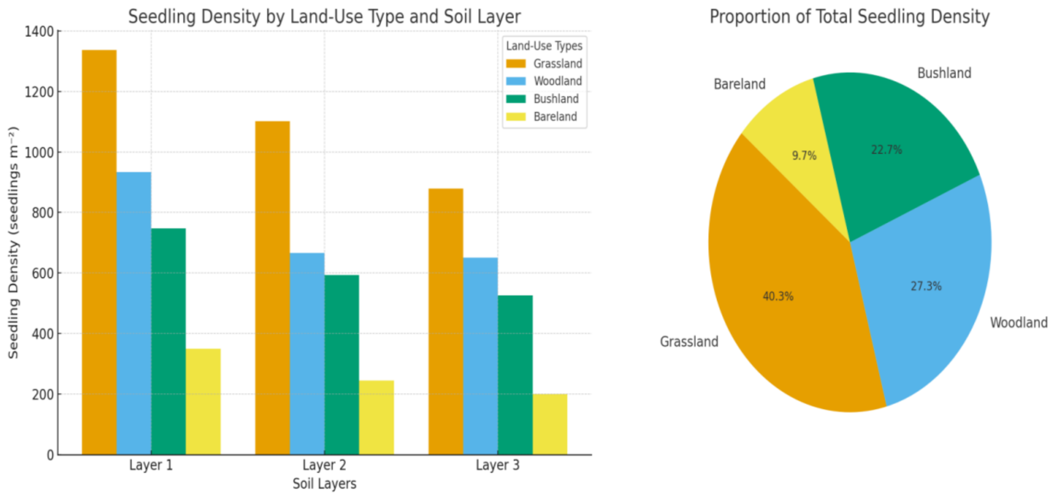

Figure 5. Comparison of seedling density across soil layers and land-use types (Left) and proportion of total seedling density contributed by each land-use type (Right).

Species Frequency by Land Use Type

Seedling frequency data across land-use types showed notable variation in species distribution. In grassland, the most frequent species were *Eleusine floccifolia*, *Hyparrhenia pilgeriana*, *Pennisetum petiolare*, *Alchemilla abyssinica*, *Argemone mexicana*, *Digitaria ternata*, *and Poa schimperiana*, which together accounted for 44% of the total frequency in this land use type.

Cynoglossum lanceolatum, *Dodonaea angustifolia*, *Galinsoga parviflora*, *Rhus natalensis*, *Bidens pilosa*, *Laggera crispeta*, *Torilis arvensis*, and *Solanum marginatum* were the most frequent species in the woodland soil seed bank, together representing approximately 30% of the total frequency for this land use type. In contrast, the least frequent species *Alchemilla abyssinica*, *Ageratum conyzoides*, *Artemisia abyssinica*, *Argemone mexicana*, and *Solanum marginatum* each contributed less than 1% to the total frequency in this land use type.

Bushland was dominated by *Solanum incanum*, *Acacia seyal*, *Senna occidentalis*, *Caylusea abyssinica*, *Indigofera articulata*, *Ocimum gratissimum*, and *Leucas martinicensis*. In contrast, *Dodonaea angustifolia*, *Rhus natalensis*, and *Bidens pilosa* exhibited the lowest frequencies in this habitat.

Conversely, the most frequent species on bare land were *Alchemilla abyssinica*, *Bidens pilosa*, *Argemone mexicana*, *Ageratum conyzoides*, *Eleusine floccifolia*, and *Hyparrhenia pilgeriana*. Most species common in other land-use types were either rare or entirely absent on bare land.

Species Composition and Similarity across Land Uses and Soil Layers

The soil seed bank analysis revealed a vertical stratification of species. Several woody species were restricted to the upper soil layer, including: *Acacia seyal*, *Euclea divinorum*, *Calpurnia aurea*, *Grewia bicolor*, *Croton macrostachyus*, *Olea europaea* and *Solanum marginatum*

Species shared between the first and second soil layers included *Crotalaria incana*, *Dodonaea angustifolia*, *Linum usitatissimum*, *Rhus natalensis*, *Senna occidentalis*, *Vernonia amygdalina*, *Solanum incanum*, and *Senna petersiana*. Overall, most woody species were confined to the first two layers, while herbaceous species were distributed throughout all three soil layers.

Jaccard's similarity coefficient (JCS) analysis revealed distinct patterns in species composition across both land-use types and soil seed bank layers.

Among land-use types, grassland and bushland exhibited the highest floristic similarity (JCS = 0.48), followed closely by woodland and bushland (JCS = 0.43). In contrast, the lowest similarity was found between woodland and bare land**.**

A similar analysis of the soil seed bank showed the highest species similarity between the first and second soil layers (JCS = 0.68). The similarity between the second and third layers was moderate (JCS = 0.42), while the first and third layers shared the least number of species (JCS = 0.36). The Jaccard's Similarity Coefficient (JCS) Values were specified (Table 1 a & b).

Table1 a. Similarity between land-use types

Land Use Type	Grassland	Woodland	Bushland	Bare Land
Grassland	—	0.41	0.48	0.27
Woodland		—	0.43	0.16
Bushland			—	0.18
Bare Land				—

Table 1b. Similarity between soil seed bank layers

Soil Layer	Layer 1	Layer 2	Layer 3
Layer 1	—	0.68	0.36
Layer 2		—	0.42
Layer 3			—

To assess the similarity between the soil seed bank and the standing vegetation across different land-use types, both Jaccard's Coefficient of Similarity (JCS) and Sørensen's Similarity Index (SI) were calculated based on species composition. In grassland areas, 22 species were exclusive to the soil seed bank, 50 spices were unique to the aboveground vegetation, and 13 species were shared, resulting in a JCS of 0.153 and an Ss of 0.265. Woodland areas had 26 species exclusive to the soil seed bank, 48 to the standing vegetation, and 15 common species, yielding a JCS of 0.169 and an Ss of 0.288. In bushland, 27 species were found only in the soil seed bank, 60 were exclusive to the standing vegetation, and 17 were common to both, resulting in a JCS of 0.163 and an Ss of 0.281. Among the three land-use types, woodland showed the highest similarity between the soil seed bank and standing vegetation, as indicated by both indices (Table 2).

Table 2. Jaccard's and Sørensen Coefficient of similarity between species composition of soil seed bank and the above ground vegetation

Land-Use Type	Exclusive to Seed Bank (A)	Exclusive to Standing Flora (B)	Shared Species (C)	JCS	Ss
Grassland	22	50	13	0.153	0.265
Woodland	26	48	15	0.169	0.288
Bushland	27	60	17	0.163	0.281

A one-way analysis of variance (ANOVA) revealed a statistically significant interaction between land-use type and vegetation component on species richness ($p < 0.001$), indicating that the difference in species richness between the soil seed bank and standing vegetation varied significantly across land-use types. Post-hoc comparisons using Tukey's HSD test showed that species richness in the standing vegetation was significantly higher than in the soil seed bank across all land-use types. Notably, standing vegetation in bushland exhibited the highest species richness, which was significantly greater than all other land-use and vegetation groups ($p < 0.05$). However, no significant differences in species richness were observed among the soil seed bank groups across land-use types (Table 3).

Table 3. Analysis of variance (ANOVA) showing a significant difference in composition between land use types of seed bank and standing vegetation (sig. at $p < 0.05$)

Comparison	Mean Difference	p-value	Significant (p < 0.05)
Grassland - Standing vs. Grassland - Seed Bank	~28	< 0.001	Yes
Woodland - Standing vs. Woodland - Seed Bank	~22	< 0.001	Yes
Bushland - Standing vs. Bushland - Seed Bank	~33	< 0.001	Yes
Bushland - Standing vs. Grassland - Seed Bank	~38	< 0.001	Yes
Bushland - Standing vs. Woodland - Seed Bank	~34	< 0.001	Yes
Woodland - Standing vs. Grassland - Seed Bank	~26	< 0.001	Yes
Grassland - Seed Bank vs. Woodland - Seed Bank	~4	> 0.05	No
Bushland - Seed Bank vs. Grassland - Seed Bank	~5	> 0.05	No
Bushland - Seed Bank vs. Woodland - Seed Bank	~2	> 0.05	No

DISCUSSION

The analysis of the Argo Forest's soil seed bank (SSB) reveals a complex ecological reservoir with significant implications for the ecosystem's resilience and restoration potential. Characterized by high species richness (62 species), the SSB composition exhibits a pronounced dominance of herbaceous life forms over woody species, a pattern consistent with findings in other seasonally dry tropical forests and woodlands (Dölle and Schmidt, 2009; Douh et al., 2018). This predominance highlights the established ecological principle that SSBs function as critical banks of viable, dormant propagules, buffering plant communities against threatening environmental stresses (Baskin and Baskin, 1998). The prevalence of herbaceous species can be attributed to a suite of adaptive traits aligned with disturbance-prone environments. Their short life cycles, high fecundity, and rapid reproductive turnover inherently predispose them to forming large, persistent seed banks (Klimešová et al., 2025). This adaptive strategy is profoundly influenced by seed morphology; herbs, grasses, and sedges typically produce smaller, more compact seeds compared to woody species. This diminutive size facilitates passive burial into deeper soil strata via abiotic processes like rain splash, thereby enhancing seed longevity by avoiding surface predation and buffering against temperature and moisture extremes (Maun, 1998; Fenner, 2017).

In stark contrast, the ecological strategy of many native woody species within this dry Afromontane system appears centered on different regeneration niches. Species within dominant genera like *Acacia* and *Combretum* often produce larger, nutrient-rich seeds adapted for immediate or rapid germination following dispersal, a trait favoring seedling establishment in competitive understory conditions or during brief favorable windows (Vandelook et al., 2008). This strategy typically results in the formation of transient or short-term persistent seed banks, where seeds either germinate quickly or lose viability within a single to a few seasons (Salazar et al., 2011). Consequently, their representation within the SSB is constrained. Additional limitations include slower reproductive cycles, higher susceptibility to vertebrate and insect predation due to larger seed size, and greater vulnerability to fungal pathogens in the soil, all factors that collectively diminish their seed bank density (Dalling et al., 2011; Tiebel et al., 2018).

This life-form contradiction drives the central finding of pronounced compositional dissimilarity between the SSB and the standing vegetation, a result corroborated by studies in analogous Ethiopian and East African ecosystems (Senbeta and Teketay, 2001; Mengistu et al., 2005). The low Sørensen similarity coefficient quantified this disconnect, indicating that the standing woody flora is poorly represented by dormant seeds in the soil. This disparity is not inconsistent but rather a predictable outcome of divergent regeneration strategies: a persistent seed bank dominated by herbaceous flora versus a standing vegetation structure dominated by woody species reliant on a transient seed bank or other regeneration mechanisms like resprouting (Chaideftou et al., 2009). Furthermore, the inherently low seed bank densities typical of dryland regions, exacerbated by the study area's drought-prone climate and sandy soils, further limit long-term seed survival and accumulation.

The observed exponential decline in viable seed density and species richness with increasing soil depth, with the majority of seeds (particularly woody species) confined to the upper 0–3 cm layer aligns with global meta-analyses. This vertical gradient reflects the interplay of dispersal mode, seed morphology, and burial processes. The confinement of larger woody seeds to superficial layers increases their exposure to predation and desiccation, while the deeper burial of smaller herbaceous seeds contributes to a persistent, though floristically distinct, reservoir (Thompson, 1996). The analysis across land-use types; Grassland, Woodland, Bushland, and Bare land demonstrated that spatial heterogeneity in disturbance regimes, microclimate, and biotic interactions significantly shapes SSB structure. The highest floristic similarity (Jaccard Index = 0.48) was observed between Grassland and Bushland, likely reflecting shared histories of intermediate disturbance and similar suites of pioneer and herbaceous species adapted to open-canopy conditions. Variations in species frequency among other land-use types can be attributed to differences in nutrient availability, light penetration (shade conditions), and the intensity and type of anthropogenic pressure, such as grazing and wood harvesting.

The synthesis of these findings yields critical, evidence-based implications for the conservation and restoration of the Argo Forest. Most significantly, the SSB, while rich in herbaceous diversity, constitutes an inadequate reservoir for the natural regeneration of the dominant standing woody flora following severe degradation or clearance. This severely limits the potential for passive natural regeneration to restore forest structure and composition. Therefore, predominant conservation policy must explicitly prioritize the direct protection and sustainable management of the existing standing forest as the primary strategy for maintaining biodiversity and ecosystem function.

For active restoration targeting the recovery of native woody species and forest structure, assisted interventions are essential. Direct seeding of native woody species may have limited success due to predation and edaphic constraints, making the planting of nursery-raised seedlings of target climax and endangered species a more reliable and effective technique (Shiferaw et al., 2018; Lin et al., 2022). Restoration frameworks must be coupled with integrated land management to address the abiotic and biotic barriers to seedling establishment. This includes controlling free-ranging livestock grazing, implementing measured erosion control measures on bare lands, and developing community-based fire management protocols to protect establishing saplings. In conclusion, while the soil seed bank of the Argo Forest features a capacity for ecosystem resilience through its persistent herbaceous component, it simultaneously highlights vulnerability in woody species regeneration. Effective stewardship, therefore, necessitates a dual approach; attentive protection of the standing forest matrix and the application of targeted, active restoration strategies informed by the clear limitations of the dormant seed reserve.

CONCLUSION AND RECOMMENDATIONS

Effective conservation and restoration of degraded ecosystems, particularly in fragile arid and semi-arid regions, requires a thorough understanding of soil seed banks, including their abundance, abundance quantity, diversity, and distribution. In the investigation of the soil seed bank of the Argo forest, 62 species from 48 genera and 29 families were recorded. Four families: Poaceae, Asteraceae, Fabaceae, and Solanaceae dominated the community and together accounted for 54% of all species. The results showed distinct spatial and structural patterns; herbaceous species had the highest density, whereas woody species exhibited very low seedling density. Moreover, bare land had the lowest species density, whereas grassland areas had the highest. With increasing soil depth, a predictable decrease in species richness was also noted. Crucially, the analysis revealed minimal correlation between the standing above-ground vegetation and the soil seed bank. When species are lost from the established flora, this suggests a limited ability for natural regeneration from the seed bank. Therefore, active interventions such as the establishment of nurseries for seedling production and plantation programs are highly recommended for the sustainable management and restoration of the region's priority indigenous species. A successful conservation strategy for the Argo Forest should address both direct threats and the ecosystem's limited natural recovery capacity.

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INTEGRATING SCIENCE AND POLICY FOR BIODIVERSITY CONSERVATION UNDER CLIMATE CHANGE: ECOSYSTEM-BASED APPROACHES IN THE HORN OF AFRICA

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ABSTRACT: The Horn of Africa, which includes desert rangelands, coastal ecosystems, Rift Valley lakes, and Afromontane forests, is a biologically rich and climate-vulnerable region. The loss of biodiversity and ecological services is being accelerated by climate change, land degradation, overexploitation, and governance issues. Forest restoration, rangeland rehabilitation, watershed management, and community-based conservation are examples of ecosystem-based approaches (EbA) that offer integrated solutions for climate adaptation and biodiversity protection. In order to find strategies to improve the science policy interface in the Horn of Africa, this systematic review synthesized peer-reviewed literature from Web of Science, Scopus, Google Scholar, and PubMed, as well as grey literature from Intergovernmental Authority on Development (IGAD), CBD, IPCC, United Nations Environment Programme (UNEP), EBI, and World Resources Institute (WRI) covering publications from 2012 to 2025. Inclusion criteria targeted English-language studies on ecosystem-based approaches in the Horn of Africa, while studies lacking relevance or methodological rigor were excluded. Data were thematically synthesized across ecosystem contexts, threats, interventions, science-policy mechanisms, and policy frameworks. This review assesses EbA programs, examines ecological and sociopolitical contexts, and analyzes obstacles such as data gaps, capacity constraints, fragmented governance, land tenure insecurity, and the impacts of conflict. A framework that emphasizes cross-border cooperation, indigenous knowledge integration, adaptive management, and decentralized governance mechanisms is proposed based on lessons learned from local and global experiences. Ecosystems and communities can be made more resilient to climate change by strengthening the science-policy interaction through capacity building, participatory governance, and targeted investments.

Keywords: Biodiversity, climate change adaptation, ecosystem-based approaches, Horn of Africa, science policy integration

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INTRODUCTION

The Horn of Africa, which includes distinctive plants and animals in Ethiopia, Somalia, Eritrea, and Djibouti, is acknowledged as a global biodiversity hotspot (CBD, 2018; EBI, 2021; Elmi and Hassan, 2025). Human pressures including deforestation, overgrazing, and land degradation are exacerbating the region's rising temperatures, unpredictable rainfall, and frequent droughts, endangering both biodiversity and local livelihoods (Holland *et al*., 2012; IPCC, 2022; Fashing *et al.*, 2022). Potential avenues for biodiversity protection and climate adaptation in this area are provided by incorporating scientific information into policy through ecosystem-based approaches (EbA) (ASSAR, 2021; Feyissa *et al*., 2025).

Pastoralist livelihoods and grassland ecosystems predominate in arid and semi-arid rangelands, including the Borana and Somali areas. These ecosystems provide grazing, biodiversity corridors, and carbon storage (Gebremedhn *et al*., 2023; Feyissa et al., 2025). Eritrean mangroves and other coastal and marine habitats support carbon sequestration, fisheries productivity, and coastline stabilization (UN, 2024; Beaumont *et al*., 2025). Climate change, habitat loss, and unsustainable land-use practices are putting these ecosystems at greater risk (Williams *et al*., 2021). The region's ecological integrity and the livelihoods it supports are under unprecedented pressure as global temperatures rise and extreme weather events occur more frequently (IPCC, 2022).

An integrated strategy that connects policy execution and scientific research is needed to address these issues. EbAs, which emphasize ecosystem restoration and sustainable management while boosting resilience to climate change, have become a potential framework for biodiversity conservation (Cohen-Shacham *et al*., 2016; CBD, 2020). By combining local expertise, adaptive management, and cross-sectoral cooperation, EbAs provide a means of balancing conservation objectives with socioeconomic growth (Reid *et al*., 2019). EbAs can offer a unified approach to coordinating conservation efforts with climate adaptation plans in the Horn of Africa, where governance structures and resource management systems are frequently dispersed (WRI, 2021). However, equitable resource distribution, stakeholder participation, and strong science policy interfaces are necessary for successful implementation (UNEP, 2023). Despite their recognized potential, significant gaps remain in the implementation of EbAs in the region, including limited empirical evidence on long-term effectiveness (Reid *et al*., 2019; Seddon *et al*., 2020), weak institutional coordination across borders, inadequate financial mechanisms (Buchner *et al*., 2022), and minimal integration of local knowledge into policy frameworks (Doswald *et al*., 2014; Ochieng *et al*., 2017).

This review aims to examine the potential of EbAs to improve biodiversity conservation in the Horn of Africa under climate change by synthesizing key scientific discoveries, policy frameworks, and case studies that demonstrate their effectiveness. Specifically, it aims to identify best practices, implementation gaps, obstacles, and prospects for scaling ecosystem-based solutions in the area through the synthesis of data from peer-reviewed literature, policy documents, and institutional reports.

METHODOLOGY

This review employed a systematic literature review approach to synthesize scientific evidence and policy documents on ecosystem-based approaches for biodiversity conservation in the Horn of Africa.

Search Strategy

A comprehensive literature search was conducted across multiple databases including Web of Science, Scopus, Google Scholar, and PubMed for peer-reviewed articles published between 2012 and 2025. The search utilized combinations of keywords: ecosystem-based adaptation, EbA, biodiversity conservation, climate change adaptation, Horn of Africa, Ethiopia," Somalia, Eritrea, Djibouti, science-policy interface, forest restoration, rangeland management, and wetland conservation.

Additionally, grey literature was sourced from institutional websites including the Intergovernmental Authority on Development (IGAD), Convention on Biological Diversity (CBD), Intergovernmental Panel on Climate Change (IPCC), United Nations Environment Programme (UNEP), Ethiopian Biodiversity Institute (EBI), and World Resources Institute (WRI). Policy documents, national reports, and strategy papers were also reviewed.

Inclusion and Exclusion Criteria

Studies were included if they: (1) focused on the Horn of Africa region (Ethiopia, Somalia, Eritrea, Djibouti, and cross-border areas); (2) addressed ecosystem-based approaches, climate change adaptation, or biodiversity conservation; (3) were published in English; (4) were peer-reviewed articles, books, reports, or official policy documents; and (5) were published between

2012-2025. Studies were excluded if they lacked relevance to the research objectives or had insufficient methodological rigor.

Data Extraction and Synthesis

From each included study, the following information was extracted: author(s), year, geographic focus, ecosystem type, EbA intervention type, key findings, policy relevance, and identified barriers or opportunities. The extracted data were synthesized thematically according to: (1) ecosystem contexts and vulnerabilities; (2) climate change and anthropogenic threats; (3) EbA interventions and outcomes; (4) science-policy interface mechanisms; and (5) policy frameworks and integration pathways. Qualitative synthesis was employed to identify patterns, gaps, and emerging themes across the literature.

RESULTS AND DISCUSIION

Ecosystem context of the horn of Africa

With a mosaic of interrelated ecosystems supporting both distinctive wildlife and human livelihoods, the Horn of Africa is a region of remarkable ecological variety (Marchant, 2021). These ecosystems, which range from desert rangelands to highland forests, are all vital to preserving ecological balance and provide necessary services. However, excessive resource usage, land degradation, and climate change are putting more strain on them. Designing successful conservation and climate adaptation strategies requires an understanding of their unique traits and vulnerabilities.

Forests: Biodiversity Refuges and Climate Regulators

For endemic species like the Ethiopian wolf (*Canis simensis*) and the mountain Nyala (*Tragelaphus buxtoni*), the Afromontane and dry forests of the Horn of Africa, especially in

Ethiopia and South Sudan, are essential havens (EBI, 2021). Additionally, by protecting watersheds, these forests boost agricultural output, sequester carbon, and control regional hydrology. However, their integrity is threatened by deforestation brought on by fuelwood collection, illicit logging, and agricultural development, which lessens their ability to mitigate the effects of climate change (Gole *et al*., 2022). To protect these vital ecosystems, conservation initiatives must place a high priority on community-based forest management, sustainable land-use planning, and reforestation.

Wetlands and Lakes: Hubs of Aquatic Biodiversity

Among Africa's most ecologically significant freshwater systems, the Rift Valley lakes including Lake Turkana and Lake Abaya support a variety of fish species, migrating birds, and regional fisheries (Holland *et al*., 2012; Wendimu and Tekalign, 2024). Additionally, these wetlands serve as natural water storage, preventing droughts and maintaining agricultural irrigation. However, pollution, overfishing, and hydrological changes brought on by climate change are destroying these ecosystems, endangering food security and biodiversity (Ogutu-Ohwayo *et al*., 2023). To protect these essential aquatic habitats, transboundary conservation agreements and integrated water resource management are required.

Rangelands: Sustaining Pastoralist Livelihoods and Carbon Storage

Pastoralist populations in the Borana and Somali regions depend on the large dry and semi-arid rangelands for livestock grazing and forage resources (Flintan *et al*., 2023). Because deep-rooted vegetation stabilizes soils and lessens erosion, these ecosystems are also essential for sequestering carbon. However, protracted droughts, excessive grazing, and land fragmentation are causing desertification, which threatens pastoral livelihoods and ecological resilience (Megersa *et al*., 2024). To preserve these ecosystems in the face of shifting climatic circumstances, sustainable rangeland management which includes drought-resistant forage cultivation and rotational grazing is crucial.

Coastal and Mangrove Ecosystems: Buffers against Climate Extremes

Large mangrove forests that prevent coastline erosion, sustain marine species, and store substantial amounts of "blue carbon" can be found in the Horn's coastal regions, especially in Somalia and Eritrea (UN, 2024). These habitats are essential to fisheries, which give coastal communities food and revenue. However, these habitats are being deteriorated by pollution from urban growth, overharvesting of mangroves for charcoal, and increasing sea levels (Huxham *et al*., 2023). Important tactics to improve coastal resilience include bolstering marine protected areas, encouraging alternative livelihoods, and repairing damaged mangroves.

Interconnected Challenges and the Need for Holistic Approaches

Despite the unique dangers that each ecosystem faces, human activity, wildlife migrations, and hydrological cycles connect them. Deforestation in highlands, for example, might worsen water scarcity downstream, impacting rangelands and wetlands (Elmi and Hassan, 2025). On the other hand, cross-system benefits might result from sustainable management in one sector. By encouraging landscape-scale conservation, climate-smart agriculture, and community-led stewardship, Ecosystem-based Adaptation (EbA) provides a framework to address these connections (Ndubuisi *et al*., 2025). Policymakers and conservationists may create integrated strategies that improve biodiversity conservation and increase climate resilience throughout the Horn of Africa by acknowledging the interdependence of various ecosystems.

Climate change and other threats

Threats to the Horn of Africa's biodiversity are numerous and interrelated. As a threat multiplier, climate change exacerbates already-existing pressures from human activity and governance issues. Extreme weather events, unpredictable rainfall patterns, and more frequent and severe droughts are all consequences of the region's warming rates exceeding global norms (Funk *et al*., 2024). By changing species ranges, phenology, and ecological interactions, these climatic changes put ecosystems under direct stress. Direct anthropogenic forces are also getting stronger at the same time. The main areas of biodiversity are being undermined by habitat loss and fragmentation brought on by urban growth, unsustainable forestry, and agricultural expansion (Ayeni *et al*., 2023). Natural capital is being depleted by overexploitation of resources, such as overfishing in freshwater and marine systems and the unsustainable harvesting of timber and non-timber forest products (Parera *et al*., 2025). Furthermore, conservation efforts are hampered and effective policy implementation is hampered by underlying socio-political factors including fragmented governance, a lack of institutional capacity, and political instability and violence in some regions (Holland *et al*., 2012; ACPC, 2020). The combination of climate change and human-caused hazards calls for immediate and comprehensive conservation strategies.

Ecosystem-based approaches (EbA)

In the Horn of Africa, ecosystem-based approaches (EbA) have become essential tactics for tackling the twin problems of biodiversity loss and climate change. According to Cohen-Shacham *et al*. (2016), these nature-based solutions improve resilience by interacting with natural systems and offer numerous advantages to human communities and ecosystems. Through case studies and best practices, the area has implemented a variety of EbA solutions across varied ecosystems, showcasing their efficacy.

Table 1. Summary of Ecosystem-based Adaptation (EbA) Approaches in the Horn of Africa

Ecosystem Type	EbA Intervention	Key Outcomes	Location/Example	Sources
Afromontane Forests	· Community managed area enclosures; · agroforestry with native shade trees	· 35% increase in woody plant cover; · 40% increase in farmer incomes; · 80% preservation of forest bird diversity	Tigray, Oromia (Ethiopia)	Beyene *et al*. 2024; Gole *et al*. 2022; Megersa and Hailu 2021
Rangelands	· Rotational grazing; · reseeding native grasses; · traditional drought coping + early warning systems	· 25% increase in vegetation cover; · 30% rise in cattle productivity; · 50% reduction in cattle mortality during droughts	Borana (Ethiopia); Somaliland	Sircely *et al*. 2022; Flintan *et al*. 2023; Megersa *et al*. 2024
Wetlands & Lakes	· Terracing; · check dams; · riparian buffer strips; · watershed restoration	· 40% reduction in sediment loads; · improved water quality for 200,000 users; · wildlife corridor restoration	Lake Tana; Awash River (Ethiopia)	CBD, 2018; Lemenih and Techel, 2020; EBI 2021
Coastal & Mangrove	· Mangrove reforestation; · community-managed marine protected areas; · sustainable fishing quotas	· 500+ ha mangrove restored; · 35% increase in fish catches; · 45% fish stock recovery	Red Sea (Eritrea); Puntland (Somalia)	UN, 2024; Huxham *et al*. 2023

Transboundary Ecosystems	· Joint cross-border programs; · standardized vulnerability assessments	within 3 years · 18% increase in plant cover; · reduced grazing-related conflicts	Kenya-Ethiopia border (IGAD initiatives)	Flintan *et al.*,2023; IGAD 2023

Forest Restoration and Sustainable Management

Degradation has been remarkably reversed in Ethiopia's highlands through community forestry and area enclosures (Megersa and Hailu, 2021). Within five years of creating enclosures, research conducted in Tigray found a 35% increase in woody plant cover, along with increases in soil fertility and water retention (Beyene *et al*., 2024). In addition to preserving 80% of the original forest bird variety, agroforestry systems that combine coffee production with native shade trees have increased farmer incomes by 40% (Gole *et al*., 2022). These strategies show how EbA can use science-informed, participatory management to balance conservation with livelihood demands.

Rangeland Rehabilitation for Pastoral Resilience

By rotating grazing and reseeding native grasses, participatory rangeland management in Borana, Ethiopia, has turned degraded grasslands into productive systems (Sircely *et al*., 2022). Over a ten year period, household surveys suggested a 30% rise in cattle productivity, whereas satellite data showed a 25% increase in vegetation cover (Flintan *et al*., 2023). Similar initiatives done in Somaliland reduced cattle mortality during dry spells by up to 50% by combining traditional drought coping techniques with contemporary early warning technologies (Megersa *et al*., 2024). These examples show how combining scientific monitoring with traditional knowledge can improve social and ecological resilience.

Watershed and Wetland Conservation

Terracing, check dams, and buffer strips are examples of integrated soil-water conservation techniques that increased agricultural yields while reducing sediment loads by 40% in the Lake Tana watershed (CBD, 2018). In addition to providing clean water for 200,000 downstream customers, riparian restoration along the Awash River established wildlife corridors that helped endangered animals like the Ethiopian wolf return (Lemenih, 2020**;** EBI, 2021). The watershed-scale thinking required for successful EbA implementation is demonstrated by such interventions.

Coastal and Marine Ecosystem Restoration

Mangrove reforestation projects in Eritrea's Red Sea coast have restored over 500 hectares of critical habitat since 2015, increasing fish catches by 35% and protecting coastal communities from storm surges (UN, 2024). In Somalia's Puntland region, community-managed marine protected areas combined with sustainable fishing quotas allowed fish stocks to recover by 45% within three years (Huxham *et al*., 2023). These successes demonstrate EbA's potential to address both conservation and climate adaptation needs in coastal zones.

Policy Integration and Scaling Up

While these case studies demonstrate the potential of EbA, greater policy integration is necessary for its broader adoption. Although EbA principles have been incorporated into national planning through Ethiopia's Climate Resilient Green Economy strategy, there are still gaps in the local implementation (Reid *et al*., 2019). Despite providing platforms for regional cooperation, transboundary projects like the IGAD Biodiversity Policy Framework require improved financial methods (UNEP, 2023). Future initiatives must concentrate on bolstering communities' land rights, integrating EbA into climate policies, and creating creative funding through carbon markets and ecological service payment (WRI, 2021).

Science-Policy Interface

Researchers, legislators, and communities must work together for EbA to be effectively incorporated into policy. Ethiopia has created a number of national frameworks, such as the Sixth National Biodiversity Strategy and Action Plan (FDRE, 2019; FDRE, 2021; EBI, 2021), National Adaptation Plan (NAP-ETH), and Nationally Determined Contribution (NDC). Cross-border coordination is made possible by regional policies like the IGAD Climate Adaptation Strategy (IGAD, 2023).

However, considerable impediments prevent its integration. Knowledge gaps, restricted data accessibility, insufficient institutional capacity, fragmented governance, and financing constraints impede EbA mainstreaming (ACPC, 2020; CBD, 2018). Socio-political instability and local disputes also decrease the effectiveness of conservation measures (Holland *et al*., 2012). Climate change poses significant challenges to the Horn of Africa's biodiversity hotspot, as warming rates exceed global norms (Funk *et al*., 2024). While Ecosystem-Based Adaptation (EbA) provides integrated solutions, there are still gaps between scientific study and governmental action.

Policy Frameworks for Ecosystem-based Adaptation Integration

An examination of Ethiopia's national plans indicates both a solid ecological underpinning and significant implementation shortcomings. The National Adaptation Plan (NAP-ETH) focuses on watershed restoration using hydrological models; however, it has weak local enforcement. The updated Nationally Determined Contribution (NDC) aims to restore 15 million hectares of land, prioritizing IUCN Red List species; however the financial options are uncertain. The National Biodiversity Strategy and Action Plan (NBSAP) encourage community protected areas based on endemic species protection; however, it does not align with regional frameworks.

Regional Policy Frameworks and Cooperation

Cooperation among Horn of Africa countries is increasingly seen as critical to addressing the transboundary character of climate and biodiversity concerns. The Intergovernmental Authority on Development (IGAD) has been instrumental in promoting collaborative initiatives, including the creation of the Climate Adaptation Strategy (2023), which promotes standardized ecological vulnerability assessments for rangeland management. Regional cooperation through IGAD has resulted in substantial ecological and sociopolitical benefits. The joint Kenya Ethiopia Programme, for example, increased plant cover by 18% while reducing grazing-related conflicts, highlighting the power of coordinated transboundary interventions (Flintan, 2023). Nonetheless, three persistent challenges continue to impede the effective integration of EbA into the region.

First, insufficient knowledge transmission limits research from reaching policymakers; just 22% of EbA studies have direct policy impact; however, focused initiatives such as Ethiopia's Climate Innovation Hub have raised research uptake by 40% (Huxham *et al*, 2023). Second, the absence of indigenous ecological knowledge from 67% of policies undermines cultural and local relevance; Somaliland's Pastoralist Charter stands out as an example of traditional drought forecasting being integrated into official governance (Megersa *et al*., 2024). Third, significant financial constraints, with less than 10% of climate funds devoted to EbA, impede large-scale implementation; nevertheless, new methods such as Kenya's $50 million Green Bond for wetland restoration demonstrate scalable funding routes (CBD, 2020). These instances highlight the importance of integrated governance, strong science-policy links, and diverse financing approaches for scaling EbA in the Horn of Africa.

Pathways for Enhanced Integration

Several pathways are necessary to overcome these hurdles. The first step is to co-produce knowledge by forming rotating scientific policy task forces to enable continual communication and cooperative decision-making. These should include equal representation from ecological researchers, politicians, and local populations to allow for the integration of scientific information with policy demands and indigenous knowledge. The second path focuses on important research areas, such as cost-benefit evaluations of EbA vs traditional "grey" infrastructure and long-term ecological monitoring to track climate and biodiversity trends. The third option entails fostering novel governance mechanisms, such as decentralized County Climate Funds for locally led EbA finance, as well as the establishment of transboundary ecological corridors to sustain biodiversity connection across national borders. A proposed framework for EbA policy integration would proceed in a cyclical manner, from Science to Policy Co-Design, Implementation, Ecological Monitoring, and Feedback, resulting in a continual learning and adaptation cycle.

Figure 1 illustrates the climate–biodiversity nexus in the Horn of Africa as a dynamic and interconnected system, linking climate drivers, ecosystem impacts, livelihoods, and ecosystem-based adaptation (EbA) interventions through bidirectional relationships. Climate stressors such as rising temperatures, variable rainfall, droughts, and extreme events interact with ecosystem processes, leading to habitat degradation, biodiversity loss, and declining ecosystem services, which in turn affect livelihoods and increase vulnerability.

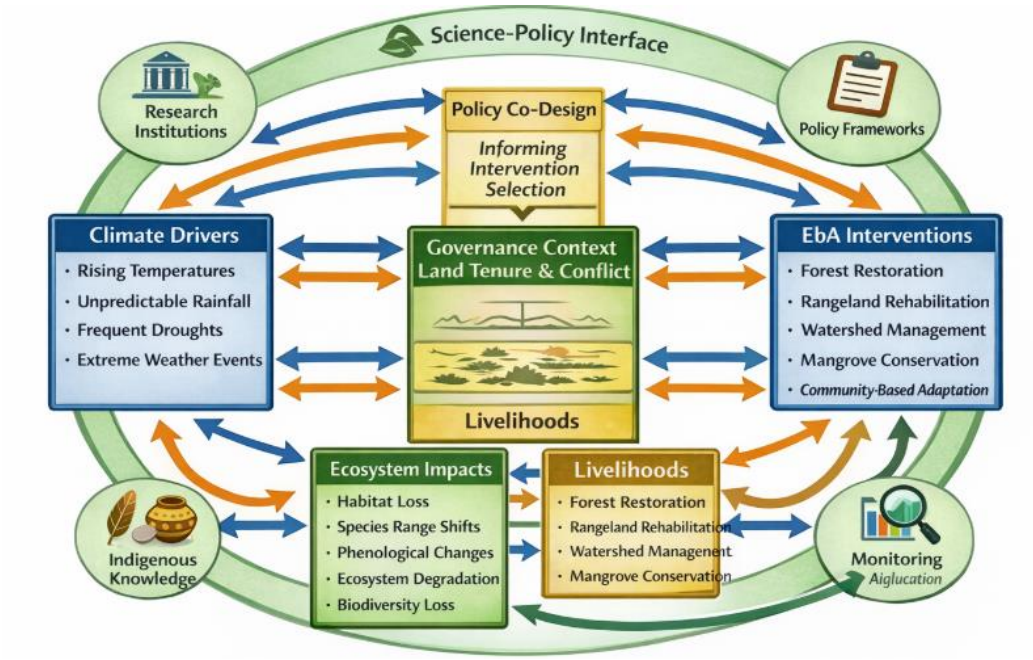

Figure 1. The climate-biodiversity nexus in the Horn of Africa illustrating the pathways from climate drivers to ecosystem impacts and the role of EbA interventions mediated by the science-policy interface.

The framework emphasizes the central role of governance encompassing land tenure, institutional arrangements, and conflict dynamics which cuts across and shapes all components. It also highlights key science–policy interface intervention points at the policy co-design stage, where evidence informs intervention selection, and at the monitoring stage, where evaluation supports adaptive management. A feedback loop from monitoring back to policy co-design underscores iterative learning and adaptive decision making. Overall, the figure demonstrates the complex, non-linear, and adaptive nature of climate biodiversity interactions and the importance of integrated EbA approaches for enhancing resilience and sustainability in the region.

Barriers to Effective Integration

The effective integration of Ecosystem-based Approaches into policy and practice in the Horn of Africa is hampered by a complex set of interconnected barriers. Knowledge gaps and limited data accessibility prevent evidence-based decision-making, while weak institutional capacity at multiple levels of governance undermines the implementation of even well-designed policies. A critical barrier is fragmented governance, where sectoral silos between ministries of environment, agriculture, water, and finance lead to uncoordinated and sometimes contradictory policies. Furthermore, chronic funding constraints limit the scaling up of successful EbA pilot projects, with less than 10% of climate funds targeting nature-based solutions. These challenges are often compounded by socio-political instability and local conflicts, which divert resources and attention away from long-term conservation planning and create an environment where unsustainable resource exploitation can thrive (ACPC, 2020; CBD, 2018; Holland *et al*., 2012).

Future Pathways

To strengthen biodiversity conservation under climate change in the Horn of Africa, a multifaceted approach is required. Key pathways include fostering knowledge co-production among scientists, policymakers, and local communities to ensure that interventions are both scientifically sound and socially relevant (ASSAR, 2021). The adoption of advanced geospatial tools and species distribution models is essential for effective planning, monitoring, and forecasting ecological responses to climate change (IPCC, 2022). Policy mainstreaming is critical, which involves integrating EbA principles into all relevant sectoral and regional development plans to ensure coherence and maximize synergies. Enhanced regional collaboration through bodies like IGAD is necessary for cross-border ecosystem management, given the transboundary nature of many ecosystems and climate impacts (IGAD, 2023). Concurrently, targeted capacity building at both institutional and community levels is needed to empower stakeholders to participate in and lead conservation efforts (ACPC, 2020). Finally, securing sustainable financing through innovative mechanisms such as blended finance, payments for ecosystem services, and green bonds is imperative to scale up successful EbA initiatives and ensure their long-term viability (Feyissa *et al*., 2025).

CONCLUSION

Ecosystem-based approaches are essential for simultaneously addressing biodiversity conservation and climate adaptation in Horn of Africa. The region's unique biodiversity, coupled with its acute vulnerability to climate change, demands solutions that are integrated, sustainable, and equitable. This review has highlighted the significant potential of EbA to deliver multiple benefits for both ecosystems and human communities, from forest restoration in the highlands to mangrove rehabilitation along the coasts. However, realizing this potential requires a concerted effort to strengthen the science-policy interface. This involves bridging critical knowledge gaps, overcoming governance fragmentation, and securing adequate and sustained financing. By prioritizing the integration of local knowledge, investing in capacity building, and fostering robust regional collaboration, stakeholders can enhance the resilience of both ecosystems and communities, securing a more sustainable future for the Horn of Africa in the face of a changing climate.

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For books with one author includes the following:

Example: One author AND first edition: Acquaah, G. 2012. Principles of plant genetics and breeding. Oxford: Wiley-Blackwell.

Example: One author AND NOT the first edition Dahl, R. 2004. Charlie and the chocolate factory. 6th ed. New York:Knopf.

Books with Two or More Authors: Example:

Desikan, S. and Ramesh, G. 2006. Software testing. Bangalore, India: Dorling Kindersley.

For Chapters in Edited Books:

Harlan, J. R. 1971. On the origin of barley: a second look. In: R. A. Nilan, ed., *Barley Genetics vol.* II *Proc. 2nd Barley Genetics Symposium*. Washington State Univ. Press, Pullman, pp. 45 - 50.

Multiple Works by the Same Author:

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Example: Brown, D. 1998. Digital fortress. New York: St. Martin's Press. Brown, D. 2003. Deception point. New York: Atria Books.

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The standard structure of a print journal citation includes the following components:

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Lemessa, D., Hylander, K. and Hambäck, P. 2013. Composition of crops and land-use types in relation to crop raiding pattern at different distances from forests. *Agriculture Ecosystems and Environment,* **167:71-78.**

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\Example .... (Tesfaye and Girma, 2019).

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Tables should be as editable text and be placed on a separate pages at the end of the manuscript. Number tables consecutively (i.e. Table 1, Table 2 etc.) in accordance with their appearance in the text and avoid vertical lines and shading in the table cells. Table captions should be descriptive and appear above the table. Footnotes and sources to tables should be placed under the table. Larger datasets can be uploaded separately as Supplementary Files.

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