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Determinants of Smallholder Farmers' Dependency on Forest Products: the case of PFM at Kaffa Zone, Southwest Ethiopia

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Abstract

Forest are one of the most essential types of resources for the existence of life which regulates environmental and ecological system, provides environmental services and economically valuable products. Significant percentage of world population relied on forests resources for subsistence, livelihoods, employment and income generation. The objective of this study was to identify and examine factors determining level of households' dependency on forest product income. It is conducted in Gawata and Tello districts of Kaffa zone southwest Ethiopia. Data was collected by household survey, key informant interview and focus group discussion. Multistage sampling method was employed to select sample households. Sample household collect wood from the forest for fire, construction, furniture production, as well as fiber, spices, ferns, stimulants, honey, wild Rhamnus prinoides for home consumption and income generation. They generate a mean income of 12,511.32Ethiopian Birr (ETB) from forest products collection and member of Participatory forest management (PFM) generate 13,263.43ETB more income than non-member households. The dependency level of sample households on forest products' income was 25.87% of total annual income. Land size of household, PFM membership of household, availability of forest land and year of residence in the area positively and significantly affect level of household dependency on forest product income. Promoting forest plantation on own land and engaging households on alternative income sources minimize the dependency level of households on PFM forest

1 Introduction

United nation confirmed that significant percentage of world population relied on forests resources for subsistence, livelihoods, employment and income generation. About 60 million indigenous people are almost wholly dependent on forest; some 350 million people who live within or adjacent to dense forests depend on them to a higher degree for subsistence and cash income (UNFF, 2019). An estimated 57 million rural populations in Ethiopia were engaged in the extraction of one or more of the forest products (UNDP, 2017).

Chilimo and Bonga PFM was established in the year 1996 with support of FARM Africa nd SOS Sahel Ethiopia as the two pilot area (Temesgen et al., 2007). Chilimo PFM have a total of 785 members with 662 male and 123 female (Mamo et al., 2007). While Bonga PFM have a total of 7948 members with 4,304 male and 3,644 females (Abebe, 2021). Study in Dendi district and Bonga forest showed PFM has had a positive contribution on improving households' livelihoods and sustainability of the forest resource as participants got more annual income than non-participants (Abebe, 2021; Getachew & Jimma, 2012).

Southwest Ethiopia, still its large parts covered with natural veg-

etation, is rich in Non-timber forest products (NTFPs), which contribute 24 to 30% of the households' annual income (Chilalo & Wiersum, 2011). Kaffa zone were one of the area with large cover of natural vegetation having large contribution for livelihood of local community.The relative contribution of forest varies from place to place, over time, author to author depending on many factors. Available empirical studies from Africa and Asia show that forest income contributes between 10% and 60% of income for households living in forest landscapes (Damte et al., 2019). In rural communities of Cameroon, Ethiopia, Malawi and Zimbabwe, forest-related activities account for 35-39% of average income of households and in Myanmar 38.82% (Htun et al., 2017; UNFF, 2019). The contributions of forest products to communities in southwest Ethiopia are more than other part of Ethiopia. A study in Bonga forest (47%), Yayu forest (44.7%), and Masha (41.17%) of household annual income were generated from forest product collection (Afeto & Tesfaye, 2022; Asfaw & Etefa, 2017; Melaku et al., 2014).

The level of use and degree of reliance on forests and its importance as a source of subsistence and cash income affected by many socioeconomic, demographic and institutional factors. The most common determinant of household level of dependency on forest product income identified by many authors are family size, sex of household head, age of household head, size of farmland, distance from market and forest, access to credit, level of education of household head, livestock unit, amount of income other than forest income (Damte et al., 2019; Fikir et al., 2016; Mamo et al., 2007; McElwee, 2008). The main focus of this study was to indicate socio-economic, demographic and institutional factors affecting the level of reliance of households on forest products income from PFM forest in Kaffa zone of southwest Ethiopia. The objective of this study was to identify and examine factors determining level of households' dependency on forest product income.

2 Materials and Methods

2.1 Description of the Study Area

This study was undertaken in southwest Ethiopia region Kaffa zone, Gawata and Tello districts. Gawata district is 86km away from Bonga town and 546km from Addis Ababa. The area lies within 07°25'- 7°50'N Latitude and 35°56'- 35°89'E Longitude. It is bordered in the South by Gimbo and Chena district, in the West by Bitta and Gesha district, in the North by Sayilem and Oromia region and in the north east bordered by Oromia region. The district has a total of 30 kebeles of which 27 are rural based kebele administration areas and 3 are urban kebeles. The total population of the district was 91,645 of which male accounts for 44,906 and female accounts 46,739 of the total. The estimated total area coverage of the district is 91,500 hectares. Gewata district is well known by high vegetation cover and most of the surrounding area is covered by tropical rain forest comprising a rich mixture of woody species arranged in many layers. The area is characterized by a long rainy season that extends from March /April to October. The mean annual rainfall of the study area ranges from 1800 mm to 2200mm. The mean temperature of the district ranges from 160c (lowest) and 220c highest. The district is dominated by midland agro ecology which is favorable for coffee production. The major crops grown in the district include coffee, maize, barley, faba bean, chickpea and teff.

Tello district is one of the districts in Keffa zone; it was about 42 km away from Bonga. Geographically it is located in latitude of 070 00′ 00″ to 070 28′ 34″ N and longitude of 220 20′89″ to 360 19′60″E. Tello district is bordered from the south by Cheta, west by Decha, north by Menjiwo, and from the east by the Konta zone and the district has 24 kebeles. The mean annual temperature of the district ranged from 14°C to 17.5°C. The mean annual rainfall of district ranged from 1400-1900 mm. Tello district has a population of 63,252, of whom 31,387 are men and 31,865 women; 3,509 or 5.55% of its population are urban dwellers. The major crops grown in the district include Enset, maize, barley, faba bean, wheat and cardamom.

2.2 Sampling Techniques and Sample Size Determination

Multiple stage sampling was employed for this study, in the first stage from kaffa zone two districts namely Gawata and Tello were selected purposely based on the natural forest availability and its management practice of community member by PFM. In the second stage from each district, two kebeles were selected based on forest availability. In the third stage, a stratified technique was employed to select member of PFM and non-member PFM households using a sampling frame. Sample size was determined by using the formula which was developed by Yamane (1967):

$$n = \frac{N}{1 + N(e)^2} \tag{1}$$

where, n is sample size; N is target population, and e is level of precision. Based on this formula, by assuming level of precision 8%, and given number of households in the study area, sample size was estimated and distributed based on probability proportion to kebele and participant and non-participant households. A total of 185 household were interviewed, 94 households from Gawata district and 91 from Tello district. Out of the sample households, 46.5% were members of participatory forest management and 53.5% were not a members.

2.3 Data Sources and Methods of Collection

Both primary and secondary data sources were used for this study regarding the forest resources, household's participation on participatory forest management, and household's socioeconomic and demographic information. Structured questionnaire were used to generate the primary data from the selected sample households. Focus group discussions (FGDs) was conducted in all four kebeles by participating elders, female, youth and kebele administrators that have better knowledge about the a area and forest resources. Key informants' interview was also conducted to gather necessary information to supplement data collected from selected respondents. Secondary data were collected from published and unpublished documents of different organizations and office report.

2.4 Status of PFM at study area

Tello districts have 15 PFM cooperatives, out of which 8 PFM were supported by Climate Resilient Forest Livelihood (CRFL) and 7

PFM were supported by Reduction of Emission from Deforestation and forest Degradation (REDD++). Gawata districts have 12 PFM cooperatives 8 PFM were supported by CRFL and 4 were supported by REDD++ and Nature and Biodiversity conservation Union (NABU). PFMs in Gawata district covers a total area of 37,971.7 ha of forest land and has total member of 10,404 having 6,147 male and 4,257 female members. Two sample PFM were selected from each district; Saja-Bogenda and Chebero PFM were selected from Gawata district and Sharasha and Deccha PFM were selected from Tello district. Saja-Bogenda PFM has a total area of 900 ha forest land having a total member of 323 having 188 male and 135 female members. Chebero PFM has a total area of 556 ha forest land with 80 members and now only 30 active participants. Decha PFM has a total area of 1904 ha of forest land having 126 total members. Sharasha PFM has a total area of 212ha forest land with 86 male and 14 female members of total of 100 members.

2.5 Methods of Data Analysis

2.5.1 *Descriptive statistics*

Descriptive Statistics such as mean, standard deviation, frequency and percentages were used in the process of describing different socioeconomic conditions of the sample households and forest product income. T-test and q-square test were done to analyses the difference between member ad non-members.

Level of household dependency on forest product income or the relative forest product income is share of forest income in total annual income of households. It is calculated by summing total income households generated from collection of forest products and dividing to total annual income and multiplying by 100.

$$DPFP = \frac{FRINC}{TTINC} \times 100 \quad (2)$$

Where:

- DPFP - Dependency on forest product income id indicated by percent
- FRINC - Total forest product income by Ethiopian Birr
- TTINC - Total annual income of households from different sources in Ethiopian Birr

2.5.2 *Econometric Model*

Determinants of small holder farmers' dependency on forest products' income

The levels of dependency of households on forest products' income are affected by many factors. The dependency level of households or relative forest income are regressed on socio-economic, demographic and other factor variables in order to estimate their effects on the level of dependency of households on forest product income. Hence, the dependent variable is the level of dependency of households on forest products' income which is a continuous variable between 0 and 100, and Ordinary Least Square (OLS) model was used (Gujarat, 2004). The OLS regression is specified as equation (3) and Table 1.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots + \beta_n X_n + U_i \quad (3)$$

Where:

- Y = dependency level of households on forest products' income or relative forest income
- β_0 = intercept
- β_i = Vector of estimated coefficient of the explanatory variables
- X_i = Vector of explanatory variables or factor determining households level of dependency on forest products' income
- U_i = disturbance term or other factor that is not included in the regression but has effect on households level of dependency on forest product income

Table 1: Hypothesized factors that affect dependency level on forest income

Variables	Type of variable	Measurement	Expected effect
Dependency level on forest income	Continuous	Percentage	
Sex of household head	Dummy	1=Male, 0=female	-
Age of household head	Continuous	Year	-
Educational status of household head	Continuous	Year	-
Family size	Continuous	Number	+
Land size	Continuous	Hectare	-
Livestock unit	Continuous	Number	-
Distance of PFM forest from home	Continuous	Kilometre	-
Logarism of total non-forest income	Continuous	Percept	-
PFM membership	Dummy	1=member, 0=non member	+
Availability of own wood land	Dummy	1=yes, 0=no	+
Year of residence	Continuous	Years	+
Training access	Dummy	1=yes, 0=no	+/-

3 Results and discussion

3.1 Socio-economic characteristics

Out of the sample households 82.7% were male headed and 17.3% were female headed. The marital status of sample household were 94.1% were married 2.2% were divorced and 3.8% were widowed. The educational level of the sample household head was 42.16% not joined formal education, 44.33% joined primary education, 12.43% joined secondary education and 1.08% joined college. The age of the sample household ranged from 22 to 75years with a mean of 42.57 years.

The sample households' family members ranged from 2 to 16 with a mean of 7 family members. The land holding size of the sample households ranges from 0 to 4.5 hectare with a mean of 1.67 hectare. There is a significant variation of land holding of PFM member and Non-member with Non-member of PFM have 1.91 ha and higher land holding than member of PFM have 1.43ha of land holding. The pairwise correlation indicates that households with large size of land were not member of PFM. The mean size of sample household wood lots was 0.21 hectare with significant variation between member of PFM and non-member with 1% significance level. The wood lot size of non-member of PFM were 0.31ha, higher than member of PFM 0.1ha, this indicate that PFM members depend on PFM forest for forest product. The correlation between distances of forest demarcated within PFM from home was negatively and significantly correlated with member of PFM. It implies that as distance from PFM forest to home increase households become non-member of PFM. Households around the forest have higher probability of becoming member of PFM. Out of the sample households 46.5% were a member of participatory forest management and 53.5% were not a member.

Table 2: Socio-economic characteristics of sample households

Variable	Total Sample Mean ± sta dev.	PFM member	Non-member of PFM	F	Sig
age of household head	42.57±11.86	43.7	41.6	1.44	0.231
family size	6.87±2.5	6.91	6.84	0.035	0.853
land size in hectare	1.67±1.16	1.43	1.91	8.017	0.05*
woodlot land size in hectare	0.21±0.24	0.1	0.31	46.019	0.000***
Livestock owning (TLU)	4.43± 0.24	4.40	4.46	0.023	0.879

*,**,*** indicates significant at 10%, 5% and 1% respectively.

3.2 Forest product income and level of dependency

Households in the study area collect diversified forest products from PFM forests of Kaffa zone. The major forest product collected by the sample households include construction material, wild food, spice biomass energy, household utensil and farm implement. All of the sample households collect at least fire wood for energy source but the variation was on other type of forest product. This study agree with finding in Masha district, found that diversified forest product collected from forest of Sheka for home consumption and cash income generation (Afeto & Tesfaye, 2022).

Households in the study area generate a mean income of 12,511.32ETB from forest product collection. There is a significant variation of income from forest product collection between member of PFM and non-member at 10% significance level. Member of PFM generate an annual income of 13,263.43ETB per year from forest product collection and non-member of PFM generate 11,857.98 ETB per year from forest product collection from their own wood lot and communal forest. The finding was similar with finding of Abebe (2021) and Girma et al. (2023), those members of PFM secure more income from forest than non-member of PFM.

The dependency level of the sample households on forest product income were 25.87% of total annual income. The sample households generate quarter of their annual income from forest product collection, which was less than the finding in Masha district, household gain 41.17% of total annual income from forest product (Afeto & Tesfaye, 2022). The finding were less than the finding of Melaku et al. (2014) said that communities around natural forest generate 47% of their total annual income from forest. This finding indicates that the dependency level of households around Kaffa forest decrease time to time by diversifying their income sources. The members of participatory forest management generate 28.35% of their total annual income and non-member of PFM generates 23.84% from forest product collection. The finding of this study agrees with earlier finding in the study are by Abebe (2021), who stated that member of PFM generate higher share of their annual income than non-member of PFM.

3.3 Determinants of household dependency on forest product Income

The results of multiple linear regressions indicate that the model best fit the regression analysis and it was significant at 1% and F-value was 22.176. The R-square value indicated that, independent variables explained 66.4% of the variation of the level of dependency of households on forest product income. From a total of twelve explanatory variables seven variables significantly affected dependency level of households on forest product income. Land size of household, PFM membership of household, availability of forest land and year of residence in the area positively and significantly affect level of household dependency on forest product income, while age of household head, family size and logarithm of total non-forest income negatively and significantly affect level of household dependency on forest product income (Table 3).

Age of household head affected the dependency of households on forest product income negatively and significantly at 1% significance level. The dependency level of households on forest product income decreased by 0.307% when the age of household increase

by one year. The finding indicate that younger household head are more dependent on forest product income than older due to labor intensive of forest product collection and limited availability of livelihood income sources for younger households. The finding were in line with Garekae et al. (2017), who indicated that, younger households were more likely to gather more forest products compared to the middle aged and the elderly.

Family size of households negatively affect the level of dependency on forest product income and are statistically significant at p<0.05. The dependency level of households on forest product income decrease by 0.662%, when the family member increases by one person holding other factor constant. Household with large family member are less dependent on forest product income than household with small family member. It is in line with the finding of Vihi et al. (2024) denoted that as household size increase they have opportunity to many livelihood activities that decrease their reliance on forest product income. It contradicts with studies finding in Hammar and northwestern and southern lowlands of Ethiopia, household with large family size depend more on forest income than households with small family member due to labor intensive of forest product collection (Fikir et al., 2016; Teshome et al., 2016).

Table 3: Result of Multiple linear regression model of factor determining household dependency on forest income

R – Square 0.664	F-value 28.302	Sig. 0.000			
Variable		**Coefficients**	**Std. Error**	**t-value**	**Sig.**
Constant		209.778***	14.713	14.258	0.000
Sex of household head		-1.024	1.663	-0.616	0.539
Age of household head		-0.307***	0.097	-3.171	0.002
Educational status		0.211	0.192	1.103	0.272
Family size		-0.662**	0.274	-2.418	0.017
Land size in hectare		3.596***	0.867	4.149	0.000
Total livestock owning		-0.099	0.383	-0.258	0.797
Distance of PFM from home		0.189	0.561	0.337	0.736
Logarithm of total non-forest income		-42.437***	3.637	-11.668	0.000
PFM membership		6.872***	1.594	4.311	0.000
Availability of wood land		5.266***	1.651	3.189	0.002
Year of residence		0.358***	0.082	4.339	0.000
Training access		1.256	1.718	0.731	0.466

*,**,*** indicates significant at 10%, 5% and 1% respectively.

Land size households have positive and significant effect on household's dependency on forest product income at 1% significance level. The dependency level of households on forest product income increase by 3.596% when the size of land holding of household increase by one hectare holding other factor constant. The finding indicates that households with large size of land holding are more dependent on forest product than households with small size of land holding. It might be due to household with large size of land be able to allocate land for forest to collect and produce diversified forest products. The finding contradict with Htun et al. (2017), said that household with small land holding are more dependent on forest income.

Logarithms of total non-forest income have negative and significant effect on household's dependency level on forest product income at 1% significance level. The results of analysis indicate that, the natural logarithm of total non-forest income increase by 1%, the dependency of households on forest product income decrease by 42.437% holding other factor constant. The finding shows that household who generate much income from other livelihood income sources are less dependent on forest product income than households with limited income sources. The result agrees with finding in Myanmar that indicated the negative relation of household income with forest income (McElwee, 2008). An increase in non-forest income decreases forest dependency of households (Mendako et al., 2022).

A member of Participatory Forest Management has a positive and significant effect on household's level of dependency on forest product income at 1% significance level. When a households become a member of PFM its dependency level on forest product income increase by 6.872% compared to non-member of PFM holding other factor constant. The finding indicates that member of PFM are more dependent on forest product income than non-member of PFM. This result is in line with Girma et al. (2023), said that member of PFM generate higher significant income over non-member of PFM and has impact on livelihood improvement of PFM member.

Availability of wood land for household has positive and significant effect on household's dependency on forest product income at 1% significance level. When households have its own woodlot its dependency on forest product income increase by 5.266% compared to household who don't have their own forest land holding other factor constant. The finding implies that households who have wood land are more dependent on forest product income; it may be due to production and collection of diversified forest product from their own forest.

Year of residence of households on specific area have positive and significant effect on households dependency on forest product income. When the year of residence of households on specific area increase by one year its dependency on forest product income increase by 0.358%. The finding indicates that households who stayed long time on specific area are more dependent on forest product income than new comer to the area, it might be due sharing of communal resource and knowledge on available resources in the area. Long-term residents were likely to learn more about the ecological structure, composition, and seasonal patterns of forests and were therefore more skillful at collecting forest products (Birben, 2022).

4 Conclusion and Recommendation

4.1 Conclusion

Forest of Kaffa was mainly managed by the active participation of community member through PFM. Larger area of forest land delineated to forest user groups community members living around forest land. The forest of Kaffa has an importance to the livelihood of local community by providing forest product including construction material, wild food, spice biomass energy, household utensil and farm implement for household consumption and cash income generation. All households in the study area collect at least fire wood for energy source due to unavailability of alternative source of energy. Households in the study area generate a significant share of their annual income from collection of forest product. Being a member of PFM, households' income from forest products will increase by 4.51% compared to non-members. Land size of household, PFM membership of household, availability of forest land and year of residence in the area positively and significantly affect level of household dependency on forest product income, while age of household head, family size and logarithm of total non-forest income negatively and significantly affect level of household dependency on forest product income.

4.2 Recommendation

Local government and supporting NGOs should give much focus for livelihood of forest managing communities and forest bordering households. As their livelihoods are not improved their dependencies on forest increases and negatively affect forest resources. The sample households generate quarter of their annual income from forest product collection and still their dependency on forest income were higher. The availability of alternative income sources and livelihood activities minimize households' dependency on forest product income. Therefore finding other livelihood activities that minimize their dependency on forest resources were needed.

Households with larger forest land on their holding are more dependent on forest product income than with small forest land. Promoting farmers to have forest on their land holding minimize the forest product they collect from PFM forest, so local government should work on planting forests on their land holding. Over exploitation forest product allowed for member of PFM are promoting deforestation, so limiting the type and quantity of forest product collected from PFM forest are beneficial for the existence of forest. Further to know the trend of biodiversity change in the forest under PFM plant biodiversity assessment is needed.

Conflict of interest

The authors declare that they have no conflict of interest.

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Data availability Statement

Data can be made available on the behave of the request

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Diurnal Activity Paflerns And Feeding Habits Of Free-Ranging Colobus Monkey (*Colobus guereza* Ruppell 1835) In Kafa Biosphere Reserve, Southwest Ethiopia

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Activity patterns; diet composition; feeding habits; habitat type; seasonality

Abstract

Understanding primate behavioral ecology is essential for developing effective conservation strategies and promoting sustainable forest management. This study investigated the diurnal activity patterns and feeding habits of free-ranging *Colobus guereza* in Kafa Biosphere Reserve (KBR), southwestern Ethiopia, during 2021. Data were collected in both dry and wet seasons using a scan sampling method, which involved instantaneous behavioral observations of visible individuals at fixed intervals. Focal groups included individuals of different sex and age classes, and observations were conducted systematically throughout the study periods to capture seasonal variation. Each scan lasted 5–10 minutes, yielding a total of 1,303 scans in the dry season and 1,191 scans in the wet season. Behavioral data were categorized into feeding, resting, and traveling activities. A Chi-square test of independence was applied to assess associations between activity type and habitat type within each season, while the Cochran–Mantel–Haenszel test was used to control for seasonal effects. Results indicated that *C. guereza* allocated the largest proportion of its daily activity budget to resting (45.3%), followed by feeding (42%). Significant differences in activity patterns were observed among sex and age classes ($p < 0.05$). Adult females spent more time feeding and resting compared to adult males, sub-adults, and juveniles, whereas younger individuals engaged more frequently in play behavior. Dietary analysis identified 13 tree species, with *Milletia ferruginea* (33%), *Sapium ellipticum* (25%), and *Olea welwitschii* (24%) as the most frequently consumed. Seasonal variation significantly influenced diet composition ($p < 0.05$), with increased consumption of leaves and flowers during the dry season and leaves and fruits during the wet season. Overall, the distribution and persistence of *C. guereza* in Kafa Biosphere Reserve are closely linked to food resource diversity and habitat integrity. The findings highlight the ecological flexibility and apparent resilience of *Colobus guereza* in the Kafa Biosphere Reserve; however, this resilience should not be interpreted as immunity to environmental change. They also emphasize the critical importance of conserving forest ecosystems to sustain primate populations in Ethiopia.

1 Introduction

Primates are among the most ecologically significant and behaviorally complex mammals inhabiting tropical and subtropical forests worldwide. Their relatively large body size, social organization, and diverse feeding strategies make them particularly sensitive to habitat alteration, while also positioning them as important indicators of forest ecosystem health (Estrada et al., 2017; Fashing et

al., 2012). Understanding primate feeding habits and activity patterns is therefore essential for elucidating species-environment interactions and for designing evidence based conservation and habitat management strategies, especially in regions experiencing rapid environmental change.

Colobine monkeys are a distinct subfamily of Old World monkeys distributed mainly across Africa and Asia and are characterized by their specialized foregut fermentation system, which enables efficient digestion of fibrous plant material (Kirkpatrick, 2011; Matsuda et al., 2020). African colobines are currently classified into three genera: *Piliocolobus* (red colobus), *Procolobus* (olive colobus), and *Colobus* (black-and-white colobus) (Groves, 2001, 2007; Zinner et al., 2019). The genus *Colobus* comprises five recognized species: *Colobus guereza*, *C. satanas*, *C. polykomos*, *C. vellerosus*, and *C. angolensis* (Kingdon, 2015). Among these, *Colobus guereza* is the most widely distributed and abundant, occurring across East and West Africa, including extensive portions of Ethiopia (Kingdon et al., 2008; Zinner et al., 2019).

Ethiopia harbors two subspecies of *Colobus guereza*: the nominate subspecies (*C. g. guereza*) and the gallarum subspecies (*C. g. gallarum*), both primarily associated with highland and montane forest ecosystems (Mekonnen et al., 2021; Zinner et al., 2019). These forests represent important refugia for colobines but are increasingly threatened by anthropogenic pressures. Despite the ecological importance and relative abundance of *C. guereza*, detailed behavioral ecological studies remain unevenly distributed across its range, with notable information gaps in southwestern Ethiopia.

Colobus monkeys are predominantly folivorous, feeding primarily on leaves, particularly young leaves that are higher in protein and lower in fiber and secondary compounds (Chapman et al., 2002; Fashing et al., 2007). However, their diet is flexible and may include mature leaves, leaf buds, flowers, fruits, seeds, bark, petioles, and occasionally soil or invertebrates, depending on habitat characteristics and seasonal food availability (Hanya & Chapman, 2013; Kibaja, 2014; Matsuda et al., 2020). Recent studies emphasize that dietary composition in colobines is strongly influenced by temporal variation in plant phenology, forest structure, and human disturbance, which in turn affects their activity budgets and ranging behavior (Mekonnen et al., 2021; Twinomugisha et al., 2018).

The diurnal activity patterns of *Colobus guereza* are shaped by ecological, physiological, and social factors, including food distribution, habitat quality, group size, and age–sex composition (Wijtten et al., 2012; Zhou et al., 2011). Typically, their daily activity budget is dominated by resting and feeding, with relatively limited time allocated to movement and social interactions. High resting time is often associated with the need for prolonged digestion of leaf material and energy conservation strategies linked to a low-quality but abundant food source (Smith et al., 2013; Zhou et al., 2013). Variations in activity budgets across habitats have been documented, particularly in fragmented or disturbed forests, where primates may adjust feeding and movement patterns to cope with altered resource availability (Estrada et al., 2017; Fashing et al., 2007; Onderdonk & Chapman, 2000).

In Ethiopia, forest ecosystems are increasingly threatened by anthropogenic pressures, including agricultural expansion, human settlement, overgrazing, fuelwood collection, timber extraction, and infrastructure development (Nune, 2008; Tolla et al., 2017; Yakob & Fekadu, 2016; Yirga et al., 2019). These drivers of deforestation and forest degradation significantly impact primate populations by reducing habitat quality, fragmenting forest landscapes, and altering plant community composition. The Kafa Biosphere Reserve (KBR), encompassing the area formerly known as Bonga Forest, represents one of the largest remaining moist Afromontane forests in southwestern Ethiopia. It is recognized as a national forest priority area and supports high biodiversity, including populations of *Colobus guereza* (NABU (Nature and Biodiversity Conservation Union), 2017; Vreugdenhil et al., 2012).

Despite its conservation significance, empirical data on the behavioral ecology of *Colobus guereza* in the Bonga Forest remain scarce. Previous studies in other parts of Africa have demonstrated that fine-scale information on feeding habits and activity patterns is critical for understanding species adaptability to habitat change and for informing sustainable forest management (Chapman et al., 2010; Mekonnen et al., 2021; Twinomugisha et al., 2018). However, such baseline ecological data are largely lacking for the KBR.

Therefore, the present study investigated the diurnal activity patterns and feeding habits of free-ranging *Colobus guereza* in Kefa Biosphere Reserve, southwestern Ethiopia. The study placed particular emphasis on diet composition (including plant species and plant parts consumed), diurnal activity time budgets, and the influence of habitat condition (disturbed and undisturbed forest), across groups with different sex–age categories and between seasons.

Specifically, the objectives of the study were to: (1) quantify the diurnal activity time budgets (feeding, resting, moving, and social activities) of *Colobus guereza*; (2) determine the diet composition and major food plant species consumed by the species, including the relative contribution of different plant parts (leaves, fruits, flowers, and others); (3) assess seasonal variation in diurnal activity patterns and feeding habits of *Colobus guereza* between the dry and wet seasons; and (4) compare activity patterns and feeding behavior among different sex–age categories of *Colobus guereza*.

2 Materials and Methods

2.1 Description of the study area

The study was conducted in 2021 in Kafa Biosphere Reserve (KBR), located in the Kaffa Zone of the South West National Regional State (SWNRS), Ethiopia (Figure 1). The Kafa Biosphere Reserve (KBR) covers an area of approximately 760,000 hectares (7,600 km²) in southwestern Ethiopia. It is one of the country's largest remaining tracts of moist Afromontane forest, recognized for its exceptional biodiversity and ecological significance.

The reserve includes a mix of dense forest, wetlands, and agricultural landscapes, and is globally important as the center of origin of wild *Coffea arabica*. Designated as a UNESCO Biosphere Reserve in 2010, KBR supports diverse wildlife, including endemic and threatened species, while also promoting sustainable use of natural resources by local communities The forest lies along the southern boundary of the Reserve, a nationally and internationally important conservation landscape (NABU (Nature and Biodiversity Conservation Union), 2017). The area covers five Woredas of Chena, Gimbo, Menjiwo, Tello, and Decha, but this study was limited to Gimbo and Decha districts, which represent key forest habitats within the KBR. The study area is situated between 7°14′24″ N and 7°16′48″ N latitude and 36°09′36″ E and 36°13′12″ E longitude, approximately 470 km southwest of Addis Ababa and 12 km from Bonga town.

The landscape is dominated by rugged ridges and valleys, forming a predominantly mountainous terrain that gradually levels out toward the Gojeb River (Deraro et al., 2003). The area experiences a humid climate, with mean annual temperatures ranging between 15°C and 22°C (Ethiopian Meteorological Service Agency (EMSA), 2019; Kebede, 2011). The warmest period occurs from February to April, while the highest rainfall is recorded between June and August, with total annual precipitation ranging from 1,401 to 2,000 mm. The Kafa Biosphere Reserve comprises moist evergreen montane forest that supports rich biodiversity, including around 100 bird species and at least 48 mammal species, among which *Colobus guereza* is prominent (Bekele, 2003; NABU (Nature and Biodiversity Conservation Union), 2017).

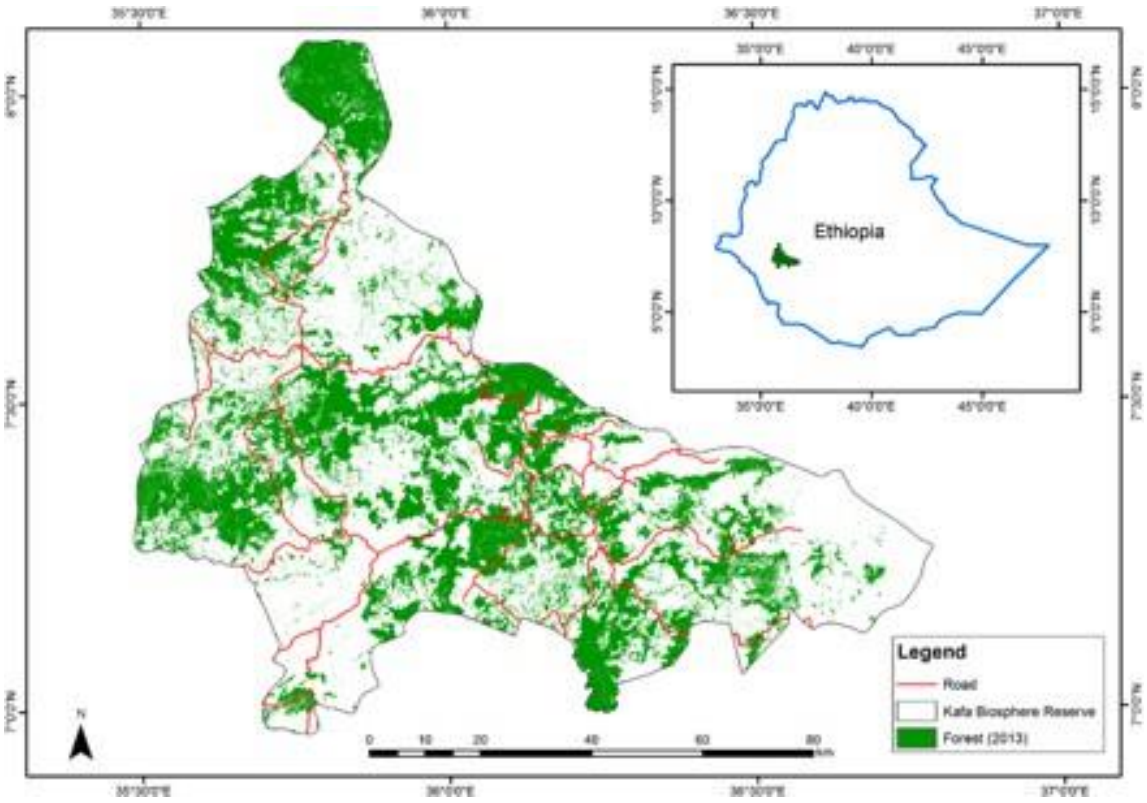

Figure 1: Overview of the UNESCO Kafa Biosphere Reserve location, where five Woredas the study area were located within the reserved. (SOURCE: GOOGLE EARTH; ETHIO-REGION AND ZONE, 2021; USING QGIS VERSION 3.8).

The map presented in this study above (Figure 1) illustrates only the overall extent of the Kafa Biosphere Reserve, highlighting the general distribution of forest cover and major road networks. It does not specifically delineate the boundaries of Gimbo and Decha woredas, which constitute the focal study areas. Furthermore, no spatial classification was applied to distinguish core (relatively undisturbed) and buffer (disturbed) zones. At the time of data collection, clear and consistent demarcations of woreda boundaries and biosphere reserve zonation were not available; therefore, these categories were not incorporated into the map.

2.2 Sampling Method

2.2.1 Preliminary Survey and Study Site Selection

Before formal data collection, a one-week reconnaissance survey was conducted to gather essential information on site accessibility, climate, topography, vegetation types, general faunal presence, and the distribution and preliminary behavior of *Colobus guereza*. Reconnaissance surveys are widely recommended in primate ecological studies to optimize sampling design, identify logistical constraints, and reduce observer bias in structurally complex tropical forests (Jones & Perelman, 2019; Rovero et al., 2018). This initial phase allowed the research team to familiarize themselves with the forest environment, assess the relative abundance and spatial distribution of *C. guereza*, and determine safe and effective observational approaches that minimize disturbance.

During the survey, key habitat types were identified based on vegetation structure, disturbance levels, and topographic variation, following stratification approaches used in forest primate studies (Nielsen et al., 2018; Tokuda et al., 2020). Preliminary observations revealed a mosaic of habitats and complex terrain within the study area. The site was subsequently stratified into disturbed and undisturbed forest zones using a framework adapted from Girma et al. (2018), previously applied for habitat classification in Ethiopian montane forests and have been widely applied in Ethiopian montane forest studies. Specifically, disturbed forests were identified based on evidence of human activities such as selective logging, firewood collection, grazing, trails, and proximity to settlements, combined with structural characteristics such as reduced canopy cover, lower tree density, and a higher proportion of secondary vegetation. In contrast, undisturbed forests were characterized by minimal human interference, continuous canopy cover, intact tree composition, and the presence of mature trees and native under-

story vegetation.

GPS coordinates for each habitat type were recorded using a Garmin GPSMAP 64st receiver to ensure spatial accuracy. These coordinates were imported into QGIS (version 3.8) to digitize habitat strata, estimate their areas, and generate spatially explicit sampling units. GIS-based stratification enhanced the representativeness of sampling across habitat gradients and reduced potential bias from unequal habitat coverage (Sabater Pi et al., 2021; Willi et al., 2019).

2.2.2 *Field Data Collection*

Field data were collected on free-ranging *Colobus guereza* during both the dry season (March–June 2021) and the wet season (July–October 2021) through direct observation. Observations were carried out in two daily sessions: morning and afternoon using established primate behavioral protocols. Behavioral data were recorded at three-minute intervals per hour using instantaneous scan sampling, which involved observing all visible individuals at fixed intervals.

Each scan lasted 5–10 minutes, resulting in a total of 1,303 scans during the dry season and 1,191 scans during the wet season. Observations included individuals from different sex and age classes and were conducted systematically to capture seasonal variation. Behavioral activities were categorized into feeding, resting, and traveling.

To assess activity budgets, scan sampling was consistently applied at regular intervals. In addition, focal animal sampling was used to examine feeding behavior in detail, including identification of plant species, plant parts consumed, foraging duration, and frequency of feeding observations. Plant species were identified using key informants and identification keys. For each observation session, one focal individual per group was randomly selected, with replacement if the individual could not be relocated, while avoiding resampling within the same scan period.

Two focal groups were studied, representing disturbed and undisturbed forest habitats, with group sizes ranging from 3 to 13 individuals. Data collection was conducted by a primary researcher and a trained local assistant to ensure representation of all sex-age categories.

All observations were made using Nikon 10×50 Aculon A211 binoculars, allowing accurate identification of feeding behavior and plant items from a safe distance without disturbing the animals.

2.2.3 *Data Analysis*

All data were analyzed using SPSS version 23. To compare differences in time allocated to various activity patterns across sex–age categories, we used MANOVA. Independent-sample t-tests were applied to examine differences in activity budgets between disturbed and undisturbed habitats. Associations between habitat types and seasonal variations, as well as differences in the proportion of time spent consuming specific plant parts, were evaluated using Chi-square tests. Seasonal variation in plant consumption was assessed with the Mann–Whitney U-test.

To control for multiple comparisons when analyzing multiple categorical variables (activity type, habitat type, and season), we first applied MANOVA to assess the overall effect of habitat type on behavior across dependent variables, avoiding inflation of Type I errors. For categorical variables, the Stratified Chi-square test was used to evaluate relationships while accounting for stratification by season and habitat type.

Feeding behavior was quantified by calculating the percentage of time devoted to specific plant species and plant parts, providing a measure of dietary preferences. Overall dietary composition was expressed as the proportion of each food type consumed during foraging bouts, offering a detailed view of seasonal and habitat-related foraging strategies. These analyses allowed identification of patterns in activity allocation and diet that may reflect ecological adaptations and habitat influences on *Colobus guereza* behavior.

3 RESULTS

3.1 Overall Frequency of Diurnal Activity Paflerns of Colobus Monkeys

At the study site, five major activity categories of *C. guereza* were recorded: feeding, resting, jumping, playing, and grooming, across both Undisturbed Forest (UDF) and Disturbed Forest (DF) habitats. A total of 1,191 activity records were obtained during the wet season and 1,303 during the dry season.

As illustrated in Figure 2, grooming accounted for the smallest proportion of observed activities in both habitats during the dry season. In the disturbed forest (DF), individuals spent a greater proportion of their time resting (25%) and feeding (24%). In contrast, in the undisturbed forest (UDF), jumping was more frequent (22%), followed by resting (21%).

During the wet season, playing behavior was observed less frequently in both habitat types, while resting constituted the largest proportion of the activity budget.

A stratified chi-square test was conducted to evaluate the relationship among activity type, habitat type, and season. The results indicated no statistically significant difference in the overall frequency of activities between habitat types across seasons ($\chi^2 = 4.000$, df = 3, $p > 0.05$)

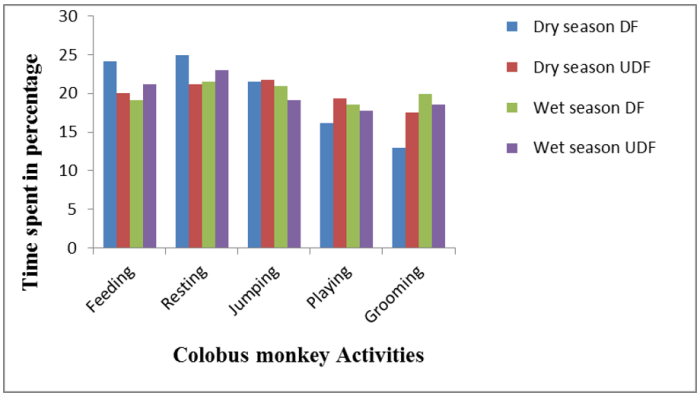

Figure 2: The proportion (%) of the total feeding budget or bout spent on a specific behavior by *Colobus guereza*.

3.2 Morning and Afternoon Variation of Activity Patterns

During the dry season, the frequency of *Colobus guereza* activity patterns observed during morning and afternoon sessions in both habitat types is presented in Figure 3. In the Disturbed Forest (DF), individuals allocated more time to feeding and grooming in the morning than in the afternoon, whereas resting was more frequent in the afternoon. In contrast, in the Undisturbed Forest (UDF), guerezas spent more time on all recorded activities in the afternoon compared to the morning.

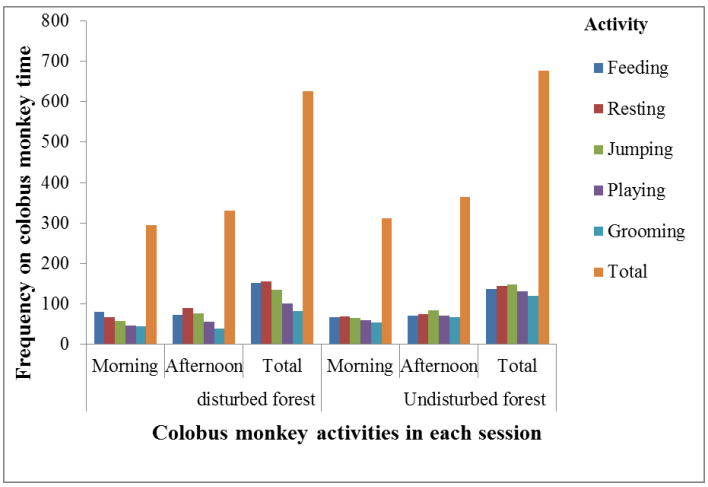

Figure 3: Frequencies of the total feeding bout spent on a specific behavior of *Colobus guereza* during morning and afternoon in disturbed and undisturbed forest in the dry season.

To evaluate differences in activity budgets between habitat types, a multivariate analysis of variance (MANOVA) was conducted, with habitat type (DF vs. UDF) as the independent variable and time spent feeding, resting, and jumping as dependent variables. The MANOVA results indicated a statistically significant overall effect of habitat type on activity patterns during the dry season ($p < 0.05$). Follow-up univariate analyses revealed that time spent feeding, resting, and jumping differed significantly between disturbed and undisturbed forests ($p < 0.05$). However, no significant differences were detected for playing and grooming activities between the two habitat types ($p > 0.05$).

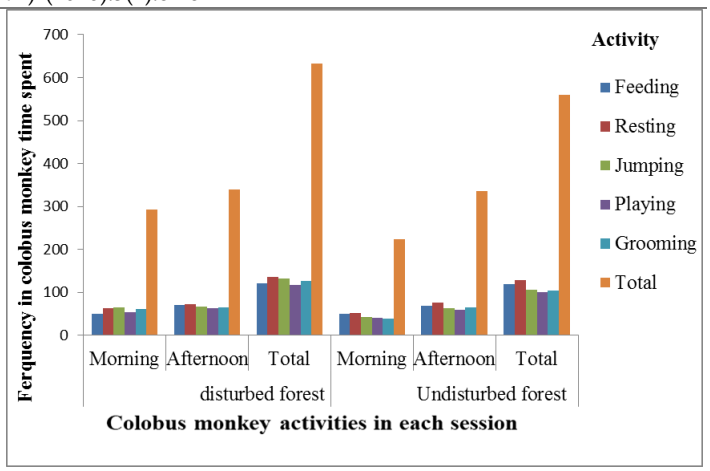

Figure 4: Frequencies of the total feeding bout spent on a specific behavior of *Colobus guereza* during morning and afternoon in disturbed and undisturbed forest in the wet season

Similarly, during the wet season (Figure 4), *C. guereza* in both DF and UDF exhibited higher activity levels across all behavioral categories in the afternoon compared to the morning. A MANOVA was performed to assess habitat-related differences in activity patterns. The analysis showed a significant multivariate effect of habitat type on the combined activity variables ($p < 0.05$). Subsequent univariate tests indicated that time spent feeding, resting, and playing differed significantly between the two habitats ($p < 0.05$), whereas no significant differences were observed for jumping and grooming activities ($p > 0.05$).

Table 1 above shows the time spent by *Colobus guereza* in different activity categories during the dry season, broken down by sex-age groups. Adult males spent less time grooming and more time resting, while adult females spent less time playing and more time feeding. Sub-adults devoted less time to grooming and more time jumping, while young individuals spent less time eating and more time jumping. Among adults, feeding was the most commonly performed activity, followed by resting, whereas for young individuals, feeding was the least frequent activity. Jumping was the most common activity for both young individuals and sub-adults, while playing was the most frequently performed activity by young monkeys compared to the other age groups. Adult females engaged in more activities overall than any other age group.

Table 1: The proportion (%) of the total feeding bout spent on a specific behavior of *Colobus guereza* across different sex and age groups during the dry season.

Activities	Adult males	Adult females	Sub-adults	Young's	Total
Feeding	6.4	8.2	4.4	3.0	22.3
Resting	6.9	7.8	4.9	3.4	23.0
Jumping	3.9	3.9	6.4	7.3	21.5
Playing	3.5	3.1	4.7	6.4	17.7
Grooming	2.5	5.3	3.4	3.9	15.1
Total	23.2	28.3	23.8	24.0	100

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The statistical analysis (ANOVA) revealed that groups containing different sex-age categories significantly influenced the amount of time spent on various activity patterns ($F = 2.790$, $df = 3$, $p < 0.05$). Notably, the mean differences between adult females and sub-adults ($p < 0.05$), adult females and young individuals ($p < 0.05$), and adult males and adult females ($p < 0.05$) were all significant. However, no significant differences were found between adult males and sub-adults ($p > 0.05$), adult males and young individuals ($p > 0.05$), or sub-adults and young individuals ($p > 0.05$) during the dry season.

3.3 Diurnal Variation in Activity Paflerns

Clear diurnal patterns in activity allocation were observed, with differences between habitats and seasons. During the dry season, morning and afternoon activity budgets showed habitat-specific contrasts. In disturbed forest, monkeys devoted more time to feeding and grooming during morning hours, while resting increased markedly in the afternoon. This pattern suggests that individuals may exploit cooler morning conditions for energetically demanding activities and reduce activity later in the day. In undisturbed forest, overall activity levels were higher in the afternoon, reflecting greater behavioral flexibility and possibly better resource availability. Independent sample t-tests demonstrated significant differences between habitats in time allocated to feeding, resting, and jumping during the dry season ($p < 0.05$). However, no significant differences were detected for playing or grooming ($p > 0.05$), indicating that these social behaviors were relatively stable across habitats.

During the wet season, *C. guereza* in both habitats showed increased activity during afternoon sessions. Feeding, resting, and playing differed significantly between disturbed and undisturbed forests ($p < 0.05$), suggesting that habitat quality influenced how monkeys responded to seasonal environmental changes. In contrast, jumping and grooming did not differ significantly between habitats ($p > 0.05$), again highlighting the consistency of certain behaviors irrespective of habitat condition.

3.4 Activity Paflerns by groups containing different Sex-Age Categories

Behavioral time allocation varied markedly among sex–age categories, reflecting differences in energetic requirements, social roles, and developmental stages. During the dry season, adult males spent a greater proportion of time resting and comparatively little time grooming. Adult females devoted more time to feeding and less to playing, emphasizing the importance of energy intake, likely linked to reproductive demands. Sub-adults were characterized by high levels of jumping, while young individuals focused primarily on jumping and playing, with relatively little time spent feeding. Overall, feeding was the dominant activity among adults, whereas locomotor and play behaviors predominated among sub-adults and young monkeys.

Analysis of variance (ANOVA) confirmed that sex–age category significantly influenced activity budgets during the dry season ($F = 2.790$, $df = 3$, $p < 0.05$). Significant differences were detected between adult females and sub-adults, adult females and young individuals, and between adult males and adult females ($p < 0.05$). In contrast, no significant differences were observed between adult males and sub-adults, adult males and young individuals, or between sub-adults and young individuals ($p > 0.05$). These findings indicate that adult females differ most strongly from other groups in their activity allocation, particularly with respect to feeding and resting.

During the wet season, similar but not identical patterns emerged. Adult males spent more time feeding and less time playing, while adult females increased time devoted to feeding and grooming. Sub-adults allocated a greater proportion of time to resting, suggesting reduced locomotor activity during wetter conditions. Young individuals prioritized playing over feeding, consistent with developmental needs and lower energetic constraints. Resting was the dominant activity for sub-adults, whereas playing remained the most frequent behavior among young monkeys. Adult females engaged more frequently in feeding and grooming than any other group, underscoring their central role in maintaining energy balance and social cohesion.

Statistical analysis again demonstrated a significant effect of sex–age category on activity time during the wet season ($df = 3$, $p < 0.05$). Significant differences were observed among adult males, adult females, and young individuals ($p < 0.05$). However, no significant differences were found between adult males and adult females or between sub-adults and young individuals ($p > 0.05$), indicating partial convergence in activity patterns under wetter environmental conditions.

Table 2: The proportion (%) of the total feeding bout spent on a specific behavior of *Colobus guereza* across different sex and age groups during the wet season.

Activity pattern	Adult males	Adult females	Sub-adults	Young's	Total
Feeding	5.4	7.3	4.4	3.2	20.3
Resting	5.1	4.6	6.9	5.6	22.2
Jumping	4.8	3.1	5.9	6.1	19.9
Playing	2.6	3.4	5.0	7.1	18.3
Grooming	3.5	6.1	4.5	5.1	19.2
Total	21.4	24.5	26.7	27.1	100

3.5 Feeding Time Budget and Diet (plant types) Composition of Colobus Monkey

Feeding Behavior and Dietary Composition

A total of 528 feeding events of *Colobus guereza* were documented through scan sampling during both the dry and wet seasons, providing a detailed overview of dietary composition and plant species use across disturbed forest (DF) and undisturbed forest (UDF) habitats. These feeding records comprised 13 tree species belonging to nine plant families, indicating a moderately diverse but selective feeding strategy. Despite this diversity, feeding was strongly concentrated on a small subset of preferred species, reflecting dietary specialization within the available forest resources.

Across both seasons and habitats, *Olea welwitschii*, *Sapium ellipticum*, and *Cupressus lusitanica* emerged as consistently important food plants, together accounting for a substantial proportion of total feeding observations (Figure 5). This pattern suggests that these species provide reliable and nutritionally suitable resources throughout the year. However, seasonal and habitat-specific variations in relative consumption frequencies were evident. During the dry season, feeding activity in disturbed forest was dominated by *Ficus vasta*, which recorded 22 feeding occurrences, followed by *Cordia africana* with 16 occurrences. These species likely serve as critical fallback resources in disturbed habitats when food availability is reduced. In contrast, *Sapium ellipticum* was least consumed in disturbed forest during this season, with only three records, indicating either lower availability or reduced preference in that habitat.

In the undisturbed forest during the dry season, *Millettia ferruginea* was the most frequently consumed species, accounting for 38 feeding records, followed by *Sapium ellipticum* (29). The dominance of *Millettia ferruginea* in UDF highlights its importance as a key dietary component in relatively intact forest conditions, while *Allophylus abyssinicus* was rarely consumed (two records), suggesting marginal dietary importance. Similar patterns persisted during the wet season. In disturbed forest, *Cupressus lusitanica* (14 occurrences) and *Croton macrostachyus* (12 occurrences) were most frequently consumed, whereas *Eucalyptus grandis* was least consumed (five occurrences). In the undisturbed forest, *Millettia ferruginea* again dominated the diet with 44 records, followed by *Olea welwitschii* (22), while *Croton macrostachyus* remained the least utilized species.

When feeding data were aggregated across seasons, *Millettia ferruginea* emerged as the single most important food species, contributing 30% of feeding records in the dry season and 36.6% in the wet season. This strong and consistent reliance underscores its year-round dietary significance. *Sapium ellipticum* and *Olea welwitschii* ranked next in importance, whereas *Prunus africana* (5.8%) and *Eucalyptus grandis* (4.1%) contributed minimally to overall feeding activity. Importantly, statistical analyses revealed no significant differences in plant species selection between disturbed and undisturbed forests (χ^2 = 0.000, df = 12, $p > 0.05$), indicating similar dietary composition across habitat types. Likewise, the Mann–Whitney U-test showed no significant seasonal differences in dietary ranks (U = 23.500, Z = −0.128, $p > 0.05$). Together, these results demonstrate a stable feeding strategy characterized by consistent reliance on a few key plant species, despite seasonal changes and habitat disturbance, highlighting the ecological importance of these species for the conservation of *Colobus guereza*.

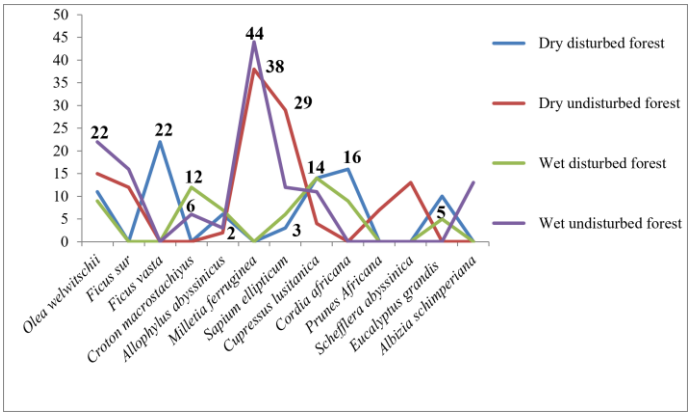

Figure 5: Feeding time spent or frequencies (shown in x-axis) by Colobus monkeys on each plant type

As shown in Table 3 below, *Millettia ferruginea* was the most commonly consumed food item by *Colobus guereza* during both seasons. In the dry season, *Millettia ferruginea* accounted for 30% of the feeding activities, followed by *Sapium ellipticum* at 26.6%. During the wet season, *Millettia ferruginea* remained the most frequently consumed food item, constituting 36.6% of the total feeding time, followed by *Olea welwitschii* at 25.8%. In contrast, *Prunus africana* (5.8%) and *Eucalyptus grandis* (4.1%) were the least consumed food items during the dry and wet seasons, respectively. These findings highlight the prominence of a few plant species in the *Colobus guereza* diet across both seasons. Despite the variation in the proportions of time spent consuming different plant species between the dry and wet seasons, statistical analysis revealed no significant difference in the rank of dietary contributions of plant species consumed by the *Colobus guereza* across the two seasons (Mann-Whitney U test; U = 23.500, Z = -0.128, $p > 0.05$). This suggests that the relative importance of different plant species in the monkeys' diet remains consistent, regardless of seasonal changes in food availability or plant abundance.

Table 3: Plant species consumed by Colobus monkeys and their frequencies and percentages with ranks

Plant species	Dry season			Wet season		
	Frequency	Percentage	Rank	Frequency	Percentage	Rank
Millettia ferruginea	38	30.0	1st	44	36.6	1st
Sapium ellipticum	32	26.6	2nd	28	23.3	3rd
Olea welwitschii	26	21.6	3rd	31	25.8	2nd
Ficus vasta	22	18.3	4th	-	-	-
Cupressus lusitanica	18	15.0	5th	25	20.8	4th
Croton macrostachiyus	-	-	-	18	15.0	5th
Cordia africana	16	13.3	6th	9	7.5	8th
Schefflera abyssinica	13	10.8	7th	-	-	-
Ficus sur	12	10.0	8th	16	13.3	6th
Albizia schimperiana	-	-	-	13	10.8	7th
Eucalyptus grandis	10	8.3	9th	5	4.1	9th
Allophylus abyssinicus	10	8.3	9th	-	-	-
Prunus africana	7	5.8	10th	-	-	-

Where '-' indicates no record, when the Colobus monkey consumed the plant species.

The plant parts consumed by the study species as a diet and the frequency of feeding time scans for each plant part during feeding activity are illustrated below (Table 4). During the dry season, the diet of Colobus monkeys was primarily made up of leaves, followed by flowers. During the wet season, colobus monkeys favored leaves, followed by fruits. During both seasons, stems/woods/barks were the least consumed food item from other plant parts. The feeding records of plant parts consumed by Colobus monkeys differed statistically across seasons ($\chi^2 = 16.00$, df = 4, $p < 0.05$).

Table 4: Overall food item selection of Colobus monkeys as diet during both seasons

Plant Parts	Dry season		Wet season	
	FSP	DSI=FSP/TSP	FSP	DSI=FSP/TSP
Leaves	84	0.7	97	0.80
Flowers	49	0.40	37	0.30
Fruits	28	0.23	41	0.34
Steams	14	0.11	6	0.05

Where DSI = Diet Selection Index, FSP = Frequency Scanning Period per plant part, and TSP = Total Scanning Period (120 for each season).

4 DISCUSSION

4.1 Activity Paflerns of *Colobus guereza*

At the study site, *Colobus guereza* devoted the majority of its daily activity budget to resting and feeding, while comparatively little time was allocated to social behaviors such as grooming and play. This pattern is consistent with previous studies conducted in Ethiopia and other parts of Africa, which have similarly identified resting and feeding as dominant activities in guereza monkeys (Hussein & Ejigu, 2017; Shumet & Yihune, 2017; Yazezew, 2018; Yemane, 2018). However, in contrast to Agnes (2019), the present study recorded slightly reduced resting time and relatively higher engagement in play behavior, suggesting a more balanced allocation between maintenance and social activities. Such variation may reflect local ecological conditions, group composition, or differences in disturbance levels.

Seasonal variation had a pronounced effect on activity patterns. During the dry season, guerezas spent more time feeding and resting compared to the wet season. This trend likely reflects the combined influence of reduced food availability and higher ambient temperatures. Increased feeding time during the dry season may enable individuals to compensate for the lower quality or patchy distribution of food resources, while extended resting periods help conserve energy and reduce thermoregulatory stress. In addition, the folivorous diet of *C. guereza*, which is rich in cellulose, requires prolonged digestion, thereby necessitating longer resting periods for efficient fermentation and nutrient absorption (Abraham Eustace et al., 2015).

Differences in activity patterns were also observed between seasons and among sex–age categories. Seasonal shifts are likely driven by fluctuations in resource availability, including food, water, and shelter, which vary with climatic conditions (Yazezew, 2018; Yemane, 2018). Significant variation among age–sex classes ($p < 0.05$) revealed that adults allocated more time to feeding and resting, whereas juveniles and sub-adults engaged more frequently in social activities, particularly play. This distinction likely reflects differing energetic and developmental requirements: adults prioritize energy conservation and reproductive fitness, while younger individuals invest in social interaction and motor skill development (Abraham Eustace et al., 2015; Shumet & Yihune, 2017).

Overall, although the general activity budget of *C. guereza* appears relatively stable, fine-scale variation is influenced by seasonal conditions, habitat characteristics, and group composition. Adults predominantly engage in energy-conserving behaviors such as feeding and resting, whereas juveniles are more active socially. This behavioral flexibility likely enhances the species' capacity to cope with environmental variability and contributes to its persistence across both disturbed and undisturbed habitats.

4.2 Feeding Ecology and Diet Composition

The present study demonstrates that *Colobus guereza* exhibits considerable dietary flexibility, feeding on thirteen plant species during the study period. The diet consisted mainly of leaves, supplemented by fruits, flowers, and occasionally bark, stems, and wood. This diversity is supported by the species' specialized digestive system, characterized by a multi-chambered stomach that enables efficient breakdown of fibrous plant material (ARKive, 2011; Gron, 2009). These findings are consistent with earlier studies describing *C. guereza* as a predominantly folivorous but adaptable feeder capable of exploiting a range of plant resources (Fashing, 2001a; Matsuda et al., 2020).

Among the plant species consumed, *Millettia ferruginea*, *Sapium ellipticum*, and *Olea welwitschii* were the most frequently utilized. Their prominence in the diet likely reflects both their relative abundance and nutritional value. Similar preferences have been reported in other Ethiopian populations, including those inhabiting fragmented habitats along the Omo River, where *Millettia ferruginea* is consistently selected (Tesfaye et al., 2021). In contrast, species such as *Eucalyptus grandis* and *Ficus sur* were rarely consumed, possibly due to limited availability or lower palatability (Hussein & Ejigu, 2017). These patterns suggest that guerezas make foraging decisions based on a combination of resource availability and nutritional quality.

Feeding time allocation further indicated a strong reliance on leaves, which comprised the majority of the diet. This finding contrasts with studies from Kakamega Forest, Kenya, where fruit consumption was more prominent (Fashing, 2001b), but aligns with other Ethiopian studies emphasizing folivory (Ibrahim et al., 2017; Shumet & Yihune, 2017; Yazezew, 2018). Leaves offer several nutritional advantages, including relatively high protein content, lower levels of secondary compounds, and greater year-round availability compared to fruits and flowers (Chapman et al., 2002; Kaplin & Moermond, 2000). Consequently, reliance on leaves provides a stable and predictable energy source, particularly in environments where fruit availability is highly seasonal.

4.3 Seasonal Variation in Diet and Effects of Disturbance

The study revealed clear seasonal variation in dietary composition. During the dry season, guerezas relied more heavily on mature leaves, likely due to the scarcity of young leaves. In contrast, the wet season was characterized by increased availability of young leaves and fruits, leading to greater dietary diversity. Fruit consumption increased during the wet season, while bark and stems were more frequently consumed in the dry season, possibly serving as alternative sources of moisture and nutrients when preferred foods were limited (Ibrahim et al., 2017). These findings highlight the species' capacity to adjust its diet in response to seasonal changes, thereby maintaining nutritional balance and energy intake.

Despite these seasonal shifts, the study found that habitat disturbance did not have a statistically significant effect on the primary behavioral activities of *C. guereza*, including feeding, resting, and traveling. This result contrasts with previous research indicating that anthropogenic disturbance can alter primate behavior, often leading to increased vigilance and reduced feeding efficiency (Estrada et al., 2017; Kokou et al., 2020).

Several factors may explain this discrepancy. First, *C. guereza* may exhibit a relatively high degree of ecological and behavioral adaptability. Although primarily folivorous, the species demonstrates flexibility in both diet and habitat use, which may buffer it against moderate levels of disturbance (Fashing, 2011; Tesfaye et al., 2022). Such adaptability is particularly advantageous in mosaic landscapes where natural and human-modified habitats coexist.

Second, the temporal scope of the study may have limited the detection of disturbance effects. Although both dry and wet seasons were included, the study represents a relatively short time frame. Long-term impacts of disturbance such as habitat degradation, resource depletion, and cumulative human pressure may not be immediately reflected in observable behavior (Chapman et al., 2019).

Third, the categorization of habitats into "disturbed" and "undisturbed" may oversimplify the complexity of anthropogenic influences. Disturbance varies in intensity, frequency, and type, including activities such as selective logging, grazing, and fuelwood collection. More detailed and quantitative measures of disturbance could provide a clearer understanding of its effects on primate behavior (Arroyo-Rodríguez et al., 2017).

Thus, the findings underscore the ecological flexibility and apparent resilience of *Colobus guereza* in the Kafa Biosphere Reserve. However, this resilience should not be interpreted as immunity to environmental change. Conservation efforts should prioritize the protection of key food species, such as *Millettia ferruginea*, *Sapium ellipticum*, and *Olea welwitschii*, as well as the maintenance of habitat heterogeneity. Long-term monitoring and more refined assessments of disturbance are essential to ensure the continued survival of this species in increasingly human-modified landscapes.

5 CONCLUSIONS

The study demonstrates the ecological flexibility and relative resilience of *Colobus guereza* in the Kafa Biosphere Reserve, while highlighting that this resilience does not imply immunity to environmental change. The species spent most of its time resting and feeding, reflecting its energy-conserving, folivorous lifestyle. Behavioral differences among age–sex classes were evident, with adults especially females focusing more on feeding and resting, while juveniles engaged more in social activities such as play. Seasonal variation strongly influenced both activity patterns and diet, with increased feeding during the dry season likely compensating for reduced food availability and higher temperatures. Leaves constituted the primary diet, particularly from *Millettia ferruginea*, *Sapium ellipticum*, and *Olea welwitschii*, while shifts in fruit and bark consumption across seasons indicated dietary adaptability. Although disturbance did not significantly affect core behaviors, this result should be interpreted cautiously due to potential long-term impacts. Overall, the species' persistence depends on diverse food resources and intact forest habitats, emphasizing the importance of conservation and continued ecological monitoring.

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Authors' contribution

Belaynew Asmamaw and Melkamu Adamu: Writing the original draft, review & editing, investigation, data collection, analyzing with software, methodology. Yosef Mamo: review & editing and formatting, validation, supervision, methodology, conceptualization.

Conflict of interest

The authors declare that they have no conflict of interest.

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Data availability Statement

All data generated or analyzed during this study are included in this manuscript [and its supplementary information files].

Ethical Clearance

As the study involved observing free-ranging colobus monkeys in their natural habitat without any physical interaction, such as capturing, tagging, or handling, no ethical clearance was required for this research. The data collected was solely through non-invasive field observations.

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Determinants of Smallholder Farmers' Participation in Beekeeping in Godere District, Gambella Regional State, Ethiopia

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Abstract

Across the world, the livelihoods of communities living in forest areas are in general dependent on subsistence agriculture and specifically on beekeeping farming. This farming system has providing different alternative as sustainable livelihood option i'e generates income, creates job opportunity, and alleviates poverty through producing honey, beeswax and other bee products for small scale farmers However, in Ethiopia, there are various factors that hold back the rural households to increase and participate on beekeeping practices. The objective of this study was to analyze the factors that affect participation of smallholder farmers in beekeeping practices in the Godere district in 2023/24. To attain the objective of the study, cross sectional data were collected from rural households and analyzed using binary logistic regression model. According to the result of maximum likelihood estimation, the marital status, household size, sex, and the educational status of the household head, number of extension visits, membership in farmers' association, and access to credit were the statistically significant variables determining beekeeping adoption in the study area. The beekeeping constraints that had statistically significant influence on beekeeping adoption were grouped as marketing, natural, and financial. Therefore, to completely undo the income potential of beekeepers and consume the benefits from the enormous potential of honeybee colonies, the government of Ethiopia, Non government organizations, Development agencies and other associated actors and stakeholders should work together to overcome the constraints faced by beekeepers in adopting beekeeping practices that could result in improving their productivity, efficiency and livelihoods.

1 Introduction

1.1 Background of the Study

Globally, the beekeeping practice is one of the oldest known methods of food production and it is almost 5,000 years dates back in Africa (Gratzer et al., 2021). From African continent, the largest bee populations with over 10 million bee colonies are found in Ethiopia, out of which about 7.5 million are confined in hives and the remaining 2.5 million are feral colonies (Bayissa et al., 2024). In addition to various honeybee floras, the diversified agro-climatic conditions found in Ethiopia have created a favorable environment for 2 million people to involve on beekeeping practice (FAOSTAT, 2015; Yadeta, 2019).

From agriculture sector, beekeeping farming has gained importance depending on increasing demand of apicultural products. Beekeeping activity not only makes rural labour productive, but also makes destroyed natural resources valuable. Beekeeping is a production line that can be done continuously without consuming large resources and is an important tool of sustainable rural development. It is environmentally friendly practices and suitable for low income households. Particularly for rural households beekeeping can coexist effortless with regular farming activities (Abro et al., 2022). Those engaged in beekeeping could earn income from production and marketing of honey and its by-products (beeswax, royal jelly, pollen, propolis, bee colonies, and bee venom). The sector could also create a non-gender-biased employment opportuni-

ties.

Recently, the contributions of beekeeping in poverty reduction, sustainable development and conservation of natural resources have been recognized and well emphasized by the government of Ethiopia and NGOs. According to Tulu et al. (2020) it is non-farm business activity that has immense contribution to the economies of segments of the society and to a national economy as a whole. Ethiopia has the potential to produce 500,000 tons of honey, but current production is limited to 43,000 tons of honey.

Gambella Region is also one of the regions in the country that is endowed with high dense natural forest in which honeybee plants are grown. The mean annual temperature of the region (17.3°C to 28.3°C), annual rainfall (900-1,500mm), altitudes (1,900-2,100mm) and existences of big rivers (Baro and Alwero) making the region an ideal place for bees to survive and produce honey and other valuable bee products. In addition, beekeeping is heavily practiced in some zones of the region with extremely important income sources as means of maintaining family livelihood (CSA (Central Statistics Authority), 2013). Anywa, Majang, Gambella city and Itang special woreda are naturally endowed for bees and beekeeping is largely practiced by the community living in them. Even though the region as well as the Majang zone is the potential areas for beekeeping, to generate income, create jobs, and alleviate poverty, there are many constraints that hinder rural households from adopting and expanding beekeeping practices. Therefore, it is necessary to identify the constraints faced by rural households to adopt beekeeping practices

2 The Status of Beekeeping Production and Productivity in Ethiopia

The Ethiopian population is increasing at an alarming rate and reached around 129.5 million peoples (Worldometers, 2024). The fundamental problems challenging the government of Ethiopia today is ensuring for millions of households living in poverty to have access to enough food to maintain a healthy life through consuming more than two times in a day. However, Agriculture sector is taking the lion share to solve this community and Government pain and headache by providing enough food to those millions of people as their level in our country.

According to Etefa et al. (2022), agriculture remains to be the principal engine of growth of the economy and building block of the social life of the people in Ethiopia. This sector contributes about 36.3% of GDP, provides employment opportunities to more than 73% of total population that is directly or indirectly engaged in agriculture, generates about 70% of the foreign exchange earnings of the country and 70% of raw materials for the industries in the country (UNDP (United Nations Development Programme), 2018).

Ethiopia is believed to have the largest livestock population in Africa. This livestock sector has been contributing considerable portion to the economy of the country, and still promising to rally round the economic development of the country. It is eminent that livestock products and by-products in the form of meat, milk, honey, eggs, cheese, and butter supply etc. provide the needed animal protein that contributes to the improvement of the nutritional status of the people. Livestock also plays an important role in providing export commodities, such as live animals, hides, and skins to earn foreign exchanges to the country.

From this large sector, the livestock sector donates around 20% to Ethiopia's GDP, at the same time it offers a livelihood to 60 – 70% of the population (Asresie, 2015; MOI/Ministry of Industry, 2016). By having varied and comfortable climatic and ecological conditions from African continent, Ethiopia have more than 10 million beehives which is feeding around 2 million peoples and it also contributes around 1.3% for GDP (Akessa, 2016; Tarekegn & Ayele, 2020). On average, beekeepers in Ethiopia produces 48,712 tonnes of honey and owns 5.89 million managed bee colonies (CSA/Central Statistical Agency, 2020).

From the world, Ethiopia ranks first in honeybee colonies, fourth in beeswax production in the world, and tenth in honey production (Girma & Gardebroek, 2015; Rivera et al., 2007). The beekeeping value chain generates jobs opportunity for nearly 2 million people in Ethiopia (Drost & Van Wijk, 2011). Beekeeping generates a non-gender-biased employment opportunities and also offers large opportunities for a lot of landless farmers – which includes many women and young people – to improve their livelihoods (Abro et al., 2022). Thus, this beekeeping sub-sector has getting attention from both government, different NGOs and development partners' (NPC (National Planning Commission), 2016).

According to The Mastercard Foundation (2020), more than70 thousand unemployed young people got job opportunity in beekeeping sector by the MasterCard Foundation which spends millions of dollars. Beekeeping is taking a lion share role in generating employment opportunities, increasing foreign exchange earnings and sustaining livelihoods of the large societies (Abro et al., 2022).

Despite the fact that, this very important sub-sector, beekeeping sector, is significantly challenged by different factors i'e diseases and pests, the indiscriminate application of agrochemicals for crop protection, low adoption of modern beekeeping practices and technologies and low quality of beekeeping products which brings honeybee colony losses and low production and productivity (Amulen et al., 2019; Chala et al., 2013; EIAR/Ethiopian Institute of Agricultural Research, 2017; Fikru, 2015; Girma & Gardebroek, 2015; Gratzer et al., 2021; Kalayu et al., 2018; Kenesa, 2018; MoA-ILRI, 2013; Pirk et al., 2016; Tassew et al., 2018; Tulu et al., 2020; Wagner et al., 2019; Wakagri & Yigezu, 2021).

To mitigate the sub-sector's challenges, the Ethiopian government has developed the national apicultural strategies and policies which assists the poor smallholder farmers to increase their production and productivity of honey by introduction and promotion of improved beehives technologies i'e Ethioribrab hive, Kenya top bar, Zender, and chefeka (Awraris et al., 2012; CSA/Central Statistical Agency, 2020; FDRE/Federal Democratic Republic of Ethiopia, 2009; MoA-ILRI, 2013).

Though the Policy designed by the government of Ethiopia admits the sub-sector's constraints, and it necessitates the sustainable and sustainable management of apiculture resources in the country (Abro et al., 2022).

The aim of the government was to create job opportunity for youth, to increase the income of the poor, to improve the living standard of the people, to reduce food insecurity and poverty as well as to

ensure the economic development and prosperity of the country through beekeeping technology adoption. Following the aims and goals of the government, different non government organizations and companies was come out along beekeeping value chain including traders, beekeeping equipment producers, and honey and beeswax processors for the successfulness and sustainability of the government aims and policies (Girma & Gardebroek, 2015).

Figure 1: Bee and beekeeping instruments

3 METHODOLOGY

3.1 Description of study area

The study was carried out at Godere districts of the Gambella People's Regional State (GPNRS). Godere is one of the districts in Majang Zone of Gambella Regional State. Majang zone is located at about 620 km away from Addis Ababa in South Western Ethiopia in between 7°10′ 0″-7°40′ 0″ N latitude and 35°0′ 2″-35°20′ 2″ E longitude. It also has an altitude ranging from 500 to 2400 m above sea level (Alemu et al., 2015). The climate of the district is a hot and humid type. It receives high rainfall between mid-March to October and low rainfall from November to February. The annual rainfall amount of the area ranges from 900mm to above 2200mm but the majority of the areas receive over 1500mm/annum. The lowest mean monthly temperature is 13.2°C and the highest mean monthly temperature is 33.1°C with an average temperature of 22.2°C (Alemu et al., 2015). The soil of the district is reddish brown, well drained and clay in texture (Yeshitela, 2008).

3.2 Sources and Methods of Data Collection

Both primary and secondary data was collected from the study area. Primary data was collected from sample of households (beekeeping participants) using structured questionnaire. Besides the structured questionnaire, Checklist and FGD was used to collect the primary data. The data was collected from relevant sources such as bureau of agriculture of the districts, traders of honey, NGOs and other relevant institutions for general description and to verify the primary data. The secondary data was collected from different books and journals. In order to facilitate data collection process, experienced enumerators was recruited based on their proficiency in the local language and then trained on data collection techniques and on the content of the questionnaire.

By using the prepared semi-structured questionnaires which was pre-tested, and translated into local language, the selected beekeepers were interviewed. From primary data i'e numbers of bee colonies, socio-economic parameters, annual honey yield of single colony, and vernacular names of honeybee flora and their flowering calendar, types of beehives, etc. were collected from sampled respondent households. Moreover, the collection of other important data like potentials and constraints of honey production and marketing systems, honey harvesting frequency and seasons and way of harvesting was also supported by group discussions with experienced beekeepers and key informants.

3.3 Sampling Technique and Sample Size

To select appropriate sample households for this study, a two stage sampling technique was employed. In the first stage of sampling procedure, depending on the information taken from secondary data of the district Agricultural office, based on their production potential, two kebeles in the rural household of godere district (i.e., smallest administrative unit), kabo and Meti Zuria was selected through random sampling method based on the history of honey production and its representativeness to the district beekeeping potential areas. Consequently, around 120 beekeeping households

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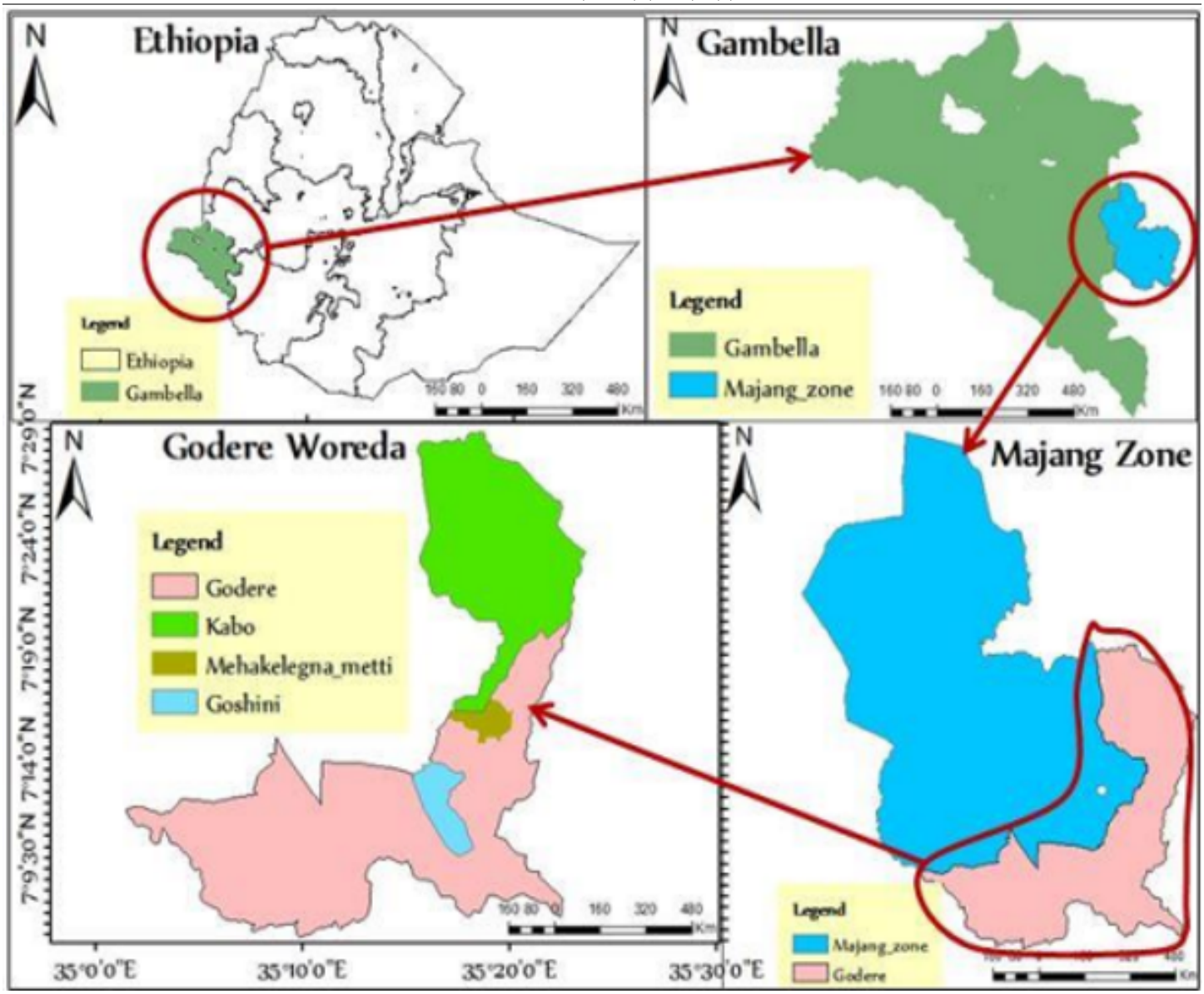

Figure 2: Map of study area: Godere district, Gambella Region

were selected, 60 from kabo and 60 from Meti Zuria kebeles by using Yemane formula (Yamane, 1967).

$$n = \frac{N}{1 + N(e^2)} \quad (1)$$

3.4 Method of Data Analysis

In order to analyze the data, both descriptive statistics and econometrics method was employed.

3.4.1 *Descriptive analysis*

The quantitative data was obtained through different data collection methods was analyzed using descriptive analysis and statistical tests. Descriptive statistics such as mean, frequency, standard deviation and percentage and correlation model were statistical tools. Moreover, statistical tests such as t-test, F-test, and chi-square test were used to test the significance of the variables under consideration.

3.4.2 *Econometric method (binary logistic regression model)*

The appropriate model applied when the dependent variable has dichotomous outcome is binary logistic regression model which is one from the non-linear econometric models. Therefore, for this study, we used binary logistic regression model to analyze the determinants of beekeeping participation in the study area. Logit model is tremendously flexible and significantly gives a very meaningful interpretation of the data (D. Gujarati, 1998). According to Wright (1995), binary logistic model is an influential instrument for estimating the individual influences of categorical and continuous

variables on a qualitative dichotomous dependent variable.

According to D. N. Gujarati (2004), in estimating the Logit model, the dependent variable (participation in this study) which takes a value of 1 if the household participated in a program and 0 otherwise. The advantage of this model is that the probabilities are bounded between 0 and 1. The dependent variable is dichotomous, taking two values, 1 if an individual participates in small-scale beekeeping and 0 otherwise. Based on D. Gujarati (1998), the logistic distribution function for the relationship between the probability of the dependent dichotomous variable and several independent variables can be specified as:

$$\frac{e^{Zi}}{1+_n e^{Zi}} \tag{2}$$

$$Zi = \alpha 0 + \beta i \sum_{i=1} Xi + \varepsilon i + Ui \tag{3}$$

$$1 - p(x) = \frac{1}{1+_t e^{Zi}} \tag{4}$$

$$\frac{p(x)}{1-p(x)} = \frac{1+e^{Zi}}{1+e^{-Zi}_n} = e^{Zi} \tag{5}$$

$$\text{Li=Ln}\frac{\text{p(x)}}{\text{1-p(x)}}\text{=Ln(e}^{\alpha 0}\text{+}\beta\text{i}\sum_{i=1} Xi + ui) \tag{6}$$

Where,

- i= 1, 2, 3, - –, n
- $\alpha 0$ Refers to intercept
- βi=Refers to regression coefficients to be estimated
- ui= Refers to a disturbance term, and
- Xi= Refers to re-intervention characteristics.

4 RESULTS AND DISCUSSIONS

4.1 Availability of Equipment for Honey Production and Processing

In this section, the availability of equipment for honeybee production and processing presented by using descriptive statistics. As Subramanian et al. (2007), processing can be described as the steps followed from the raw honey harvest to bottling of honey

From the results obtained in this study, only 30% of the households in the study area processed the honey produced and around 70% of rural households did not process honey produce. In the study area, honey processing also includes converting/processing honey to traditional honey beer called Tej (made from mixing honey, Rhamnus prinoides (gesho), and malt). The Table 1 illustrates descriptive statistics of the percentage of the adopters who have access to equipment for honeybee production and processing. As illustrated in Table below, the greater part of the sampled respondents (72%) have no access the strainer equipment for honey production and only the remaining 28% had the access of it (Table 1).

Table 1 also Concern the availability of packaging and transporting in the study area. Accordingly, only around 30% and 32% of the beekeepers did have packaging and transporting equipment, respectively; whereas 70% and 68% of the adopters did not have the said equipment in the study area. Additionally, from the results of the descriptive statistics, only around 22% of adopters had harvesting gear and the remaining 78% responded that they did not have harvesting gear in the study area.

Table 1: Availability of equipment for honeybee production and processing in the study area

Equipment needed for activities	Category	Percent
Sieve (Strainer)	Yes	28%
	No	72%
Packaging	Yes	30
	No	70
Transporting	Yes	32
	No	68
Harvesting gear	Yes	22
	No	78

Source: Survey result (2024)

4.2 The Test Statistics Of Reliability Of The Principal Components (Pcs)

Table 2 illustrates the test statistics of the composite and the reliability of individual PCs that confirm the values of the Cronbach's alpha (α) are greater than the required value. As recommended in Cronbach (1951), the composite reliability of PCs and the standards of the reliability coefficient for the individual PCs is $\alpha \geq 0.7$ and $\alpha \geq 0.6$ respectively. As illustrated on Table 2, the Cronbach's α values were 0.991, 0.987, 0.994, 0.929, and 0.921 for the first, second, third, fourth, and fifth PC, respectively. The overall Cronbach's α value was 0.927. Therefore, the PCs are reliable indicators of the data set and hence explain a meaningful amount of the variance.

Table 2: Reliability test statistics of principal components

Name of principal component	Number of items (constraints)	Individual reliability (Cronbach's alpha)	Overall reliability
Marketing constraints	15	0.991	
Natural constraints	11	0.987	
Honeybee production constraints	11	0.994	0.927
Management constraints	5	0.929	
Financial constraints	4	0.921	

4.3 Determinants of Beekeeping Participation By Rural Households in Godere District

By using appropriate techniques, different econometric assumptions were tested before performing the econometric estimation. Consequently for binary logit model, initially, the presence of strong multicollinearity among continuous explanatory variables

was tested via variance inflation factors (VIF) and the data obtained can be concluded that the data set had no serious problem of multicollinearity. Second, contingence coefficient (CC) was used to check the existence of multicollinearity between discrete variables. There was no any continuous or discrete explanatory variable dropped from the estimated model since no serious problem of multicollinearity were detected from both the VIF and contingency coefficient results. As a result, all the explanatory variables were retained and moved to the analysis.

Table 3 below shows the results of the maximum likelihood estimation of the binary logistic regression model which we used to determine the significance of the determinants and of the constraints for beekeeping adoption. As shown on the table, among the 14 explanatory variables, 11 of them significantly influence beekeeping adoption in the study area. The result of the table concluded that, the model is well fitted since the value of the likelihood ratio $\chi 2$ was highly significant.

The sex of the household head was positively and significantly affects the beekeeping adoption in the study area which indicates that male headed rural households are more likely to adopt beekeeping practices than female headed rural households (Table 3). More specifically, the odd ratio in favor of beekeeping participation, being a male headed household increases the probability of beekeeping adoption by 32%. The similar result was found by Mushonga et al. (2019) and Amulen et al. (2019). They reported that gender bias is one of the challenges of beekeeping adoption and male headed farmers were more likely to be beekeepers than female headed households.

Regarding the household size of the household, the study found that, it's negatively and significantly affects the adoption of households in beekeeping, which indicates that having a large household size reduces the probability of beekeeping adoption in the study area (Table 3). More generally, the odd ratios in favor of beekeeping adoption, an increase in household size by one person decrease the probability of beekeeping adoption by 20.2%. This may be due to large household sizes require a larger proportion of their income to be exhausted on basic needs, which in turn limits larger size rural households head from adopting beekeeping practices. The result was consistent with the result of Abro et al. (2022), who got similar result in North West Ethiopia.

The study also found that, the marital status of the household head positively and significantly affects the household adoption in beekeeping, which shows that married rural household were more likely to adopt beekeeping practices than their counterparts' i'e single, divorced, and widowed (Table 3). The odd ratios in favor of beekeeping participation, being married household head increases the probability of beekeeping practice by 87%. This result was consistent with Abro et al. (2022) and Jeil et al. (2020).

According the result of the study, the coefficient of the number of visits by extension agents was positive and significant for beekeeping participation (Table 3). Specifically, odds ratio in favor of beekeeping adoption increases by 0.2% as the household head had more extension visit than those who doesn't. Consistent result was obtained by Tarekegn et al. (2017), Tarekegn and Ayele (2020) and Tulu et al. (2020).

Table 3: Marginal effects of the determinants of beekeeping adoption after Logit analysis

Explanatory variable	Marginal Effect	P-value
Sex of the household head (dummy)	0.32	0.014**
Age of the household head in number of years	-0.019	0.923
Marital status of the household head (dummy)	0.87	0.003***
Household size measured by the number of persons in the family	-0.202	0.011**
Educational status of the household head (dummy)	0.561	0.012**
The number of years a household lived in the district	-0.015	0.401
Number of visits by extension agents in the previous year	0.002	0.062*
Membership in a farmers' association (dummy)	0.647	<0.001***
Access to credit to the household (dummy)	0.490	0.046**
Whether a household processes honey produce (dummy)	0.004	0.743
Marketing constraints (PC1)	-0.110	0.064*
Natural constraints (PC2)	-0.029	0.075*
Constraints for honeybee production (PC3)	-0.162	0.057*
Management constraints (PC4)	0.018	0.661
Financial constraints (PC5)	-0.288	0.034**

Note: ***, **, and * represent significance at the 1%, 5%, and 10% level of significance, respectively.

Being membership in association of farmers' was positively and significantly influenced the beekeeping adoption by rural households in the study area (Table 3). This means, the odds ratio in favor of beekeeping participation, being a membership of a farmers' association increases the chance of adopting beekeeping practices by 64.7%. Similar result was found by Tarekegn et al. (2017) and Tarekegn and Ayele (2020). In the study area, the credit access was positive and had a significant influence on beekeeping adoption, which shows that household heads who had access to credit have greater probability to be adopter and to have necessary technologies and equipment for beekeeping practice easily (Table 3). More specifically, the odd ratios in favor of beekeeping practice; having more credit increases the probability of beekeeping adoption by 49%. This result is consistent with that of Amulen et al. (2019) and Tulu et al. (2020).

Table 3 shows that, the marketing constraints were affects the beekeeping practices in the study area negatively and significantly. Specifically, the odd ratios in favor of beekeeping adoption, facing more marketing problems and challenges decreases the probabil-

ity of beekeeping adoption by 11% in the study area. Similar result was found by Mushonga et al. (2019) and Tulu et al. (2020).

5 Conclusions And Recommendations

To attain the objective conducted research, binary logistic regression model was used with its maximum likelihood estimation results. According to the output of the model, seven variables from the stated variables i'e educational level, marital status, household size, sex, number of extension visits, membership in a farmers' association, and access to credit influence beekeeping adoption significantly in the study area.

There are also other constraints which are statistically affecting beekeeping participation in the study area accordingly marketing constraints, natural constraints, constraints for honeybee production, and financial constraints. The findings of the study forwarded some policy implications for the beekeeping sector specifically as well as for the whole economy in general.

Ethiopia has a huge potential in the beekeeping sector from livestock sector from east Africa. Although the country in general and the households specifically consuming the benefits obtained from the beekeeping sector even though it's very low. To harvest more benefits from beekeeping sector in the country, the concerned bodies i'e government, non government organizations and different companies related to this sector should be able to focus on training programs, credit schemes, women-focused interventions related to beekeeping practices.

Above all, specifically for regional government and Godere district, it's better to design policies focusing on improving the education level of the household, the financial access of rural, the aware and motivate female headed households in beekeeping, increasing the frequency of visits of agricultural extension agents, and enabling farmers to share their experience and knowledge and giving training by organizing them in a group or association.

Additionally, we recommend that, to obtain more output from the sector, concerned stakeholders, including community beekeeping groups, local processors, NGOs, and packagers, and researchers should focus on the constraints to solve properly and should introduces modern beekeeping by constructing from locally available materials to reduce the cost of production in the study area.

Most of all, given the time and budget constraints, the study focused only on the factors that affect the participation of small holder farmers in beekeeping practices in Godere district. In these regard future research in the area is needed to investigate the impact of adoptions of modern technologies and roles of women in beekeeping.

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Conflict of interest

The author declare that no competing interests

Data availability Statement

Data can be made available on the behave of the request

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Influence of Watering Regimes and Irrigation Quantities on Seedling Growth and Biomass Accumulation in *Tetrapleura tetraptera* (Schumach and Thonn.) Taub

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Beekeeping; Constraints; Households; Logit model; Ethiopia

Abstract

Effective water management is essential for producing high-quality tree seedlings, particularly under increasing climate variability. This study investigated the effects of watering regimes and water quantities on seedling growth and biomass accumulation of *Tetrapleura tetraptera* under controlled greenhouse conditions. Seeds were germinated, and 108 juvenile seedlings were transplanted in polythene bags in 12×14×16cm dimensions. A 3×4 factorial design was used, exposing seedlings to combinations of watering regimes (once daily, twice daily, once every 3days, once every 5days) and water quantities (30, 40, and 50ml). Growth parameters (height, collar diameter and number of leaves) and biomass (leaf, stem, root and total dry weight) were measured. Results revealed that both watering frequency and quantity significantly influenced all growth and biomass parameters ($P \leq 0.05$). Seedlings irrigated more frequently consistently outperformed those watered at longer interval. Interestingly, seedlings receiving 40ml twice a day achieved the highest values for height (26.51±3.96cm), collar diameter (5.57±0.37mm), and total biomass (61.16±29.72g). In contrast, seedlings watered once in every five days exhibited markedly reduced growth and biomass, underscoring the species' sensitivity to water stress. Increasing the quantity of water beyond the optimal level did not yield further growth, highlighting the importance of optimizing rather than maximizing irrigation. Overall, this study provides species-specific empirical evidence on the water requirements of T. tetraptera seedlings and demonstrates that frequent, moderate, irrigation promotes superior growth and biomass accumulation. The findings offer practical guidance for nursery management, and support optimized seedling production strategies in afforestation, agroforestry and conservation initiatives within water-limited tropical environments.

Keywords: biomass accumulation; growth parameters; *Tetrapleura tetraptera*; water quantity; watering regimes.

1 Introduction

Water availability is a critical determinant of plant growth, productivity and survival, particularly during the early stages of seedling development. Soil moisture directly regulates key physiological processes, including (cellular growth, photosynthesis and nutrient uptake), while prolonged water deficits often result in reduced biomass accumulation and stunted growth (Mo et al., 2025). The increasing unpredictability of precipitation whether from (natural rainfall or anthropogenic irrigation) can therefore exert significant influence on seedling developmental trajectories and biomass al-

location patterns in both natural ecosystems and nursery environments.

Watering frequency and magnitude are key determinants of seedling quality in forest nurseries, though the optimal combination of these factors often varies across species and environments. Regular watering maintains stable soil moisture, supporting continuous vegetative growth and development. In contrast, irregular watering regimes can impose recurrent water stress, thereby inhibiting growth (Ibeh & Akinyele, 2024). As climate variability intensifies, marked by prolonged dry seasons and increasingly unpredictable rainfall patterns in many tropical regions management strategies that optimize water supply have become increasingly critical for sustaining seedling performance and ensuring nursery success.

Recent empirical studies have underscored the critical role of water availability in enhancing seedling performance across diverse plant taxa. For instance, research in a Peruvian tropical forest demonstrated that regular watering regimes improved seedling growth and survival by increasing the stem density and total overall recruitment rates (Ezekiel et al., 2024). Similarly, an experimental study on Adansonia digitata showed that watering frequency significantly influenced key morphological and physiological traits, including seedling height and biomass accumulation (Ezekiel et al., 2024). Controlled irrigation experiments with Quercus acutissima further showed that reduced soil moisture led to declines in seedling height, basal diameter, and total biomass compared to the well-watered controls (Luo et al., 2025). Collectively, these findings highlight the strong link between water management practices and seedling developmental outcomes, emphasizing the need for species-specific irrigation strategies in both natural and nursery settings.

Although there is increasing evidence on the effect of water supply on seedling growth, many indigenous tropical tree species of ecological, agronomic, and cultural importance still lack species-specific data. *Tetrapleura tetraptera* (Schumach & Thonn.) Taub., a valued leguminous species native to West and Central African forests, is widely recognized for its medicinal and nutritional qualities. However, the species faces regeneration challenges in degraded landscapes. Despite its significance, empirical studies examining the effects of varying watering regimes and water quantities on the growth and biomass accumulation of T. tetraptera seedlings remain limited, underscoring the need for targeted research to inform nursery management and conservation practices.

1.1 Objectives of the study

The general objective of this study is to evaluate the effects of watering regimes and water quantities on growth and biomass accumulation of T. tetraptera seedlings.

1.1.1 Specific Objectives

1. To determine the effect of watering frequency on seedling growth and biomass accumulation.
2. To assess the influence of water quantity on seedling growth and biomass accumulation.
3. To evaluate the interaction effects of watering regime and quantity.

1.1.2 Research Questions

1. How does watering frequency influence seedling growth and biomass accumulation?
2. What is the effect of water quantity on biomass accumulation and biomass accumulation?
3. Is there an interaction effect between watering regime and quantity?

1.1.3 Hypotheses

H0: Watering regime and water quantity have no significant individual or interaction effects on seedling growth and biomass accumulation.

H1: Watering regime and water quantity significantly influence seedling growth and biomass accumulation.

2 Materials and Method

2.1 Experimental Site

The experiment was conducted at a greenhouse in the Faculty of Agriculture, Adekunle Ajasin University, Akungba-Akoko, Ondo State, Nigeria between the months of December 2024 and May 2025. The location of Akungba-Akoko is approximately 7°28'11" N latitude and 5°44'10"E longitude, and its height is 357 meters above sea level (Omonijo et al., 2023). The climate of the region is tropical with the bimodal precipitation mode and the mean annual precipitation of about 1500 - 2000mm. The main rainy season lasts between April and July and is followed by another peak in late August to October, the dry season lasts between November and March.The mean daily temperatures are 23 to 35oC (Obateru et al., 2023).

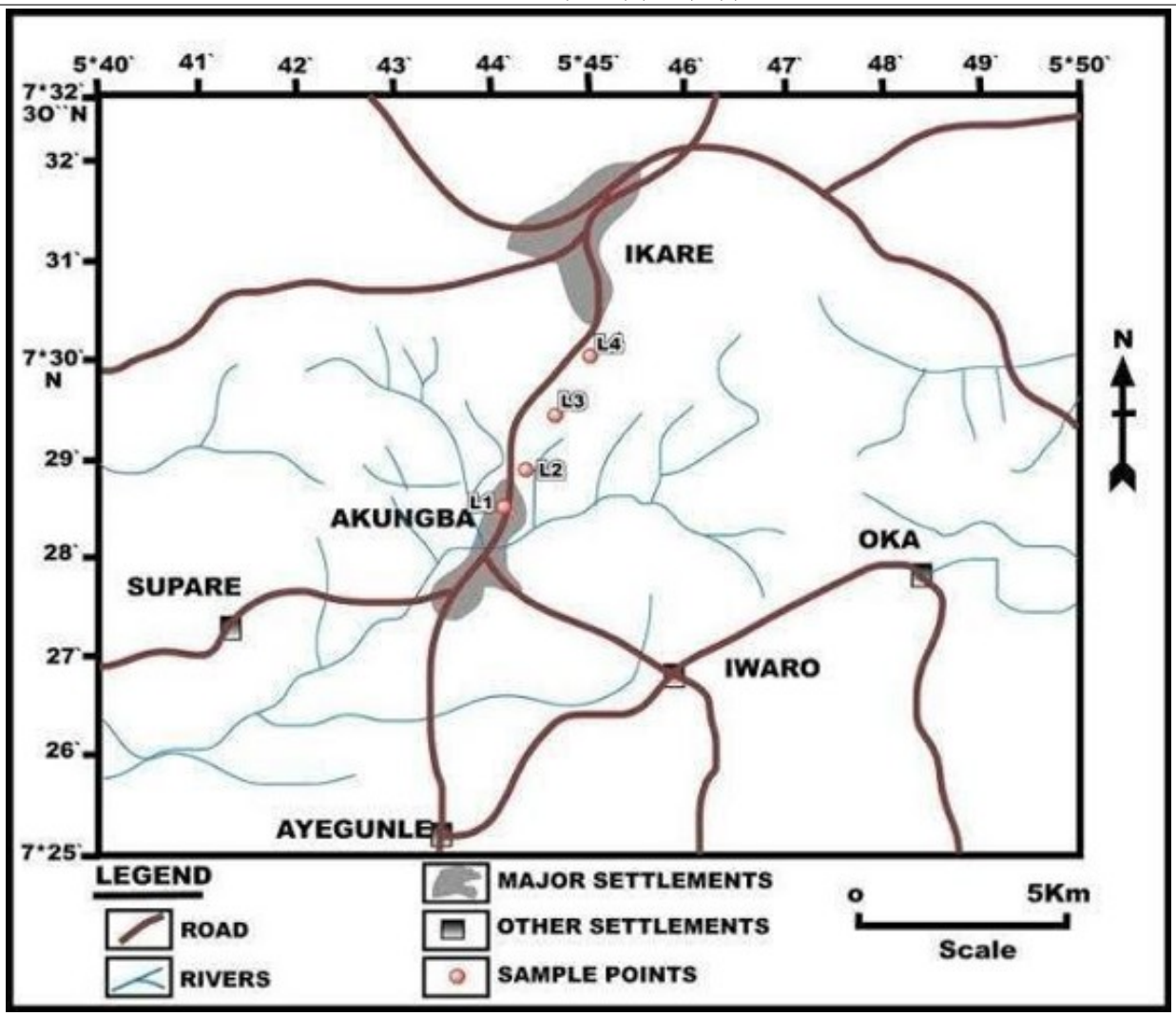

Figure 1: Map of the Study Area

2.2 Collection and Processing of Seed

Mature pods of *Tetrapleura tetraptera* were collected from healthy, naturally growing trees in Omuo-Ekiti, Ekiti State, Nigeria (7°43′N; 5°37′E). Fruits were manually depulped to extract seeds, which were subsequently air-dried under ambient laboratory conditions. Seed viability was assessed using the floatation method in which seeds were immersed in water for 30-minutes, with floating seeds considered non-viable and discarded, while submerged seeds were retained for further use in the experiment. The viable seeds were thoroughly mixed to form a homogenous seed lot prior to sowing.

2.3 Seed Germination

Viable seeds were sown in germination boxes filled with sterile, washed river sand to ensure uniform germination. The boxes were placed in a greenhouse and watered daily to maintain adequate moisture until sprouting occurred. Germination was monitored at regular intervals, and seedlings were allowed to develop to the two-leaf stage before being transplanted.

2.4 Experimental Design and Watering Treatments

Uniform seedlings at the two-leaf stage (108 seeds) were transplanted into medium-sized polyethylene bags (12×14×16cm) filled with topsoil collected from the forest nursery site and sieved to remove debris. The seedlings were transplanted and acclimatized under partial shade for three weeks and watered every day to reduce transplant shock.

Following acclimatization, the experiment was arranged in a Completely Randomized Design (CRD) with twelve watering treatments, combining frequency and volume, resulting in 108 experimental units.

2.5 Growth Measurements

Growth parameters were measured fortnightly over a five month period. Seedling height was measured between the collar region and the apical bud using a graduated ruler. The number of fully expanded leaves per seedling was counted and recorded, while collar diameter at the stem base was measured using a digital vernier cal-

liper. These parameters were chosen indicators of seedling vigour and establishment potential.

2.6 Biomass Assessment

Biomass accumulation was measured three months after transplant, which corresponds to the active vegetative growth phase of tropical tree seedlings (Maruyama et al., 2024). Destructive sampling was done on two seedlings randomly chosen at each fortnightly interval for every treatment. Seedlings were carefully uprooted and washed with water to remove adhering soil without damaging the roots. They were then separated into leaves, stems, and roots, and placed in labelled envelopes.

Fresh weights of each component were measured using a digital electronic balance. Samples were subsequently oven dried at 80o C for 24 hours until constant weight was achieved, after which dry weights were recorded. Total biomass was determined as a sum of leaf, stem, and root dry weights, serving as an indicator of biomass accumulation.

2.7 Statistical Analysis

Data on growth and biomass parameters were subjected to two-way Analysis of Variance (ANOVA) using Statistical Package of Social Sciences (SPSS). Duncan's Multiple Range Test (DMRT) was used to separate treatment means at 5% probability level whenever differences were detected. Results are presented as mean values with their corresponding standard error.

3 Results

3.1 Effects of Watering Regimes and Water Quantities on Seedling Growth

The two-way analysis of variance (ANOVA) indicated that watering frequency and water quantity significantly ($P \leq 0.05$) influenced the seedling height, collar diameter, and the number of leaves of the *Tetrapleura tetraptera* seedlings (Table 3.1). The interaction effect between watering frequency and water quantity was significant to collar diameter and number of leaves but not significant to seedling height.

3.1.1 Effects of Watering Regimes and Water Quantities on Seedling Height

Seedling height of T. tetraptera was significantly influenced (P≤0.05) by both watering frequency and water volume. The highest mean height was recorded in seedlings watered twice a day with 40ml (26.51±3.96cm), followed by those watered twice a day with 50ml (23.84±2.45cm). In contrast, seedlings subjected to prolonged watering intervals exhibited markedly reduced growth. The lowest mean height (9.22±0.47cm) was observed in seedlings watered with 30◉ml once every five days (Table 1).

Table 1: Analysis of Variance for Growth Variables of *Tetrapleura tetraptera* Seedlings under Different Watering Regimes and Water Quantities

Parameter	Source of Variation	SS	df	MS	F	Sig.
Height	Water Quantity	1820.45	2	910.23	4.55	0.013*
	Watering Frequency	2890.67	3	963.56	4.82	0.004*
	Quantity × Frequency	1519.63	6	253.27	1.27	0.276ns
	Error	21579.03	108	199.81		
	Total	27809.78	119			
Collar Diameter	Water Quantity	38.20	2	19.10	10.22	0.000*
	Watering Frequency	47.60	3	15.87	8.49	0.000*
	Quantity × Frequency	26.17	6	4.36	2.33	0.038*
	Error	201.91	108	1.87		
	Total	313.88	119			
Number of Leaves	Water Quantity	320.10	2	160.05	23.56	0.000*
	Watering Frequency	510.50	3	170.17	25.05	0.000*
	Quantity × Frequency	227.68	6	37.95	5.59	0.000*
	Error	733.83	108	6.79		
	Total	1792.11	119			

Significant at $p \leq 0.05$; ns = not significant

SS = Sum of Squares; df = Degrees of Freedom; MS = Mean Square; F = F-value

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Table 2: Means values of growth variables of *Tetrapleura tetraptera* under different watering regimes and water quantities

Treatments	Height(cm)	Collar Diameter(mm)	Number of Leaves
50ml once/day	20.91±2.57ab	4.53±0.36ab	15.10±1.20ab
40ml once/day	22.47±1.85ab	5.01± 0.25a	15.96±1.09ab
30ml once/day	13.98±1.14c	3.91± 0.25b	13.30±1.09bc
50ml twice/day	23.84±2.45ab	5.15±0.37a	17.86±1.13a
40 ml twice/day	26.51±3.96a	5.57±0.39a	17.77±1.13a
30ml twice/day	19.55±1.48b	4.49±0.31ab	14.8±0.83ab
50ml once/3 days	14.428±1.34c	3.54±0.23b	12.27±1.09bc
40ml once/3 days	12.42±0.74cd	3.49±0.18b	12.31±0.84bc
30ml once/3 days	10.57±0.75cd	3.11±0.14bc	12.33±0.73bc
50ml once/5 days	9.35±0.55d	2.85±0.13bc	9.20±0.67c
40 ml once/5 days	9.38±0.48d	2.75±0.17c	9.58±0.95c
30ml once/5 days	9.22±0.47d	2.66±0.11c	8.95±0.55c

Mean values with the same superscript alphabets in the columns are not significantly different from each other at (P>0.05)

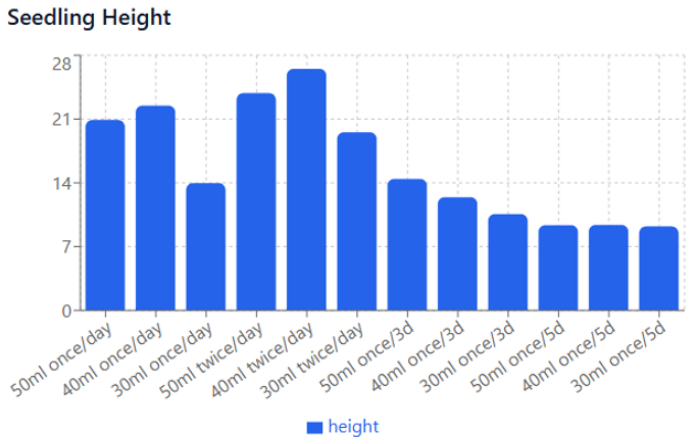

Figure 2: Effect of watering regimes and water quantities on seedling height (cm) of *Tetrapleura tetraptera*

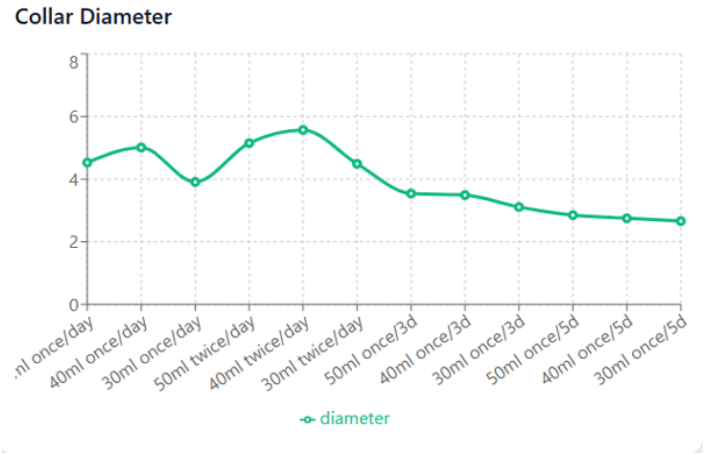

Figure 3: Effect of watering regimes and water quantities on collar diameter (mm) of *Tetrapleura tetraptera* seedlings

3.1.2 *Effects of Watering Regimes and Water Quantities on Collar Diameter*

Significant differences (P≤0.05) in collar diameter were observed among seedlings subjected to different watering regimes and volumes, as well as their interaction. The largest mean collar diameter was recorded in seedlings watered twice daily with 40◉mL (5.57±0.39 mm), followed closely by watered twice daily with 50ml (5.15 ±0.37 mm). In contrast, seedlings receiving less frequent watering and lower volumes exhibited markedly smaller collar diameters, with the minimum value (2.66±0.11 mm) observed in seedlings watered with 30ml once every five days (Table 1).

3.1.3 *Effects of Watering Regimes and Water Quantities on Leaf Production*

Watering treatments had a significant effect (P≤0.05) on the number of leaves produced by T. tetraptera seedlings. The highest mean leaf number (17.86 ±1.13) was achieved in the seedlings watered twice daily with 50ml, closely followed by those watered twice daily with 40ml (17.77 ± 1.13). In contrast, seedlings subjected to prolong watering intervals produced markedly fewer leaves. The lowest mean value (8.95±0.55) was observed in seedlings watered with 30ml once every five days (1).

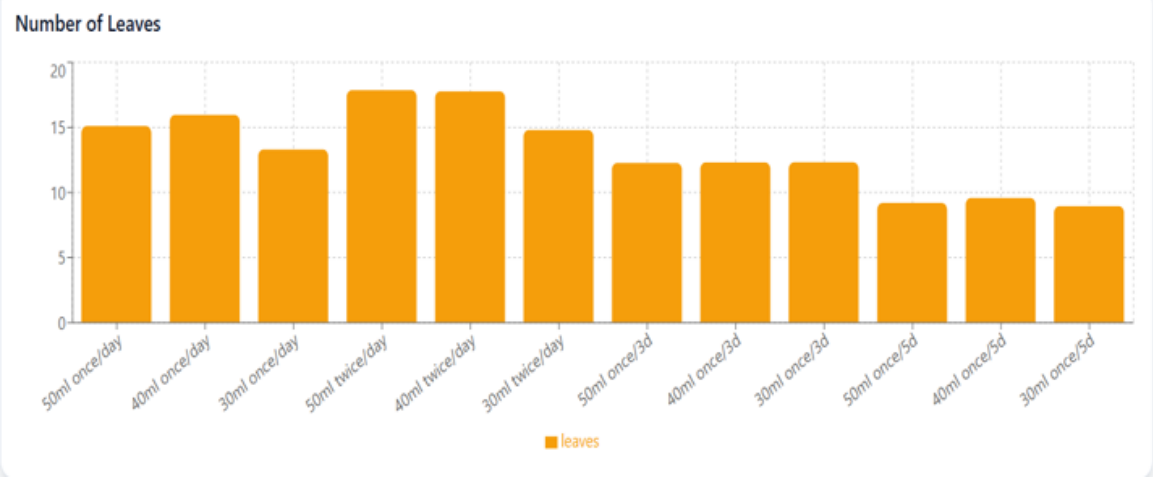

Figure 4: Effect of watering regimes and water quantities on leaf production of *Tetrapleura tetraptera* seedlings

3.2 Effects of Watering Regimes and Water Quantities on Seedling Biomass Accumulation

The two-way ANOVA (Table 3.3) results revealed that the watering frequency and water quantity had significant ($p \leq 0.05$) impact on the leaf dry weight (LDW), stem dry weight (SDW), root dry weight (RDW), and total dry weight (TDW). The interaction effects of the two factors, however, were not found to be significant to biomass parameters.

3.2.1 Leaf Dry Weight

The watering regimes and volumes had a significant effect ($P \leq 0.05$) on the leaf dry weight of T. Tetraptera. The highest mean leaf dry weight (23.99±0.117 g) was observed in seedlings watered twice daily with 50ml and 40ml. In contrast, seedlings subjected to low water volumes at prolonged intervals accumulated substantially less leaf biomass. The lowest mean value (0.94±0.26g) was recorded in seedlings watered with 50ml once every five days (Table 3).

Table 3: Analysis of Variance for Biomass Parameters of Seedlings of *Tetrapleura tetraptera* under Different Watering Regimes and Water Quantities

Parameter	Source of Variation	SS	df	MS	F	Sig.
LDW	Water Quantity	1245.382	2	622.691	7.29	0.002*
	Watering Frequency	1398.614	3	466.205	5.46	0.004*
	Quantity × Frequency	485.800	6	80.967	0.95	0.470ns
	Error	3076.124	36	85.448		
	Total	6205.921	47			
SDW	Water Quantity	745.120	2	372.560	5.86	0.006*
	Watering Frequency	702.400	3	234.133	3.69	0.021*
	Quantity × Frequency	391.667	6	65.278	1.03	0.420ns
	Error	2287.187	36	63.533		
	Total	4126.374	47			
RDW	Water Quantity	812.500	2	406.250	7.96	0.001*
	Watering Frequency	730.833	3	243.611	4.78	0.007*
	Quantity × Frequency	394.880	6	65.813	1.29	0.280ns
	Error	1836.101	36	51.003		
	Total	3774.314	47			
TDW	Water Quantity	1035.600	2	517.800	9.36	0.000*
	Watering Frequency	980.120	3	326.707	5.90	0.002*
	Quantity × Frequency	447.360	6	74.560	1.35	0.260ns
	Error	1992.236	36	55.340		
	Total	4455.316	47			

Significant at $p \leq 0.05$; ns = not significant

SS = Sum of Squares; df = Degrees of Freedom; MS = Mean Square; F = F-value

LDW = Leaf Dry Weight; SDW = Stem Dry Weight; RDW = Root Dry Weight; TDW = Total Dry Weight

Table 4: Mean values of biomass parameters of seedlings of *Tetrapleura tetraptera* under different watering regimes and water quantities

Treatments	LDW(g)	RDW(g)	SDW(g)	TDW(g)
50ml once/day	15.34±11.81b	14.32±11.72ab	11.33±10.17b	40.99±33.7b
40ml once/day	6.72±3.30c	9.59±5.15c	9.66±4.51bc	25.97±12.96c
30ml once/day	5.18±2.53cd	5.95±2.46cd	3.5±1.81a	14.63±6.8d
50ml twice/day	23.99±11.18a	18.46±3.52a	17.84±2.02a	59.85±8.71a
40 ml twice/day	23.99±11.18a	17.39±8.59a	19.78±9.96a	61.16±29.72a
30ml twice/day	7.81±3.42c	8.39±4.70c	6.30±3.96c	22.50±12.08c
50ml once/3 days	4.49±0.69d	5.36±0.52cd	4.24±0.65cd	14.09±1.86d
40ml once/3 days	2.74±0.57de	2.44±0.4d	2.47±0.58d	7.65±1.55e
30ml once/3 days	2.01±0.51de	2.14±0.24d	1.83±0.41d	5.98±1.16ef
50ml once/5 days	0.94±0.26e	0.93±0.03e	0.88±0.06e	2.75±0.35f
40 ml once/5 days	1.11±0.28de	0.90±0.38e	0.78±0.18e	2.79±0.84f
30ml once/5 days	1.06±0.08de	0.95±0.10e	0.70±0.24e	2.71±0.47f

Mean values with the same superscript alphabets in the columns are not significantly different from each other at (P>0.05)

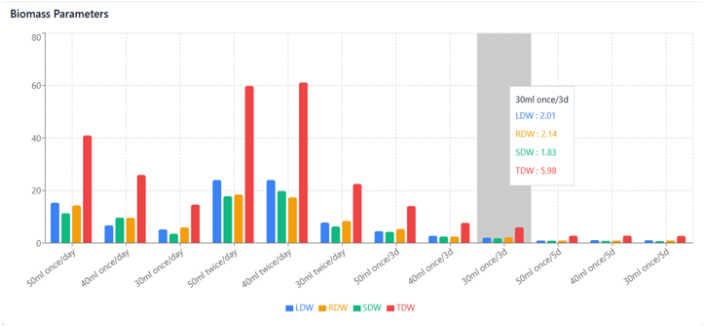

Figure 5: Effects of watering regimes and water quantities on biomass accumulation (g) of *Tetrapleura tetraptera* seedlings

3.2.2 *Root Dry Weight*

Significant differences (P≤0.05) in root dry weight were observed among treatments. The highest mean root dry weight (18.46 ±3.52 g) was observed in seedlings watered twice daily with 50ml, followed by those watered twice daily with 40ml (17.39±8.59 g). In contrast, seedlings watered with 40ml once every five days exhibited the lowest root biomass (0.90 ± 0.38 g) (Table◉3.2).

3.2.3 *Stem Dry Weight*

Significant differences (P ≤ 0.05) in stem dry weight were observed across watering regimes and volumes. The highest mean stem dry weight (19.78 ±9.96g) was recorded in seedlings irrigated twice daily with 40ml. In contrast, the lowest value (0.70 ± 0.24 g) was recorded in seedlings irrigated with 30ml once every five days; highlighting the negative impact of infrequent and low volume watering on stem biomass accumulation (Table 3.2).

3.2.4 *Total Dry Weight*

Watering regimes and volumes had significant impact (P≤0.05) on the total dry weight of T. tetraptera. The highest mean total dry weight (61.16±29.72g) was recorded in seedlings watered twice daily with 40ml, followed closely by those watered twice daily with 50ml (59.85±8.71g). In contrast, seedlings subjected to the lowest watering frequency and volume exhibited minimal biomass accumulation. The lowest mean total dry weight (2.71±0.47g) was observed in seedlings watered with 30ml once in five days (Table 3.2).

Overall, frequent watering with moderate to high volumes consistently promoted greater growth and biomass development in T. tetraptera seedlings, whereas infrequent watering with low volumes severely constrained seedling performance.

4 Discussion

This study demonstrates that both watering frequency and water quantity exert profound effects on the growth and biomass accumulation in *Tetrapleura tetraptera* seedlings. Across all measured traits, seedlings subjected to higher watering frequencies, particularly twice daily with moderate volumes, consistently outperformed those exposed to prolonged intervals. These findings highlight the pivotal role of soil moisture dynamics in determining seedling performance under controlled nursery environments.

The strongest responses to repeated watering at moderate quantities (40ml) were observed in seedling height and collar diameter, suggesting that consistent moisture availability stimulates cell division and stem thickening. Continuous irrigation likely alleviated transient water stress, thereby facilitating sustained vegetative development. Comparable influences of irrigation regimes on seedling growth have been reported in other tropical taxa. For instance, Yisau et al. (2023) found that Khaya senegalensis seedlings irrigated daily exhibited significantly greater collar diameters, leaf numbers, and biomass compared to those watered less frequently, underscoring the causal role of regular water supply in promoting growth.

Similarly, Djaha et al. (2022) reported that irrigation frequency strongly influenced morphological traits in Anacardium occidentale with seedlings watered 2-4days outperforming those subjected to longer intervals. In Albizia lebbeck Ibeh and Akinyele (2024) observed enhanced height and leaf production under irrigation schedules of 1–3 days, supporting the hypothesis that moderate irrigation maintains soil moisture conducive to growth. Evidence

from non woody taxa, such as Festuca kryloviana, also indicates that sufficient water supply facilitates both structural and metabolic activities during early ontogenesis (Shi et al., 2024).

Leaf production exhibited a slightly different response pattern, with the highest number of leaves recorded under twice-daily watering at higher volumes (50ml). Leaf initiation and expansion are closely linked to water availability and turgor maintenance, which, in turn, promote leaf surface development. Under extreme or low watering conditions, reduced leaf production may represent an adaptive response to minimize transpirational losses, consistent with patterns observed in species exposed to water-stress gradients (Lu & Yeh, 2024).

Biomass accumulation (leaf, stem and root dry weight) was significantly constrained under infrequent watering and reduced volumes. Seedlings watered once every five days showed drastic reductions in biomass, reflecting limited carbon assimilation and altered dry-matter partitioning. Conversely, seedlings irrigated twice daily displayed statistically significant increases in biomass, underscoring the cumulative benefits of uninterrupted water supply. These findings align with reports that reduced soil moisture inhibits growth and overall biomass accumulation in tree seedlings subjected to experimental watering stress (Lim et al., 2017).

Interestingly, seedlings irrigated twice daily with 40ml achieved slightly higher total biomass than those irrigated with 50ml twice daily. This suggests that excessive watering may not enhance growth beyond a certain threshold. Excessive moisture in container nurseries can inhibit soil aeration, reduce oxygen availability to root tissues, potentially offsetting the benefits of high soil moisture. Recent nursery studies emphasize the importance of optimizing rather than maximizing irrigation inputs, particularly in the context of increasing water scarcity and climate unpredictability (Zhang et al., 2024).

Overall, the results indicate that T. tetraptera seedlings perform best under moderate, frequent watering conditions. While general evidence exists on the effects of water stress on plant growth, this study provides species-specific insights into an indigenous tropical tree of considerable medicinal and socio-economic importance. The findings offer practical guidance for nursery managers and contribute to the limited empirical evidence on water-management requirements of T. tetraptera, demonstrating that moderate irrigation frequencies and volumes are optimal for growth and biomass accumulation.

5 Conclusion

This study evaluated the effects of watering regimes and water quantities on the growth and biomass accumulation of *Tetrapleura tetraptera* seedlings under controlled nursery conditions. The findings reveal that both variables exert statistically significant effect on the seedling performance where growth responses strongly dependent on the interaction effect between watering frequency and volume.

Key growth parameters, such as seedling height, collar diameter, leaf production, and other biomass components, consistently showed superior performance under frequent watering schedules. In particular, bi daily irrigation with moderate volumes (40 ml) proved most effective, resulting in enhanced structural development and total biomass. Conversely, extended watering intervals, especially once every five days, significantly inhibited growth and biomass accumulation, underscoring the sensitivity of young T. tetraptera seedlings to water stress during early development.

The results further indicate that increasing water quantity beyond an optimum threshold does not yield proportional gains in growth, highlighting the importance of optimizing rather than maximizing irrigation. This insight is practically relevant to water-efficient seedling production, in regions facing rainfall variability and water scarcity.

Overall, the study provides species-specific empirical evidence on the water requirements of T. tetraptera, a tropical tree of considerable ecological, medicinal, and socio-economic importance. The findings offer practical guidance for nursery managers, afforestation initiatives, agroforestry systems, conservation programs, presenting a viable model for improving seedling quality while ensuring efficient water utilization under changing climatic conditions.

6 Recommendations

1. Nursery managers should adopt twice-daily irrigation with moderate water volumes (≈40ml).
2. Further studies should investigate physiological responses under varying irrigation.
3. Field validation trials are recommended.

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Conflict of interest
The authors declare that they have no conflict of interest.

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Data availability Statement
Data can be made available on the behave of the request

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Effect of Vegetation Cover Removal on the Environment and Forest products in Burbur district, North Kordofan, Sudan

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Vegetation Degradation; Environment; Forest ecosystem services; Sudan

Abstract

Forest products and environment are significantly impact by the removal of vegetation cover, which lead to deforestation and land degradation. The objective of the study was to investigate the effect of vegetation cover removal on environment and forest products production in Burbur district, North Kordofan, Sudan. Data were collected using questionnaires and direct observations, and 80 farmers were interviewed. The findings, based on respondents' perception, indicated that vegetation removal increased wind speed (92.4%), runoff (81.2%), and temperature (72.5%), while 78.8% reported a decline in rainfall. Respondents also noted a reduction in fruit production from key species, including Baobab (83.8%), desert date (82.5%), and *Grewia tenax* (85%). Moreover, forage availability and firewood collection decreased, whereas charcoal production showed a moderate rate due to intensified extraction. The study concludes that vegetation removal has negatively affected forest products, environmental stability, and local livelihoods. The findings emphasize the need for community-based management, reforestation, improved energy alternatives, and awareness programs to promote sustainable resources use. . .

1 Introduction

Forests is home for varieties of fauna and flora, which support biodiversity maintenance and conservation, regulating climate and pest activities (Musa & Sahoo, 2023). In dry land of Sudan, forest resources are particularly important for livelihoods, offering food, fodder, fuelwood, and income opportunities (Brockerhoff et al., 2017; Damptey et al., 2021; Jenkins & Schaap, 2018; Musa & Sahoo, 2023). However, vegetation cover has been declining due to agriculture expansion, overharvesting, population pressure, and other anthropogenic activities (Mohammed et al., 2022, 2025). Such disturbance reduces the availability of forest products, degrade land, and influence local climatic condition (Musa et al., 2023; Mustafa, 2007; Thom & Keeton, 2020). Conversely, population and economic growth are likely intensified uses and pressure on natural resource (Khalifa, 2016), and natural disturbances acting as a key role in shaping ecosystem services, biodiversity, and regeneration in forest ecosystems (Barnosky et al., 2012; Franklin et al., 2002; Rammer et al., 2021; Thom et al., 2017). Vegetation loss exposes soil to erosion, increases surface runoff, intensifies temperature fluctuations, and contributes to declining rainfall (Khalifa, 2016; Ziervogel et al., 2006). On the other hand, anthropogenic disturbances such as illegal cutting, farming, mining in forest areas significantly impact tree species diversity, density of stands and mature trees (Bentsi-Enchill et al., 2022; Himshikha et al., 2022). Moreover, in dryland ecosys-

tems such as those in Sudan, frequent and severe disturbances particularly illegal cutting, overgrazing, and land clearing generally reduce forest canopy cover, hinder natural regeneration, and accelerate degradation processes (Mohammed et al., 2022; Musa et al., 2024) as well as increase weather extremes e.g. drought and heat (Thom et al., 2020).

Forest ecosystems contribute significantly to climate change mitigation (Keenan et al., 2016; Locatelli et al., 2015), therefore changes in vegetation composition negatively influence climate regulation (Thom et al., 2017), while extreme climatic event directly af-fect agricultural production (TNA, 2013). Several studies in Su-dan have focused on forest products (Adam et al., 2013; Musa et al., 2023), tree diversity and species distribution (Dafa-Alla et al., 2024; Mohammed et al., 2022; Musa et al., 2024), and forest degra-dation (Yasin et al., 2024), In the meantime, limited research ex-ists on how vegetation removal affects environmental conditions and forest ecosystem services in North Kordofan. This study addressed this gap by assessing community perceptions of vegetation removal impacts on climatic variables, fruit production, fuelwood and charcoal extraction, forage availability, and agriculture land. The study hypothesized that; a) vegetation removal significantly reduces fruits collection, b) forest product availability decreases with increasing disturbance, and c) vegetation removal negatively affects local climatic conditions. The findings of this study will help the policymakers in conserving forest resources and managing illegal cutting and other anthropogenic factors that lead to vegetation cover removal.

2 Methodology

2.1 Study area

The study was conducted in Barbur district of the North Kordofan state which lies between latitude 12˚15 and 13˚35 North and longitude 29˚30 and 30˚35 East longitude. It occupies a total area of about 185,302 km² (Fig. 1). The climate is hot and semi-arid with mean annual rainfall varying from 300 mm in the north to over 900 mm in the south. Rainfall is concentrated in a single short season which increases in reliability and length from north (July–September) to south (May–October).

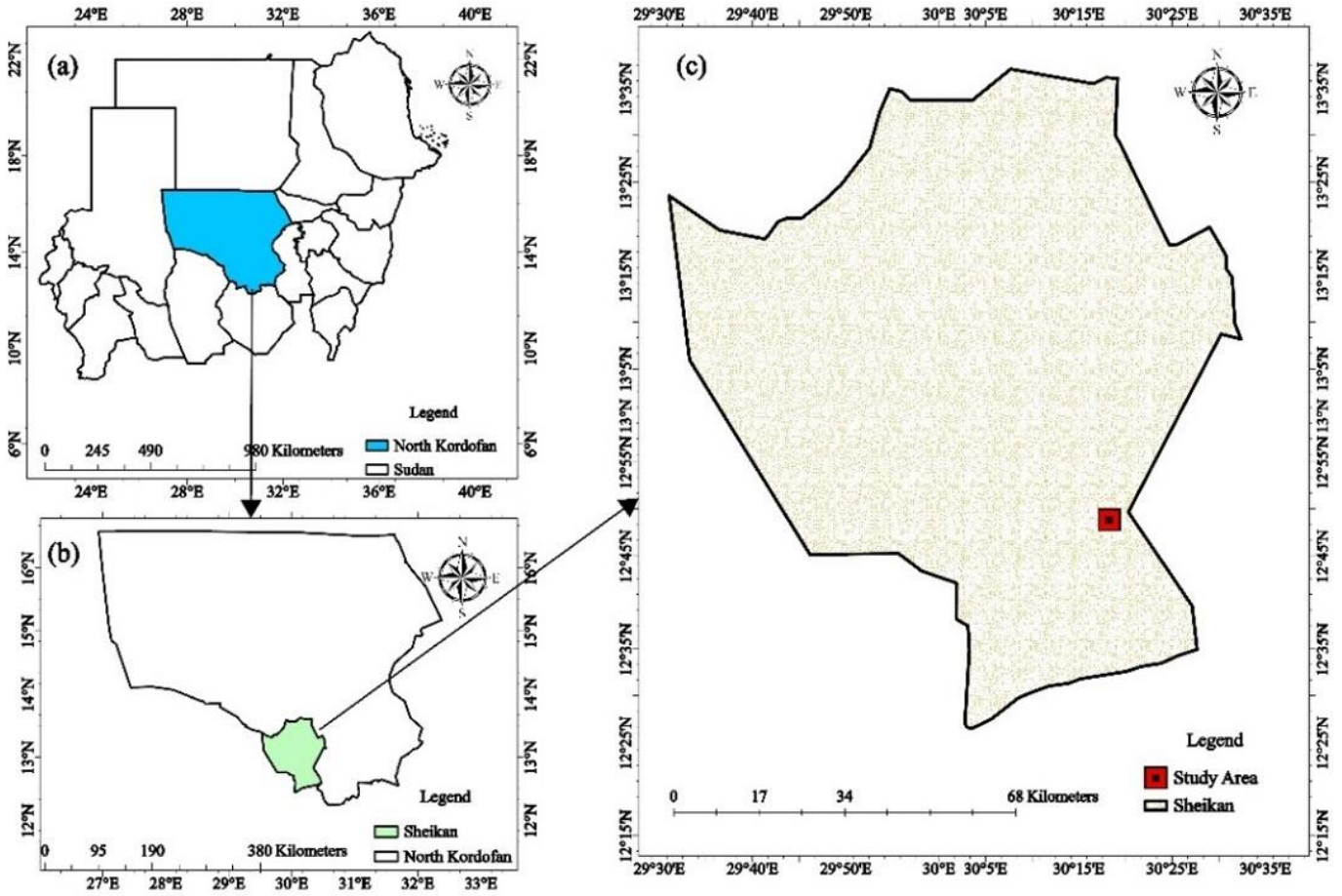

Figure 1: Study area, a) Sudan and North Kordofan state, b) Sheikan locality, and c) location of study site. The map is create using ArcGIS pro and can be accessed via (https://pro.arcgis.com/en/pro-app/latest/get-started/download-arcgis-pro.htm)

Generally, the rainy season normally extends from June/July to September/October. However, the period between the first and last useful rains is limited from 70 to 90 days only. Average maximum monthly temperatures range from 29.9 °C in January to 39.6 °C in May with annual average of 34.5 °C, while the minimum vary from 13.3 °C in January to 24.7 °C in June with annual average of 20.3 °C.

Burbur district it is one of the most important forested areas and well known by gum Arabic from *Senegalia senegal*, baobab (*Adansonia digitata*), Tamarind (*Tamarindus indica*), Ziziphus (*Ziziphus spina-christi*) and Guddim (*Grewia tenax*) fruits production and dominant tree species in the area. On the other hand, the farmers in the study are cultivate varieties of agricultural crops including sorghum, sesame and ground nut.

2.2 Data collection

A semi-structure questionnaire was designed, and pre-tested to cover local residence in the study area deals with non-wood forest product collection and depend on forest for their fuelwood and forage. Multi-stage sampling techniques was applied where 80 farmers were selected. The questionnaire was developed based on a review of relevant literature to ensure content validity. A pilot test was conducted with a sample of 20 respondents to assess its reliability and clarity. However, the internal consistency of the questionnaire was evaluated using Cronbach's alpha which yielded a value of 0.88, indicating excellent reliability.

2.3 Data analysis

The data analysis was made using descriptive statistics, whereas frequencies, averages and percentages were calculated. Data were analyzed using Statistical Packages for social Sciences (SPSS) (version 2022) and Excel. Results were interpreted in tables and figures.

3 Results and discussion

3.1 Sociodemographic characteristics of Respondents

The study presented the important sociodemographic characteristic of respondents such as sex, education level, occupation and family size (Table 1). The majority of respondents (55%) are male which consider have more frequent appearance in the forest for collection of timber and non-timber forest products. The findings align with Eltahir et al. (2024) who stated that the participation of men and women are mostly similar in agriculture and non-agriculture activities. The findings also reflect the active participation of both gender in supporting livelihood income generation. However, 42% of the respondents have studied up to primary school, 33% of them are farmers, 31% free labors, and 27% employees (Table 1). The findings revealed that in rural area of Sudan most of residences are farmer and during agriculture off season they collect forest products to support their livelihoods. In the meantime, education level is believed to be one of the decision factor determinants the engagement of respondent to particular field (Musa et al., 2025). In general education levels remain low, which may influence awareness about sustainable resources management practices. Conversely, larger families may also exert greater demand for fuelwood and forage, potentially intensifying vegetation removal.

Table 1: Sociodemographic of respondents in the study area

Category	Variables	Respondent (%)
Sex	Male	55
	Female	45
Education level	Primary	42
	Secondary	22
	University	36
Occupations	Employees	27
	Free labors	31
	Farmers	33
	Others	9
Family size	1-2 persons	20
	3-5 persons	41
	> 5 persons	39

Source: Field work, 2023

3.2 Effect of vegetation removal on climatic factors

The respondents' perception on effect of vegetation removal on climatic variabilities are shown in (Table 2). Most respondents perceived increased in wind speed (92.4%), higher runoff (81.2%), and rising temperature (72.5%), while 78.8% reported a decline in rainfall. These perceptions align with established literature showing that vegetation loss intensifies erosion, reduces moisture retention, and alters microclimates (Khalifa, 2016; Thom et al., 2017; Ziervo-gel et al., 2006). In contrast, vegetation cover act as a buffer that regulates microclimatic conditions by reducing wind velocity, fa-cilitating water infiltration, stabilizing soil, and moderating tem-perature fluctuations. A study by Chen et al. (2013) and Mohamed et al. (2024) described that, based on climatic projection, tempera-ture is expected to increase while rainfall will decrease, and this will significantly impact vegetation cover and agriculture production.

Table 2: Respondent's perception on effect of vegetation removal on climatic factors

Item	Increased (%)	Decreased (%)	Fixed (%)
Wind Speed rate	92.4	7.6	-
Rainfall status	18.8	78.8	2.5
Run-off status	81.2	15.0	3.8
Temperature status	72.5	20.0	7.5

Source: Field work, 2023

3.3 Effect of vegetation removal on fruit collection

Respondents reported significant declines in fruit production from baobab (83.8%), desert date (82.5%) and Guddim fruits (85%) (Table 3). Reducing tree density, poor regeneration, erratic rainfall, and soil degradation likely contribute to this decline. Although vegetation removal is a major driver, ecological interactions such as drought and nutrient depletion also play roles. The substantial decline in fruit production from baobab, desert date, Guddim and other species reflects both reduced in the tree density and impaired regeneration caused by vegetation removal. Similarly, Mohammed et al. (2025) observed that decreases in

tree density significantly impacts households' income. In contrast, many forest species rely on mature trees with large canopies, which are increasingly lost due to land clearing, fuelwood extraction, and agricultural expansion. Additionally, vegetation degradation modifies soil fertility, reduces moisture ability, and increases exposure to drought, all of which negatively impact fruit yield. The respondents' perceptions align with ecological evidence that, disturbances in dryland directly reduce fruit productivity (Dafa-Alla et al., 2024; Mohammed et al., 2022; Musa et al., 2024). This decline threatens rural food security and household income, given the high reliance on these species for nutrition and livelihoods. On the other hand, Eltahir et al. (2025) reported that gum Arabic producer associations started promoting agroforestry in most part of Sudan to increase vegetation cover and production of gum Arabic.

Table 3: Respondent's perception on effect of vegetation removal on fruit collection

Item	Increased (%)	Decreased (%)	Un-changed (%)
Baobab	2.5	83.8	13.8
Tamarind	83.8	16.2	-
Desert date (Lalob)	11.2	82.5	6.2
Grewia (Guddim)	1.2	85.0	13.8

Source: Field work, 2023

3.4 Effect of vegetation removal on charcoal, firewood, forage, and agricultural land

Perceptions indicated that forage availability (87.5%) and firewood collection (50%) have decreased. Charcoal production increased moderately (53.8%) (Table 4), likely due to rising demand despite decreasing tree stocks. Agricultural land decreased (78.8%) (Fig. 2) due to sand encroachment, soil degradation, and reduced productivity linked to vegetation loss. On the other hand, most of respondents (56%) stated that tree cutting has benefit (Fig. 3). However, as vegetation becomes scarce, households intensify extraction to meet economic needs, especially for charcoal, which has a high market value. Conversely, forage and firewood availability showed marked declines, reflecting the sensitivity of grasslands and shrubs to overharvesting and land degradation. Reduced forage limits livestock productivity, while reduced firewood availability increases the burden on women and children who collect fuelwood. The reported decline in agricultural land indicates soil degradation, sand encroachment, and loss of soil structure following vegetation removal.

Moreover, the quantitative estimates provided by respondents demonstrate significant reductions in key natural resources. The sharp decline in firewood and forage production reflects the loss of biomass and ground cover following vegetation removal. Similarly, the reduction in agricultural land suggests compromised soil productivity driven by erosion, nutrient depletion, and shifting sand accumulation. The moderate increase in charcoal production despite vegetation decline indicates short-term extraction pressure driven by market needs a process that is unsustainable and further accelerates forest degradation. These quantified changes reinforce the perception-based findings and highlight the need for urgent action to restore vegetation, regulate resource extraction, and rehabilitate degraded land and also observed by Hammad et al. (2025).

Table 4: Respondent's perception on effect of vegetation removal on charcoal production, firewood collection and forage production at the study area

Item	Increased	Decreased	Unchanged
Charcoal production	53.8	46.2	-
Firewood collection	47.5	50.0	2.5
Forage production	10.0	87.5	2.5

Source: Field work, 2023

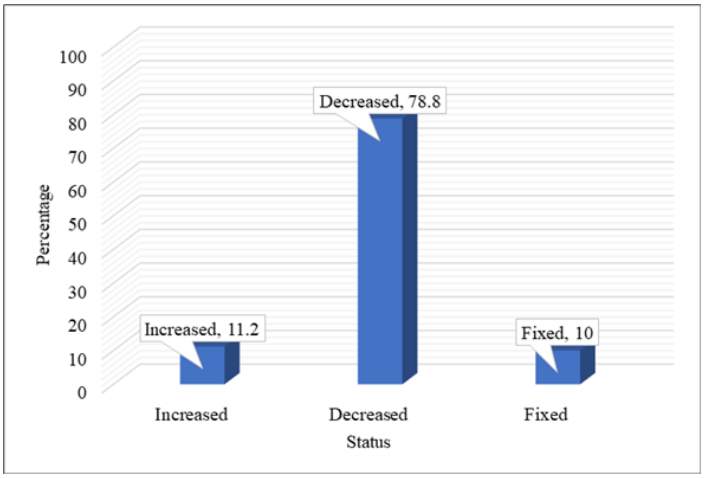

Figure 2: Respondent's perception on effect of vegetation removal on agricultural area
Source: Field work, 2023

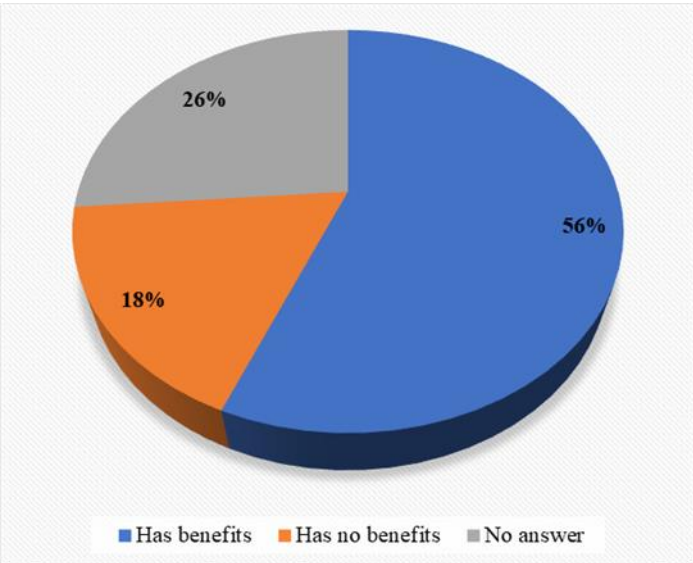

Figure 3: Respondents' perception on tree cutting status
Source: field work, 2023

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4 Conclusion and recommendations

Vegetation cover removal has significantly affected environmental stability, forest products availability, and local livelihoods. Increase in wind speed, runoff, and temperature, coupled with declines in rainfall and fruit production, indicate severe socio-economic and ecological degradation. Charcoal and firewood pressures remain high, while agriculture land and forage resources are shrinking. The study recommends implement afforestation and reforestation using drought-tolerant species, establish commu-nity forests to meet local fuel and fodder needs, promote agro-forestry and tree planting within farms, introduce alternative en-ergy sources (e.g., improved stoves, LPG), strengthen community awareness on sustainable forest management, and support natural regeneration through grazing control and seed broadcasting.

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Conflict of interest
The authors declare that they have no conflict of interest.

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Data availability Statement
Data can be made available on the behave of the request

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Effect of selected soil moisture conservation practices on the bean physical quality attributes and damage caused by the major pests and diseases on Robusta coffee, *Coffea canephora* (Pierre ex Fröhner)

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Abstract

Robusta coffee, *Coffea canephora* (Pierre ex A) contributes significantly to Uganda's foreign exchange and livelihood of its citizen. However, climate variability threatens coffee production and quality by increasing pests and diseases. This study aimed to determine how soil moisture conservation practices affect coffee defects, bean size, and relationship with pests and diseases. This study evaluated the effects of soil moisture conservation practices (SMCPs) on coffee bean defects, bean size, and their relationships with major pests and diseases. The study was conducted at the National Coffee Research Institute using an incomplete randomized block design with four SMCPs: coffee under open sun, coffee intercropped with *Desmodium intortum*, coffee mulched with *Miscanthidium violaceum*, and coffee under *Albizia coriaria*. Each treatment was replicated three times, and data were collected from four coffee plants per plot. Results showed no significant differences ($p \geq 0.05$) in coffee bean defects or screen size distribution across SMCPs. Overall, coffee grown under *Albizia coriaria* recorded the highest proportion of sound beans (82.31%), while coffee with mulch had the lowest (72.47%). Similarly, coffee bean size did not vary significantly ($p \geq 0.05$) among SMCPs. In contrast, pest and disease incidence differed significantly among systems ($P \leq 0.001$), except for berries with red blister disease, which showed no significant variation ($P = 0.709$). Coffee under open sun recorded the highest damage from leaf skeletonizers (10.43%), berry moth (20.11%), brown eye spot (3.48%), and clusters with red blisters (45.36%), whereas coffee with mulch consistently exhibited the lowest pest and disease pressure, except for berry moth (13.49%). Coffee under *Albizia coriaria* showed higher incidence of several pests and diseases, including black coffee twig borer (25.64%), leaf miners (11.82%), and berries with red blisters (32.29%), but had the lowest levels of berry moth (13.07%) and coffee berry borer (0.37%). In contrast, coffee with cover crop recorded the highest coffee berry borer infestation (3.05%). Overall, the findings indicate that although soil moisture conservation practices did not directly influence coffee bean physical attributes, they significantly affected pest and disease incidence, which in turn has implications for coffee quality. The results highlight the importance of integrating soil moisture conservation with pest and disease management strategies, with coffee mulching systems showing particular potential for reducing pest pressure and enhancing coffee quality.

1 Introduction

Robusta coffee (*Coffea canephora*, Pierre ex A. Froehner) is an essential export for many developing nations and makes up to 44.1% of the world's coffee production in 2022/23 (ICO (International Coffee Organization), 2023). During the financial year 2022/23, Uganda exported 5.76 million bags of coffee, valued at $845.94 million (UCDA (Uganda Coffee Development Authority), 2023). More so, Robusta coffee is the primary source of income for millions of smallholder farmers in the world's tropical regions (Kath et al., 2021). With 9 million Ugandans, living in over 1.7 million households, depend on activities associated to coffee value chain for their income (Hill, 2005; Kagezi et al., 2021; Mugoya, 2018; NCP (National Coffee Policy), 2013). In 2011, Chotamonsak et al. (2011) and Dai (2013) predicted that the future of coffee production is threatened by the changes in temperatures and rainfall in many significant coffee-producing areas. The effects of climate change as predicted may be more detrimental to Robusta coffee sector since it is grown in rainfed systems (Dekens & Bagamba, 2014). Bracken et al. (2023) further alluded that the coffee plant development can be impacted by the amount and seasonal variance of precipitation. According to Läderach et al. (2017), coffee quality along with coffee yield, are susceptible to changes in climate as a results of increased temperatures. Crucially, the decline in quality takes place in an environment where customer knowledge has raised expectations for higher-quality products. This emphasizes how critical it is to increase climate resilience on farms.

The physical and chemical properties of coffee beans have a significant impact on the quality of the cup. The physical and chemical characteristics of coffee beans are greatly influenced by the species and genotype of coffee, microclimatic variables (temperature, water availability, irradiance), conditions during the fruit/bean maturation process, soil characteristics, agricultural crop management techniques (e.g., fertilization, irrigation), and post-harvest processing. The environmental conditions that prevail during fruit development are particularly important for the final bean quality (Carelli et al., 2006; Cheng et al., 2016; DaMatta & Ramalho, 2006; Ramalho et al., 2018). In addition coffee pests and disease have been reported to negatively affect coffee quality (Ribeyre & Avelino, 2012) and their incidence is predicted to increase with climate changes (Chengappa et al., 2017). On a brighter side, R. G. Muschler (2001) and Vaast et al. (2006) noted that soil moisture conservation practices can reduce the incidence of pests and disease. Soil moisture conservation practices such as mulching, covercrop and agroforestry improve soil moisture retention, improve soil physical and chemical properties which in turn improve coffee's tolerance to pests and disease. However, information on how these soil moisture conservation practices influence pests and diseases in coffee is still limited.

Defective beans can result in off-flavors and a reduction in the overall quality of the cup (e.g., discolored, immature, broken, insect-damaged, wrinkled, withered, shell/elephant, triage beans) (Casas et al., 2017; Hameed et al., 2020; Marie et al., 2020). Defective coffee beans also exhibit lower weight, density, brightness, and amounts of some biochemical quality precursors (such as total polyphenols, protein, fat, sucrose, and caffeine) as compared to normal (graded) beans (Ramalakshmi et al., 2007). This demonstrates that defective beans affect coffee's weight and out-turn in addition to lowering cup quality. However, a thorough investigation into the relationship between crop management and overall coffee quality has not been fully explored (Deribe, 2019). In order to secure the future financial security and sustainability of small-scale Robusta farmers across the global tropical regions, it is crucial to comprehend and mitigate the effects of unfavorable climatic circumstances on Robusta coffee beans (Kath et al., 2021). In turn, this will contribute to lowering the possibility of flaws, low out-turn and underweight coffee beans (Ayala et al., 2022; Oberthür et al., 2011). This will increase the price that farmers may obtain for their crop, particularly in unfavorable weather conditions (Kath et al., 2021). Additionally, focused research must be done to discover how soil moisture conservation practices that affect coffee quality amidst the changing climate. This will inform farmers on quality enhancing management practices (Läderach et al., 2011). This study therefore determined the influence of selected soil moisture conservation practices on coffee bean physical characteristics, pests and diseases. This will inform on climate adaptation in the coffee system for better bean quality.

2 Materials and Methods

2.1 Study site description and selection

The study was conducted at National Coffee Research Institute (NaCORI) which is located in Mukono district about 16km along Mukono-katosi road. NaCORI is situated at 0015'26.9874"N and 32047'27.69648"E (Kobusinge et al., 2023) (Fig 1). The annual minimum temperature ranges from 150C to 180C whereas the annual maximum temperature ranges from 250C to 280C. The annual rainfall is bimodal, varying between 1,400 and 1,600 mm (Kobusinge et al., 2023; Mukono District Local Government, 2015). The study site's soils are Ferrallisols (sandy clay-loams) (Kobusinge et al., 2023).

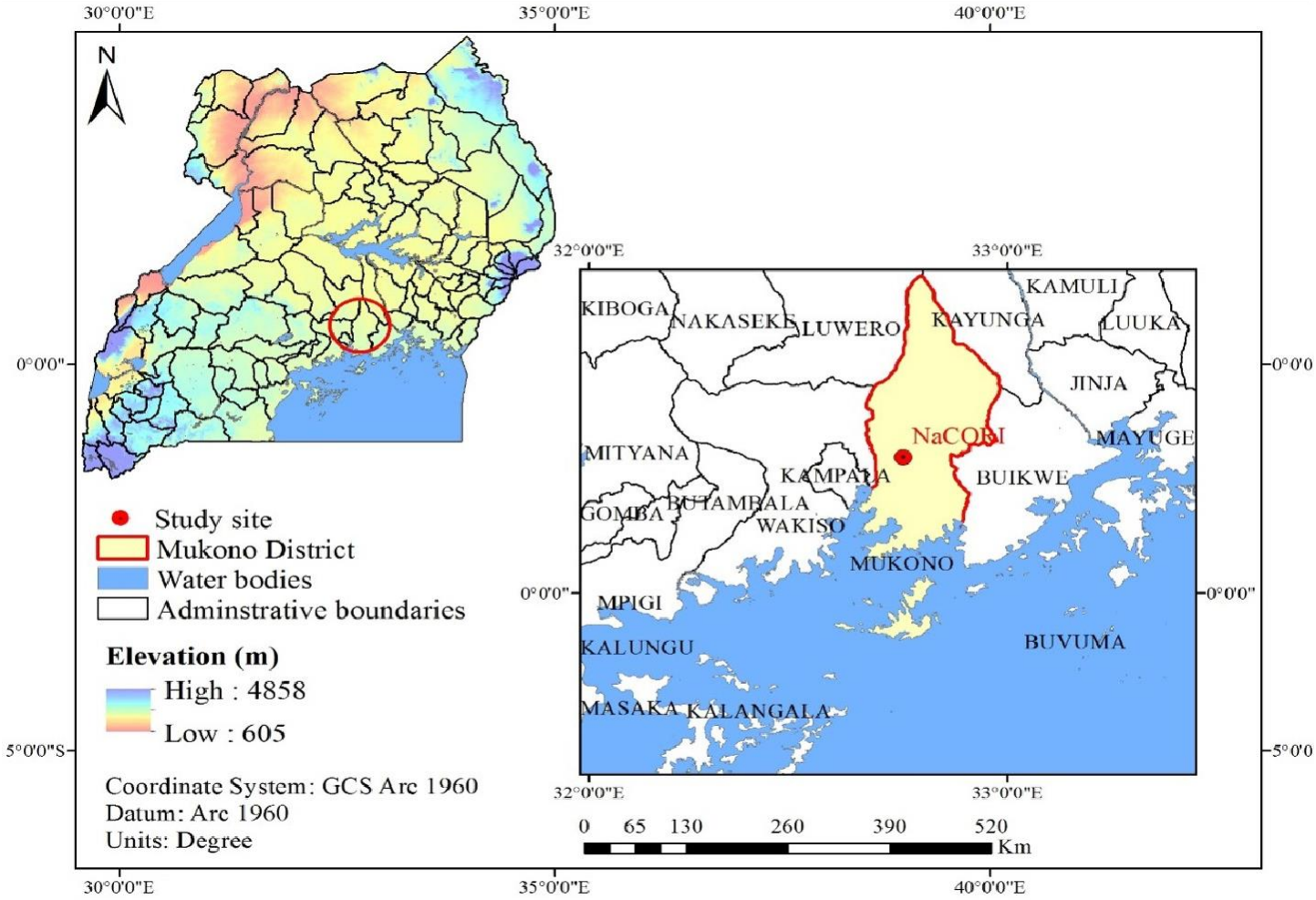

Figure 1: Location of study site, NaCORI, Mukono district (Adopted from Kobusinge et al., 2023)

2.2 Experimental design

The experiment was superimposed on Robusta coffee (*Coffea canephora* Pierre ex A. Froehner) of 2.2 acres that was planted in 2009. The coffee garden included a breeding population that gave raise to the Coffee Wilt Disease resistant (CWDr) varieties. This coffee was last stumped in 2019. All plots were uniformly managed with respect to weeding, pruning, and other cultural practices. An incomplete randomized block design was used with four soil moisture conservation practices (SMCPs) replicated three times. These consisted of; open sun coffee (COSS), coffee cover crop- *Desmodium intortum* (CCS), coffee mulch-*Miscanthidium violoceum* (CMS) and coffee *Albizia coriaria* (ACS). Replicate two didn't have ACS. Coffee was planted at a spacing of 3m by 3m while the shade tree was planted at a spacing of 15m by 15m. Mulch was maintained at a thickness of 10cm. Each treatment was of area 81m2 consisting of 16 Robusta coffee plants, with four plants used for data collection. This study ran from April 2022 to April 2023.

2.3 Methods of data collection

Harvesting and sample preparation of coffee cherries:

For physical analysis, 1 kg of well ripened coffee cherries from each tree under the four SMCPs was hand-picked, floated to remove any leaves, debris, and coffee cherries that looked diseased. The good beans were dried using a solar dryer on raised bed, made of stainless wire mesh and dried to attain a moisture content of 13-14% (UCDA (Uganda Coffee Development Authority), 2019). The moisture was evaluated using digital moisture meter (Draminski GMM mini, Poland).

Coffee physical quality analysis

The 44 samples (four trees per plot, 11 plots) were assigned a random identification code to avoid biased judgement during the analysis. The raw quality parameters of coffee were determined following the ISO 10,470 procedures (ISO (International Organization for Standardization), 2011). Three replicates of a 350g per sample were used for analysis as recommended by UCDA (Uganda Coffee Development Authority) (2019) for screen size.

a) Screen size (%):

Bean size percentage within the sample (350g) was analyzed using standard series of sieves with standard diameter holes. The sieves were arranged in descending screen sizes (19 being the largest and 12 being the smallest). The beans retained on each screen were weighted using an electric sensitive balance (0.01g) and recorded as percentages.

b) Weight of 100 sound beans (g):

100 green coffee beans were randomly picked from the each of the replicate 350g sample and weighed using an electric sensitive balance (0.01g). The means were computed for the three samples and used for analysis.

c) Raw quality (%):

The coffee quality attributes evaluated were bean colour, diseasing, pinhole, withered beans, chalky beans and other defects. From each of the 350g sample, weights of each category were taken and expressed in percentages and used for analysis. Colour of the green beans was defined as; bluish, brown, and greenish, blue greenish, or faded.

d) Raw beans odour:

The raw coffee bean odour (smell) was evaluated by experienced testers. The odour of coffee beans was evaluated subjectively as clean, fairly clean, off odour or strong off odour. Each category was weighed and expressed as percentages.

Collection of coffee pest and disease data

Throughout the course of a year (April 2022–April 2023), data on pests and diseases were collected on all the stems of the study four Robusta coffee plants per plot. The number of primary branches and BCTB-infested branches per stem were counted in order to determine the damage caused by the Black Coffee Twig Borer (BCTB). One primary branch (a twig) was chosen at random for data collection after the coffee plant was split into two sections, the upper and lower portions of the coffee plant. The overall number of leaves on selected primary and those affected by the (i) leaf miners (LM), (ii) leaf skeletonizers (LS), (iii) tailed caterpillars (TC) (iv) leaf eating beetles (LEB) and v) Brown Eye Spot (BES) were counted. The number of coffee clusters on the sampled primary twig were then counted, together with the number of clusters injured by (i) canopy mealy bugs (CM), (ii) canopy scales (CS), (iii) berry moth (BM), and (iv) red blister (CRB). The number of berries as well as those affected with the coffee berry borer (CBB) and red blisters (CRB) were counted in one (1) center cluster of the primary branch that was chosen.

2.4 Data Analysis

Prior to analysis, data on coffee bean physical attributes were tested for homogeneity of variances using Bartlett's test. The test indicated significant differences in variances among treatments ($P < 0.05$); therefore, the data were square root transformed and retested for homogeneity of variances, after which the assumption of homogeneity was met. The transformed data were analysed using ANOVA with an unbalanced treatment structure due to unequal treatment numbers. In Pest and disease data, outliers were removed and the homogeneity test done and then ANOVA was also conducted. Where treatment effects were significant, the Least Significant Difference (LSD) test was used for mean separation. Treatment means presented in brackets are the original values and were used for discussion. Pearson correlation analysis was conducted between coffee bean physical attributes and coffee pests and diseases to determine the magnitude and direction of relationships, using untransformed data. All statistical analyses were performed using GenStat (12th Edition).

3 Results

3.1 Effects of selected Soil Moisture Conservation Practices (SMCPs) on coffee bean defect

Results of our study showed that all the coffee bean quality defects did not significantly ($p \leq 0.05$) differ across the SMCP's (Table 1). The highest percentage (3.9%) were recorded under CMS while the lowest (1.2%) was under ACS. CCS and COSS registered the highest number of floats (1.0%) while ACS had the least (0.3%). The highest number of insect damaged beans (0.1%) was recorded in ACS whereas, the least was in CMS (0.0%). CMS had the highest number of nipped beans (13.3%) while CCS had the least (11.3%). Percentage number of partly black beans were highest under CMS (10.2%) and lowest under ACS (3.2%). ACS had the highest number of holes (0.03%) while CCS had the least (0.01%). The percentage of sound beans ranged from 72.5% under CMS to 82.3% under ACS, with ACS consistently exhibiting superior numerical performance in overall bean quality. Correspondingly, defective beans were highest under CMS (27.5%) and lowest under ACS (17.7%), although these differences were not statistically significant ($p = 0.261$). Furthermore, all the coffee beans sampled in ACS, CCS and COSS were clean while the small of 8.3% of the coffee samples from CMS was earthly (Table 2). In addition, >50% of the coffee beans in all the SMCPs were brownish green in colour, with CCS registering the highest percentage (85.7%) and ACS having the lowest (57.1%). Homogeneity of variance tests indicated no significant heterogeneity for any variable ($p \geq 0.05$), confirming that the assumptions for ANOVA were met.

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Table 1: Percentage of coffee beans (Mean± sem) with defects under selected soil moisture conservation practices (SMCPs) on Robusta coffee

System	% Blacks	% Floats	% Insect	% Nipped	% Partly black	% Hole	% Sound beans	% Defects beans
ACS	1.0(1.2) ± 0.28(1.0)	0.29(0.6)± 0.23(0.5)	0.15(0.1)± 0.07(0.1)	3.55(12.8)± 0.26(2.0)	1.60(3.2)± 0.51(3.5)	0.00(0.0)± 0.05(0.02)	9.06(82.3)± 0.27(4.4)	4.10(17.7)± 0.41(4.3)
CCS	1.61(3.2)± 0.27(1.0)	0.75(1.0)± 0.22(0.5)	0.0(0.0)± 0.06(0.1)	3.28(11.3)± 0.25(1.9)	2.81(9.6)± 0.49(3.4)	0.01(0.01)± 0.05(0.02)	8.62(74.7)± 0.26(4.2)	4.91(25.3)± 0.39(4.2)
CMS	1.86(3.9)± 0.20(0.8)	0.68(0.6)± 0.17(0.4)	0.0(0.0)± 0.05(0.0)	3.55(13.3)± 0.19(1.5)	2.92(10.2)± 0.38(2.6)	0.01(0.02)± 0.04(0.01)	8.49(72.5)± 0.20(3.3)	5.16(27.5)± 0.31(3.3)
COSS	1.56(3.0)± 0.22(0.8)	0.78(1.0)± 0.18(0.4)	0.01(0.0)± 0.05(0.0)	3.47(12.5)± 0.21(1.6)	2.57(8.4)± 0.41(2.8)	0.01(0.02)± 0.0(0.01)	8.62(75.1)± 0.22(3.5)	4.83(24.9)± 0.33(3.5)
p value	0.141	0.373	0.339	0.864	0.141	0.871	0.443	0.261
Cv	40.12	88.49	98.22	18.85	51.24	98	7.89	21.54
Lsd	0.7099	0.5789	0.1734	5.048	1.317	0.1391	0.6901	1.047
Homogeneity test, p	0.846	0.186	1.00	0.494	0.181	0.449	0.114	0.478

ACS: coffee *Albizia coriaria*; CCS: coffee cover crop; CMS: coffee mulch system; COSS: Open sun coffee

Table 2: Percentage of coffee beans with different levels of smell and colour under selected soil moisture conservation practices (SMCPs) on Robusta coffee

Levels of variable	ACS (%)	CCS (%)	CMS (%)	COSS (%)
Smell of the coffee beans				
Clean	100.0	100.0	91.7	100.0
Earthly	0.0	0.0	8.3	0.0
Colour of the coffee beans				
Blue green	14.3	0.0	0.0	0.0
Greenish Brown	28.6	0.0	16.7	20.0
Brownish green	57.1	85.7	83.3	80.0
Pale	0.0	14.3	0.0	0.0

3.2 Effects of selected Soil Moisture Conservation Practices (SMCPs) on coffee bean size

Results further showed that there was no significant difference ($p \leq 0.05$) in coffee bean size among SMCPs (Table 3). Under ACS, the highest proportions were observed in screen 16 (27.9%) and screen 15 (21.6%), indicating a tendency toward medium-sized beans. CCS showed a more evenly distributed size profile, with comparable contributions from screens 14, 15, 16, and 17, each ranging between 14.8% and 19.3%. CMS exhibited a notable numerical shift toward larger beans, recording the highest proportions of screens 18 (17.0%) and 19 (9.4%) among all systems, suggesting improved bean filling under mulched conditions. Conversely, COSS was dominated by screen 17 (25.5%), followed by screen 16 (20.7%), indicating that open sun conditions favored the production of medium-to-large beans. Smaller beans (screens <12 and 13) constituted a relatively small proportion of the total across all systems, ranging from 4.8% to 8.4%, with CCS recording the highest proportion of the smallest beans (<12). The coefficients of variation were generally higher for the larger screen sizes (18 and 19), reflecting greater variability in the occurrence of larger beans across treatments. Homogeneity of variance tests confirmed that the assumptions for analysis of variance were met for all screen size classes ($p \geq 0.05$), supporting the reliability of the statistical.

Table 3: Effects of selected Soil Moisture Conservation Practices (SMCPs) on coffee bean size (Mean± sem)

System	Screen size							
	<12	13	14	15	16	17	18	19
ACS	2.56(7.0)± 0.29(1.6)	2.43(6.3)± 0.28(1.5)	3.39(12.1)± 0.31(2.1)	4.53(21.6)± 0.32(2.6)	5.22(27.9)± 0.26(2.5)	3.85(15.9)± 0.37(3.2)	2.17(6.9)± 0.53(3.6)	1.17(2.7)± 0.47(2.5)
CCS	2.77(8.4)± 0.28(1.6)	2.94(9.3)± 0.27(1.4)	3.75(14.8)± 0.30(2.0)	3.91(15.6)± 0.31(2.5)	4.37(19.3)± 0.25(2.4)	4.27(19.3)± 0.36(3.1)	2.85(9.2)± 0.51(3.5)	1.81(4.2)± 0.45(2.4)
CMS	2.18(4.8)± 0.21(1.2)	2.27(5.4)± 0.21(1.1)	3.13(10.3)± 0.23(1.6)	3.85(15.5)± 0.24(1.9)	4.48(20.5)± 0.19(1.9)	4.21(18.1)± 0.28(2.4)	3.82(17.0)± 0.40(2.7)	2.73(9.4)± 0.35(1.9)
COSS	2.50(7.1)± 0.23(1.3)	2.32(5.9)± 0.23(1.2)	2.92(9.0)± 0.25(1.7)	3.57(13.1)± 0.26(2.1)	4.52(20.7)± 0.21(2.0)	4.98(25.5)± 0.30(2.6)	3.69(14.1)± 0.43(2.9)	2.17(5.0)± 0.38(2.0)
p value	0.395	0.241	0.209	0.168	0.099	0.11	0.082	0.084
Cv	29.7	29.06	24.57	20.67	14.33	21.65	41.35	56.53
Lsd	0.7374	0.7175	0.8051	0.8175	0.6676	8.247	1.369	1.195
Homogeneity test, p	0.23	0.784	0.944	0.435	0.338	0.603	0.11	0.106

ACS: coffee *Albizia coriaria*; CCS: coffee cover crop; CMS: coffee mulch system; COSS: Open sun coffee

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3.3 Effects of selected Soil Moisture Conservation Practices (SMCPs) on major Robusta coffee pests and diseases

Table 4 below summarizes the effect of selected SMCPs on the major Robusta coffee pests and diseases. Significant differences among systems were observed for all pests and diseases (P ≤ 0.001), except berries with red blister disease (BRB), which did not differ significantly among systems (P = 0.709). COSS recorded the highest LS (10.43%), BM (20.11%), BES (3.48%), and CRB (45.36%) damage. In contrast CMS consistently exhibited the lowest pest and disease damage except for BM (13.49%). ACS had higher BCTB (25.64%), LM (11.82%), CS (1.20%), CM (6.53%), LEB (14.94%), BRB (32.29%) and TC (25.26%) damage but least levels of BM (13.07%) and CBB (0.37%) damage. CCS had only the highest CBB (3.05%) damage. Homogeneity of variance tests indicated no significant heterogeneity for any variable (p≥0.05), confirming that the assumptions for ANOVA were met.

Table 4: Effects of selected Soil Moisture Conservation Practices (SMCPs) on the major Robusta coffee pests and diseases (Mean± sem)

System	LS	CBB	BCTB	LM	TC	CM	LEB	BM	CS	BES	CRB	BRB
ACS	9.26±	0.37±	25.64±	11.82±0.24a	25.26±	6.53±	14.97±	13.07±	1.20±	3.40±	42.74±	32.29±
	0.30b	0.17c	0.601a		0.34a	0.49a	0.18a	0.49c	0.08a	0.12a	1.07a	1.03
CCS	8.06±	3.05±	21.25±	10.79±	22.76±	3.81±	13.38±	15.24±	0.84±	2.99±	37.12±	32.50±
	0.25c	0.14a	0.49b	0.19b	0.28c	0.37b	0.18b	0.41b	0.07b	0.12c	0.88b	0.84
CMS	4.34±	1.94±	20.85±	8.43±	18.70±	3.92±	11.06±	13.49±	0.14±	2.39±	32.65±	31.44±
	0.27d	0.15b	0.55b	0.21c	0.31d	0.42b	0.20c	045c	0.07c	0.13d	0.97c	0.93
COSS	10.43±	2.15±	25.26±	10.45±	23.81±	4.34±	13.66±	20.11±	0.03±	3.48±	45.36±	31.31±
	0.24a	0.14b	0.49a	0.20b	0.28b	0.38b	0.18b	0.41a	0.07c	0.12a	0.88a	0.84
p-value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	0.709
Cv	28.1	65.05	19.7	17.27	11.34	76.69	12.57	23.83	125.88	36.6	20.52	24.38
l.s.d	0.7462	0.4253	1.5	0.5876	0.8424	1.143	0.5467	1.232	0.2159	0.369	2.664	2.555
Homogeneity test, p	0.267	0.243	0.411	0.483	0.389	0.340	0.707	0.425	0.637	0.256	1.00	0.552

LS, leaf skeletonizers; CBB, coffee berry borer; BCTB, black coffee twig borer; LM, leaf miner; TC, tailed caterpillars; CM, canopy mealy bugs; LEB, leaf eating beetles; BM, berry moth; CS, canopy scales; BES, brown eye spot; CRB, clusters with red blister disease; and BRB, berries with red blister disease; ACS, coffee *Albizia coriaria*; CCS, coffee cover crop; CMS, coffee mulch system; and COSS, Open sun coffee.

3.4 Correlation between coffee pest and disease and coffee bean physical aflributes

Table 5 below summarizes the relationship coffee bean physical attributes and Robusta coffee pests and diseases. Among the coffee bean defects, positive and significantly (p≤0.05) correlations were observed in case of %blacks and BRB (r=0.47); %floats and CBB (r=0.36); %insect and CS (r=0.77); %insect and BM (r=0.43); %insect and CM (r=0.34) and %insect and CRB (r=0.49). Negative significant (p≤0.05) correlations were observed between colour and CS (r=-0.63); colour and BRB (r=-0.37); colour and CRB (r=-0.44) and %nipped and BRB (r=-0.34). For the screen sizes, positive and significant (p≤0.05) correlations were recorded in case of screen 15 and CS (r=0.41).

Table 5: Correlation between coffee pest and disease and coffee bean physical attributes

Coffee physical Attributes	Coffee pest and disease											
	CBB	BCTB	CS	BES	BM	LEB	BRB	CM	CRB	LS	TC	LM
Colour	0.1207	0.0816	-0.6338***	-0.1696	-0.234	0.4724*	-0.3417*	-0.367*	-0.4368**	0.1073	0.0735	-0.2374
% Blacks	0.3066	0.1418	0.2765	-0.2454	0.2361	0.2156	0.4745*	0.2233	0.2367	-0.2596	-0.0853	-0.2076
% floats	0.3618*	0.0012	0.0583	-0.132	-0.07	0.2417	-0.0283	-0.0418	-0.1391	-0.1893	0.0788	0.0609
% insects	0.0833	-0.0191	0.7723***	-0.0789	0.4303**	-0.1445	0.3881*	0.3364*	0.4926**	0.092	-0.1209	0.1703
% nipped	-0.3248	0.0398	-0.05	-0.0462	-0.1211	-0.0913	-0.3398*	0.07	-0.2216	-0.1134	-0.0218	0.0269
% partly	0.0647	0.1198	-0.1144	-0.3233	-0.2374	0.1076	-0.3161	-0.2146	-0.2622	-0.1415	-0.2987	0.0762
% hole	-0.1652	0.319	-0.0702	0.1312	-0.2058	-0.2043	-0.0898	0.0385	-0.1066	-0.076	-0.0502	-0.1387
Smell	0.0368	0.0249	-0.0601	-0.1548	0.1163	-0.0887	-0.3417	0.1336	0.0015	-0.0015	-0.0802	0.02
% sound	-0.0079	-0.1571	0.0302	0.3322	0.2033	-0.1155	0.2953	0.088	0.269	0.1778	0.2363	0.1277
% defect	0.0079	0.1571	-0.0302	-0.3322	-0.2033	0.1155	-0.2953	-0.088	-0.269	-0.1778	-0.2363	-0.1277
<12	-0.0006	0.117	0.2289	-0.1954	-0.1205	0.1843	-0.1008	0.1081	-0.0709	0.0078	0.0885	0.116
13	0.1474	0.0234	0.1093	-0.1104	-0.2447	0.1561	-0.1306	0.0351	-0.1767	-0.0788	0.1481	0.2276
14	0.1259	-0.0481	0.1935	-0.0234	-0.2266	0.07	0.0287	0.1643	-0.0526	-0.0855	0.0731	0.2858
15	-0.0004	-0.0479	0.4134*	0.0699	-0.0006	0.0081	0.2319	0.3092	0.2196	0.0714	-0.0443	0.1986
16	-0.0815	0.0794	0.2201	0.0666	0.1317	0.0959	0.1097	0.137	0.1265	0.2947	-0.1245	-0.0556
17	0.0302	0.0603	-0.3157	0.0773	0.2217	0.0973	-0.1458	-0.3005	-0.0133	0.1859	0.1066	-0.3286
18	-0.089	-0.0412	-0.2878	0.034	0.0124	-0.2009	0.0059	-0.1639	-0.0482	-0.2216	-0.0503	-0.117
19	-0.0242	0.082	-0.2063	-0.1708	0.0147	-0.1781	0.0422	-0.0454	-0.053	-0.174	-0.1432	-0.0712

LM, leaf miners; LS, leaf skeletonizers; TC, tailed caterpillars; LEB, Leaf eating beetles; BES, Brown Eye Spot; CM, canopy mealy bugs; CS, canopy scales; BM, berry moth; CRB, Clusters with Red blister; CBB, coffee berry borer, and BRB, Berries with Red blisters

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4 Discussion

The demand for high-quality coffee is rising globally (Byers et al., 2008) and this quality is s mostly driven by the coffee's physical and chemical characteristics (Barbosa et al., 2012). These are in turn influenced by the interactions between the coffee species/genotype, environment as well as management of the coffee field and plant (Barbosa et al., 2012; Cheng et al., 2016; Decazy et al., 2003; Joët et al., 2010; Vaast et al., 2006). Results of our study showed that there was no significant ($p \geq 0.05$) difference across the SMCPs for all the coffee defects. These findings are in agreement with finding of Silva Neto et al. (2018) who observed that different management practices had no significant effect on the coffee bean defects. Nevertheless, though there was not significantly different in defects across the different treatments, the slight difference in percentage defective beans could negatively affect the final cup quality of coffee (Franca & Oliveira, 2008). ACS had generally the lowest number of blacks, floats, partly beans and highest percentage of sound beans. Our results agree with Odeney et al. (2015) who found that shade lowers the percentage of rejects which includes diseased, mummified or dried berries. Similarly, R. Muschler (1998) observed a decrease in coffee rejects from 10% to less than 1% for coffee grown under shade in Costa Rica. This could in part be due to the fact that shade reduces incidence of physical defects by delaying ripening and influencing uniformly ripening (R. G. Muschler, 2001; Vaast et al., 2006). According to DaMatta and Ramalho (2006), Obso (2006) and Vaast et al. (2006), shade creates a microclimate that decreases heat stressors in plants, boosts the leaf to fruit ratio and net photosynthetic rate, and extends berry maturity period. However, it has been noted that shade increases the yield of large coffee beans (Guyot et al., 1996; R. G. Muschler, 2001). Kathurima et al. (2012) noted that the shade in Kenya played a major role in the rise in premium grades, AA and AB, which are highly prized in the global coffee trade. Lower temperatures in shaded areas cause berries to grow and develop more slowly, giving them more time to fill and accumulate more sugar and phenolic compounds linked to aroma. This results in coffee that has a higher overall sensory quality (R. G. Muschler, 2001; Tolessa et al., 2017; Vaast et al., 2006).

However, Bosselmann et al. (2009) discovered that the presence of shade trees on plantations at high altitudes resulted in a drop in coffee quality. In addition, attacks of insect pests and diseases have a direct impact on the quality of the harvest because they impair the physical and sanitary quality, thereby altering the organoleptic characteristics of beans (Ribeyre & Avelino, 2012). Although all systems had percentages that were very near to zero, as also reported by Silva Neto et al. (2018), our data indicated that the greatest number of insect-damaged beans were recorded under ACS. Coffee berries may be attacked by a range of insect species but most of the damage observed on coffee beans is due to infestation by the coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari), coffee berry moth, *Prophantis Smaragdina* (Butler) and coffee bean weevil, *Araecerus fasciculatus* (De Geer) (Abedeta et al., 2011; Barrera, 2018; Gaitán et al., 2015). The coffee berry borer infestation is favored by shade, as evidenced by the greater infestation rates in shaded coffee plants as opposed to those planted in the sun (Bosselmann et al., 2009; Mariño et al., 2016; Soto-Pinto et al., 2002; Staver et al., 2001).

As Silva Neto et al. (2018) also revealed, our data further demonstrated that there was no significant difference in coffee bean size among SMCPs. However, CMS dominated in screen 18 and 19, COSS in screen 17, ACS in screen 15 and 16 while CCS in screen 14, 13 and <12. CMS dominated the upper screen sizes because bean size distribution has been reported to be affected by soil properties, particularly soil pH, organic matter, texture, and manganese (Mn) (Yadessa et al., 2020a, 2020b) and application of mulches in the coffee agro-systems increases soil organic carbon and plant nutrients (Nzeyimana et al., 2017, 2019). Mulching also enhances moisture retention in coffee agro-systems (Mohammedsani et al., 2018) and this could also have contributed to the bigger beans in CMS (Kobusinge, unpublished data) since mulching prevents shedding off coffee leaves as a result of insufficient water in the soil (Wangui, 2012). One of the main factors influencing bean size, according to Wrigley (1988), is soil moisture. This is because the size of the final bean is influenced by the elasticity of the parchment, which is the ovule's outer layer, and the volume of integument inside each ovule before the parchment lignifies and forms an embryonic sac that is eventually filled with endosperm. Soil moisture during the berry development's expansion phase determines the integument volume (Worku et al., 2022). Conversely, low soil moisture under ACS may have played a role in the small bean sizes (Kobusinge, unpublished data). However, coffee grown in shade produced larger beans than coffee grown in open sun because of fewer flowers and fewer fruits per plant.

Additionally, the findings demonstrated pests and disease damage were significant across the SMCPs demonstrating role of SMCPs in shaping pests and disease dynamics. The highest infestation of coffee leaf skeletonizers (LS), *Leucoplema dohertyi* (Warren) was recorded under COSS, implying that infestation by this insect pest significantly increased with reducing shade intensity. Similarly, studies conducted by Biru (2019) in Ethiopia showed that the incidence of L. dohertyi had a negative relationship with shade intensity in the dry season, though not significant. However, contrary to our finding, some authors have reported a positive association between shade and L. dohertyi (e.g. Samnegård et al., 2014; Nurihun et al., 2022; Shimales et al., 2023). On the other hand, the highest infestation of coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari) was recorded under CCS and this could be in part due to the fact that the cover crop used in this study, *Desmodium intortum* is a suspected potential host of H. hampei (Messing, 2012). However, Feliz Matos et al. (2004) and Bosselmann et al. (2009) observed more H. hampei infestation under shade than cover crop (Pohlan et al., 2008), while Jonsson et al. (2015) observed that H. hampei was more in open sun coffee. By promoting the formation of fungal toxins, H. hampei infection has a detrimental effect on coffee's organoleptic quality as well as its sanitary quality (**Taniwaki2007**). As a matter of fact, the International Organization for Standardization (ISO) assigns a medium influence (0.5) on the sensory quality of beans damaged by H. hampei, classifying them as "insect-infested beans" or "insect-damaged beans" (ISO (International Organization for Standardization), 2004). It has been observed that beans with H. hampei damage roast unevenly and turn darker. The bean may break if it is attacked more than once. Because broken beans are smaller, they roast more quickly and could burn. It also makes mold growth easier, which results in odd tastes and ochratoxin contamination (Ribeyre & Avelino, 2012). In addition, X. compactus infestation was highest under ACS and least under CMS. Our results are consistent with past research that have found higher infestation of X. compactus on Robusta coffee under shade systems compared to other coffee agro-systems (Anuar, 1986; Bukomeko et al., 2018; Hultman, 2016; Kagezi et al., 2013). One possible explanation for this could be that shade systems offer micro-environments that promote growth and the conclusion of the organism's life cycle (Bukomeko et al., 2018; Kagezi et al., 2013).

The development of the related ambrosia fungus may similarly be aided by these humid microclimates. Though damage caused by other pests and diseases did not vary significantly across the SMCP's, their attack on coffee beans can have a substantial effect on coffee quality (Etana & Merga, 2021). The highest damage caused by tailed caterpillar (TC), *Epicampoptera andersoni* (Tams), canopy mealybugs (CM), *Planococcus* spp., leaf eating beetles (LEB) and red blister disease on berries (BRB) caused by *Cercospora coffeicola* (B. & CKE.) was recorded under ACS. This implies that the damage caused by these insect species is increased by shade, agreeing with other research studies. Waller et al. (2007a) recorded severe damage caused by E. andersoni on coffee bordering forests where the canopy is generally higher whereas, a positive but not significant correlation was reported between *Planococcus* spp. and shade (Biru, 2019). Also, higher damage caused by LEB on coffee under closer spacing, which is more shaded due to self-shading (Long et al., 2015). However, contrary to our finding, Staver et al. (2001) and Karungi et al. (2015) reported lower incidence and damage of *Planococcus* spp. on coffee under shade since shade lowers the temperature (Lara-Estrada et al., 2023; Wagner, 2020) and this does not favor the presence of mealybugs (Jayakumar & Rajavel, 2019).

Likewise Staver et al. (2001) also reported low C. coffeicola on coffee grown under shade. Our findings demonstrated that the highest damage caused by the canopy scales (CS), *Coccus* spp. was recorded coffee grown highest under ACS. In contrast, Karungi et al. (2015) also reported low *Coccus* spp., on coffee growing under shade. BES caused by *Cercospora coffeicola* (B. & CKE.) however Staver et al. (2001) reported low C. coffeicola on coffee growing under shade. In addition, the incidence of leaf miner (LS), *Leucoptera coffeella* (Guérin-Mèneville & Perrottet) was highest on coffee under ACS and lowest under CMS. Similarly, Shimales et al. (2021b, 2021a) reported lower incidence of L. coffeella has been reported on coffee under mulch compared to other coffee agrosystems. However, in contrast to our finding, lower incidence of L. coffeella has been reported in coffee agroforestry systems compared to other coffee agrosystems (Androcioli et al., 2018; Nestel et al., 1994). On the other hand, the highest damage of the coffee berry moth (BM), *Prophantis smaragdina* (Butler) and coffee clusters with red blister disease caused by C. coffeicola was recorded on coffee growing under open sun and lowest under ACS. Our findings agree with earlier studies that show that shade decreases the damage caused by both BM and CRB (Biru, 2019; Staver et al., 2001). However. BM was highest under CMS, suggesting that ground cover creates favorable conditions (increased humidity) for the larvae to pupate (Kagezi et al., 2023). Insect damage has been reported to be the most commonly seen defect in coffee beans (Chen et al., 2020). The relatively high CV values observed for some variables reflect the inherent spatial heterogeneity associated with soil moisture conservation practices, where micro-environmental conditions vary considerably. Additionally, the experiment was conducted under field conditions representative of smallholder coffee systems, where higher variability is expected and enhances the applicability of the findings.

The positive and significant correlation between the percentage of black beans and berries with red blisters (BRB; r = 0.47) suggests that BRB infestation interferes with normal berry maturation, leading to incomplete filling and discoloration. Red blister associated disorders have been linked to disrupted nutrient translocation and localized tissue necrosis, which ultimately manifests as black or partially blackened beans at harvest (Waller et al., 2007a). Similarly, the positive correlation between floats and CBB (r = 0.36). CBB directly damages the endosperm by boring into developing beans, reducing bean density and increasing the proportion of lightweight beans that float during wet processing (Damon, 2000; Infante et al., 2014). The strongest relationship observed was between insect-damaged beans and CS (r = 0.77), followed by BM (r = 0.43), CM (r = 0.34), BRB (r=0.39) and CRB (r = 0.49). These results reflect the cumulative effects of sap-sucking and berry-feeding pests, which weaken berries, predispose them to secondary infections, and increase vulnerability to internal damage. Mealybugs and scales are known to reduce photosynthate availability through sap extraction and honeydew production, indirectly impairing bean filling and increasing insect-related defects (Perfecto et al., 2014). Berry moth larvae, on the other hand, cause direct penetration and feeding within the berry, producing visible insect damage similar to that of CBB (Le Pelley, 1968). The negative significant correlations between bean colour and CS (r = –0.63), BRB (r = –0.34), CM (r=-0.37) and CRB (r = –0.44) indicate that higher pest and disease incidence is associated with poorer bean appearance. Uniform bean colour is a key quality attribute, reflecting proper maturation and drying. Discoloration has been linked to stress-induced metabolic changes during berry development, including altered phenolic oxidation and uneven drying following pest damage (Chu, 2012; Clarke, 2012). Scale insects and mealybugs, by impairing canopy function, may reduce carbohydrate allocation to berries, resulting in uneven ripening and pale or blotchy beans (Wintgens, 2004). The negative association between nipped beans and BRB (r = –0.34). Red blister attacks cause a lot of light or empty berries (Waller, 1985), early coffee berry fall, and/or hollow, irregularly shaped grains, which lowers the bean's quality (Lima et al., 2012). Immature beans also cause loss of acidity, increased bitterness, distinctive aromas and green flavor (reminiscent of fresh green grass, green foliage, unripe fruit) (Wintgens, 2004). For screen sizes, the positive correlation between screen 15 and canopy scales (CS; r = 0.41) suggests a selective effect of pest pressure on bean size distribution. Under stress conditions, plants may produce a higher proportion of medium-sized beans due to constrained assimilate supply, rather than well-filled larger beans (Vaast et al., 2006). Sap-sucking pests such as scales can exacerbate this effect by continuously diverting plant resources, leading to altered size grading at harvest. The results reinforce previous evidence that effective pest management is not only critical for yield protection but also for maintaining bean quality and market value (Infante et al., 2014; Waller et al., 2007b). Integrated pest management strategies that reduce canopy pests (CS, CM), berry feeders (BM, CBB), and disease complexes such as BRB and CRB are therefore essential for improving both physical quality attributes and downstream cup quality.

5 Conclusion

The results show that SMCPs did not significantly alter coffee bean physical quality or size grades, but they significantly influenced pest and disease incidence. The results indicate that coffee bean defects are influenced by a combination of factors rather than solely by pest and disease incidence. Notably, the coffee mulch system (CMS) produced the highest proportion of large beans (screen sizes 18 and 19) while maintaining the lowest levels of most pest and disease damage. These findings suggest that CMS can enhance Robusta coffee resilience to pests and diseases and support the production of high-quality beans. Farmers are therefore encouraged to adopt mulching as a key soil moisture conservation strategy to improve both yield and bean quality in Robusta coffee systems.

Conflict of interest

The authors declare that they have no conflict of interest.

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Data availability Statement

Data can be made available on the behave of the request

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Selecting Adaptive Tree and Shrub Species for Rehabilitating Degraded Drylands in Northeastern Ethiopia

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Agro-ecology; Adaptive capacity; Degraded Lands; Rehabilitation; Survival rate

Abstract

Climate change threatens forests and ecosystems. Introducing adaptable trees and shrubs can mitigate impacts. This study aimed to assess and evaluate different native and exotic species for rehabilitating degraded, moisture-stressed areas in Northeastern Ethiopia. Data were collected quarterly over four years to investigate the rehabilitation and moisture stress conditions in the study areas. The results of the study showed that the root collar diameter, height, DBH, and survival rates were measured to evaluate species suitability for restoration. There were significant differences between the species in terms of height, root collar diameter, and survival. In the low-altitude at P<0.05 level. Acacia saligna and Leucaena glabrata recorded the highest heights and root collar diameters, respectively, while L. glabrata (95.5%), Dodonea angustifolia (91.6%), and Ziziphus spina christii (75%) showed the highest survival rates. Cordia Africana (85.4%) and A. saligna (73.1%) had the highest mid-altitude survival rates. Top-performing species in diameter and height growth showed higher survival rates. Poor performers included C. equisetifolia, J. curcas, and S. sesban (low altitude) and H. abyssinica and O. africana (high altitude). The study found no significant differences in performance between native and exotic species. Instead, the adaptive capacity of the species varied based on drought tolerance during dry seasons. Species with the highest growth and survival metrics in each agroecology are recommended for the study areas and similar regions. Sustainable forest restoration requires continuous selection of resilient trees and shrubs.

1 Introduction

The world's forests are attracting international attention due to various environmental issues, including the serious effects of climate change, which threaten many lives and resources (Reynolds et al., 2007; White et al., 2019). According to the FAO (2005a) and Rashid (2004), the world's forests cover approximately 3.9 billion hectares, or 29.8% of the Earth's land surface. Out of this total, about 1,751 million hectares, or 44.9%, are found in developed countries, while 2,149 million hectares, or 55.1%, are in developing countries. Roughly 95% of these forests are natural, while 5% are plantation forests. Forest resources are continuously declining due to various natural and human-made reasons, and they are currently facing rapid degradation (UNEP, 2018).

Widespread deforestation in tropical regions has led to large areas of degraded vegetation, which support significantly reduced biodiversity. For instance, since 2000, millions of hectares of forest have been cleared each year worldwide, with most of the deforestation occurring in the tropics (FAO, 2015). Tropical deforestation is often followed by converting forestlands to agricultural uses, mainly to replace land that has lost productivity due to poor farming practices (Harwood, 1993). These degraded lands are often abandoned

as wastelands that could potentially regenerate to forests. However, in areas affected by intense human activities, the natural processes of recovery are often very slow due to soil degradation, repeated disturbances, and isolation from intact forests.

Many studies show that establishing tree plantations on degraded lands can help overcome physical and biological barriers to forest recovery and support the regrowth of native forest communities (Lugo, 1997; Parrotta et al., 1997). Most reforestation projects aim to restore the forest's productivity for future timber products, but combining short-term economic goals with long-term conservation of biodiversity is becoming increasingly important (FAO, 2001; Lamb, 1998; Lugo, 1997). Because of a lack of detailed knowledge about native tree species, only a few exotic timber species, like Acacia, Eucalyptus, and Pinus, along with a few others like Gmelina arborea, continue to be favored in reforestation projects for their ability to grow quickly on degraded lands (FAO, 2001).

Seasonal changes in rainfall distribution are also key ecological factors in tropical dry forests. Generally, just two to three dry months can change the composition and structure of the forest ecosystem (Murphy & Lugo, 1986). For example, significant forest destruction occurred on Mount Badda in the Arsi region of Ethiopia around 1850 BP, suggesting widespread deforestation in the Afromontane forests. Dodonaea is among the species showing increasing pollen quantities, thought to be linked to human disruptions of the vegetation (Bonnefille & Hamilton, 1986). In addition to deforestation for fuel and building materials, the start of agricultural activities has greatly impacted the natural vegetation of the Ethiopian highlands, particularly in Wollo, over thousands of years (e.g., Hurni, 1986, Egziabher, 1988, Tadesse, 1991, Teketay, 1996). Recently, there has been a sharp decline in forest cover, indicating that forest resources in the country are quickly disappearing (Aklog, 1990).

Therefore, integrated conservation, rehabilitation, and community-based management of natural resources are crucial not just for maintaining local biodiversity and livelihoods, but also for protecting downstream ecosystems and communities (German et al., 2006). In Ethiopia, forest rehabilitation through the introduction of enrichment planting is commonly practiced to regenerate degraded forest lands. However, there is a limited information regarding the alternative and best adaptable trees and shrub species for the various types of agro-ecological zones of the South-eastern Ethiopia particularly the Eastern Amhara Region degraded landscapes. It is crucial to provide an agro-ecological and site specific adaptable tree species to support the ambigious rehabilitation objectives of the region and the country, Ethiopia, general. Before any tree species can be introduced to a specific agro-ecology, well-conducted field surveys and trials are necessary to match the species or provenance to the site (Abebe et al., 2000; Mebrate et al., 2004; Zobel & Talbert, 1984). Therefore it is essential to conduct an experiment to evaluate the survival rates, and growth parameters of different tree and shrub species to recommend for these types of degraded landscapes. The primary objective of this study is to select the best-performing tree and shrub species for rehabilitating degraded forest land across three agro-ecological zones (low, mid, and high-altitude) in Eastern Amhara, North Eastern Ethiopia.

2 Material and Methods

2.1 Study sites Description

The study was conducted in three purposively selected drought prone areas of Eastern Amhara Region of the North Eastern Ethiopia from 2020 to 2023. Three agro-ecological zones (AEZ) were selected and one site were selected from each AEZ. The mid-altitudinal agro-ecological zone (AEZ) chosen for studying the selection of tree and shrub species for the restoration of degraded lands was the Chorisa study site, South Wollo Zone, Amhara Region. Every year, it receives roughly 800 mm of rainfall. The soil is deep and black, and the slope is mild. The Borkena River, which flows through the valley and into the Afar region, is roughly 15 kilometers away.

Keyou Gariya in Kobo District was the location of the tree planting (testing) site in the low-altitude, severely moisture-stressed areas of the North Wollo Administrative Zone. The elevation is 1450 meters above sea level, and the annual precipitation is 692.8 mm (1973-2000 average, SARC 2010). The average high and low temperatures in the region are 30°C and 22°C, respectively. Eutric fluvisols is the type of soil. Were-illu-Woreda, also known as Segno-Gabeya, is home to the tree planting (testing) locations in the south Wollo Administrative Zone's high-altitude, severely moisture-stressed woreda. Based on an estimate from the local weather station. According to meteorological data from 1973 to 2000, Were-illuWoreda experiences 998.4 mm of rainfall annually, with mean maximum and mean minimum temperatures of 26.19°C and 13.43°C, respectively.

2.2 Planting of experimental trees and data collection

Seedlings of the selected species were initially raised at Sirinka Agricultural Research Center's nursery in 2019/2020 and later planted across three agro-ecological zones using site-specific field establishment techniques. Site-appropriate water-harvesting structures were implemented. The experiment followed a randomized complete block design with three replications, using 2m × 2m spacing between seedlings, 3m between blocks, and 2m between plots.

Number of seedling: Sixteen seedlings per species per plot were planted (Table 1). While standard species adaptation trials recommend 25–100 seedlings per species (Franzel et al., 1996; Zobel & Talbert, 1984), this study used 16 seedlings per species per plot across three replications, resulting in 48 seedlings per species per agro-ecological zone. This sample size aligns with similar adaptation studies in resource-limited dryland regions (Mebrate et al., 2004; Tilahun et al., 2006) and provides statistically valid results for screening species under field conditions, as supported by the significant differences detected in growth and survival parameters. The main reason for reducing the number of seedlings was the undulating terrain across the experimental sites, which prevented us from placing more than this limit. Additionally, to minimize external factors such as slope, soil vertical profiles, and moisture variation, we decided to use 16 seedlings per plot with three replications. This resulted in a total of 48 seedlings per species at each experimental site.

Data collection frequency: The data were collected quarterly (every three months) over four years. This allowed continuous monitoring of growth and survival trends across seasons and years. The final year's data were used to assess long-term adaptability (survival rates) and growth performance (height, DBH), consistent with similar long-term species trials (Lamb, 1998; Parrotta & Knowles, 1997). Seedlings were arranged in a staggered pattern within water-harvesting structures. Statistical analysis was performed using R-software (v4.3.10), with treatment comparisons evaluated via ANOVA.

Table 1: Tree and shrub species used for the experimentation for different agroecology

Tree/shrubs selected at the low-altitude AEZ	Tree/shrubs selected at the mid-Altitude AEZ	Tree/shrubs selected at the high-altitude AEZ
Ziziphus mouritania, Leucaenea glabirata, Dodonaea angusstifolia, and Acacia saligna	Acacia saligna, Gravilia robusta, Olea europaea, and Cordia africana	Acacia saligna, Acacia melanoxilon, Chamaecytisus paleminensis, Dodonaea angusstifolia, Acacia abyssinica, and Acacia decurrence

N.B: Seeds where purchased from Ethiopian Environment and Forestry Research Institute.

3 Results

3.1 Growth and survival rates of selected species at low-altitude agro-ecologies

Seven tree/shrub species were tested for rehabilitating degraded lands in the low-altitude agro-ecology of Kobo (Keyu-Gariya) (Table 1). After 48 months, significant differences ($P < 0.05$) were observed among species in root collar diameter, height, and survival rate (Table 2). L. glabrata, D. angustifolia, and Z. mauritiana showed the highest survival rates (95.5%, 91.6%, and 75%, respectively). Maximum height and root collar diameter were recorded in the plots of A. saligna and L. glabrata. Species with superior growth in height and diameter generally exhibited higher survival rates except A. saligna, which underperformed in survival despite its acceptable growth. In contrast, C. equisetifolia, J. curcas, and S. sesban had the poorest performance, with zero survival and minimal growth across all measured parameters (Fig. 1).

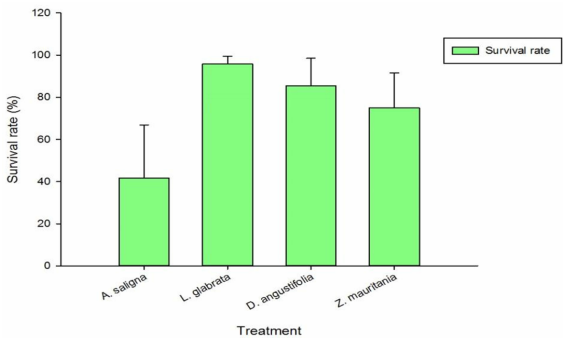

Figure 1: Survival rates of tree/shrub species tasted in the low-altitude agro-ecologies of Kobo- Keyu Garya research sites

Table 2: Growth performance of different tree species at the age of 39 months (Kobo Woreda)

Species	Root collar diameter (cm)	Height (cm)
L.glabrata	3.8a	168.42a
A.saligna	3.5a	199.7a
D.angusstifolia	2.8b	160.5ba
Z.mouritania	0.8b	47.67bc
LSD (0.05)	*	*
CV (%)	13.88	8.78

3.2 Growth and survival rates of the selected species at mid-altitude agro-ecologies

Similar to the low-altitude study sites, seven tree species were evaluated in this study. After 48 months, significant differences ($P < 0.05$) were observed among species in root collar diameter, height, and survival rate. C. africana and A. saligna exhibited the highest survival rates (85.4% and 73.1%, respectively; Table 3).

While most top-performing species in growth also had high survival rates, O. africana was an exception, declining below 50%. The poorest performers, A. decurrens, A. abyssinica, and C. equisetifolia, had minimal growth (near-zero values) and survival rates of 8.3%, 6.3%, and 4.2%, respectively (Fig. 2).

Table 3: Growth performance of different tree species at the age of 48 months (Kalu Woreda)

Species	Root collar diameter (cm)	Height (m)
A.saligna	7a	231.2a
C.africana	0.3b	53.58b
O.africana	1c	34.67cb
G.robusta	0.1dc	17.67cb
LSD (0.05)	*	*
CV (%)	12.89	18.5

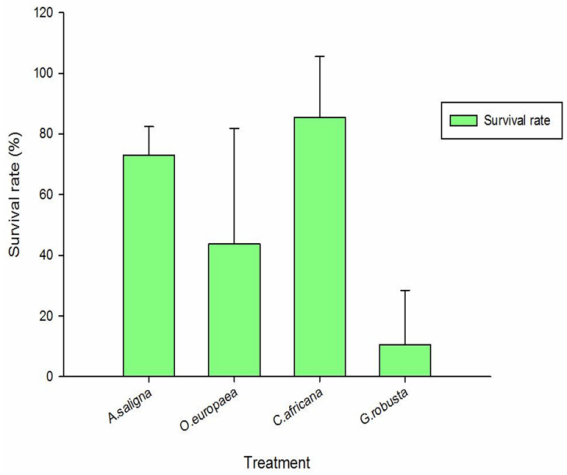

Figure 2: Survival rates of tree/shrub species tasted in the mid-altitude agro-ecologies

3.3 Growth and survival rates of selected species at High-altitude agro-ecologies

After 51 months of growth, significant differences ($P < 0.05$) were observed among species for root collar diameter, height, and survival rate. A. saligna demonstrated superior performance with the largest root collar diameter (4.6 cm) and greatest height. Root collar measurements for A. decurrens, A. abyssinica, and D. angustifolia measured 2.5 cm, 2.22 cm, and 1.64 cm, respectively (Table 4).

Table 4: Growth performance of different tree species at the age of 39 months (Wereilu woreda)

Species	Root collar diameter (cm)	Height (cm)
A.saligna	4.6a	177.33a
A.decurrens	2.5ba	149ba
A.abyssinica	2.22ba	96.5ba
D.angusstifolia	1.64b	80.33ba
C.paleminensis	0.9b	33.33ba
A.melanoxilon	0.8b	44.17ba
LSD (0.05)	*	*
CV (%)	51.81	30.41

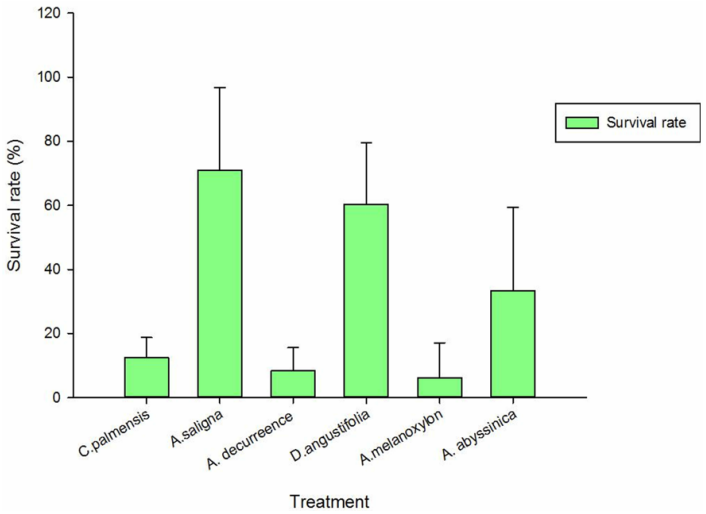

Figure 3: Survival rates of tree/shrub species tasted in the high-altitude agro-ecologi

4 Discussions

The quarterly data collection over four years allowed for tracking seasonal and annual variations in growth and survival, addressing the reviewer's concern regarding one-time data. This approach aligns with long-term species adaptation studies in drylands (Lamb, 1998; Parrotta & Knowles, 1997). The results indicate that species such as D. angustifolia and A. saligna exhibited consistent performance across multiple agro-ecological zones, demonstrating their drought tolerance and adaptability to moisture-stressed conditions. The current study on the survival rates of seedling are aligning with findings by Chibssa et al. (2006) with exceptional contrasting with G. robusta, which showed lower survival. A. saligna and C. africana also achieved the greatest height and root collar diameter in the current study report. Survival rates were highest for D. angustifolia and A. saligna, consistent with findings reported by Chibssa et al. (2006).

The study's findings show that, with careful species selection that is appropriate for the area, enrichment planting can rehabilitate degraded land (Mebrate, 2004). The establishment of tree plantations can support the recovery of native forest ecosystems and reduce the effects of biological and physical obstacles to forest regeneration (Lugo, 1997; Parrotta et al., 1997). By employing various restoration approaches, trees can transform degraded or unproductive areas into productive ones (Marcar et al., 1999).

As a result of many environmental, human, and animal issues, the treatments eventually forced them to lose the competition by slowing down their development and survival rates. The principal obstacles to the regeneration of degraded fields were prolonged drought, animal trespass, human destruction of seedlings, and lack of awareness. Every year between April and June, the majority of the treatments experienced drought stress. One of the most significant and prevalent biological elements in tropical dry forests is seasonal variation in rainfall distribution (FAO, 2001). It just takes two to three dry months to change the structure and content of the forest ecosystem (Murphy & Lugo, 1986). The majority of reforestation initiatives seek to increase the forest's potential for future timber production, but it's becoming more and more crucial to balance immediate financial goals with long-term biodiversity preservation (FAO, 2001; Lamb, 1998; Lugo, 1997).

The use of 16 seedlings per plot, though below the conventional threshold of 25–100 seedlings per species, was logistically feasible in these remote, resource-limited dryland sites and provided statistically significant results. Similar studies in Ethiopia have used comparable sample sizes and yielded valid recommendations for species selection (Mebrate et al., 2004; Tilahun et al., 2006). Future studies could increase seedling numbers to further validate these findings.

5 Conclusion

Based on the multi-year evaluation of native and exotic tree and shrub species across three agro-ecological zones in northeastern Ethiopia, this study provides clear, evidence-based recommendations for rehabilitating degraded drylands. The results demonstrate that species selection must be agro-ecology-specific, as performance varied significantly across altitude and moisture regimes.

Dodonaea angustifolia and Acacia saligna emerged as the most resilient and adaptable species, showing consistently high survival and growth across multiple zones. D. angustifolia exhibited remarkable ecological plasticity, thriving from low to high altitudes, while A. saligna excelled in low and mid-altitude drylands. Other promising species include Leucaena glabrata and Cordia africana in low and mid-altitudes, respectively, though their suitability is more zone-specific.

Conversely, species such as Casuarina equisetifolia, Jatropha curcas, Sesbania sesban, and Olea africana showed poor adaptation

and are not recommended for restoration in moisture-stressed environments without intensive management.

Critically, the study found that drought tolerance and adaptive capacity, not native versus exotic origin, determined species success. This supports a pragmatic, trait-based selection approach for dryland restoration. The quarterly monitoring over four years captured seasonal survival patterns and reinforced the importance of long-term, climate-resilient species evaluation.

To promote sustainable reforestation in northeastern Ethiopia and similar dryland environments, we recommend a targeted strategy that prioritizes proven, resilient species such as Dodonaea angustifolia and Acacia saligna in restoration portfolios. Effective rehabilitation also requires carefully matching species to specific agroecological conditions using evidence-based performance data, integrating supportive silvicultural practices like water harvesting to improve seedling establishment, and adopting continuous monitoring and adaptive management practices to proactively address biotic and abiotic stresses throughout the restoration process

This research contributes to the growing body of knowledge on dryland restoration and provides a practical framework for species selection that balances ecological resilience, restoration goals, and local livelihood needs. Future studies should scale up seedling numbers and include socioeconomic evaluations to support community-based implementation.

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Conflict of interest

The author declare that no competing interests

Data availability Statement

Data can be made available on the behave of the request

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All ethical considerations were fully adhered during data collection, analysis and writing.

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Land use land cover analysis for sustainability in waste management optimization in the Durgapur municipality and surrounding area

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Industrial waste; Waste Management; Land Use and Land Cover; Analytical Hierarchy Process; Durgapur Municipality Corporation.

Abstract

India's largest industrial complex, the Durgapur Steel Plant, is suffering from sanitation and health problems due to the unwanted disposal of solid waste. The West Bengal plant is trying to convert trash into something worthwhile and minimize pollution in the environment. The disposal of industrial waste is governed by environmental protection. However, uncontrolled waste collection, illegal dumping, and poor public awareness are challenges in developing nations such as India. India needs to focus on recycling, regionalized solid waste treatment, and green technology to overcome these challenges. Smart cities need various strategies for implementation. The study designs open-ground waste facilities, maximizes vacant land space utilization for green waste management, examines the relationship between residential land use and the generation of waste, and minimizes pollution. Comparison and evaluation are two elements of the multicriteria decision-making methodology referred to as the analytical hierarchy process (AHP). It simplifies the problematic task by attributing normalized weights to each groundwater prospecting factor theme tier. The consistency ratio (CR), which should be no more than 0.1, informs one about how reliable the judgment is. In this research, the CR value was 0.089, which is no more than 0.1. GIS is employed to delineate land use and land cover classes, such as bare land, settlement, dense vegetation, cultivated land, sand, and water bodies, from expert judgment. Different land use and land cover categories of different waste management suitability scores were grouped by the AHP analysis of the Durgapur Municipality Corporation. Scatter land and,barren land and ground is highly suitable (15-22%) for waste management, followed by agricultural land and dense vegetation are suitable (12-14%). Settlement, sand and waterbody is medium suitable (5-11%) for waste management, next to the ground. The research highlights the importance of considering such factors in ascertaining whether waste management is appropriate.

1 Introduction

Unwanted solid, liquid, and gaseous wastes from industrial processes must be collected, transported, processed, disposed of, and monitored as part of the crucial process of industrial waste management (Prakash et al., 2019). Because industrial waste has a detrimental effect on the air, water, and land, as well as on human health, proper management of this garbage has become increasingly crucial (Geetha & Rajalakshmi, 2020; Prakash et al., 2019). Numerous approaches have been developed for effective industrial waste management, including end-of-waste, cradle-to-cradle, circular economy, sustainable materials management, zero waste, and environmental design (Mohamed et al., 2023). Although waste management practices differ by area, wealthy nations such as Japan have extensive rules and regulations that emphasize proper treatment, disposal standards, and generator accountability (Hirota,

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1986). However, issues including erratic garbage collection, unlawful disposal, and low public awareness continue to exist in developing nations (Muiruri et al., 2020). Waste management requires a systems approach that integrates the five functional components of generation, reduction, collection, recycling, and disposal with more general environmental, social, and economic considerations (Sushil, 1990). India produces over 90 million tons of solid trash a year, making waste management extremely difficult due to the country's rapid industrialization, urbanization, and population expansion (A. Singh et al., 2021). India's trash generation rate ranges from 0.12 to 0.60 kg/capita/day (S. Singh & Singh, 2021). Hospital solid waste is composed of glass (3–5%), plastics (7–10%), disposable syringes (0.3-0.5%), infectious waste (30–35%), and general garbage (40%–45%), including food (Patil & Shekdar, 2001). Concern over e-waste is also growing, since India is the world's fifth-largest producer. India's current waste management methods are mostly unscientific, with a considerable amount of solid garbage being carelessly disposed of on the outskirts of cities without first being treated (Das, 2020). Increased air pollution and groundwater contamination result from this. With disorganized units handling 95% of e-waste, the informal sector controls the recycling of e-waste (Borthakur & Sinha, 2014).

Recent rules have increased the awareness of biomedical waste management, but execution is still difficult (Patil & Shekdar, 2001; S et al., 2019). Rapid urbanization, population expansion, and rising per capita trash generation rates have made municipal solid waste management (MSWM) a major environmental concern for Indian towns (A. Kaur & Deswal, 2019). There are serious threats to the environment and public health because almost 90% of India's municipal solid waste is unscientifically dumped in open landfills and dumps (Sharholy et al., 2007). By working with self-help organizations like SWaCH and the informal garbage industry, Pune has attained a 95% waste segregation rate (Saifi & Jha, 2024). In conclusion, effective waste management in Indian smart cities requires a multifaceted approach (Fig 1). This includes the implementation of IoT-based solutions, smart bins, and integrated systems that involve various stakeholders. Additionally, sustainable planning, waste characterization, and the development of waste-to-energy potentials are crucial for long-term success (Cheela et al., 2021).

Major landfill location criteria consist of settlement distance, land cover, slope, road pattern, wind direction, geology, soil category, and water bodies (Mussa & Suryabhagavan, 2019). The Analytical Hierarchy Process (AHP) is commonly used to assign weights to these criteria based on their relative importance (Fagbohun & Aladejana, 2016; Wijesinghe & Fernando, 2023). GIS analysis then combines the weighted factors into suitability maps ranking locations as highly favorable, favorable, moderately favorable, less favorable, or unfavorable for waste disposal (Mussa & Suryabhagavan, 2019; Wijesinghe & Fernando, 2023). Studies suggest that while most focus on landfilling locations, some emphasize increasing waste management facilities, as demonstrated in Ethiopia where 20.8% of solid waste is recyclable (Doboch Wanore et al., 2023). Additionally, the availability of land for landfills is a major challenge in highly urbanized areas, sometimes necessitating compromises between environmental concerns and waste management needs (Ali & Ahmad, 2020). GIS-MCDA is a cost-effective solution for determining landfill locations, promoting sustainable urban waste management and improving public health and environmental protection in cities (Mondal et al., 2014; Usman Kaoje, 2016).

Indian cities face environmental challenges due to improper municipal solid waste management, with the daily waste generation in Lucknow causing public health hazards and potential groundwater contamination (Archana et al., 2014). Similarly, about 90% of MSW in Indian cities is disposed of unscientifically in open dumps and landfills (Sharholy et al., 2007). It is interesting to note that only a small portion of Mumbai's 17.20% recyclable waste is recovered by rag-pickers, underscoring the unrealized potential in the informal waste sector (Yedla & Kansal, 2003). Ranchi's waste management issues underscore the need for improved strategies, as common practices in developing nations like Nigeria are inefficient and harmful to the environment and public health (Omole et al., 2016). This suggests that Ranchi's waste management challenges are part of a broader global concern. Ranchi could benefit from introducing more modern technology, educating the general public, and successfully enforcing laws to overcome these problems (Aman & Srivast, 2020). Additionally, implementing cutting-edge solutions such as mobile applications, artificial intelligence (AI), and the Internet of Things (IoT), as suggested for Rajshahi City Corporation in Bangladesh, could greatly increase Ranchi's waste management effectiveness (Hossain et al., 2024). Groundwater pollution from open MSW disposal is a result of the landfill leachate. Water quality fluctuated throughout time and space, according to a study of groundwater samples taken near Ranchi's open MSW disposal site (Chakraborty & Kumar, 2016).

This research proposes a systematic approach to select an alternative MSW dumping ground in the city of Mumbai, keeping in view all the aspects of MSW management as a whole. The absence of uniform site evaluation procedures due to a mix of complex factors and parameters is tackled by the proposed MCDM-based approach (Khan et al., 2016). MCDM uses a hierarchical multi-level framework for organic waste management decision support, enabling comparison and analysis of competing criteria for effective conclusion-making. Social justice and environmental health movements place importance on sustainable waste management and recognize how to build cross-sector and cross-class alliances for alternative sustainable practices (Randhawa et al., 2020). In developing countries such as Turkey, economic development, population expansion, and industrialization have led to municipal solid waste management issues due to water resource pollution and climatic alteration (Yildirim et al., 2021).

By combining quantitative and qualitative factors and applying weights based on relative importance, MCDM methods chiefly consider and prioritize potential landfill locations while providing spatial information for land choice (Ghobadi, 2024). As per research, it is those families that had rightful area/society waste collectors that recorded greater log probabilities of garbage segregation, and hence, they know more about the practice. The gap effect is not strong, however (P. Kaur et al., 2023). Based on a survey, 60% of middle-class and upper-class households are financially and physically ready to adopt municipal solid waste management methods, while 30% of poor families are equally ready (Kumar & Anand, 2017). Failure to manage waste in an appropriate manner and going against national waste management codes in most large metropolitan cities due to poor infrastructure and services create economic and environmental issues. India is estimated to produce 5% more MSW each year.

Serious health risks of injury and infection are posed by biomedical waste, and unsound waste management is highly likely to have a negative impact on public health, especially among medical stu-

dents who are exposed to it during hospital training (A. Singh et al., 2022). According to the survey, the more educated dealers and the higher socioeconomic status dealers are more concerned about the dangers of radioactive waste (Makkar et al., 2014). India, one of the most populous countries in the world, also has a significant waste disposal problem because of its urbanization, emerging economy, and shifting consumer trends (Poddar, 2023).

In several industries, including plumbing, toys, furniture, packing, and interior design, plastic items have supplanted conventional materials due to their low manufacturing costs, simplicity of manufacture, and water resistance. In India, packaging accounts for around 42% (Rode, 2015). Although medical professionals' knowledge and awareness of biomedical waste management are limited, regular education can improve procedures and keep medical workers from becoming discouraged. With the help of other groups, the ALM program, which started out as a local project, has grown into a city-level initiative. Critics claim that because ALMs are mostly found in affluent neighbourhoods, they have an elitist and middle-class bias. Through creative communication techniques, music, talk programs, lectures, ads, and pledges, the Residents Association ALM runs a radio station that addresses social, educational, and environmental issues in the community (Mukherjee Basu & Punjabi, 2020).

Figure 1: Planning of a Smart City (**Shahab2022**)

To guarantee that waste is managed within the facility, biomedical waste produced during diagnosis, treatment, and immunization as well as radioactive and laboratory waste require minor revisions to the Biomedical Waste Management Rules of 2016. Because of poor and disorganized waste disposal procedures, hospitals' current biomedical waste management is subpar, leading to the dangerous mixing of hospital and general garbage (Balaji, n.d.). The disposal of hospital waste, which is divided into hazardous and general wastes, presents significant issues. Hazardous wastes are more dangerous and are more likely to become polluted than general wastes, which are always clean. This research proposes a new method of market verification of recycling machines based on qualitative and quantitative parameters. A fuzzy pairwise comparison matrix and fuzzy AHP are used in the model, and factor weights are provided with predetermined linguistic terms ("the Market Validation of Device Recycling Motor Oils," 2016). Apart from examining the economic advantages and on-site and off-site recycling activities, this study tries to quantify, account for, and assess the likely scale of these activities. It also discusses the environmental and public health hazards (Muisa Zikali et al., 2022). Building demolition, renovation, and repair generate low-risk and low-volume solid waste that is referred to as construction and demolition waste (C&D). Effective management, cleaning, and screening in the industrial crushing plants can facilitate recycling and reuse because of increasing environmental and public health concerns. Enviro-Vigil is treating biomedical waste for Thane Municipal Corporation and the surrounding districts for over 3500 customers. They treat 2000 g/day, out of which 1200 kg is incinerated at 8500C as anatomical and contaminated waste (Iyer, 2016).

2 Materials and methods

2.1 Study Area

The coordinates of Durgapur are-Latitude Range: Approximately 23.4° N to 23.6° N, Longitude Range: Approximately 87.3° E to 87.5° E. Despite being a part of the Faridpur-Durgapur block, DMC is managed independently due to its significance. Within 15 km, Kanksa is located in the eastern part of the DMC, Faridpur Block is located in the northern section, and Andal is located in the western portion. It is 65 meters (213 feet) above sea level on average. The districts of Asansol Sadar to the west, Purba Bardhaman to the east, Bankura to the south over the Damodar, and Birbhum to the north across the Ajay River encircle the Durgapur subdivision. West Bengal, India's Durgapur Municipality Corporation (DMC) is a lowland area with a variety of land cover and land use. The Damodar River is one of several tiny rivers and bodies of water that are located within the city. There are sizable residential, business, and industrial areas in Durgapur, a significant metropolitan center. The complexity of waste management is increased by the abundance of sand, dense vegetation, and woods in the surrounding areas. To field investigate some site are found for waste disposal Site-1: (Latitude: 23.529075°, Longitude: 87.35033°), Site-2:(Latitude: 23.530673°, Longitude: 87.350479°), Site-3: Latitude: 23.530116°, Longitude:87.350236°), Site-4: (Latitude: 23.541007°, Longitude:87.359212°), Site-5: (Latitude: 23.541373°, Longitude: 87.359491°), Site-6: (Latitude: 23.538258°, Longitude: 87.299657°), Site-7: Latitude: 23.538097°, Longitude: 87.299549°) (Fig. 2).

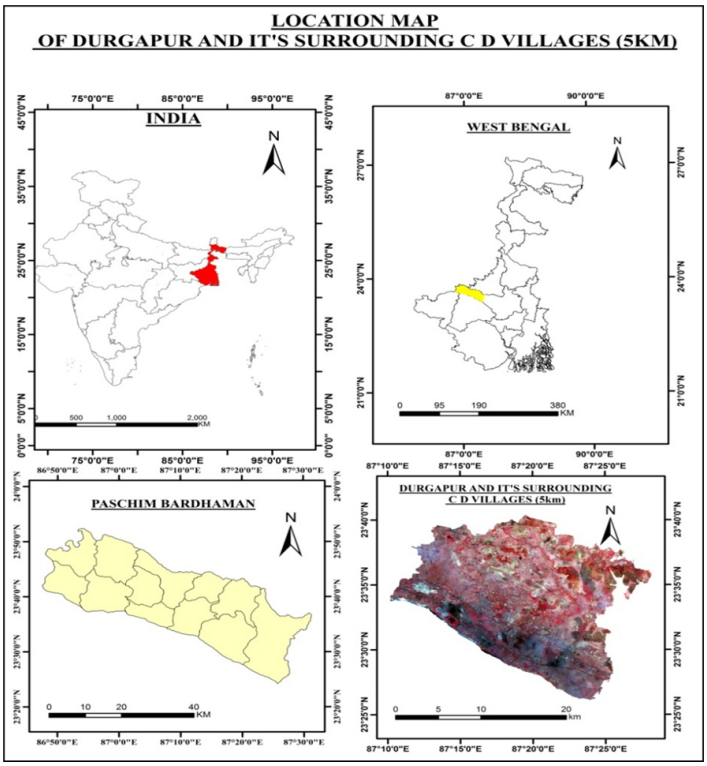

Figure 2: Map of study area

2.2 Methods

2.2.1 *Field Observation*

Field visits to a sample of DMC locations have shown open dumping to be extensive and pervasive. The photos below are a typical city street garbage dumping scene. areas where there is rubbish from home and market as in Plate- A to R these include plastic and other trash along streets and surrounding environments (Fig. 2).

2.2.2 *Maximum likelihood method for collecting data of LULC*

To address these challenges, several studies have proposed using Geographic Information Systems (GIS) and multi-criteria decision-making (MCDM) methods for selecting suitable MSWD sites. These approaches consider various factors such as elevation, slope, permeability, distance from water bodies, roads, and settlements (Bilgilioglu et al., 2021). Integrating the Analytical Hierarchy Process (AHP)-based MCDA with geospatial techniques can help identify suitable waste dumping sites, as demonstrated in studies from other developing countries (Wijesinghe & Fernando, 2023). Adopting these cutting-edge methods and putting smart city ideas into practice can help Indian towns create waste management systems that are more effective and ecologically friendly. In order to solve growing problems in emerging nations, GIS and AHP are useful tools for locating appropriate landfill sites for the disposal of solid waste in Indian cities (Dara & Reddy, 2018; Sk et al., 2020). The integration of GIS and AHP allows for the consideration of multiple criteria in landfill site selection. Common criteria include land elevation, slope, soil, geology, land use, distance to surface water, roads, industrial belts, sensitive places, and land cost (Sk et al., 2020). Some research has broadened these standards to incorporate elements such as protected areas, groundwater level, and the distance to tube wells (Dara & Reddy, 2018; Fatima et al., 2021). It is interesting to note that some research has used variants of the AHP approach, including fuzzy AHP, to overcome the imprecise nature of language evaluations in landfill site selection (Fatima et al., 2021; Islam et al., 2020). Furthermore, some academics have created environmental decision support tools, such EDSS-MSWI, to offer a comprehensive strategy for managing municipal solid waste in India (Nas & Singh, 2013).

In Indian cities, GIS and AHP techniques work well for analyzing the suitability of urban dumping sites while taking social, economic, and environmental aspects into account. By improving the site selection accuracy, fuzzy logic integration offers a methodical, data-driven approach to solid waste management. Mumbai, the financial hub of India, produces an astounding 6256–9000 tonnes of municipal solid waste (MSW) every day, making waste management extremely difficult (Yedla & Kansal, 2003).

The Saaty method, commonly known as the analytical hierarchy process (AHP) method, is a multicriteria decision-making approach that combines comparison and evaluation (Stofkova et al., 2022). (Saaty, 1987). AHP is a widely accepted model used to assign a normalized weight for each thematic layer of groundwater prospecting factor (Melese & Belay, 2022). The pairwise comparison matrix simplifies the complex decision-making process be-

tween criteria, allowing for the derived comparative relevance values. The reliability of the judgment is dependent on the Consistency Ratio (CR), and its value must be less than or equal to 0.1 (Sajil Kumar et al., 2022).

Plate 1. *Plate: A-Scatter forest distance from 4 km to Durgapur Municipal Corporation, B-Open dumping site, C- Systematic waste disposal container at Scattered Forest, D- Areas maintained for green cover within urban planning (Dumping site near dense forest area), E-This area includes both crop fields and orchards (Waste disposal at agricultural land area), F- Waste disposal at agricultural land area, G-Waste island type, H-Dumping site at open ground and sand area, I- Areas not covered by vegetation or structures (Open ground) (Source-The Authors)*

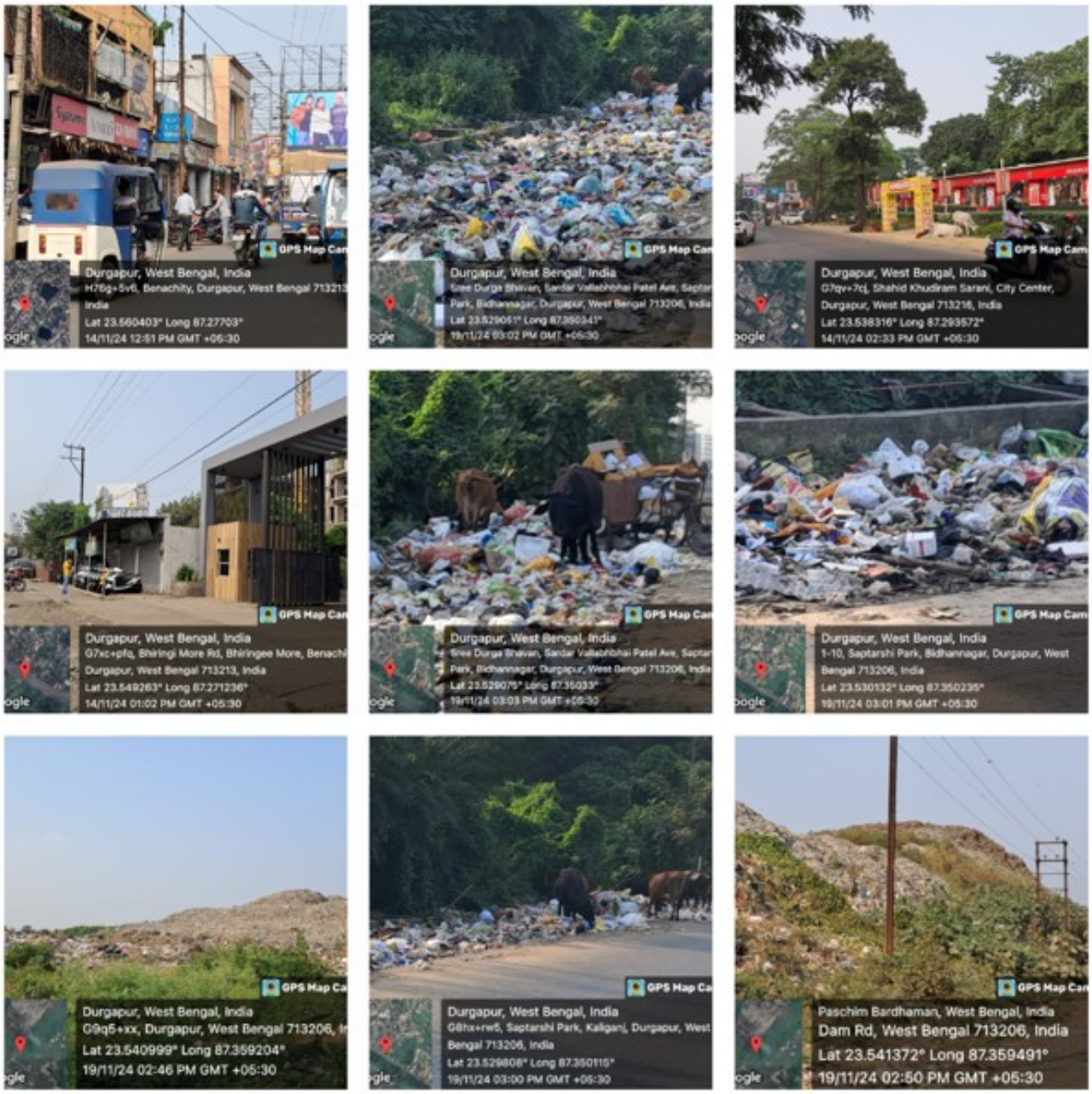

Plate 2. *Plate: A-Scatter forest distance from 4 km to Durgapur Municipal Corporation, B-Open dumping site, C- Systematic waste disposal container at Scattered Forest, D- Areas maintained for green cover within urban planning (Dumping site near dense forest area), E-This area includes both crop fields and orchards (Waste disposal at agricultural land area), F- Waste disposal at agricultural land area, G-Waste island type, H-Dumping site at open ground and sand area, I- Areas not covered by vegetation or structures (Open ground) (Source-The Authors)*

The authors provided the judgment the pairwise comparison matrix was derived. The AHP model involves defining thematic layers, generating a pairwise comparison matrix using Saaty's 1-9 scale, and determining the final weight of the layers using normalized eigenvalues. The consistency ratio (CR) is calculated using a formula. CR = CI/RI where, RI indicates the random consistency index whose value depends on the order of the matrix (Table 2) and CI indicates the consistency index, which can be obtained from the following formula: CI = λmax-n/n-1. Where, i principal eigenvalue of the matrix, n = number of groundwater prospecting factors. The value of CR must be <0.1. Table 1.

Table 1: Saaty's 1-9 scale of relative importance

Scale	Importance
1	Equal importance
2	Weak
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Strong importance
8	Very strong importance
9	Extreme importance

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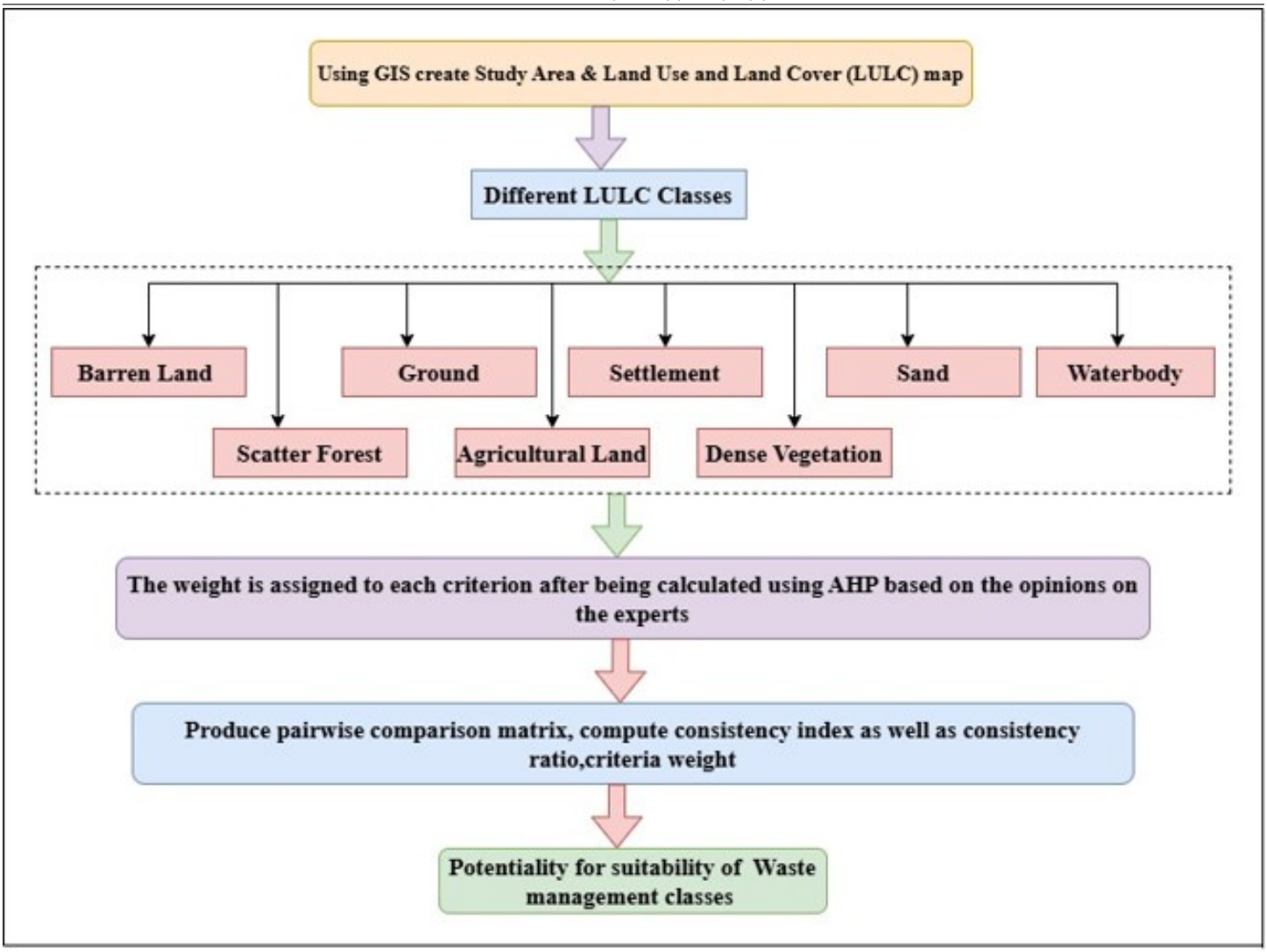

Figure 3: Methodology

2.2.3 *Sources of waste in the Durgapur Municipal Corporation*

Waste can come in a variety of forms, including food processing waste, biomedical waste, nuclear waste, construction waste, industrial waste, oil factory waste, e-waste, household waste, trash, home waste after slaughter, etc. Waste can be categorized as follows (Agarwal Professor et al., 2015):

- Solid waste, which includes home, kitchen, and vegetable waste.
- E-waste: abandoned electronic equipment, including computers, TVs, and music players systems, etc.
- Liquid waste: water used in tanneries and various industries, distillation facilities and thermal power plants
- Plastic garbage, such as buckets, bottles, and bags.
- Metal waste, such as scraps and unwanted metal sheets.
- Unused materials from nuclear power facilities are known as nuclear waste.

Additionally, we can classify all of these types of waste as wet waste (biodegradable) and non-biodegradable dry waste.

a) Household Waste: One of the main sources of MSW is household garbage, which includes food scraps, paper, plastic, rags, metal, and glasses from residential areas (Fadhullah et al., 2022). Domestic garbage from residential areas varies according to cultural and socioeconomic circumstances. Waste production is higher in low-income areas and lower in developed areas. Waste production is higher in commercial areas and prosperous towns.

b) Waste from shops/vegetable/fruit market: Sixty percent of the municipal solid trash is made up of biodegradable materials, such as food waste. Food waste in Delhi amounts to 2700 MT every day, and because of insufficient collection and monitoring, it causes eutrophication and choking. To enhance municipal solid waste management (MSW) services, municipalities lack the necessary infrastructure, management techniques, and resources. The optimization of MSW disposal is hampered by significant issues such as door-to-door garbage collection, a shortage of containers, ineffective collection, and ineffective disposal techniques. Degradable trash, such as polythene, paper, and dried plantain leaves, is produced by stores and fruit and vegetable markets and is used to wrap agricultural

products.

c) Waste from hospital/nursing home/medical stores: Significant amounts of solid waste, including leftover medication, saline bottles, and non-biodegradable medication covers, are produced in DMC by hospitals, assisted living facilities, and medical stores.

d) Waste from hotels/restaurants/eating stalls: Both biodegradable and non-biodegradable garbage are produced by hotels and restaurants; household rubbish needs to be removed every day and collected in separate receptacles.

e) Waste generated by street hawkers: Large amounts of waste are produced by street food vendors and hawkers, especially food waste and plastic paper plates.

f) Waste from slaughterhouses/fish markets: Fast-decomposing garbage from slaughterhouses and fish markets causes rot and unpleasant odors in the area because proper procedures for collecting and removing paper are not followed.

g) Industrial Waste: Waste produced in factories, mines, or mills during the processing of raw materials for new products is referred to as industrial waste (Amasuomo & Baird, 2016).

3 Results

Table 2: Different types of Land Use and Land Cover (Full study area was not covered by the LULC analysis) in DMC (Source-The Authors)

Class Name	Area (sq km)	Percentage (%)
Barren land	54.886134	12.61867
Settlement	149.734103	34.42481
Ground	8.1482	1.873323
Dense vegetation	37.445503	8.608957
Agricultural land	77.933911	17.9175
Scattered forest	6.633421	1.525065
Sand	5.969817	1.372499
Water body	12.452264	2.862854

Table 3: Land use class and change detection of 2001-2011

Land Use Class	Percentage Change (2001-2011)
Barren land	6.573249% (Increase)
Settlement	13.71964% (Increase)
Ground	-17.9083% (Decrease)
Dense vegetation	1.819068 % (Increase)
Agricultural land	0.07346% (Increase)
Scattered forest	-7.34066% (Decrease)
Sand	1.155663% (Increase)
Water body	1.503805% (Increase)

Increase Classes (2001-2011)- Barren land (6.573249%), Settlement (13.71964%), Dense vegetation (1.819068 %), Agricultural land (0.07346%), Sand (1.155663%), Water body (1.503805%) Decrease Classes (2001-2011)- Ground (-17.9083%), Scattered forest (-7.34066%)

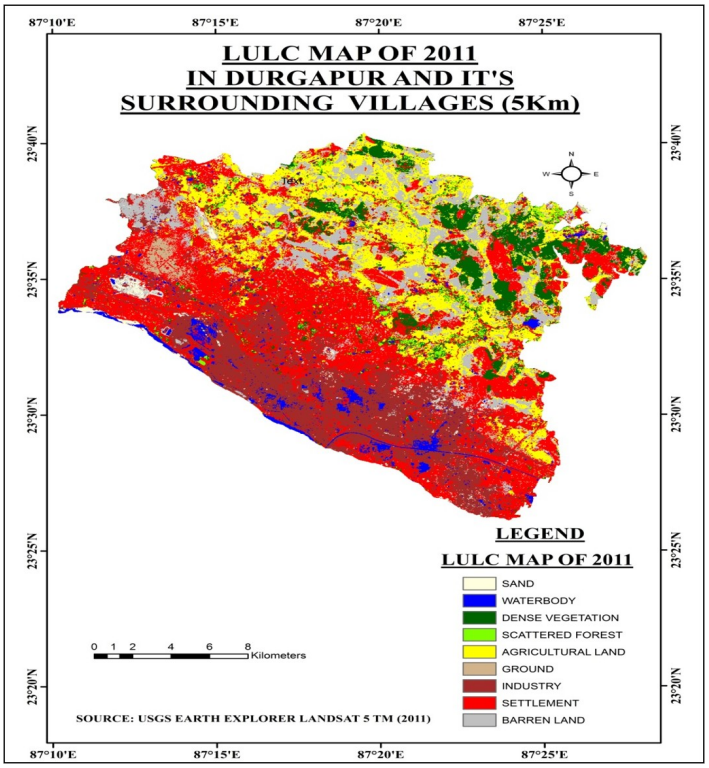

Figure 4: LULC pattern and change detection (Source-The Authors)

Table 4: Different types of LULC and waste management suitability class using AHP methods (Highly suitable: 15-22%, Suitable: 12-14%, Medium suitable: 5-11%)

LULC Type	SF	BL	DV	G	AL	S	Sa	WB	Percentage	Rank	Suitability Class
Scatter forest	1	1	2	1	2	3	3	2	18.1	2	Highly Suitable
Barren land	1	1	3	2	2	2	3	3	21.1	1	Highly Suitable
Dense Vegetation	1/2	1/3	1	1	1	3	2	3	12.3	5	Suitable
Ground	1	1/2	1	1	3	3	1	2	15.0	3	Highly Suitable
Agricultural land	1/2	1/2	1	1/3	1	4	2	3	12.4	4	Suitable
Settlement	1/3	1/2	1/3	1/3	1/4	1	3	3	8.7	6	Medium suitable
Sand	1/3	1/3	1/2	1	1/2	1/3	1	2	7.2	7	Medium suitable
Water body	1/2	1/3	1/3	1/2	1/3	1/3	1/2	1	5.2	8	Medium suitable

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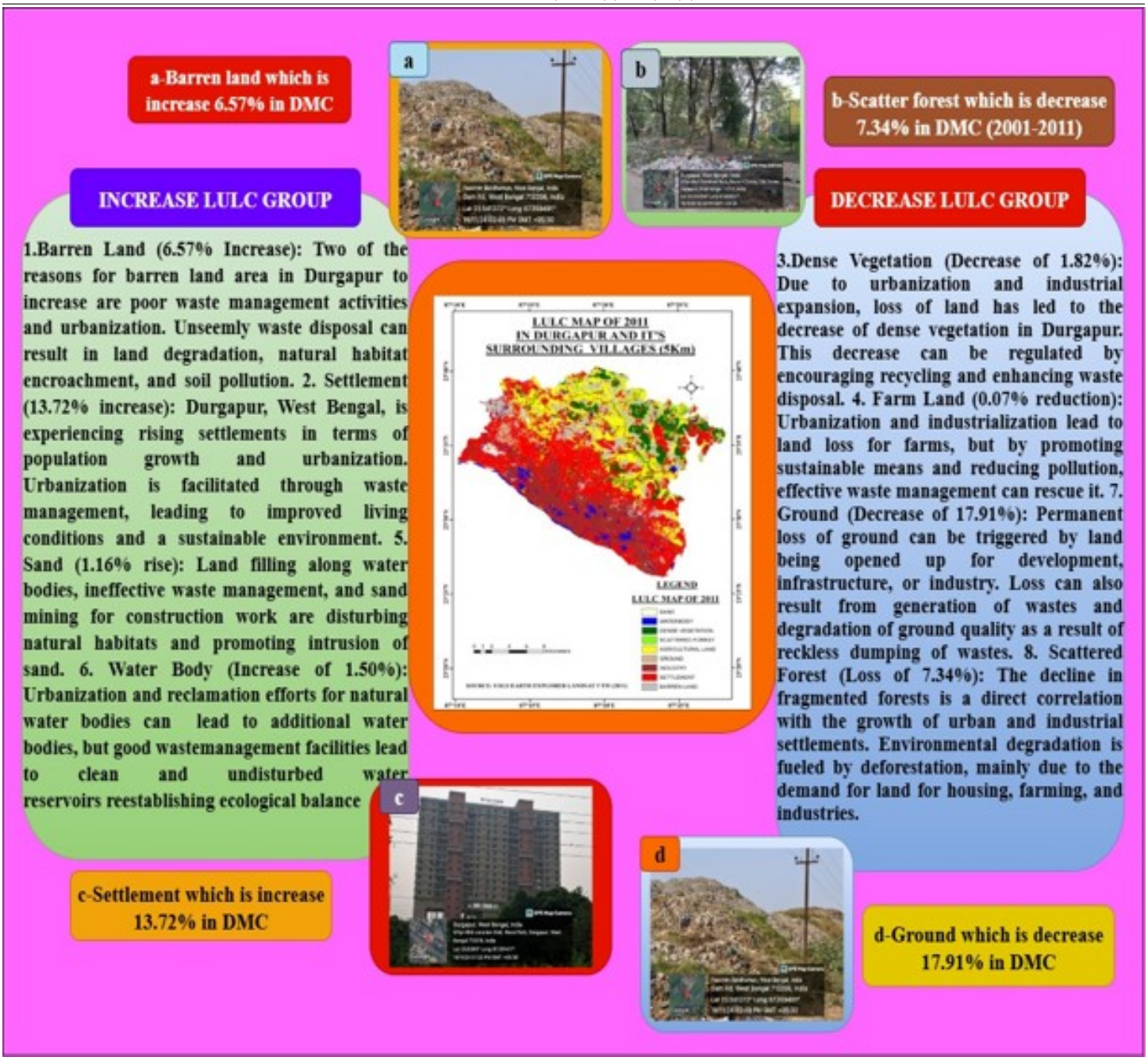

Figure 5: LULC pattern and change detection (Source-The Authors)

4 Discussion

The best land use category for disposing of solid waste is open land, which includes grazing and nonagricultural regions. Evidence from Plate-A to Plate-R and discussed below:

1. Barren Land (12.62%)–Waste Management Suitability Rank 1: The most suitable land for waste management is barren land, which comprises 12.62% of the entire area. Because these plots of land lie vacant most of the time, there is a potential in constructing landfills, recycling plants, or units of wastage treatment (Evidence from Plate-P).

2. Scattered Forest (1.53%) – Waste Management Suitability Rank 2: In terms of suitability for waste management, the scattered forests that occupy an area of 1.53% in Durgapur fall under rank (evidence from Plate-C) 2. Due to their sensitive ecosystem, these forests can prove to be waste management difficult despite being central to managing biodiversity and ecological equilibrium.

3. Ground (1.87%) – Waste Management Suitability Rank 3: Ground lands at rank 3 of suitability for waste treatment occupy 1.87% of Durgapur. Open spaces containing parks, fields, and lots are among the areas that can be used for the dumping and collection of wastes (evidence from Plate-H).

4. Agricultural land (17.92%)–Waste Management Adaptability Rank 4: Durgapur has 17.92% agricultural land as part of its geography, ranking fourth in waste management adaptability. Such

places have the scope to convert organic waste into compost, which can be used to enhance the fertility of the land. Irresponsible dumping of garbage, particularly from urban areas, also pollutes agricultural land.

5. Dense Vegetation (8.61%)–Waste Management Suitability Rank 5: Dense vegetation ranks fifth in suitability for waste disposal at a cover of 8.61%. Although these areas have numerous environmental benefits, including water and air purification, the dense vegetative cover is not well-suited for trash dumping.

6. Settlement (34.42%)–Waste Management Suitability Rank 6: Based on the study, in order not to cause pollution, waste-related diseases, and social disturbance, solid waste dumpsites should be situated far away from urban settlements. For waste disposal, residential areas–which constitute most of Durgapur at 34.42% rank number six. Most of the population resides there, and hence it generates a lot of waste. In urban neighborhoods, efficient garbage collection systems, such as door-to-door collection and segregation bin points–are important.

7. Sand (1.37%) – Waste Management Suitability Rank 7: Sand areas cover only 1.37% of the area in Durgapur and are ranked number six in suitability for garbage disposal (evidence from Plate-H).

8. Water Bodies (2.86%)–Waste Management Suitability Rank 8: Water bodies covering 2.86% of the land are the most inappropriate for garbage management. Solid waste management regulations and antipollution measures need to be followed so that garbage does not enter water bodies. The protection of water quality and minimization of pollution must be the top priority of waste management in these areas.

5 Conclusions

The study explores the impact of residential land use on waste output, optimizes underutilized land for sustainable waste management, develops open ground waste processing infrastructure, and changes land use detection. The suitability analysis clearly identified scattered land, barren land, and ground surfaces as the most advantageous areas (15–22%) for setting up waste management facilities. These land types present few ecological or socio-economic disputes, making them perfect for enduring infrastructure development. Agricultural areas and thick vegetation (12–14%) demonstrate moderate suitability but necessitate careful management owing to their ecological and productive significance. Settlements, sandy regions, and water bodies (5–11%) show only moderate suitability, suggesting that these areas should be steered clear of significant waste management activities due to possible environmental hazards, conflicts with human activities, and sensitivity to hydrology. Safeguard and Rank Extremely Appropriate Unused and Dispersed Land Lots Promptly identify and officially protect the recognized high-suitability barren and dispersed lands for upcoming waste management facilities. This measure will deter swift settlement expansion and guarantee the lasting availability of low-conflict areas. Create Safeguard Buffer Areas Around Delicate LULC Categories. Establish a compulsory 500-m buffer zone surrounding all areas with dense vegetation and agricultural land to safeguard ecological integrity and reduce human–environment conflict when locating waste facilities.

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Conflict of interest

The author declare that no competing interests

Data availability Statement

Data can be made available on the behave of the request

Ethical considerations:

All ethical considerations were fully adhered during data collection, analysis and writing.

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Journal of Forestry and Natural Resources (JFNR)

Authors Guideline

Abbreviation J. for. nat. resource.
ISSN 3005-4036

1. Editorial policy and Author's Guidelines

1.1. Background

The Journal of Forestry and Natural Resources (J. for. nat. resour., or JFNR) (JFNR) is a peer- reviewed online open-access published annually by the Wondo Genet College of Forestry and Natural Resources, Hawassa University. JFNR publishes original research findings in all subject-matter areas of forestry and natural resources. It seeks disciplinary and interdisciplinary research articles, review articles, featured articles, and short communication.

- Name of the publisher: Wondo Genet College of Forestry and Natural Resources, Hawassa University
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Author's Guideline | 2026

1.2. Aims and Scope

Aims:

- serve as a communication medium among scientific communities in forestry, natural resources research, and other related fields
- publish original and innovative scientific works relevant to forestry and natural resources situation of Ethiopian as well as global problems
- encourage Ethiopian researchers, graduates, and postgraduate students to align their disciplinary and interdisciplinary researches in the direction of solving major problems in the areas of forestry and natural resources and conservation needs of the country, and
- serve as a platform to foster scientific knowledge sharing among researchers, scientists, policymakers, and practitioners working on sustainable forestry, green economy transition, issues of sustainable development goals, desertification, and dryland agriculture and forestry, combating desertification and drought, natural resource management, and conservation and other related topics.

Scope of the journal

The JFNR publishes scientific articles related to social, economic, policy, and environmental aspects: forestry, agroforestry, wildlife, soil, water and land resources, renewable energy, tourism, urban forestry, and greening, environmental science, GIS, and remote sensing.

2. Submission Guidelines

Submission system: Online

General contents of the journal JFNR uses the following format:

2.1. Research articles

These papers treat both disciplinary and interdisciplinary (thematic) types of researches encompassing basic and applied researches, graduate and postgraduate studies researches related to forestry and natural resources. JFNR will consider for publication articles from the regional and international forest and natural sources covering tropical and subtropical regions.

2.2. Review articles

Encompass critically reviewed scientific papers covering the state of the art knowledge in various aspects of forestry and natural resources. Review articles will be submitted by experts in the fields of forestry and natural resources with their expertise and experiences or invited by the editor-in-chief, associate editors, or editorial board.

2.3. Featured articles

These include topics in forestry and natural resources management, conservation, utilization, education, and non-conventional research articles.

Technical papers in the areas of forestry and natural resources development encompassing different aspects of socio-economics, policy issues, wildlife, environment, rehabilitation efforts and forestry and natural resources inventory and surveys, biodiversity conservation, processing and value addition of forest products, agroforestry, non-timber forest products, medicinal plants and their domestication and commercialization, integrated watershed management, green economy transition, green initiative related studies, climate change and development, land degradation and drought, aquatic ecosystem management, fisheries, etc.

2.4. Short communications

This includes articles of brief scientific notes on preliminary results, scientific observations, experimental techniques, and recent technological advances in forestry and natural resources. It also included information on specific cases and limited applications. Manuscripts for this column should not be more than six typed pages. They should have a brief abstract and not contain more than two figures and/or two tables.

2.5. Book Reviews

A critical evaluation of recently published books in any discipline of forestry and natural resource sciences will be published under this column.

3. Manuscript evaluation process

The manuscript must be written and prepared in English. Grammar and language quality are the responsibilities of the authors to submit the manuscripts in clear and communicable language quality. Once manuscripts are submitted the editor-in-chief or associate editors will check the manuscript for possible plagiarism results, originality of the work and contents of editorial policy and scope, and authors' guidelines of JFNR. Submission of a manuscript to the Journal must be accompanied by a cover letter stating that no similar paper, other than an abstract or an oral presentation, has been or will be submitted for publication elsewhere. The manuscript should be submitted online or by email to the editorial manager, who gives the manuscript number and notifies the author of receipt of the manuscript. The manuscript number will be used in all correspondence regarding the manuscript. The editor-in-chief will consult associate editors to decide whether the manuscript is within the scope of JFNR and whether the contents are worthy of further review. Manuscripts that do not meet the minimum criteria will be returned back to the author within two weeks' time. Those that meet the minimum criteria will be passed to associate editors for quick check-ups and suggestions of potential reviewers. The associate editor is an expert selected in certain disciplinary areas and who has a wide network among professionals in their field of specialization.

3.1. Peer review process

The peer-review process will follow double-blind where the manuscript will first be evaluated by the editor-in-chief or associate editors, followed by at least two reviewers. The names of the authors will be kept anonymous while sending

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Authors whose manuscript has been accepted for publication will receive a letter of acceptance. The authors will also receive the proofreading to send their opinion in five days. The pdf version of the published manuscript will be sent to the author and co-authors via their email addresses and also will be available online on the website of the college and university. The hard copy of published articles will be dispatched to various institutions upon request free of charge.

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Reviewers are requested to evaluate the manuscript on originality of the work, state of the art and nobility of the study topic, relevant objectives, soundness, latest and appropriate methodology, results in quality to address the objectives, adequate discussion, and relevant conclusion made.

And also, the way references are presented both in the text and reference lists. Reviewers are expected to give their comments and suggestions clearly (referring to the line numbers in the paper) to the authors to assist the author (s) to address all comments and suggestions given. Language correction is not part of the review process but suggestions can be made by reviewers.

3.3. Submission checklist

You can use this list to carry out a final check of your submission before you send it to the journal for review.

One author has been designated as the corresponding author with contact details:

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Where the family name may be ambiguous (e.g., a double name), please indicate this clearly. Present the authors’ affiliation addresses (where the actual work was done) below the names. Indicate all affiliations with a lowercase superscript letter immediately after the author’s name and in front of the appropriate address. Provide the full postal address of each affiliation, including the country name, and, if available, the e-mail address of each author.

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3.5. Changes in Authorship

Change in authorship requests is only made by the corresponding author to editor-in-chief.

Author’s Guidline | 2025

4. Format for mansucripts

The manuscript should be prepared in Times New Roman with 11 font sizes, double space, and 2.5 cm marginal indentions on all sides. The maximum number of words should be 8000. The first page should contain the full title of the manuscript, the name(s) of the author(s) including address (es), and the institution(s) in which the research was carried out. For ease of communication, authors are requested to include their email addresses. For manuscripts with multiple authors, an asterisk should indicate the author to whom all correspondence is to be addressed.

Second and consecutive paragraphs after a heading should be indented while the first paragraph after a heading should start flush left. No space should be left between two consecutive paragraphs. Scientific names should be written in full when mentioned for the first time in the text. They should be italicized. Subsequent citations should abbreviate the genus name.

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The title of the manuscript should be concise, descriptive, in good order, and

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The major findings in response to objectives set in the study. Be selective and focus on reporting your results.

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This can be written in a separate section or can be part of the discussion. It should also be concise, clear, and align to stated objectives and major findings.

4.8. Acknowledgments

Brief acknowledgement including the assistance received during data collection, lab analysis, and writing/editing can be included. Acknowledgements related to financial support shall be indicated in 'Funding statement section', not here.

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The statement showing approval of ethical procedure for study involving human (tissue and related) and animal (such as vertebrates and/or higher invertebrates) element can be included in the method section of the study.

This must clearly indicate approval of the experiment by the responsible committee or institution that supposed to license or approve the procedure/method/experiment. Including the statement that confirms 'all experiments were undertaken by complying to the institution's guideline or rule and regulation' is obligatory.

For human participating in the research, example, in interview, focus group discussion, consent of participation must be assured. This must be declared in the method section by including the statement about: consent of participation by all participants, and informed consent. Author/s must indicate this in the study involving human element. Unless and otherwise agreed by the participant, the identifiable information of a person must not be published in any form including image, text, or table.

4.13. Submission system

The manuscript should be prepared by Microsoft Word or an equivalent word-processing program. They should be submitted electronically according to JFNR Author's instructions.

4.14. References:

This follows author-year style taking the last author's last name in the text and alphabet refereeing system in the reference lists. As much as possible, recent references should be cited and the numbers kept to a minimum. It is the responsibility of the authors to check the accuracy of references. Papers by one or two authors are given as shown in the examples below:

- In the case of Ethiopian names, the author's given (first) name precedes that of the
- father's name; e.g., Mesfine Bekele and not Bekele, don't abbreviate Ethiopian names.
- (Kumar and Nair 2012)
- (Dhyani 2014; Kahiluoto et al. 2014; Lasco et al. 2014; Mbow et al. 2014a) - chrono- logically.
- For three or more authors, use et al. (no italics) i.e., Bekele Lemma et al. (2007), in the text (but spell out all authors' names in the reference list).

Examples of acceptable formats for listing references in the reference section are shown below.

Journal article

Kuyah S, Dietz J, Muthuri C et al (2012a) Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. Agric Ecosyst Environ 158:216–224.

Assegid Assefa and Tesfaye Abebe (2014). Ethnobotanical study of wild medicinal trees and shrubs in Benna Tsemay district, Southern Ethiopia. J. Sci. Dev. 2, 17–33.

Book

Chapman DH and Pratt PF (1961) Methods of Analysis for Soils, Plants, and Waters. University of California, Riverside, California.(N.B. initials appear

before the last author's family name).

Chapter in book

Cunningham AB, Shanley P, Laird S (2008). Health, habitats, and medicinal plant use. In: Pierce CJ (Ed.), Human Health and Forests: A Global Overview of Issues, Practice, and Policy.Earthscan, London, pp. 35–62.

Paper in proceedings

Tesfaye Awas, Sebsebe Demissew (2009) Ethnobotanical study of medicinal plants in Kafficho people, Southwestern Ethiopia. In: Svein Ege, Harald Aspen, Birhanu Teferra and Shiferaw Bekele, Trondheim (Eds.), Proceedings of the 16th International Conference of Ethiopian Studies. Addis Ababa, Ethiopia.

4.15. Provide full names of periodicals in the reference list. Do not abbreviate.

Unpublished materials

Citation of unpublished and other source materials not readily available in libraries should not be included in the reference list but should be mentioned in parentheses in the text or as a footnote.

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Main headings and sub-heading should be numbered consecutively 1, 1.1, 1.1.1…, 2, 2.1, 2.1.1…. Main headings should be bold, capitalize the first letter, followed by lowercase letters. Sub-headings should be lower case letters. Minor sub-headings should be light font italics.

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Units

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4.16. Editorial policies

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- Research involving human subjects should be carried out as per the

international assertions and should be endorsed by an appropriate ethics committee. A statement detailing ethical approval procedures should be included in the manuscript during submission. The editorin-chief or the associate editors deserves the right to reject manuscripts that are not carried out as per the ethical framework.

- Experimental research on plants (either cultivated or wild), including the collection of plant material vertebrates or any regulated invertebrates, must be carried out in accordance with institutional, national, or international guidelines, and where possible should have been endorsed by an appropriate ethics committee. Plant voucher specimens must be deposited in the national herbarium or other public collection providing access to deposited material considering all the herbarium protocols and identification techniques. Written informed consent for the publication should be obtained for manuscripts that comprise details, images, or videos relating to an individual person.
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