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Assessment on Potato Production Practice, Opportunities, and Constraints, in Semi-arid areas of Tigray, Northern Ethiopia

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Abstract

Potato is widely grown in mid and highland areas of Tigray. However, productivity is below the national average due to many factors. To address this issue, a survey was conducted in Tigray's major potato production districts to assess potato production practice and identify key constraints, and opportunities related to potato production. A purposive sampling technique used to select Zone, Wereda, and Kebeles. Accordingly, three zones, eight weredas, and 386 farmers were selected. Structured questionnaires were employed to gather data on potato production practices, constraints, and opportunities. The collected data were analyzed using descriptive statistics and index ranking. The result of the survey indicated that 83.4% of the farmers interviewed produce potatoes under irrigation and rainfed conditions. Potato produced as a primary crop by 98.7% of farmers for sale purposes. Potato planting occurs between December 15 and January 15, as well as May 15 and June 30, depending on the irrigation and rainfall conditions respectively. Among the farmers interviewed, 98.9% use inorganic fertilizers, while 82.2% use organic fertilizers for potato production. 72.3% of the farmers interviewed used the Shashemene cultivar as planting material and obtained it from the local market, while 36.01% of use improved Gudanie variety. The study showed that under irrigation and rainfed conditions, farmers achieved an average potato tuber yield of 13.9 t/ha and 13.4 t/ha, respectively, with variability among individual farmers. The key opportunities in the study areas, as ranked by the index, include favorable agroecology, good soil type, access to irrigation water source and available labor. On the other hand, the most significant constraints in potato production are diseases and pests, drought, lack of improved varieties, and market demand. Therefore, it is recommended that research centers and higher educational institutions should focus on development of improved varieties.

Key words: Interview, Farmers, Purposive, Sample

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INTRODUCTION

Potato (*Solanum tuberosum* L.) is an important crop that contributes to food security, poverty alleviation, and income generation (Nyunza and Mwakije 2012). Potato production provides food, employment, and income as a cash crop and helps in increasing food availability while contributing to a better land use ratio by raising the aggregate efficiency of agricultural production systems (Gastelo et al., 2014). It is rich in easily digestible carbohydrates, essential vitamins, and high-quality plant proteins, including lysine, which is often lacking in other crops (Pęksa et al., 2013; Waglay et al., 2014). It has a short growing period, high yield potential, and nutritious tubers with high edible dry matter content. Additionally, potatoes are used in various food-processing industries and can supplement diets when other grains are less available or unaffordable (Camire et al, 2009). They are affordable to buy, easy to grow, and can thrive in challenging conditions where other crops may fail (Lutaladio and Castaldi, 2009). Factors affecting potato yields include water and soil management, seed quality, fertilization, soil moisture, elevation, slope, and irrigation (Maqsood et al., 2020.). Potatoes require 400 to 800 mm of rainfall or water, depending on meteorological variables, and suitable temperatures ranging from 14-23°C with a suitable daytime temperature of 23–24 0C (Xu et al., 2020)

Potato is the fourth most important food crop worldwide in terms of the volume of production after rice, wheat, and maize (Adane et al., 2010). It is also the most important tuber crop, ranking first in volume produced among root and tuber crops (Kebede, 2024). Ethiopia has the largest potential for potato production, with approximately 70% of its arable land deemed suitable for cultivation (Shamil & Dereje, 2021). This high potential is attributed to the country's favorable climatic and soil conditions, which enhance both productivity and yield (Chen, 2023). In addition, the Ethiopian government and research institutions have invested a significant amount of money and time in upgrading potato technology and quality to enhance smallholder production (Basha et al., 2017).

In recent years, Ethiopia has experienced a substantial rise in potato exports, both in volume and value. The country exported around 71,000 tons of potatoes to regional markets, with Djibouti being the primary destination, accounting for 80–90% of total exports (Brasesco et al., 2019). Ethiopia's annual potato production has also increased from 349,000 tons in 1993 to 743,153 tons in 2018 (Kebede, 2024). Despite this growth, Ethiopia's average yield of 13.77 tons per hectare (CSA, 2017) remains low compared to average yield of 35 and 45 tons per hectare in Europe and North America respectively (CIP, 2017). In Tigray, Ethiopia, potato is cultivated on nearly 622 hectares of land, approximately 12,156 small-scale farmers, with an average yield of 8.10 tons per hectare (CSA, 2017). The productivity of potato in the region is very low compared to the national average yield of 13.77 tons per hectare (CSA, 2017), as well as the yields obtained under experimental conditions, which can reach up to 40 tons per hectare (Amare et al., 2022). Despite suitable agro ecological conditions and available labor, potato yields remain low in the region, hindering its potential benefits. The potato sector faces various challenges, including a lack of improved tuber seeds, disease and pest issues, water stress, and market limitations (Meresa et al., 2024: Merga and Haji, 2019). Moreover, there is a lack of area-specific information on potato production practices, potentials, and constraints in the study areas. In addition, there are some studies and observations of the area's suitability for potato production but not proved. Therefore, assessing potato production potential, major constraints and practices is important to identify the major constraints and tackle the problems in the future. The objective of this survey was to assess the production practices of potato by smallholder farmers in the study areas and identify the major opportunities and constraints associated with potato crop production.

MATERIALS AND METHODS

Survey Sites and Descriptions

The assessment was conducted in eight districts across three major potato producing zones of Tigray namely, East, South-East and South zones, of Tigray regional sate between Feb-May 2020, which is in the northern escarpment of Ethiopia between 36^0 – 40^0E longitude and $12^{\ 0}$ – 15^0 N latitude. It borders with Amhara Regional State in the southwest, Afar Regional State in the east, Eretria in the north, and Sudan in the west. The zones were selected purposively based on the Regional Bureau of Agriculture expertise perception and ranked potato as their most important crop in the areas. It has diversified agro ecological zones with varying soil, vegetation, and natural resources. The climate is mainly semi-arid, with the main rainy season (kiremt) from June-mid September (Araya et al., 2010; Gebrehiwot and van der Veen, 2013). According to CSA (2016/17), in Tigray 16,564 households cultivated potatoes on 622.22 hectares. In addition to potato, Wheat and Barley are the dominant crops grown in the study

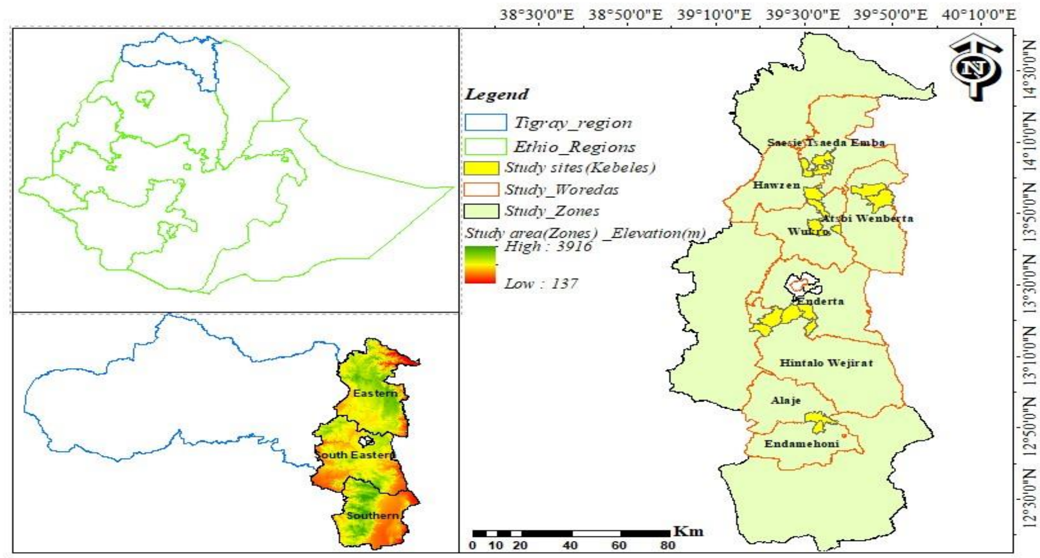

Figure 1. Study areas

Sampling Procedures and Sample Size

To study the Survey, I obtained permission letters from Tigray Agricultural Research Institute and from Tigray Agricultural Bureau to districts and kebeles. I prepared questionnaires, discussed them with experts, and engaged farmers and development agents."

The assessment covered eight districts within the three zones such as Saesi-Tsadaemba, Hawzen, Kilte Awlaelo, Atsbi, Enderta, Hintalo-Wejerat, Enba-Alage, and Endamehoni Districts (Woreda) (Figure 1). Two kebeles were chosen from each district for the study. The population for the study consisted of the household heads, especially men and women. A purposive sampling technique was adopted to select Zone, Wereda and kebeles. A total sample size of 386 farm households was drawn from a population of 11,595 potato-producing households, which represents 70% of the total 16,564-potato producer households identified in the Tigray CSA report for 2016/17 by employing equation 1.

The distribution of the population size to each district had been obtained from the total potato producer in Tigray by using proportional sampling. The number of farmers (n) selected from the potato-producing farmers was calculated as sample size by using a simplified formula of Yemane (1967).

$$n = \frac{N}{1+N(e)^2} \qquad \text{Eq 1}$$

Where n = sample size, N = population size, and e = level of precision (0.050).

The interviewer conducted randomly from a list of farmers who produce potato in the kebele.

Focal group discussions had conducted in 16 kebeles comprising a diverse group of 8-10 members, including model farmers representing various demographics such as men, women, youth, and individuals with different administration levels in the kebele.

Survey Data Collection Procedures

The primary data had collected by using a structured questionnaire. During the preliminary survey, a list of relevant guidelines and questions was used to guide the discussions with the focal groups. The main reason for pretesting was to identify any shortcomings and assist in making modifications to some questions before the actual data collection. The second stage was basic data collection. These data included information of households on demographic characteristics, production experience, production and productivity, use of potato production inputs (improved varieties, recommended spacing, Fertilizer, soil fertility management), opportunities, constraints and variability. The survey was implemented through face-to-face interviews in individual households and focus group discussion (FGD) in each Kebele. Interviews conducted carried out in the local language Tigrigna. Open-ended questions added to investigate deeply for additional insights into the information collected. The focus group discussion had used to get more insight in certain topics and to check whether the group validates patterns found in the surveys. FGDs are very suitable to analyze a certain situation or problem in more detail and to identify and evaluate potential solutions to these problems. Specific topics discussed under my guidance. The observed data on what was happening in the field and general appearance of the area were noted in a notebook. Secondary data was obtained from CSA, Bureau of Regional Agriculture and Natural resources and Research reports and other documents from various offices of bureaus of agriculture at different levels. Family size categories and age group was grouped according to (Jirčíková et al., 2013, Butani, 2006)

Data Analysis and Interpretation

Data analyzed using the Statistical Package for Social Science (SPSS, version 20). The important descriptive statistical measures such as percentage, frequency, and mean used to summarize and categorize the research data. In addition, chi square test was used to assess the association between potato production variables. Potato production opportunities and constraints had ranked by using index ranking based on the respondents' rankings of variables that calculated using the formula adopted from (Kosgey et al., 2004) ranking technique. According to this method, farmers were asked to specify the rank of all factors of potato production constraints and opportunity, and the results of such ranking have been converted into index value with the help of the following formula:

Index = sum of the number respondents ranks the variable in each rank divided to the sum of all variables ranked in each rank that is the weighted sum formula as indicated in equation 2.

$$Index = Sum\ \{(w * Nrank1\text{^}st\ ) + (w - 1 * Nrank2\text{^}nd) + \cdots + (w - n * Nrankn\text{^}th\ )\}/(over\ all\ sum\ (Sum1 + \cdots + Sumn)\ ) \quad (Eq\ 2)$$

Where N number of respondents in each specified rank, w….wn the weights assigned to each variable (number of variables in the computation), rank1, ... rank n are the rankings given by the respondents for each variable and Sum1…Sumn is the sub total of the individual variables under computation (sum) of all individual variables The weighted sum formula allows you to give more importance to certain variables by assigning higher weights to them. Similarly, this technique also applied to determine the major horticultural crops.

RESULTS AND DISCUSSION

Demographic Characteristics of Households

The result revealed that the majority (87.3%) of respondents were male household heads, while the remaining were female household heads (Table 1). Similar results were reported in previous studies by Muthoni et al., 2013, and Gebru et al., 2017, which found that a large majority of farmers interviewed in Welayta Zone, Ethiopia, and Kenya were male. Additionally, in the study area, men typically handle land preparation, plowing, planting and harvesting while women are involved in cultivation, weeding, marketing of farm products, and purchasing food and non-food items for consumption, indicating women's involvement in potato production. Furthermore, the survey revealed that most farmers (97.5%) were married, while a small percentage were unmarried (2%) and divorced (0.5%). Given the labor-intensive nature of potato crop farming, the involvement of multiple individuals is necessary, and this could be facilitated by the participation of the wife, husband, and children.

About 55.18% of farmers interviewed had family sizes >7, regardless of their active participation in the labor force. Whereas 31.87 and 12.95% had family sizes ranging from 4-6 and 1-3 respectively (Table 1). In the same way, Simonyan and Obiakor (2012) reported that majority of the rural residents had family sizes of more than five. According to

FGD, the labor available for work per household had influenced by family size and relies on the participation of household members in agricultural activities.

As the number of household members increases, tasks related to agriculture, including potato production, could be completed in a timely manner due to shared responsibilities. The amount of labor available for agricultural activities is also determined by factors such as family size, age, and gender. This suggests that farmers with a higher labor equivalent are more likely to engage in agricultural and potato production activities, leading to increased income, regardless of having a large family size. Similar to the findings of this study, Simonyan and Obiakor (2012) observed that a large household size does not necessarily guarantee increased labor efficiency, as the family members may have different ages, sexes, and labor capacities. However, Okoye et al. (2008) and Udensi et al. (2011) reported that relatively larger household sizes are more likely to provide the necessary labor for farm operations, such as weed control and fertilizer application.

Table 1. Demographic characteristic of the respondents

Variable	Zones			Total (Frequency)	Percent (%)
	East	South east	South		
Sex of HH head:-					
• Male	159	91	87	337	87.3
• Female	28	11	10	49	12.7
Total	187	102	97	386	--
Percent (%)	48.6	26.3	25.1	--	100
Age of HH head					
• 18-24	2	0	0	2	0.52
• 25-54	152	95	68	315	81.61
• 55-65	16	7	26	49	12.69
• >65	17	0	3	20	5.18
Total	187	102	97	386	
Family Size					
○ 1-3 (small)	37	12	1	50	12.95
○ 4-6 (medium)	60	27	36	123	31.87
○ >7 (large)	90	63	60	213	55.18
Total	187	102	97	386	100
Educational level of HH head					
▪ No education	65	25	33	123	31.9
▪ 1-5	62	34	27	123	31.9
▪ 6-8	39	23	23	85	22.0
▪ 9-10	17	9	6	32	8.3
▪ 11-12	1	7	0	8	2.1
▪ Diploma and above	3	4	8	15	3.9
Total	187	102	97	386	100

About 31.9% of household heads lacked formal education, while the majority (68.10%) had received formal education at various levels ranging from Grade 1 to BSc. This proportion (68.1%) is notably higher than the national adult literacy rate of 46.7% (Doss, 2003). Education and training

contribute to increased productivity among farmers and facilitate the adoption of new production technologies. Similarly, Kateta et al. (2015) reported that high literacy level, improved potato production practices can be reached to the farmers through reading materials such as pamphlets, leaflets, and other aids. Additionally, literacy enables farmers to access reading materials such as pamphlets and leaflets, facilitating the dissemination of improved potato production practices. Fikadu and Gebre (2021) reported that farmers with higher levels of education and skills in farm organization tend to achieve better productivity**.** In addition, they reported that literacy levels positively affect the adoption of agricultural technologies.

Land scarcity is a significant constraint on agricultural production in Ethiopia, particularly in the study area. The average land holdings of farmers in the eastern and southeastern zones of Tigray had found to be 0.83 to 1.54 hectares, respectively (Figure 2). When it came to potato production, farmers allocated 0.4 to 0.46 hectares of land for rainfed cultivation and 0.14 to 0.17 hectares for irrigation. These findings indicate that most farmers in the region operate on smallholdings of less than 2 hectares, likely due to the prevailing land tenure system. Furthermore, there were variations in land size between zones, with farmers in the southeastern zone owning larger plots, averaging 1.54 hectares (Figure 2). In contrast, those in the eastern zone owned less than one hectare and allocated smaller areas for potato cultivation, whether under irrigation or rainfed conditions. This discrepancy could be attributed to water scarcity for irrigation and farmers prioritizing other crops with lower water requirements, such as barley and chickpea. In agreement to this result, Girma and Ayalew (2024) reported that Ethiopian farmers manage small plots of land, often less than 2 hectares, due to historical land tenure systems and population pressures. They also reported that smallholder farmers often operate below their potential due to limited land availability, which affects their efficiency and productivity. The allocation of land for potato cultivation was consistent with the study (Senbeta and Worku, 2023) who reported that farmers allocate limited resources like land based on water availability and market demand.

Farm size is supposed to correlate positively to family size in most rural areas only and only when the family members are available and aged during the land allocation; this implies that large family size is not guaranteed to have large land. In General, the present study implies that land size is one factor for potato production of in the region either under irrigation or under rainfed condition. Therefore, it is important to introduce high yielding, disease and pest tolerant variety with appropriate agronomic practice to increase productivity in small land. In addition, there are mountain-traced areas in the study areas as a potential, this could be important to allocate the mountain-traced areas for youths to produce potato.

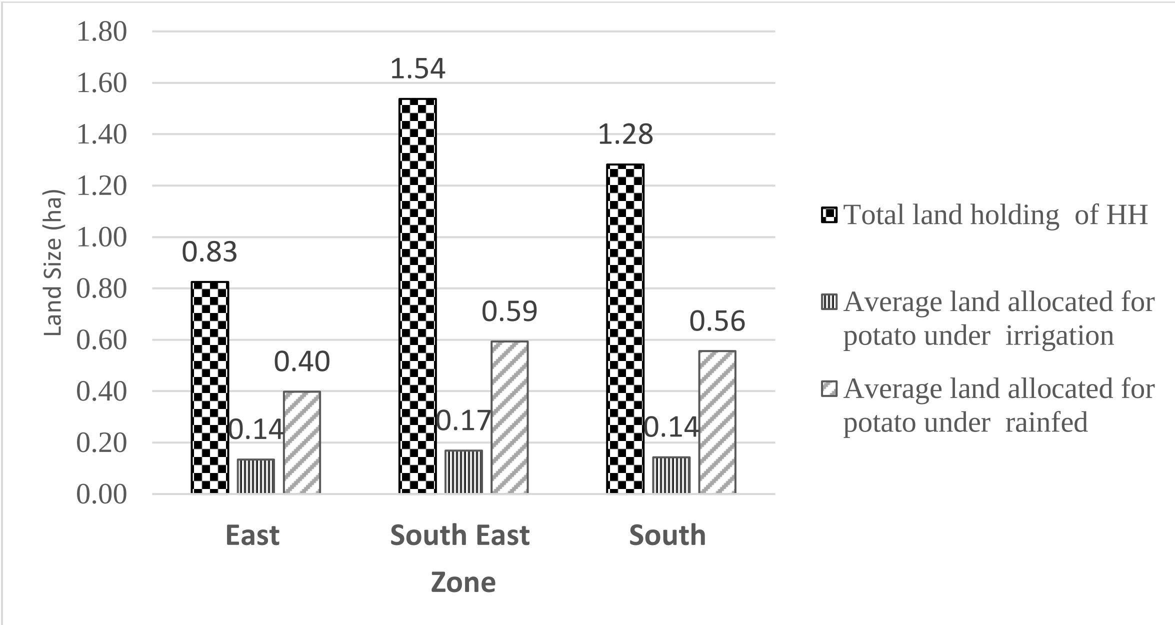

Figure 2. Land holding of the household

Potato Production Condition and Practice

More than 80% of the farmers in each Zone grow potatoes under both rainfall and irrigation conditions. Specifically, 83.4% of the farmers interviewed cultivate potatoes using both irrigation and rainfall, while 14.5% rely solely on rainfed conditions and 2.1% solely on irrigation (Figure 3). About 81.7, 86.3 and 83.5% of the interviewed farmers in East, Southeast and South zones produce potato under both rainfed and irrigation conditions respectively and less than 10% of the farmers interviewed produce only under irrigation conditions (Figure 3). This suggests that only a small number of farmers exclusively use irrigation for potato production. According to farmers' perception and focal group discussions, the agroecology of the study area is suitable for cultivating potatoes under both irrigation and rainfall conditions. Most farmers plant potatoes between May 15 and June 30 in rainfed conditions, although some wait until June 30 to July 15, depending on the onset or expected onset of rainfall. A few farmers plant potatoes based on the start of rainfall. In the highlands, especially in the South zone, farmers plant potatoes earlier compared to farmers in the Southeast and East zone mid-highlands. Furthermore, most interviewed farmers' plant potatoes from December 15 to January 15 under irrigation conditions. Some farmers also plant potatoes between September and October when the land becomes flooded during the main season, and they supplement irrigation. Therefore, adjusting the planting time of potatoes to coincide with the low temperatures required for tuber formation is critical for potato production.

All the farmers interviewed used the furrow irrigation method for irrigating potato crops. The main sources of water in the study area were streams (through diversion and water pumps), dams, groundwater (shallow well/borehole), and ponds. Most farmers obtained their irrigation water from diversion, while a smaller percentage relied on dams and shallow well/boreholes. A few farmers in the eastern zone (2.14%) depended on rivers through water pumps. Some farmers (7.81%) used multiple water sources. To increase potato productivity, it recommended improving streams, implementing water, and soil conservation measures. The predominant planting methods for potato among the farmers in the study area were flat and ridge planting. Ridge planting is commonly practiced under both rain-fed and irrigation conditions, while some farmers used flat planting and later created ridges during cultivation in rainfall conditions. The spacing between potato plants ranged from 30 -40 cm, while the spacing between rows varied from 50-75 cm. Focal group discussions revealed that the recommended spacing for potato was 30 cm between plants and 80 cm between rows in the study area. Therefore, it is important to provide training and advice to farmers on the significance of spacing and ridge creation.

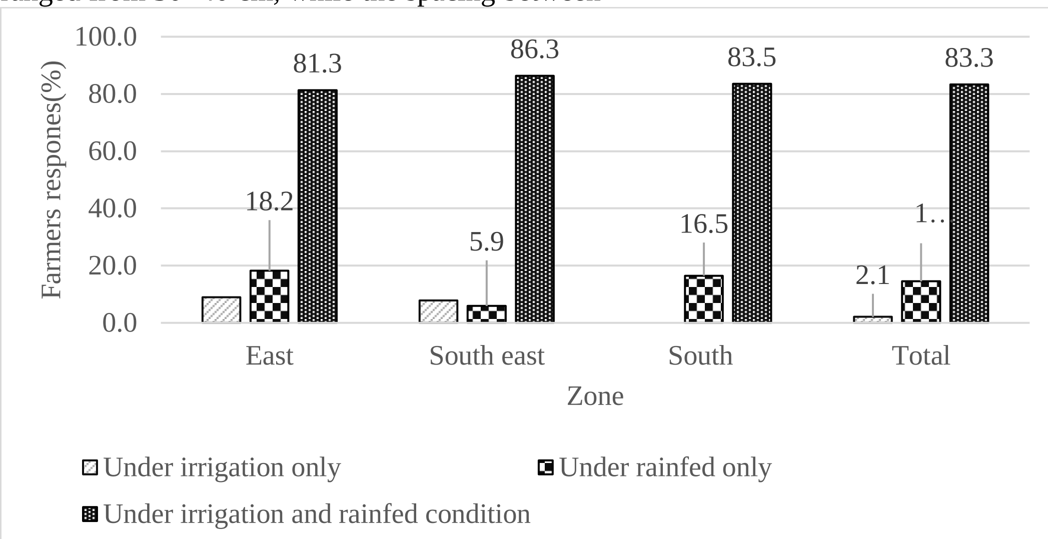

Figure 3. **Farmers that Produce Potatoes under Irrigation and Rainfall Conditions in Each Zone**

Potato Production Inputs and Management Practices in the Study Areas

The result of multiple responses of the farmers indicated that inorganic fertilizers, organic fertilizers, agro-chemicals and improved seed are the major inputs used to increase potato production in the study areas (Table 2). According to the focal group discussion on inputs for potato crop production, organic and inorganic fertilizers, chemicals and improved seed had a significant effect on potato production. Table 2 indicates that 98.9, 100 and 97.94 % of the farmers interviewed in East, Southeast and South Zone used inorganic fertilizer for potato production**.** According to the chi-square (χ^2), result there is no statistically significant difference in the use of inorganic fertilizer among the zones. The variation in the use of inorganic fertilizer across the zones is not statistically significant, indicating that the differences in usage are likely due to random variation rather than a systematic difference between the zones. 82.1% of the farmers in the study areas used organic fertilizer for potato production: There is a statistically significant difference in the use of organic fertilizers across the zones. This suggests that different zones may have varying practices or preferences regarding organic fertilizer application. This study agrees with the findings by Gebru et al. (2017) who reported that most of farmers (88.5%) in Wolaita zone, southern Ethiopia used fertilizers for potato production. In addition, Nyamwamu et al. (2014) in Kenya who reported that farmers using recommended types of fertilizers were 96 %and farmers using recommended fertilizer rates were 58 % for potato production.

Table 2. Potato production inputs used by the farmers (%) in the study areas

Potato production inputs	Zones				
	East	Southeast	South	Average	χ^2
Inorganic fertilizer	98.93	100.0	97.94	98.96	2.06^{ns}
Organic fertilizer	82.35	74.5	89.69	82.12	7.82*
Improved tuber seed	48.66	18.6	42.27	39.12	25.54***
Agro-Chemicals	67.91	78.4	35.05	62.44	44.54***
χ^2	79.96***				

χ^2 is Chi-Square, Source: Compiled by the author

Note: χ^2 is Chi-Square, ns is Not significant association between categorical variables at 5% probability level (P > 0.05) * is a significant association between categorical variables at 5% probability level (P ≤ 0.05), ** is highly significant association between categorical variables at 0.01≤ P >0.001 and highly significant association between categorical variables (***) P≤ 0.001.

About 48.7%, 18.6%, and 42.3% of the farmers interviewed in the East, Southeast, and South zones, respectively, used improved seeds. This indicates that most farmers in all zones, especially in the Southeast, did not use improved tuber seed in potato production. Additionally, there is a highly significant difference in the use of improved seeds among the zones, suggesting that the availability and adoption of improved seeds vary greatly by zones. In the Eastern and Southern zones, there are some seed tuber multiplier cooperatives and individuals. The use of improved tuber seeds shows a highly significant difference across the zones. This indicates that some zones may be more effective or willing to use improved seeds than others may which could affect overall potato production. Regarding agro-chemicals, there is a highly significant difference in the use of agro-chemicals across the zones, indicating that some zones rely more heavily on these inputs than others. Ridomil and Mancozeb were the common chemicals used by the farmers in all study areas. Moreover, over 60% of farmers used chemicals to protect their potato crops from diseases and pests (Table 2). There is a highly significant difference in the use of agro-chemicals among the zones. This discrepancy could reflect varying agricultural practices, pest pressures, or economic factors influencing the use of these chemicals. Gebru et al. (2017) reported that 43.05% of the respondents applied chemicals (Ridomil and Mancozeb) to control late blight in potato farms. The overall chi-square indicates that the inputs for potato production differ significantly across the zones. This suggests that factors such as geography, local agricultural policies, and farmer preferences affect how inputs are utilized in potato production**.**

In general, the data suggests that while the use of inorganic fertilizers is consistent across zones, organic fertilizers, improved seeds, and agro-chemicals show significant variation. This could be due to local agricultural practices, preferences, or availability of resources. The highly significant differences in improved seeds and agro-chemicals could warrant further investigation into the factors influencing these disparities.

Potato Variety (ies) in the Study Areas

Most farmers interviewed, commonly used cultivar was Shashemene (72.28%), which introduced from Shashemene, Oromia Region, Ethiopia, followed by local (55.70%). Gudene (36%), and Belete (20.5%) have moderate usage, while Jalene (8.8 %) and Gera (5.96%) are the least used. The Chi-square values indicate the statistical significance of the differences in variety usage across Zones (Table 3). All varieties show a highly significant difference (indicated by ***), meaning the distribution of potato varieties used is not uniform across the Zones. The highest number of farmers in Southeast and East Zone used Shashemene is notably favored, especially in the East and Southeast. This is due to lack of access to improved seeds in the study areas related to problems with seed. Farmers selected and used the Shashemene cultivar based on criteria such as high yield, market demand, early maturity, low seed cost, access to seeds in the market, but its drawback is susceptibility to diseases and pests was not considered. On the other hand, the criteria for selecting and using improved varieties were high yield, quality, market demand, and tolerance to water stress, disease and pest resistance. However, the drawbacks of improved varieties were limited access to seed tubers and high seed costs, which led to most farmers not using them. Gudanie also has strong usage, particularly in the East, but shows less preference in the Southeast. Belete and Jaleni are used less frequently, indicating they may not be as popular or well adapted in these regions. Gera is rarely used, which could suggest poor performance or lack of awareness among farmers. The significant Chi-square values reveal that the choice of potato variety is influenced by Zonal factors, emphasizing the need for targeted agricultural strategies that consider local preferences and conditions. In other studies (Gebru et al., 2017) reported that Gudene (32.2%) and Jalene (31.0%) were cultivated more than the other by smallholder farmers in Welayta Zone, Ethiopia.

Table 3. Potato varieties used by the farmers in the study areas (%)

Potato varieties and cultivars	East	Southeast	South	Total	χ^2
Gudene	47.06	16.67	35.05	36.01	26.508***
Belete	24.60	4.90	28.87	20.47	21.346***
Jalene	14.97	0.00	6.19	8.81	19.531***
Gera	12.30	0.00	0.00	5.96	26.027***
Shashemene	73.26	92.16	49.48	72.28	45.360***
Local	59.89	31.37	73.20	55.70	39.799**
χ^2		169.943***			

Source: Compiled by the author

Note: χ^2 is Chi-Square, ns is Not significant association between categorical variables at 5% probability level (P > 0.05) * is a significant association between categorical variables at 5% probability level (P ≤ 0.05), ** is highly significant association between categorical variables at 0.01≤ P >0.001 and highly significant association between categorical variables (***) P≤ 0.001.

The data suggests a clear Zonal preference for specific potato varieties, primarily influenced by factors such as suitability to the environment, farmer experience, and market dynamics. This information can be crucial for agricultural development programs focusing on improving potato cultivation and ensuring food security.

The overall chi-square indicates that the varieties or cultivars used for potato production differ significantly across the zones. This suggests that factors such as seed availability, market, cost of seed, and farmer preferences affect the variety /cultivar used for potato production

Seed Sources of Potato

Local market, farmers' seed multiplier associations, non-governmental organizations (NGOs), and research centers are the main sources of seed potatoes in the study areas (Table 4). The local market is the predominant source across all zones, with a perfect response rate in the Southeast and South. A high chi-square value indicates a significant association between the source and the zones, as 100% of interviewed farmers in the Southeast and South zones obtained their seed from the local market. In the East zone, 87.7% of farmers relied on the local market, while 30.6% obtained their seeds from farmers' seed multiplier associations. The latter source is less utilized, particularly in the Southeast zone, where no respondents reported using it; however, 33.7% of farmers in the East zone did use it. NGOs have moderate usage, especially in the Southeast, with significant differences among zones, albeit less pronounced than the previous sources. Research centers are minimally utilized, with no responses from the Southeast or South zones, indicating that this source is not favored in these areas (Table 4). In general, most farmers in the study area acquired their seed potatoes from the local market, while small number of farmers received them as gifts from NGOs. A small portion of farmers obtained their seed from research centers, particularly in the East zone's Atsbi district, where a seed multiplier association exists. Research institutions played a minor role, representing only 8.6% as a source of potato seed (min-tuber). Farmers primarily purchased seed potatoes with cash from the local market and seed multipliers, whereas NGOs and research institutes provided seed potatoes as gifts. Most respondents purchase potato seeds every year instead of keeping seed from their harvest. Some farmers interviewed, however, do keep their potato seed from their harvest and use it for 2nd and 3rd seasons, renewing their seed every two to three years. Farmers perceive that changing the soil texture for potato crops, such as planting potatoes in different types of soil each year; can also renew the potato seed tuber.

Table 4. Seed sources of potato

Source of potato seed tuber	Zone						
	East		Southeast		South		
	N	%	N	%	N	%	χ^2
Local market	164	87.7	102	100	97	100	26.027***
Potato seed tuber multiplier	63	33.7	0.0	0.0	8.0	8.2	58.791***
Non-government organization	20	10.7	28	27.5	20	20.6	13.572**
Research centers	16	8.6	0.0	0.0	0.0	0.0	16.977***
χ^2			116.153***				

χ^2 is chi-square, N is number of respondents, Source: Compiled by the author

Note: χ2 is Chi-Square, ns is Not significant association between categorical variables at 5% probability level (P > 0.05) * is a significant association between categorical variables at 5% probability level (P ≤ 0.05), ** is highly significant association between categorical variables at 0.01≤ P >0.001 and highly significant association between categorical variables (***) P≤ 0.001.

The data indicates substantial variation in the sources of potato seed tubers across different zones. The local market is the most common source, particularly in the Southeast and South zones. There is marked preference sources in specific regions, highlighting the importance of geographical context in agricultural practices. The high chi-square values across categories suggest that interventions or policies could be tailored based on these regional preferences. This study reveals that most farmers in the area do not have access to clean and healthy improved seed in local market, which negatively affects potato crop production and productivity. The study recommends that research centers, seed producer associations, agro-industrial organizations, and other non-governmental organizations collaborate to improve the production of quality seed tubers. This result supported by the result (Forbes et al., 2020) they reported that in many low-income countries, farmers often rely on informal seed systems, which include local markets and farmer-to-farmer exchanges. These informal systems are crucial for providing access to planting material, especially in regions where formal seed systems are underdeveloped or inaccessible. In addition, they indicated that in some areas, farmers might prefer local markets due to familiarity and immediate access, despite the potential benefits of organized seed multiplication. Furthermore, (Forbes et al., 2020) reported that in many agricultural systems formal research does not adequately address the realities faced by smallholder farmers.

Inorganic and Organic Fertilizer Use and Management in the Study Areas

Farmers use chemical fertilizer, such as NPS and Urea, along with animal manure and compost to improve soil fertility and increase crop production. The use of manure and compost had been found to enhance crop productivity in the study areas. Most farmers in all zones use this combination Urea and NPS, with the highest usage in the East (94.7%) and Southeast (91.2%). This suggests that farmers prefer combining these fertilizers for better yield. A small percentage of farmers do not use inorganic fertilizers, notably higher in the South (4.2%). The Chi-square statistic (105.549, $p < 0.01$) indicates a significant association between the type of inorganic fertilizer used and the zone, suggesting that the choice of inorganic fertilizer varies significantly by zone (Table 5). According to discussions with farmers and interviews conducted, both inorganic and organic fertilizers have a significant impact on improving potato crop production. While most farmers interviewed use both types of fertilizers, some are unable to afford inorganic fertilizer due to financial constraints. Additionally, a few farmers do not use organic fertilizer because they have a limited number of animals and lack the necessary materials to make compost. Although farmers in the three zones apply similar rates of inorganic fertilizers, they have different soil types and fertility levels.

Table 5. Type of Inorganic and organic fertilizer used by the farmers in each Zone (%)

Fertilizer		Zone		
		East	Southeast	South
inorganic	Urea only	3.73	7.8	1.0
	NPS only	0.54	1.0	22.9
	Both urea and NPS	94.7	91.2	71.9
	Not used inorganic	1.1	0.0	4.2
Chi-square (χ^2)			105.549**	
Organic	Manure only	43.0	63.7	78.4
	Compost only	4.8	2.9	1.0
	Both compost &manure	32.8	7.8	8.2
	Not used	19.9	25.5	12.4
Chi-square (χ^2)			80.068***	

Source: Compiled by the author Note: χ^2 is Chi-square, ** is highly significant association between categorical variables at probability level $0.01 \leq P > 0.001$ *** is highly significant association between categorical variables at probability level ($P \leq 0.001$)

Most interviewed farmers in in East and South zones apply (100 kg ha^{-1}) urea and 200 kg ha^{-1}of NPS for potato production, while in Southeast 36.3and 50.9% of the interviewed farmers apply >200 kg ha^{-1} urea and NPS respectively. Conversely, some farmers exceed the recommendation by applying higher amounts urea greater than 165 kg ha^{-1} and 200 kg ha^{-1} NPS. Regarding NPS, most respondents (200 kg ha^{-1}) follow the recommended regional and national dosage for potato production. However, a significant portion applies a lower amount of NPS kg ha^{-1}, and only a few farmers exceed the recommended dosage (Figure 4). According to FGD, all farmers apply a full NPS rate and half urea rate at planting, with the remaining urea applied at early flowering. Most farmers use the drill application method at planting, while a smaller percentage employ spot application. Some farmers also use spot and broadcast methods for applying inorganic fertilizers. These findings suggest that farmers possess awareness of the importance of fertilizers, but economic constraints limit their usage among some individuals

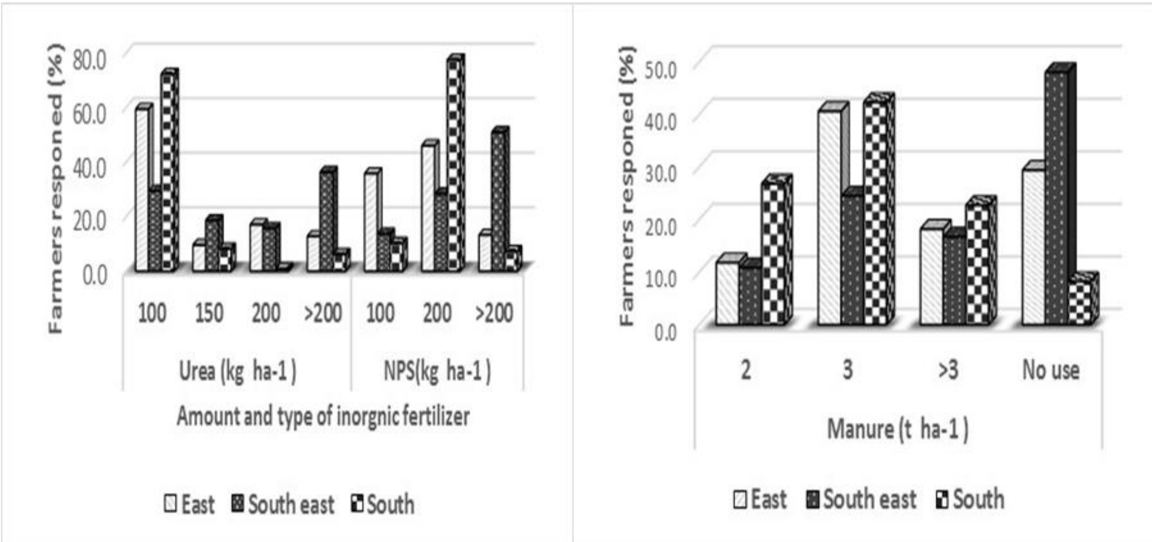

Figure 4. Amount and type of inorganic and organic fertilizers

Farmers in the study area utilize both inorganic and organic fertilizers, including manure and compost, for their potato farms. Among the farmers surveyed, most of them apply manure only while small percentage of farmers apply or use both manure and compost and compost alone (Table 5). The Chi-square statistic (80.068, $p < 0.001$) indicates a significant association between the type of organic fertilizer used and the zone, highlighting regional differences in organic fertilizer practices. In general, both inorganic and organic fertilizer usage varies significantly by zone, with distinct preferences observed. Farmers in the East and Southeast predominantly use both urea and NPS, while manure is the favored organic option, especially in the South. These findings can inform targeted agricultural policies and support programs to enhance fertilizer use efficiency in the respective zones. Like this result Gebru et al. (2017) reported that most farmers in Welayta Zone use fertilizer for potato production and most of the respondents were aware on the method and time of application. Furthermore, (Nyamwamu et al., 2014) reported that most farmers use recommended fertilizer type for potato production

The quantity of manure applied to potato fields varies greatly, ranging from 2 to 3t ha^{-1} depending on factors such as the availability of resources like animals and the distance of the farm from home The majority of farmers apply manure at a rate of 2-3 t ha^{-1} 40.6, 24.5 and 42.3 % of the interviewed persons in East, Southeast and South zone respectively apply 3 t ha^{-1} of manure for potato production (Figure 4). Small percentage of the farmers apply greater than 3 qt ha^{-1}. According to the farmers' response there was no difference in the amount of manure and compost applied to potato fields. In agreement to this, (Gebru et al., 2017) reported that farmers in Welayta Zone, Ethiopia apply 2.1 t ha^{-1}compost to potato farm but small amount farmyard manure of 1.1 t ha^{-1}. In addition, Negasi et al (2013) reported that farmers in the central rift valley of Ethiopia applied 1.71 and 1.56 t ha^{-1} of FYM and compost, respectively, to their onion farms. In general, most farmers use inorganic and manure fertilizers, which contribute to increased potato yield and quality, as well as the improvement, soil organic carbon levels. However, most farmers do not utilize compost fertilizer. Therefore, further research is necessary to determine the optimal rates, types, and timing of organic fertilizer application to fully maximize potato productivity.

Potato Productivity in the Study Areas

Timely harvesting and careful handling are crucial for the perishable potato crop. In this study, most potato varieties reached maturity between 90 and 120 days after planting, regardless of the season.

Under rainfall conditions, tuber yields ranged from 12.4 to 14.6 t ha^{-1} in the South zone and the Eastern zone respectively, and from 12.6 to 15.0 t/ha in the South zone and the Eastern zone, respectively (Figure 5). The average yield of potatoes under irrigation was 13.9 t ha^{-1}, while under rainfall conditions it was 13.4 t/ha. The highest average tuber yields of 15.0 t ha^{-1} and 14.6 t ha^{-1} were recorded in the East zone under irrigation and rainfed conditions, respectively. The lowest yields were observed in the South zone, with average tuber yields of 12.4 t ha^{-1} and 12.6 t ha^{-1} under rainfed and irrigation conditions, respectively (Figure 5). Farmers achieved higher average yields under irrigation due to sufficient water, fewer disease and pest issues, and better management practices.

In agreement to this, (Gebru et al., 2017) reported that most of the farmers obtained 11.5 to 17.2 t ha^{-1} yield of potato in Welayta Zone, South Ethiopia. Furthermore (Bezabih and Mengistu, 2011) reported that yield of 14.2 t ha^{-1} in Southern Nations, Nationalities and People Region, but lower yield of 9.3 t ha^{-1} in Tigray Regions of Ethiopia. In another study conducted in southern Ethiopia, (Mitiku et al., 2015) reported average tuber yields of 16.6 t ha^{-1}.

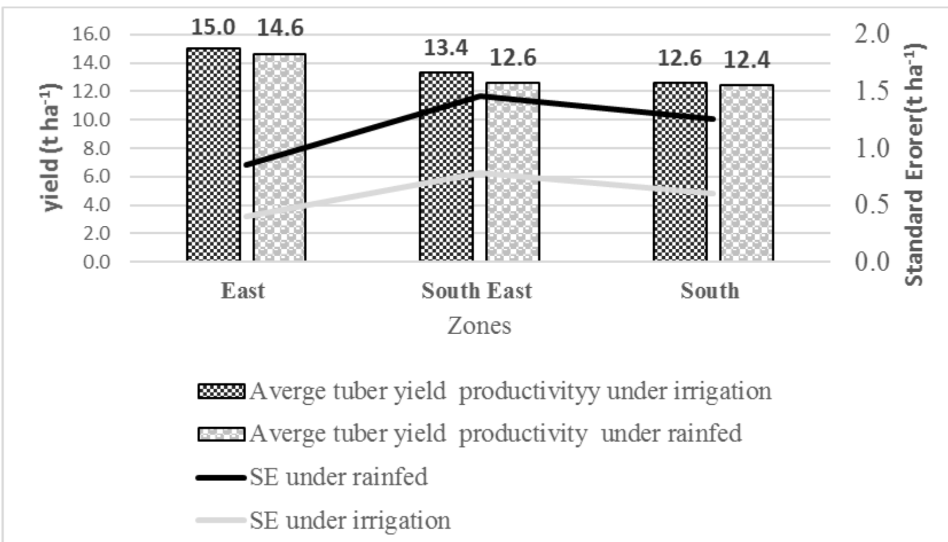

Figure 5. Average productivity of potato in the study areas under rainfall and irrigation condition

According to a survey, farmers agree that there is variability in potato production. Factors contributing to this variability include management practices, input quantities and types, soil fertility, access to water and improved seed, knowledge, and income. To enhance productivity among all farmers, the study suggests promoting experience sharing on potato crop management and protection measures, improving technical knowledge and skills through training on agronomic practices, water and fertilizer management, and providing effective extension services to increase potato yield.

Potato Production Opportunities in the Study Area

The study findings highlight key opportunities for potato production in the study areas (Table 6). These opportunities include suitable agro-ecology, good soil type, access to irrigation and labor, availability of improved seed, rainfall, access to local markets, and transportation. The most mentioned opportunities by farmers had related to suitable agro-ecology, good soil type, access to irrigation water, and labor across all study areas. However, certain opportunities, such as availability to improved seed, access to market and transport and rainfall are ranked lower and may pose challenges for potato production. It is important to note that opportunities identified by farmers in one area may not necessarily apply to other areas within the same zone. For example, an available improved variety may be an opportunity in one Wereda but a constraint in another. Overall, the analysis indicates that suitable agro ecology, good soil type and access to irrigation are the most significant factors for enhancing potato production in the semi-arid regions of Tigray. While access to improved seeds, market, and transport are less favorable, improving these areas could potentially enhance overall production opportunities. Addressing these key factors can facilitate better agricultural practices and increase potato yields in the region. Furthermore, developing and promoting potato production will require research and development of improved varieties adapted to different stresses and enhanced management practices. Similar to this study, previous research has shown that certain regions in Ethiopia, such as west and southwest Shewa zones of Oromia, have favorable conditions for potato production, including suitable agro-ecology, soil types, water sources, and fertile lands (Alemayehu, 2016). Ethiopia also has opportunities for various vegetable commodities due to favorable climate, proximity to markets, government policies, and cheap labor, as reported by Hunde, 2017.In summary, identifying and capitalizing on the specific opportunities in each region, such as agro-ecology, soil quality, and access to resources, will play a crucial role in advancing potato production and productivity in Ethiopia

Table 6. Potato production opportunities in Semi-Arid Areas of Tigray

List of production opportunities	East Zone			Southeast Zone			South Zone			Overall, in the study area		
	Sum	Index	Rank	Sum	Index	Rank	Sum	Index	Rank	Sum	Index	Rank
Suitable agro ecology	1478	0.220	1	802	0.217	1	772	0.221	1	3052	0.219	1
Good soil type	1303	0.194	2	728	0.197	2	683	0.195	2	2714	0.195	2
Availability of improved seed	633	0.094	6	236	0.064	7	166	0.047	8	1035	0.074	7
Access to irrigation	981	0.146	3	561	0.152	3	564	0.161	3	2106	0.151	3
Enough rainfall	820	0.122	4	419	0.114	5	417	0.119	4	1656	0.119	5
Access to labour	749	0.111	5	467	0.127	4	462	0.132	5	1678	0.121	4
Access to market	511	0.076	7	300	0.081	6	257	0.073	6	1068	0.077	6
Access to transport	256	0.038	8	178	0.048	8	176	0.050	7	610	0.044	8

Source: Compiled by the author

Production Constraints in the Study Area

Potato production faces numerous constraints, including biotic and abiotic factors as well as institutional issues. In the study area, all farmers (100%) identified drought, disease, pests, lack of improved seed varieties, market challenges, soil fertility, frost, input availability, and lack of extension services (training, advice and access to credit) were identified as major constraints in producing potato production despite of their rank difference (Table 7). Regardless of the vast merits of potato to farmers, their production has been constrained by numerous factors. According to the index ranking among the different production constrains the farmers were identified diseases and pest, water stress(drought), improved variety seed tuber and market were the most important (1st–4th rank) constraints related with the production of potato in the study areas in general and in eastern zone in particular (Table 7).

Farmers in the South and East Zone face disease and pests, water stress, improved variety, and market as their main challenges. In the Southeast Zone, the major constraints are Disease and pests, improved variety, water stress, and market. This indicates that the primary issues in one area may not be the same in another, requiring location-specific solutions. However, regardless of location, Disease and pest, water stress (drought), improved variety seed, and market consistently emerge as the four major constraints across all districts and zones. The study highlights that diseases, pests, water stress, and insufficient quality seed tubers hinder potato production in semi-arid areas of Tigray. Some farmers also struggle with water scarcity during dry seasons, leading to reduced potato production. The analysis indicates that disease and pests, along with water stress, are critical challenges facing potato production in Tigray. Addressing these issues may significantly improve agricultural productivity in the region. To address these challenges, there is a need to strengthen the research-extension linkage and develop improved varieties and management practices that can withstand various stresses affecting potato production. In general, the study highlights the constraints faced by potato farmers, the ranking of these constraints, the location-specific challenges, the common constraints across different areas, and the need for tailored solutions and recommendations to improve potato production. (Gebru et al., 2017) identified key constraints in potato production in Welayta Zone, south Ethiopia, including diseases, storage problems, low market prices, and insufficient seed tubers. Another study by (Emana and Gebremedhin, 2007) highlighted major constraints in horticulture production in Ethiopia, such as pests, drought, limited seed variety, high fuel prices for irrigation, and fertilizer limitations. (Muzari et al., 2012) attributed the low national mean yield of potatoes to various factors, including low adoption of improved agricultural technologies, drought, and lack of improved varieties, poor cultural practices, diseases, and environmental degradation. Insufficient or irregular rainfall and limited irrigation water also led to moisture stress and reduced yields. (Alemayehu ,2016) reported that major challenges in fruit and vegetable production in West and Southwest Shewa Zones of Oromia Region, Ethiopia included the unavailability of improved varieties, price fluctuations, and diseases and pests.

Table 7. Potato production constraints in Semi -Arid Areas of Tigray

List of production constraints	East Zone			Southeast Zone			South Zone			Overall, in the study area		
	Sum	Index	Rank	Sum	Index	Rank	Sum	Index	Rank	Sum	Index	Rank
lack of improved seed	1068	0.159	3	700	0.194	2	576	0.166	3	2344	0.170	3
Disease and pest	1380	0.206	1	704	0.195	1	696	0.200	1	2780	0.202	1
Market	998	0.149	4	538	0.149	4	550	0.158	4	2086	0.151	4
Water stress	1290	0.192	2	558	0.155	3	582	0.168	2	2430	0.176	2
Frost	710	0.106	5	420	0.116	5	438	0.126	5	1568	0.114	5
Input (other than seed)	703	0.105	6	383	0.106	6	340	0.098	6	1426	0.103	6
Poor soil fertility	302	0.045	7	165	0.046	7	179	0.052	7	646	0.047	7
lack of extension service	259	0.039	8	141	0.039	8	112	0.032	8	512	0.037	8

Source: Compiled by the author

CONCLUSIONS

The assessment confirms that potato is the main horticultural crop in the study areas, serving as cash food, and seed purposes under both irrigation and rainfall conditions. All farmers in the study have experience with potato production. In Tigray, potatoes were typically planted between Dec 15 and Jan 15, as well as May 15 and Jun 30, under irrigation and rainfall conditions. Most farmers use both inorganic and organic fertilizers for potato production, regardless of the amount and application method. The average land holdings allocated for potato was 0.83 to 1.54 ha, which is very small. The average tuber yield under irrigation ranges from 15.0 to 12.6 t ha^{-1}, while it ranges from 14.6 to 12.4 t ha^{-1} under rainfall condition. The study findings reveal that the availability of suitable agroecology, good soil type, access to irrigation water, and labor are the major opportunities for potato production in eastern, southeastern, and southern zones of Tigray. However, farmers face several challenges, including diseases and pests, lack of improved varieties, drought, and limited access to markets (low crop prices at harvest but high seed tuber prices at planting) in the semi-arid areas of Tigray, Northern Ethiopia. Moreover, the amount, type, and timing of fertilizer application, land size and fertility, access to improved seed varieties, and water availability (irrigation and rainfall) are the key factors influencing potato production and productivity variability among farmers in the study areas.

The agricultural bureau and research centers should support farmer-based seed tuber production in the region. Cooperation with nearby stakeholders such as higher education institutions and research centers is important for area-specific fertilizer use programs and appropriate land-use systems. This will help maintain soil fertility and ensure the availability of clean seeds. Training should provide farmers and development agents to improve their technical knowledge and skills in potato crop production, disease and pest protection measures, and agronomic practices. Collaboration between the International Potato Center (CIP), research centers, seed producer associations, agro-industrial organizations, and non-governmental organizations recommended focusing on quality seed production and overall potato productivity in Tigray, Ethiopia.

DISCLOSURE STATEMENT

The authors declare that they have no conflicts of interest.

AUTHORS' CONTRIBUTIONS

Niguse Abebe: Writing-review; editing, Writing-original draft, Visualization, Validation, Software, Methodology, Investigation, Formal Analysis, Data curation, Conceptualization. Derbew Belew: Writing-review & editing, Methodology, Validation, Visualization, Supervision, Conceptualization. Gebre Hadgu: Writing-review & editing, Methodology, Validation, Visualization, Supervision, Conceptualization. Hussien Mohammed Beshir: Writing-review & editing, Methodology, Validation, Visualization, Supervision, Funding acquisition, Conceptualization.

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Original Research Article||

Determinants of Underweight Children: A Cross-sectional Study in Enset-based Systems of Sidama Regional State, Ethiopia

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Abstract

Undernutrition is a significant public problem in Ethiopia. The country has made some progress in reducing malnutrition rates over the past decade, but the problem remains acute, particularly in rural areas where most of the population resides. The Sidama region of Ethiopia is one of the areas with a high prevalence of malnutrition, with underweight children being a particular concern. The region is characterized by enset cultivation, a starchy plant with high nutritional value. Despite the potential benefits of enset-based diets, undernutrition remains a significant problem in the region, suggesting that other factors beyond food availability and quality may contribute. Therefore, the study investigated the determinants of underweight children in the enset-based system of Sidama Regional State, Ethiopia. The study employs a cross-sectional research design, and data were collected from 620 households using a survey questionnaire. Chi-square and binary logistic regression analyses were used to analyze the data. Various factors influence the weight of a child. Among them are the mother's age, educational background, access to clean drinking water, the time interval between successive births, the frequency of antenatal visits, and the mother's hand-washing practices. Moreover, the age of younger siblings and the household's level of wealth, measured by an asset index, also play a significant role in determining a child's weight. However, certain factors can negatively impact a child's weight, including the total number of individuals living in the household, the incidence of diarrhea in the child, and the child's age. Considering these factors when evaluating a child's weight is essential, and interventions should be designed accordingly to address them. The study's findings offer stakeholders and decision-makers insightful information to develop effective interventions to address the issue of underweight children in the study area.

Key words: Body weight, Children, Enset, Sidama

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INTRODUCTION

Undernutrition remains a critical public health challenge globally, particularly in low- and middle-income countries (LMICs). Recent estimates indicate that 149 million children under five suffer from stunting, while 45 million experiences wasting. Sub-Saharan Africa bears a disproportionate burden, with Ethiopia reporting a 24% prevalence of underweight children, disproportionately affecting rural areas (Amare et al., 2019).

Ethiopia has implemented various initiatives to address undernutrition nationwide. The 2019 Food and Nutrition Policy, introduced to enhance nutritional health across all age groups, emphasizes an integrated strategy combining targeted nutritional interventions with broader socioeconomic measures. Furthermore, the Seqota Declaration reflects Ethiopia's pledge to eradicate undernutrition among children under two by 2030. To strengthen these efforts, the country launched the National Nutrition Program (NNP) I (2008–2015) and NNP II

(2016–2020), prioritizing cross-sector collaboration to deliver effective nutrition-focused solutions (FDRE, 2015; NiPN, 2020).Despite these efforts, the problem of undernutrition remains a significant public health challenge in the country(Korir et al., 2024).The second phase of the NNP, launched in December 2016, focuses on the critical 1000-day window from pregnancy to a child's second birthday (Kennedy et al., 2020).

The Ethiopian Demographic and Health Survey 2019 report indicates that in Ethiopia, 37% of children under age five are stunted, 7% are wasted, 21% are underweight, and 2% are overweight (EPHI & ICF, 2021). Likewise, the Sidama regional state is one of the regions in Ethiopia with a high prevalence of undernutrition among children. The region has a unique food system, where the staple food is enset corm, and pseudo-stems are used to make a variety of foods, and where most of the population relies on it for their livelihoods (G. Egziabher et al., 2020). Existing studies in Ethiopia have examined the socio-economic determinants of malnutrition (Sahiledengle et al., 2022). However, gaps remain in understanding how these factors interact within enset-dependent communities. Specifically, the role of health-related practices (e.g., antenatal care, hygiene) alongside socio-demographic variables remains understudied in this context. This study addresses this gap by examining the multifactorial drivers of underweight children in Sidama, providing evidence for targeted interventions.

RESEARCH METHODS

Study Area and Population

One of Ethiopia's regional states is the Sidama Region. Following a 2019 referendum in which 98.52% of voters supported increased autonomy, the Sidama Region was officially established on June 18, 2020. This involved its separation from the Southern Nations, Nationalities, and Peoples' Region (SNNPR) and the restructuring of the former Sidama Zone. The region derives its name from the Sidama ethnic group, who are indigenous to the area. Geographically, Sidama is bounded by the Oromia Region to the south—except for a small central stretch bordering the Gedeo Zone—and to the north and east. Its western edge is demarcated by the Bilate River, which separates it from the Wolayita Zone. Major urban centers include Hawassa (the regional capital), SNNPRS, Yirgalem, and Wendo. As of 2017, the population stood at approximately 3.2 million. The region's infrastructure includes 879 kilometers of year-round accessible roads and 213 kilometers of seasonal highways, yielding a road density of 161 kilometers per 1,000 square kilometers (NEBE, 2019).

The Sidama Region, Ethiopia's primary coffee-producing area, plays a pivotal role in bolstering the nation's foreign currency reserves. Data from the Central Statistics Agency (CSA) reveals that during the fiscal year ending in 2005, the combined output of Sidama and Gedeo reached 63,562 metric tons of coffee, as verified by the Ethiopian Coffee and Tea Authority's inspection records (ICO, 2019).

The region also possesses extensive yet underutilized water resources. Inadequate infrastructure, limited access to clean water, poor sanitation practices, and low public awareness of hygiene and environmental health contribute significantly to disease prevalence and mortality rates in the broader SNNP area. Culturally, livestock—particularly cattle—hold immense value in Sidama society, where ownership signifies wealth and social standing. Individuals without cattle are often marginalized, viewed as incomplete members of the community (MoWIE, 2018).

Operational Definition

Child nutritional status: Nutritional indicators were analyzed using the WHO Anthro software (version 3.1.0) and categorized based on the World Health Organization's growth reference criteria. Three anthropometric indices were derived for children: height-for-age (HAZ), weight-for-height (WHZ), and weight-for-age (WAZ), Z-scores, which assess stunting, underweight, and wasting, respectively.

Asset Index: Constructed using Principal Component Analysis (PCA) based on household ownership of 15 assets. Households were categorized into quintiles: very poor, poor, middle, rich, very rich (Vyas & Kumaranayake, 2006).

Enset Dominance: Defined as households deriving >50% of dietary calories from enset products, verified through dietary recall surveys.

Sample selection

The study participants were children under five years and their mothers (mother–child pair). The number of respondents included in the study was 620. The sample size was determined based on the formula suggested by Groves et al. (2009) as follows:

$$n = (z^2)(r)(1-r)(f)(k)/(p)(n_h)(e^2)$$

- **Zα/2**(1.96) = critical value from the standard normal distribution at a 95% confidence level (α=0.05),
- ***r*** = expected prevalence of the outcome,
- ***f*** = design effect (deff) accounting for clustered sampling, assumed as **1.5** based on standard household survey practices,
- ***k*** = non-response adjustment factor (**1.1**), applied to mitigate incomplete participation,
- ***p*** = proportion of the target subgroup within the total population (**15%** or **0.15**),
- ***nh*** = average household size (**5** individuals),
- ***e*** = margin of error (**5%**), the maximum acceptable threshold for precision.

In order to capture a representative respondent, a multi-stage sampling technique was used. In Woredas, encompassing both enset-growing and non-enset-growing areas, were strategically selected through purposive sampling, prioritizing regions where enset (or alternative crops) served as the primary staple food. The woredas were Wondogenet, Shebedino, Hawassa Zuria, Malga, Goricha, and Boricha. In the second stage, one Kebele per Woreda was randomly selected through simple random sampling to ensure representative inclusion. In the third stage, households were selected from each Kebele proportionally. A total of 620 participants were systematically selected to ensure proportional representation and minimize selection bias. Household lists, obtained from Woreda and Kebele administrative offices in the sampled areas, served as the sampling frame, with systematic sampling applied to finalize participant selection.

Data Collection and Measurements

The data were collected using a survey questionnaire and a key informant interview schedule. Both closed and open-ended questions were prepared to generate the required data. After developing a questionnaire, the researcher conducted a pre-test before carrying out a survey to improve the questions in terms of content clarity and language usage to collect appropriate data during the survey.

Data Analysis

The data collected through the survey questionnaire were entered into SPSS 26 software after checking for its completeness manually. Then, the data were cleaned for inconsistency and missing values. Finally, the data were analyzed using *Chi*-square and binary logistic regression analysis. Binary logistic regression analyses were employed to identify the socio-economic and demographic factors that influence underweight children. The model is specified as:

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k$$

Where p = probability of underweight, β_0 = intercept, and β_k = coefficients for predictors (e.g., maternal education, household size).

Variable Definitions and Hypothesis

Below is the list of variables from the attached document, categorized by name, type, unit of measurement, and expected sign based on the study's hypotheses and results:

Table 1. List of variables and expected signs based on the study's Hypothesis

Variable Name	Variable Type	Unit of Measurement	Expected Sign
Mother's Age	Continuous	Years	Positive (+)
Mother's Educational Status	Categorical (Ordinal)	Levels (e.g., no education, primary, etc.)	Positive (+)
Total Household Size	Continuous	Count of individuals	Negative (-)
Source of Drinking Water	Categorical (Binary)	Piped vs. non-piped	Positive (+)
Toilet Facility Type	Categorical (Binary)	Improved vs. non-improved	Positive (+)
Birth Interval	Categorical (Ordinal)	Categories (e.g., <2 years, >2 years)	Positive (+)
ANC Visits	Categorical (Binary)	Yes/No	Positive (+)
Experience Diarrhea	Categorical (Binary)	Yes/No	Negative (-)
Hand Washing Practice	Categorical (Binary)	Yes/No	Negative (-)
Child's Sex	Categorical (Binary)	Male/Female	Negative (-) (Male as risk)
Child's Age	Continuous	Years	Negative (-)
TLU (Tropical Livestock Unit)	Continuous	Livestock count (standardized)	Positive (+)
Enset Dominance	Categorical (Binary)	Enset vs. non-enset	Negative (-)
Asset Index	Categorical (Ordinal)	Quintiles (very poor to very rich)	Positive (+)

RESULTS AND DISCUSSION

In this section of the article, the researchers present the results of the study on the effect of socio-economic and demographic factors on underweight children as follows:

Table 2. The relationship between Selected Characteristics and Children's Body Weight

Characteristics	Weight for Age (WAZ)				Total		x^2 (p-value)
	Under weight		Normal				
	n	%	*n*	%	*n*	%	
Educational status of mother							
Unable to read and write	86	51.2	194	42.9	280	45.2	
Able to read and write	46	27.4	115	25.4	161	26.0	13.10
Only primary education	22	13.1	50	11.1	72	11.6	(0.011)
Secondary education	11	6.5	73	16.2	84	13.5	
College diploma and above	3	1.8	20	4.4	23	3.7	
Source of drinking water							
Others	70	41.7	107	23.7	177	28.5	19.44
Piped into dwelling	98	58.3	345	76.3	443	71.5	(0.000)
Kind of toilet facility							
Others	131	78.0	303	67.0	434	70.0	6.98
Improved	37	22.0	149	33.0	186	30.0	(0.008)
Birth interval							
First birth	2	1.2	20	4.4	22	3.5	24.26
1-2 years	96	57.1	162	35.8	258	41.6	(0.000)
>2 years	70	41.7	270	59.7	340	54.8	
ANC visit							21.41
No	20	11.9	12	2.7	32	5.2	(0.000)
Yes	148	88.1	440	97.3	588	94.8	
Experience diarrhea							17.36
No	133	79.2	413	91.4	546	88.1	(0.000)
Yes	35	20.8	39	8.6	74	11.9	
Hand washing practice of the caregiver							
No	67	39.9	120	26.5	187	30.2	10.34
Yes	101	60.1	332	73.5	433	69.8	(0.001)
Sex of children							
Female	62	36.9	232	51.3	294	47.4	10.22
Male	106	63.1	220	48.7	326	52.6	(0.001)
Enset dominant							
Non-enset dominant	71	42.3	250	55.3	321	51.8	8.351
Enset dominant	97	57.7	202	44.7	299	48.2	(0.004)
Asset index							
Very poor	53	31.5	74	16.4	127	20.5	
Poor	37	22.0	84	18.6	121	19.5	23.07
Middle	30	17.9	105	23.2	135	21.8	(0.000)
Rich	27	16.1	87	19.2	114	18.4	
Very rich	21	12.5	102	22.6	123	19.8	

n = 620: Underweight *n* = 168, Normal *n* = 452

The results of table 2 showed a statistically significant relationship between the educational status of a mother and the body weight of children (x^2 = 13.01, p< 0.05). That means mothers' education promotes the healthy weight of children. Likewise, there is a statistically significant relationship between drinking water source and children's body weight (x^2 = 19.44, p< 0.001). Similarly, there is a statistically significant relationship between the kind of toilet facility and children's body weight (x^2 = 6.98, p< 0.01).

There is a statistically significant relationship between birth interval and children's body weight (x^2 = 24.26, p< 0.001). Furthermore, there is a statistically significant relationship between ANC visit and body weight of children (x^2 = 21.41, p< 0.001). In addition, there is a statistically significant relationship between experiencing diarrhea and body weight of children (x^2 = 17.36, p< 0.001).

There is a statistically significant relationship between the sex of children and body weight of children (x^2 = 10.22, p< 0.001). Likewise, there is a statistically significant relationship between enset dominance and the body weight of children (x^2 = 8.35, p< 0.001). Moreover, there is a statistically significant relationship between the asset index and body weight of children (x^2 = 23.07, p< 0.001).

Table 3. Mean Comparison of Continuous Variables*

Variables	Weight for Age (WAZ)				t-test	p-value
	Underweight (n=168)		Normal (n=452)			
	Mean	SD	Mean	SD		
Age of mother	30.4	4.71	31.4	5.05	-2.13	0.034
Total household size	5.6	2.00	5.1	1.69	2.82	0.005
Child age	3.6	1.02	3.4	0.92	2.20	0.028
TLU	5.6	6.74	7.4	6.85	-2.99	0.003

*****'Independent Samples t-tests (sig 2-tailed) were used to compare means of variables between Underweight and Normal in the households'

The results of Table 3 showed that there is a significant difference between children with normal weight and those who are underweight, depending on the mother's age. The result of the independent samples *t*-test was significant (t = -2.31, *p*<0.05), indicating that the average age of mothersignificantly differed between the normal weight (Mean = 31.40) and underweight children (Mean = 30.40). Thus, a child with older aged mother has a better chance to have normal weight than those who has younger aged mother.

As summarized in Table 3, there was a significant difference in the size of the total household between children with normal weight and those who were underweight.The result of the independent samples *t*-test was significant (*t* = 2.82, *p*<0.01), indicating that the average total household sizesignificantly differed between the normal weight (Mean = 5.10) and underweight children (Mean = 5.60). Therefore, a child living with large household has a greater chance of being underweight than those who livewith small household.

According to Table 3, there is a significant difference between normal weight children and underweight children in the child's age. The result of the independent samples *t*-test was significant (t = 2.20, *p*<0.05), indicating that the average child agesignificantly differed between the normal weight (Mean = 3.40) and underweight children (Mean = 3.60). Thus, a child with an older age experience underweight than those who has younger aged mother.

As indicated in Table 3 showed a significant difference between normal weight children and underweight children on the TLU. The result of the independent samples *t*-test was significant (t = -2.99, *p*<0.01), indicating that the average TLUsignificantly differed between the normal weight (Mean = 7.40) and underweight children (Mean = 5.60). As a result, a child living in a household with a large amount of livestock has a better chance of being of normal weight than a child living in a household with a small amount of livestock.

Table 4. The Binary Logistic Regression Output

Variables	B	S.E.	Wald	Sig.	Exp(B)	95% C.I.for EXP(B)	
						Lower	Lower
Age of the mother	0.12	0.03	23.72	0.000	1.13	1.08	1.19
Educational status	0.25	0.11	5.62	0.018	1.28	1.04	1.57
Total Household Size	-0.33	0.07	25.28	0.000	0.72	0.63	0.82
Source of drinking water	0.85	0.23	13.90	0.000	2.33	1.49	3.64
Kind of toilet facility	0.42	0.25	2.82	0.093	1.52	0.93	2.49
Birth interval	0.44	0.19	5.21	0.022	1.55	1.06	2.25
ANC visit	1.34	0.47	8.17	0.004	3.82	1.52	9.57
Experience diarrhea	-1.04	0.30	11.93	0.001	0.35	0.20	0.64
Hand washing practice	0.83	0.23	13.04	0.000	2.29	1.46	3.60
Sex of Children	-0.63	0.21	8.63	0.003	0.54	0.35	0.81
Child age	-0.31	0.11	7.58	0.006	0.73	0.59	0.92
TLU	0.01	0.02	0.47	0.495	1.01	0.98	1.05
Enset dominant	-0.33	0.22	2.29	0.130	0.72	0.47	1.10
Asset index	0.19	0.09	4.75	0.029	1.21	1.02	1.44
Chi-square			138.58				
Sig.			0.000				

The age of a child's mother has a positive and statistically significant effect on their children's body weight status ($B = 0.12$, $p < 0.001$) as shown in table 4. The odds ratio value indicates that if a mother's age increases by one unit, a child has a 1.13 chance of having a normal body weight regardless of the other independent variables in the model. This indicated that a mother's age positively affects the body weight status of her children.

A mother's education level has a positive and statistically significant effect on her children's body weight status ($B = 0.25$, $p < 0.05$). The odds of respondents with a higher education level having normal-weight children are 1.28 times higher than those with a lower education level. This revealed that sampled mothers with a higher education level have a better chance of having normal-weight children than those with a lower education level.

The total household size of the sampled child's mother has a negative and statistically significant effect on the body weight status of children ($B = -0.33$, $p < 0.001$). It can be inferred from the odds ratio values that if the total household size of a sampled child's mother increased by one unit, a child has a 0.72 chance of being underweight regardless of other independent variables in the model. This indicates that total household size has a negative effect on the body weight status of children.

The source of drinking water has a positive and statistically significant effect on the body weight status of children ($B = 0.85$, $p < 0.001$). The odds of respondents with piped water being normal-weight children is 2.33 times higher than those without piped water. This revealed that sampled mothers with piped water have a better chance of being normal-weight children than mothers without.

Birth interval has a positive and statistically significant effect on body weight status of children ($B = 0.44$, $p < 0.02$). The odd of respondents with high birth interval being normal weight children is 1.55 times higher than those with low birth interval. This revealed that sampled mothers with high birth intervals have a better chance to be normal weight children than mothers with low birth intervals. ANC visit has a positive and statistically significant effect on body weight status of children ($B = 1.34$, $p < 0.001$). The odd of respondents with ANC visits being normal-weight children is 3.82 times higher than those without ANC visits. This revealed that sampled mothers with ANC visits have a better chance of being normal weight children than mothers without ANC visits.

Diarrhea has a negative and statistically significant effect on children's body weight status ($B = -1.04$, $p < 0.001$). The likelihood of a mother experiencing diarrhea being normal weight children is 0.35 times lower than the likelihood of a mother not experiencing diarrhea. This revealed that sampled mothers who had diarrhea had a higher chance of having underweight children.

Hand washing practice has positive and statistically significant effect on body weight status of children (B

=0.83, p <0.001). The odds of respondents who have hand washing practice being normal weight children is 2.29 times higher than those respondents who have no hand washing practice. This revealed that sampled mothers who have hand washing practice have better chance to be normal weight children than those mothers who have no hand washing practice.

Children's sex has a negative and statistically significant effect on their body weight status (B =-0.63, p<0.001). Male children are 0.54 times less likely than female children to be normal weight. This revealed that male children have a better chance of being underweight than female children.

Age of achild has a negative and statistically significant effect on theirbody weight status (B = -0.31, p <0.01). It can be inferred from the values of odds ratio that if a child increased their age by one unit, a child has a 0.73 chance of decreasing their weight regardless of other independent variables in the model. This indicated that child age has a negative effect on body weight status of children.

Asset has positive and statistically significant effects on body weight status of children (B =0.19, p <0.03). The odds of respondents who were Enset dominant have normal weight children is 0.73 times higher than those respondents who were non-enset dominant. This revealed that Enset dominant households have a better chance of being normal-weight children than non-enset dominant.

DISCUSSION

There has been much research on the relationship between a mother's age and her children's body weight, and the findings generally support a positive correlation between these variables. Fall et al. (2015), Dhana et al. (2018), and Heslehurst et al. (2019) found that maternal age was positively associated with children's body weight, even after controlling other factors such as maternal education, income, and race/ethnicity. The study further indicated that each one-year increase in maternal age at childbirth was associated with a 0.03 increase in children's BMI z-score, even after adjusting for other factors. This means that older mothers tend to have children with higher body weight compared to younger mothers. One possible explanation for this finding is that older mothers may have different dietary or lifestyle habits compared to younger mothers, which could also influence their children's body weight. Likewise, the finding of Haile et al. (2020) approved that children whose mother's age is below 20 (OR = 5.75, 95%CI = 1.44, 23.1)) were more likely to be underweight compared with children whose mother's age is above 45.

The study found that there is a positive relationship between the education status of mothers and the body weight of their children. The finding of Haile et al. (2020) indicated that children whose mothers had no education and primary education only (OR = 1.65, 95% CI 1.05, 2.59 and OR = 1.43, 95% CI 1.15, 1.78, respectively) were more likely underweight compared to children whose mothers had higher education. This relationship can be attributed to various factors, such as increased knowledge and awareness of healthy eating habits, access to healthier foods, and the ability to make informed decisions about nutrition and physical activity. Mothers with higher education levels tend to have greater knowledge and awareness of the importance of healthy eating habits and physical activity for their children's health. They are more likely to understand the nutritional needs of their children and to provide them with balanced meals that contain adequate amounts of essential nutrients. Moreover, education is associated with socio-economic status, which can impact access to healthy foods. Mothers with higher education levels are more likely to have better-paying jobs, which can provide them with the financial resources to purchase healthy food for their families.

The study found that household size has a negative effect on the body weight status of children. This means that as the size of a household increases, the likelihood of children being overweight or obese also increases. There are several possible explanations for this relationship. One reason may be related to food availability and access within larger households. As the number of people in a household increases, there may be more competition for food resources, which can lead to a decrease in the amount of healthy food available to everyone (Chen, et al., 2021). Additionally, larger households may have more limited access to healthy food options due to economic constraints or geographic location. Another possible explanation is related to social dynamics within larger households. For example, children in larger households may be exposed to more sedentary behavior, such as watching TV, and less physical activity due to limited space or resources. Furthermore, children in larger households may be subject to more stress and lower levels of parental involvement due to the demands of managing a larger household, which can lead to unhealthy coping mechanisms and behaviors.

The finding proved that there is a positive relationship between the source of drinking water and children's body weight. According to VanCooten et al. (2019), access to clean and safe drinking water can have a significant impact on children's growth and development, including their body weight. One reason for this relationship is that access to safe drinking water can help prevent waterborne diseases and infections, which can affect children's overall health and nutrition. When children are sick, they may experience reduced appetite and energy levels, which can lead to weight loss and stunted growth. By contrast, children who have access to clean and safe drinking water are less likely to suffer from waterborne illnesses and can maintain better health and nutrition. In addition, Abdulahi et al. (2017) indicated that access to clean water can also promote hydration, which is important for maintaining healthy body weight. Studies have shown that dehydration can lead to overeating and weight gain, as the body may mistake thirst for hunger. By ensuring that children have access to clean and safe drinking water, parents and caregivers can help them maintain proper hydration levels. Furthermore, providing children with clean and safe drinking water that is free from harmful contaminants can help promote healthy growth and development.

Birth interval, the time elapsed between the birth of a child and the conception of the next child, has a positive effect on children's body weight. That means short birth intervals were associated with decreased weight gain in children. The results of Gizaw and Kumera (2018) indicated that longer birth intervals were associated with higher body weight in the second-born child, even after controlling for a variety of demographic and socio-economic factors. That means, longer birth intervals may also have positive effects on child health, specifically in terms of body weight. Therefore, the positive effect of birth interval on children's body weight found in this study adds to the growing body of evidence supporting the importance of family planning and the potential health benefits of longer birth intervals.

According to the results of the study, ANC (Antenatal Care) visits have a positive effect on children's body weight. ANC visits are an important aspect of maternal and child health care services, as they provide expectant mothers with essential health care and education to ensure a healthy pregnancy and delivery. The study conducted by Woldeamanuel and Tesfaye (2019) found that ANC visits have a significant impact on children's body weight. The study analyzed data from the Ethiopian Demographic and Health Survey (EDHS) and showed that children born to mothers who received at least four ANC visits during their pregnancy had a significantly higher body weight than children born to mothers who had fewer ANC visits. The study found that the positive effect of ANC visits on children's body weight was mediated by various factors. For instance, mothers who received ANC visits were more likely to be informed about the importance of exclusive breastfeeding, which could lead to better nutrition for their infants. Additionally, mothers who received ANC visits were more likely to receive treatment for anemia and other infections, which could improve their overall health and lead to better nutrition for their infants.

Diarrhea is a common problem among children that can have a negative impact on their overall health, including their body weight. According to a study conducted by Kassie et al. (2019), experiencing diarrhea can result in a significant reduction in a child's body weight. The researchers found that children who had experienced diarrhea in the previous two weeks had a significantly lower body weight compared to children who had not experienced diarrhea. The negative impact of diarrhea on body weight can be attributed to several factors. One of the main factors is malabsorption, which occurs when the body is unable to absorb nutrients from food due to the rapid passage of stool through the intestines (Wasihun et al., 2018). This can result in a deficiency of important nutrients, such as vitamins and minerals, which can lead to stunted growth and lower body weight. Another factor that can contribute to the negative impact of diarrhea on body weight is loss of appetite. Children with diarrhea may experience nausea, vomiting, and abdominal pain, which can lead to a decreased desire to eat (World Health Organization, 2017). This can result in a reduced intake of calories and nutrients, further exacerbating the negative impact of diarrhea on body weight.

Hand washing is a common hygiene practice that has been shown to have a positive impact on health outcomes. The study found that mothers' hand-washing practices can positively influence their children's body weight. Research by Kwami et al. (2019), Nalule et al. (2022), Petermann-Rocha et al. (2023), and Taddese et al. (2020) examined the relationship between mothers' hand-washing practices and children's body weight. These studies revealed that mothers who frequently washed their hands had children with lower body weights compared to mothers who did not wash their hands as often. Additionally, the positive association between mothers' hand-washing practices and children's body weight was found to be stronger in children who were breastfed. The mechanisms underlying the relationship between mothers' hand washing practices and children's body weight are not entirely clear. One possible explanation is that hand washing reduces the transmission of infectious agents that can lead to diarrhea and other illnesses, which can cause children to lose weight (Dreibelbis et al., 2014). Another possible explanation is that mothers who practice good hygiene may also engage in other healthy behaviors that can influence their children's body weight, such as providing healthier foods and encouraging physical activity (Muthuri et al., 2016).

The study found that the sex of children may have an impact on their body weight. For example, Sahiledengle et al. (2022) found that males were 1.8 times more likely to become underweight than females [AOR: 1.8 (1.14– 2.85)]. Likewise, EDHS (2016) also indicated that children were more likely to be underweight if they were male (OR = 1.16, 95%CI = 1.02, 1.33).Another study by Hsu et al. (2018) reported that the sex of the first-born child might also influence body weight, with girls who are the first-born more likely to be overweight or obese than boys who are the first-born. Similarly, a study by Bohn et al. (2020) and Shah et al. (2020) found that the sex of the second-born child may influence body weight, with second-born boys being more likely to be overweight or obese compared to second-born girls.

The study found that a child with older age is more likely to be underweight than those who have younger. A longitudinal study conducted in urban Ethiopia by Mezmur et al. (2017) indicated that as the age of children increases, they have a higher probability of being underweight. The study analyzed data collected between 2000 and 2011 and assessed the trends in socio-economic and behavioral determinants of maternal, neonatal, and child health and nutritional status. On the other hand, a study conducted by Biro and Wien (2010) examined the association between child age and body weight status in a sample of 1,034 children aged 2 to 18 years. The researchers found that older children were more likely to be overweight or obese than younger children, with the most significant increase in risk occurring during adolescence. Specifically, the odds of being overweight or obese were 1.17 times higher for each year of age beyond five years, with the most significant increase in odds occurring between ages 10 and 14 years. Older children may have more opportunities to engage in sedentary behaviors, such as watching television or playing video games, which can contribute to excess calorie intake and weight gain.

The study established a positive correlation between the household asset index and children's body weight. That means children from households with a higher asset index were less likely to be underweight and more likely to be overweight or obese. Similarly, a study conducted in Vietnam by Amugsi et al. (2020) found that children from households with a higher asset index had a lower risk of being underweight than those from lower asset index households. These findings can be explained by the fact that households with higher asset indexes tend to have better access to food, healthcare, and other resources that promote healthy growth and development in children. Tesfaw and Zewotir (2021) also added that wealthier higher quality and more nutritious food, contributing to better overall health and growth. They can also afford to provide their children with better healthcare, which can prevent and treat conditions that may lead to being underweight or overweight.

CONCLUSIONS

The study highlights the importance of various demographic, socio-economic, and health-related factors on the normal body weight of a child in the Sidama regional state. The findings suggest that maternal factors, such as age and educational status, play a crucial role in ensuring the healthy growth of their children. Access to clean drinking water, practicing hand washing, and timely antenatal visits were also found to positively impact a child's normal weight. In contrast, household size, diarrhea episodes, and child age were found to negatively impact children's normal body weight. Therefore, interventions should focus on improving maternal education, increasing access to clean drinking water, and promoting healthy hygiene practices to improve the nutritional status of children. This study can serve as a valuable resource for policymakers, healthcare providers, and other stakeholders working towards improving child health and nutrition in low- and middle-income countries.

AUTHOR CONTRIBUTIONS

Atsede Seyoum was responsible for data management, statistical analysis and drafting of the manuscript. Admasu Tsegaye and Aregash Samuel contributed to data analysis and manuscript development and review. All authors have read and approved the final version of the manuscript.

DECLARATION

The authors declare that there is no conflict of interest.

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Original Research Article||

Forage and economic benefits of Desho (*Pennisetum glaucifolium*) grass-legume intercrops in southern Ethiopia

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Abstract

Forage grass-legume intercropping is not common in Ethiopia despite its potential to improve forage productivity and farm income. This study evaluated forage mass production and the economic benefits of desho grass (*Pennisetum glaucifolium*)—one of the few native forage crops in Ethiopia—intercropped with alfalfa (Medicago sativa L.) and greenleaf desmodium (Desmodium intortum) at Hulbareg district in the mid-highlands of southern Ethiopia. The field experiment was conducted during the main growing season of 2020 using a randomized complete block design with three treatments; sole desho grass, desho–alfalfa, and desho–greenleaf desmodium intercrops. Results showed that intercropping increased desho herbage yield by 2.5 t ha−1 (up to 63% increase) over the sole desho stand. The economic analysis indicated higher net returns from intercropping system, amounting to US$ 5219 ha−1 for desho-greenleaf desmodium and US$ 3866 ha−1 for desho-alfalfa, compared to US$ 2567 ha−1 for the sole desho grass. Partial land equivalent ratio and income equivalent ratio values of desho exceeded 0.5 in intercrops, indicating yield and income advantages for the grass component under intercropping. Overall, desho-greenleaf desmodium intercropping was identified as the most promising option due to its higher herbage yield, superior economic returns, and lower production costs. The findings suggest that integration of legumes into a desho grass-based fodder system can enhance forage productivity and profitability in the Ethiopian mid-highlands. Further validation under farmers' conditions is recommended prior to large-scale promotion.

Key words: Desho-legume intercropping, forage mass, partial income equivalent ratio, partial land equivalent ratio, sole desho grass

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INTRODUCTION

Ensuring a reliable year-round forage supply is a major constraint to improving livestock production in Ethiopia. Improved utilization of promising indigenous grass species offers a potential strategy to mitigate the problem. Among these species, desho grass (*Pennisetum glaucifolium;* previously known as *P. pedicellatum*) has received increasing attention. Desho is a non-invasive perennial grass, adapted to a wide range of agro-ecological conditions. It is well known for its tolerance to moisture stress, and its ability to grow on degraded lands or soil bunds, and is suitable for a cut-and-carry system (Leta et al., 2013; Asmare, 2016; Maass and Pengelly, 2018). Desho grass is widely cultivated in the mid- and high-altitude regions of southern Ethiopia, where it is predominantly grown in pure stands. Despite its high yield potential and thrives under drought stress and poor soil conditions (Leta et al., 2013), current yields obtained on smallholder farms are generally poor (own observation and focus group interviews; Appendix A). In addition, the relatively high costs associated with establishment and maintenance constrains its production and wider adoption (Leta et al., 2013).

Intercropping desho grass with forage legumes could address several limitations associated with monocropping that include high initial growing costs, low realized yields relative to potential and high labor demand for gap filling and weed control. Legume integration has also the potential to improve both the nutritive and economic value of the crop (Maass and Pengelly, 2018), suppress weeds and improve land use efficiency (Chimonyo et al., 2016; Gitari et al., 2020; Glaze-corcoran et al., 2020). Hence, the inclusion of forage legumes into the existing desho grass fodder production system could be a viable option to improving forage supply and cash income for smallholder farmers. Alfalfa (*Medicago sativa* L.) and greenleaf desmodium (*Desmodium intortum*) could be suitable companion perennial legumes for desho grass in Ethiopia because of their wide adaptability (Assefa et al., 2012; Mengistu et al., 2017).

However, forage grass-legume intercropping remains rarely practiced or studied in Ethiopia. In southern Ethiopia, for example, planted forages including desho are commonly grown in monocultures (which is also a widespread focus for current pasture and forage research as well (Asmare 2016; Feyissa et al., 2022). Moreover, research in Ethiopia predominantly focused on the most commonly practiced cereal-grain legume intercrops used for human consumption, with limited attention given to forage crop combinations.

Therefore, this study aimed to evaluate the forage mass production and economic benefits of desho grass intercropped with alfalfa and greenleaf desmodium at Hulbareg, a site representative of the mid-highlands agroecological zone of southern Ethiopia.

MATERIALS AND METHODS

Site Description

The experiment was conducted at the Farmers' Training Center Demonstration Field in Hulbareg district, Ethiopia (7°58′19″ N, 38°37′59″ E; 1450 m above sea level) during the period from April to July 2020. The study area is characterized by a cereal-livestock mixed system within the tepid to cool sub-humid mid highlands agroecological zone of Southern Highlands (MoA, 1998; Elias, 2016). The rainfall during the 2020/21 growing seasons was 1200 mm and the mean annual temperature was 24°C. The dominant soil is a clay loam.

Treatments and Experimental Design

The treatments comprised of: (i) sole desho grass (*Pennisetum glaucifolium*); (ii) desho intercropped with alfalfa (*Medicago sativa* L.); and (iii) desho intercropped with greenleaf desmodium (*Desmodium intortum*). The forages were planted in the first week of April and harvested in early July. Desho was planted using rooted splits (each approximately 0.3 m in height) at spacing of 0.5 × 0.5 m under sole cropping. In the intercrops, desho was planted at spacing of 1 x 0.5 m. One row of alfalfa and greenleaf desmodium was drilled between the desho grass rows at a recommended seeding rate of 15 and 3 kg ha–1, respectively (Mengistu, 2002). The experiment was performed in a randomized complete block design with three blocks. Each plot measured 4 × 3 m. All plots received 100 kg ha−1 of NPS (19:38:7) at planting and an equivalent amount of urea (46% N) 23 days after planting. Due to the unavailability of rhizobium inoculants, the legumes were sown without inoculation. Weed control was carried out manually in all plots. The weeding was done 23 days after planting and the second weeding was performed 30 days after the first weeding.

Evaluation of Forage Mass Production, Land and Income Equivalent Ratios

Herbage yield was measured at 90 days after planting (early July 2020). Grasses in the inner two-thirds of each experimental plot were hand-harvested at 8 cm stubble height. Fresh mass (green herbage yield) was weighted immediately in the field. Subsequently, a 500-g representative subsample was oven-dried at 105℃ for 24 h to determine dry matter yield of the desho grass. Desho grass is widely cultivated by local farmers both as a source of forage and cash income, as confirmed by farm visits and focus group interviews with local extension officers (Appendix A). Therefore, yield and economic evaluations in this study considered this forage grass as the focus crop.

The advantage of intercropping relative to the sole desho grass in terms of herbage yield and land use efficiency was quantified using partial land equivalent ratio (pLER). As the primary objective of the study was to evaluate the feasibility of inclusion of legumes into the existing desho grass production system (the focus crop) to improving both forage supply and economic returns (of the crop), pure stands of the legumes were not included in the experimental design (Willey, 1979, 1985). Hence, the LER and income equivalent ratio (IER) (see below) results should be interpreted within this context.

The LER was calculated as: pLERdesho = Yid/Yd where pLERdesho represents the partial LER of the desho grass and Yid and Yd denote the yield of desho grass in the intercrop and the yield of the sole desho, respectively.

The economic efficiency of the desho grass-legume intercropping system was analyzed using partial income equivalent ratio (pIER). The pIER represents the area needed under sole cropping to produce the same gross or net income, under the same management level, as that obtained from intercropping (Francis, 1986). The IER is conceptually similar to the LER, except that yield is measured in terms of net/gross income, rather than plant productivity. For reason stated above, we employed the partial IER, which was calculated as: pIERdesho = (Yid * Pd) / (Yd * Pd); where pIERdesho is the partial IER of the desho grass and Yid and Yd are the yields of desho (as green feed) in the intercrop and pure stand, respectively. Pd is the average farm gate price of desho grass, estimated at US$ 920.12 per unit of fresh herbage (green feed).

Economic Analysis

A partial budget analysis was conducted to evaluate the economic feasibility of including legumes into the existing desho grass cropping system (CIMMYT, 1988; Mamerto, 2001). The analysis was based on the costs of variable inputs and the economic value of the forage mass produced (i.e. value of desho as green feed) (Table 1). Because desho grass is commonly marketed and utilized as green fodder rather than hay, both the IER (see previous section) and the economic analysis were based on the value green forage production.

The total variable costs included expenditures for fertilizers, rooted-splits, machinery and labour across all treatments, as well as the cost of legume seed for the intercropped treatments. These costs were estimated using prevailing field prices at the time of the experiment (Table 1). Gross income was calculated by multiplying the green herbage yield (t ha^{-1}) with the field price of US$ 920.12 for desho fodder at harvest. Net return was determined as the difference between gross income and total variable costs. Costs associated with plowing, harvesting and fertilizers were uniform across treatments and were thus excluded from the analysis, as they did not contribute to differences in economic returns among treatments. All monetary values were converted to US$ at the 2020 average exchange rate (US$ 1.0 = Ethiopian Birr (ETB) 34.95). Benefit/cost ratio was calculated by dividing gross income by total variable costs. A benefit/cost ratio >1 indicates a treatment whose benefits outweigh the costs, making the treatment a viable option for on-farm forage production, while those < 1 denote a treatment whose costs exceed the benefits hence, adopting the treatment would not be a worthwhile option (i.e. not cost effective) (Kebede et al., 2024).

Statistical Analysis

One-way ANOVA using the GLM procedure of IBM SPSS Statistics (version 22) was used to determine the fixed effects of treatments on forage mass production (herbage yield of the main crop), net returns and production costs, and benefit/cost ratio. Although we were interested on the main factor (i.e. the treatment), blocks (treated as a fixed effect; Dixon, 2016) were kept in the model (Dean and Voss, 1999; Frey et al., 2024). Means among treatments were compared using the least significant difference (LSD) test at $p<0.05$. The data from this study is deposited in the Mendeley Data repository (Nasir et al., 2025).

Table 1. Variable costs of production and field price of desho green fodder (US$) used in the economic analysis

Items		Unit	Field price unit^{-1}	Sole desho		Desho + alfalfa		Desho + GD	
				Quantity	Amount (US$)	Quantity	Amount (US$)	Quantity	Amount (US$)
Purchased inputs									
Alfalfa seed		kg ha^{-1}	7.44	–	–	15.00	111.59	–	–
GF seed		kg ha^{-1}	20.03	–	–	–	–	3.00	60.09
Desho rooted splits		plants ha^{-1}	0.04	29167	1030.04	17500	618.03	17500	618.03
Total input costs					1030.04		729.61		678.11
Labour input		Days ha^{-1}							
Planting[a]			1.61	19.07	30.70	11.44	18.42	11.44	18.42
Weeding	First[b]		1.5	17.67	26.51	12.40	18.60	16.00	24.00
	Second		1.5	16.14	24.21	16.14	24.21	13.35	20.03
Total labour costs					81.42		61.23		62.45
Total variable costs[c]					1111.46		790.84		740.56
Output									
Green fodder[d]		t ha^{-1}	920.18						

GD, Greenleaf desmodium. [a]Includes labour required to apply NPS. [b]Includes labour required to apply urea. [c]Costs that did not vary by treatment were excluded from this calculation. [D]The value of desho grass as green fodder (fresh forage) was used in the economic evaluation of tested treatments.

RESULTS

Produced Herbage Mass

Desho grass produced greater herbage yield (notably dry mass) under intercropping than in the corresponding pure stand (Figure 1). The highest fresh herbage yield was obtained when desho was intercropped with greenleaf desmodium (6.49 t ha−1), which was significantly higher than both the deso-alfalfa intercrop and the sole desho treatment ($p<0.05$). Although the difference between sole desho and desho-alfalfa intercrop was not significant ($p=0.67$), fresh herbage yield was slightly higher under intercropping than under sole desho (5.06 versus 4.0 t ha−1). Herbage dry matter yield was significantly higher in both desho-greenleaf desmodium/alfalfa intercrops compared with sole desho, with no significant difference between the two intercrops. Notably, intercropping desho with greenleaf desmodium increased fresh and dry herbage yields by 2.5 t ha−1 (~63 % increase) and 2.29 t ha−1 (64 % increase) respectively, relative to the sole desho (Figure1).

Economic Returns

Net return differed among treatments, with both intercropping systems generating significantly higher net returns than sole desho (Table 2). The, desho-greenleaf desmodium intercrop earned the highest net return compared to the sole desho (US$ 5219 versus US$ 2567 ha−1) and the desho–alfalfa intercrop (US$ 5219 versus US$ 3866 ha−1). In contrast, sole desho incurred significantly higher total variable costs (by US$ 321 to 354 ha−1), mainly due to greater labour requirements for planting and weeding and higher costs of planting materials (Table 1). Benefit/cost ratio differed among treatments with the highest significant value recorded for desho-greenleaf desmodium (6.9), whereas sole desho had the least ratio (2.3). Overall, the desho-greenleaf desmodium intercrop generated US$ 1353 more net return than the desho-alfalfa intercrop, indicating its potential as a promising option, in terms of both profitability and production costs, for further evaluation.

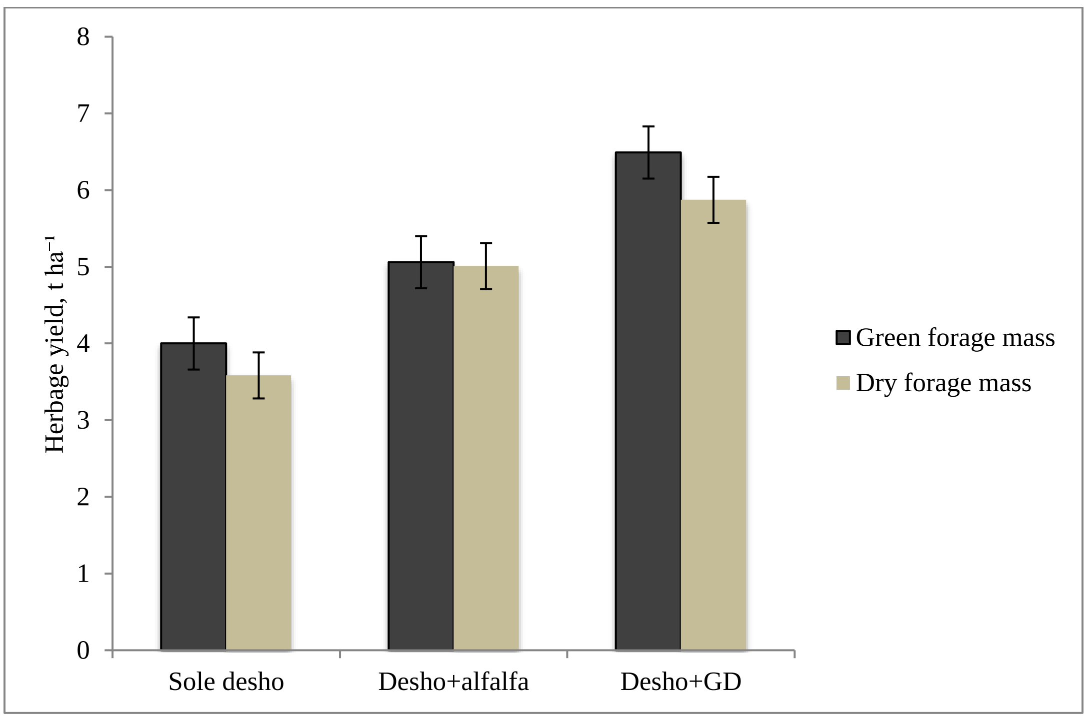

Figure 1. Forage mass production of desho grass grown in sole cropping and in desho-legume intercrops. Bars sharing same letter within each yield component are not significantly different at $p<0.05$. Bars represent standard error of the mean. GD, Greenleaf desmodium.

Table 2. Economic benefits of desho grass grown in sole cropping and in desho-legume intercrops

	Treatment			LSD (0.05)	p value
	Sole desho	Desho + alfalfa	Desho + GF		
Green forage mass, t ha−1*,†	4.00	5.06	6.49		
Gross income (GI), US$ ha−1	3678.81a	4656.97a	5976.18	1099.80	0.011
Total variable costs (TVC), US$ ha−1	1111.5	790.84a	757.32a	38.32	<0.001
Net return (GI- TVC)§	2567.35	3866.13	5218.86	1106.52	0.007
Benefit/cost ratio	2.31	4.89	6.89	1.47	0.002

*Adjusted yield. †See Figure1 for mean comparison. §Value of desho as green feed was used to estimate the net returns from the fodder. Values with a common letter within the same row are not significantly different at p<0.05. GD, Greenleaf desmodium

Land and Income Equivalent Ratios of Intercrops

The partial LER values of desho grass were markedly higher than 0.5 (Table 3), indicating that the herbage yield of the desho grass under intercropping exceeded half the yield obtained from the sole desho. Although differences in partial LER between treatments were not included in the objective of the study, important differences were found. Of the tested intercrop treatments, the desho-greenleaf desmodium intercrop had the highest LER (1.63) in comparison to desho-alfalfa (1.27) suggesting superior productivity per unit area when desho was grown in association with greenleaf desmodium.

A similar pattern was observed for the partial IER (Table 3). In all intercrop treatments, the partial IER values for desho were exceeded 0.5, further confirming the economic advantage of desho-legume intercropping (Table 2). The highest partial IER value for desho was obtained from the desho-greenleaf desmodium intercropping, indicating its greater economic efficiency relative to the desho–alfalfa combination.

Table 3. Partial land and income equivalent ratios of desho grass intercropped with alfalfa or greenleaf desmodium.

Treatment	Partial LER (desho)	Partial IER (desho)
Desho + alfalfa	1.27	1.27
Desho + GD	1.63	1.63

GD, Greenleaf desmodium

DISCUSSION

Forage Production and Economic Benefits of Desho-Legume Intercropping

Despite the lower net area devoted to the crop under intercropping, desho grass in intercrops was generally more productive and profitable than in the corresponding pure stand. Among the intercrop treatments, desho-greenleaf desmodium improved desho fresh herbage and dry matter yields by 63% and 64% respectively compared with the sole crop. Thus, there is a potential to intensify desho grass forage production in the study location. The lowest forage mass production (dry mass, for example) recorded in the present study, 5.05 t ha−1 in deso-alfalfa intercrop (cf. Figure 1), was higher than yields reported for desho-vetch intercrops under comparable agro-ecological conditions in Ethiopia, where desho produced only 2.29–3.58 t ha−1 of dry matter (Abera et al., 2021). This suggests that that the selected legume species evaluated in the present study are generally compatible with the desho grass. Nonetheless, of the tested options, desho-greenleaf desmodium emerged as the most promising intercrop and warrants further evaluation. The suitability of greenleaf desmodium for integration with native grasses for improved forage production under east African highlands conditions has been acknowledged in previous studies (Mwangi et al., 2004; Jørgensen et al., 2023). The better herbage yields obtained under intercropping are likely attributed to improved soil nitrogen availability resulting from biological fixation by the legumes (e.g., Jensen et al., 2020; Rao & Mathuva, 2000; Tow & Lazenby, 2001).

The higher net returns obtained under desho-legume intercropping systems indicate clear economic gain from legume inclusion. Reduced input costs compared to the conventional desho cropping system, together with increased herbage yields of desho in the intercrops contributed to the improved net returns. In contrast, lower net returns from sole desho resulted from relatively low herbage yields and higher production costs (cf. Table 2), making this system economically less attractive. Consequently farmers could benefit more from intercropping desho with legumes, especially greenleaf desmodium. The desho-greenleaf desmodium treatment increased net returns by 103% over the sole desho. Similarly, the benefit/cost ratio, an indicator of the economic efficiency, was highest for the desho-greenleaf desmodium treatment, confirming its superior profitability.

Effect of Legume Inclusion on Land and Income Equivalent Ratios

The partial LER of desho exceeded 0.5 in both desho-alfalfa and desho-greenleaf desmodium intercrops, suggesting that there was an advantage for the desho in the intercropping (Pelzer et al., 2014). The higher partial LER values observedunder the intercrops indicate that the inclusion of legume in the sole desho system favored faster crop establishment and early plant growth and plant vigor as reflected by early biomass production of the intercropped grass. Although comparable data for direct comparison are lacking, extensive evidence from cereal-legume intercropping evaluation, higher partial LER values observed in the present study were presumably due to a positive effect of legumes on the companion grass. These effects may include reduced interspecific competition and weed pressure, as well as improved nitrogen availability (Chen et al., 2004; Kermah et al., 2017; Gitari et al., 2020; Xu et al., 2020). The highest partial LER value of 1.63 was obtained in the desho-greenleaf desmodium intercrop (cf. Table 3). Similarly, the higher partial IER values recorded for desho in both intercrop treatments were an indication of economic gain with legume integration, probably due to the positive effect of legumes on desho when grown in association. A partial IER >0.5 implies that intercropping resulted in greater economic efficiency compared with sole cropping. This larger partial IER of the grass might also mean that the intercropped desho benefited from a legume inclusion (Dzvene et al., 2022). Among the tested intercrops, desho-greenleaf desmodium was the most remunerative with a higher IER value (1.63) compared with the other intercrop treatment.

CONCLUSIONS

Intercropping desho grass with legumes provides a viable alternative to sole desho cropping. Irrespective of legume species, desho grown in intercrops produced higher forage mass and achieved superior net returns compared with sole cropping. The observation that partial LER and IER values of desho were higher in intercrops showed that there can also be advantages to desho in intercropping. Among the tested treatments, the desho-greenleaf desmodium intercrop was particularly promising due to its higher herbage yields, improved net returns, and reduced production costs. However, the findings are based on a single-season experiment, which is a limitation of the present study. Future research should therefore validate the agronomic and economic performance of this promising intercrop under farmers' conditions prior to wider recommendation and adoption.

DECLARATION OF FUNDING

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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APPENDIX

Appendix A. Results of Focus Group Interview and Preliminary Field Observation

To elucidate aspects of the local farming system, problems and potential solutions related to livestock feed resources, we conducted field observations and focus group discussion with key informants in three purposively selected *kebeles* (the smallest administrative unit in Ethiopia) of the district where desho grass (*Pennisetum glaucifolium*) cultivation is prevalent. The state of desho production, its role within the farm feedbase and the problems faced in growing the crop were also discussed with the participants. These activities were held prior to the field experimentation. The three *kebeles* were selected because significant number of farmers inhabiting in these *kebeles* were engaged in on-farm desho cultivation. Group interviews with local key informants involved model farmers, *kebele* administrators and extension officers (in charge of forage and livestock production) as well as district livestock extension staffs. General data such as average family size, livestock and number and area of farm fields were obtained from official statistics from the *kebele* level extension offices. The following report analyses the results of this preliminary study.

The Farm and Farming System Characteristics

Cereal-based mixed crop-livestock (mostly cattle) farming system is the dominant economic activity in the district. Farmers cultivate maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), teff (*Eragrostis tef (Zucc.)*), and pulses such as haricot beans (*Phaseolus vulgaris* L.) and chickpea (*Cicer arietinum*). Most farmers in the study area owned about 2 ha of land and 6 tropical livestock units (TLU; equal to 250 kg of body weight). The average family size was 6 people per household. Most households had two land holdings, a homestead plot with a small cropped area, and a larger contiguous cropped area located away from the farmhouse. According to the interview participants and our field observations, the homestead fields were mainly used for growing desho grass and some perennial crops and timber trees while the grain crops were planted in the main crop field. Natural pasture and crop residues together with cultivated grasses (primarily desho grass) provide the bulk of feed for livestock. Feed is the main limiting resource for livestock production in the area, mentioned by all interview participants. They also mentioned that intra-year variability in feed supply is common in the area. However, based on our field observations and informal interviews with the extension officers, there is a possibly to improve forage availability through intensification of desho grass production.

Current State of Desho Grass Production and Factors Limiting its Production and Use

The district can be considered one of the areas where cultivated forage grass is widely practiced in Ethiopia. During the study year (i.e., 2020), for example, about one-third of the farm households in the district cultivated desho grass on-farm (not published data). This figure is large compared to the national average of less than 1% (CSA, 2017). Desho grass production in the area was largely rain-fed. The grass is one of the most important sources of fodder, planted on homestead fields (though the specific cropping pattern varies among farmers) and is also a cash crop for some farmers who sell the fodder to other farmers during periods of shortage. Most farmers grew desho in monocultures (Figure A1b) while few farmers planted in between rows of perennial crops such as *chat* (*Catha edulis*), Banana and timber trees (Figure A1a). As mentioned above, desho is grown for livestock feed and is harvested as greenchop. Greenchop is cut directly from the field and is fed immediately to animals or sold to other farmers (during periods of shortage). Extension officers involved in the discussion unanimously indicated that, although the grass has the potential to provide stable forage supply and improve profitability for farmers, current yields on farmer fields are often poor. The low yields of desho were probably due to inadequate management of the crop and limited input use, among others. For example, weeding of desho grass was uncommon in the area, mainly attributed to lack of awareness and shortage of labor as revealed by all the interview participants. The field experiment was thus initiated to identify a cropping system that can increase yields of this native grass and simultaneously contribute to reduced input/labor costs linked to the conventional production system of the grass.

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Figure A1. Images of the conventional desho cultivation practices at Hulbareg, Ethiopia: (a) desho grown between rows of perennial crops and timber trees; (b) desho grown in pure stand. Photos: A. Nasir.

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Original Research Article||

Smallholder Farmers' Adaptation strategies to Climate change and Determinant Factors in Gedeo and West Guji Zones, Southern Ethiopia

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Abstract

Now a day climate change is becoming the global concern particularly in agricultural sector. The problem is even worse in subsistence agriculture. Due to the negative impact of climate change in agricultural sector farmers are practicing different climate change adaptation strategies to minimize the negative impact on agricultural production. The purpose of this study was to identify the most prevalent adaptation strategies used by farmers and determinants in southern Ethiopia. Data was collected from 386 households using structured and semi-structured questionnaires. Descriptive statistics and Multinomial logit equation model were employed to identify types of adaptation options prioritized by the local community, to examine factors that influence the choice of farmers to employ adaptation options to climate change and to provide suitable policy implications on adaptation options to climate change. The result showed that different districts had different strategies for adapting to climate change. Therefore, the most important adaptation strategies in Abaya district were soil and water conservation, tree planting, and grain storage; in Bule district the most important adaptation strategies were soil and water conservation, tree planting, and agroforestry practices; and in Dilla-zuria farmers prioritized tree planting and enset planting. Farmers' decisions to implement climate change adaptation strategies have been influenced by determinants of climate change in both positive and negative ways. According to the results, policies and methods that promote farmers' involvement in the design and implementation of adaptation alternatives using a bottom-up approach are necessary for improved climate change anticipation rather than concentrating on minimizing the adverse impact. This can be accomplished by strengthening farmers' organizations for the purpose of exchanging experiences in order to increase public adaptation capacity, incorporating climate change training into educational policies, improving agricultural extension systems in light of climate change, and strengthening institutional capacity to produce climate information at the local level.

Key words: Adaptation strategies, Climate change, Gedeo zone, West Guji zone

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INTRODUCTION

Agriculture is one of the most vulnerable sectors to the growing risks of climate change (Ado et al., 2019; Alves et al., 2020; Getahun et al., 2021), placing pressure on global food supply networks (Gebru et al., 2020). Smallholder farmers are particularly vulnerable to the consequences of climate change, according to a number of studies (Berger et al., 2017; Mulwa et al., 2017; Fahad and Wang, 2018; Marie et al., 2020; Antwi-Agyei and Nyantakyi-Frimpong, 2021). The impact of climate change is greatest in developing nations because of their limited capacity for adaptation and lack of access to other revenue streams (Ali and Erenstein, 2017; Fahad and Jing, 2018).

Limiting the harm caused by climate change is a pressing challenge for the international community. Sub-Saharan Africa is expected to warm more than the rest of the world, and some parts of the region will get less rainfall (Niang et al., 2014). According to a growing amount of data, extreme events such as droughts and floods have occurred often (Dasgupta et al., 2014). These affect smallholder farmers in developing countries, whose primary source of income is rain-fed agriculture (Pachauri et al., 2014).

Ethiopia is among the poor countries most vulnerable to the consequences of climate change, according to Paul et al. (2018). Ethiopia's vulnerability is exacerbated by its heavy reliance on rain-fed agriculture (Paul et al., 2018). Rainfall patterns have a direct impact on this industry's success (Gebru et al., 2020). Food shortages and, in the worst situations, famines are brought on by changes in seasonal patterns or inadequate rainfall. Climate change-related disasters, such as droughts, floods, and erratic rainfall, have made the country's need for food aid more urgent. To reduce the possible effects of climatic variability and change, farming communities should adapt on their own (Khan et al., 2021). Several common Adaptation strategies have been identified in the literature, including the use of drought-resistant crop varieties (Anik et al., 2021; Marie et al., 2020; Ponce, 2020; Bedeke et al., 2019; Kebede et al., 2019), crop diversification (Antwi-Agyei et al., 2021; Asfaw et al., 2018; Simotwo et al., 2018); crop rotation (Mairura et al., 2021); use of irrigation technologies (Antwi-Agyei et al., 2021; Ureta et al., 2020); and modifying planting dates (Ponce, 2020, Jamshidi et al., 2019; Masud et al., 2017). Policymakers may learn a lot by evaluating how farming communities are coping with the effects of climate change. Furthermore, evaluating the elements that affect the household's adaptation strategy selection is essential to reducing the effects of climate change (Bedeke et al., 2019).

According to a number of studies, farmers encounter different adaptation strategies based on the size and type of their farm s, the climate, and additional contexts such as ecological, cultural, local, political, institutional, and socioeconomic factors (Gemeda et al., 2023; Getahun et al., 2021; Hirpha et al., 2020; Mihiretu et al., 2019; Alemayehu & Bewket, 2017; Tofu, 2016). Additionally, research was done on the factors that influence farmers in various regions of Ethiopia to adopt climate change and variability adaptation strategies (Kemal et al., 2022; Adego & Woldie, 2022; Eshetu et al., 2021; Regasa & Akirso; Gebru, et al., 2020).

Although numerous studies have been conducted to identify the climate change adaptation strategies used by Ethiopian farmers, there are relatively few area-specific studies that concentrate on these strategies, and the factors influencing the adoption of climate change adaptation mechanisms are scarce in southern Ethiopia (Saguye, 2016). In the study area there are few researches has been done in the subject area. As a result, research on adoption factors and climate change adaptation is needed in the field. Understanding climate change adaption techniques may be crucial in swaying decision-makers. Therefore, the objective of this study was to determine the most significant climate change adaptation strategies used by smallholder farmers and to identify determinant factors.

METHODOLOGY

Description of the Study Area

The study was conducted in Abaya district of West Guji Zone and Dilla-zuria and Bule districts of Gedeo zone, southern Ethiopia. The Dilla-zuria district lies between latitudes 6º15′05″ N and 6º26′35″ N and longitudes 38º15′55″ and 38º24′02″ E. The district's slope ranges from 39.4% to 51.5% and its altitudinal range is between 1350 and 2550 meters. The monthly rainfall is between 83.7 and 310 mm, with an average rainfall of 172.9 mm. It has bimodal rainfall between March and June and September and October, with the largest rainfall between May and September and the lowest between October and February. The average monthly temperature is between 15.4°C and 17.9°C. Agriculture, agroforestry, trade, handicrafts, temporary jobs in coffee processing, and labor work are the main sources of income.

Bule district is located between latitudes 60 04' 16" and 60 23' 50" North and 38° 16' 20" and 38° 26' 11" East longitudes. The Bule district experiences an average annual temperature of 15.1°C to 22.5°C and an average annual rainfall of 1,200–1,800 mm. Bule district has 65% highland (Dega) and 35% mid-highland (Woina Dega) agro-ecology. There are two distinct wet seasons in the district: the long rainy season, which runs from July to December, and the short rainy season, which runs from March to May. Rain-fed annual crop production, which includes barley, wheat, maize, and pulse crops like beans and peas, dominates the district's main land use types. Coffee, enset, bamboo, apples, and other tree species including Aningeria attissima (Kerero), Erythrina Abbyssnica (Korch), Cordia africana (Wanza), Millettica ferruginea (Birbira), and Eucalyptus (especially Eucalyptus globules) are the common ones.

Abaya is situated in latitude 6°14′N and longitude 30°10′E. The district lies between 1200 and 2060 meters above sea level. The average annual temperature ranges from 16°C to 28°C, and the average annual rainfall is 1223 mm. The district has two different agro-climatic conditions: lowland (70%) and midland (30%). A transitional land use type between the upstream and downstream areas reflects a sedentary agro-pastoral lifestyle. Maize, groundnuts, barley, "teff," sorghum, haricot beans, wheat, field peas, and faba beans were the main crops grown. Although coffee is a major source of income, enset is also grown in the area, which provides some food security during dry seasons.

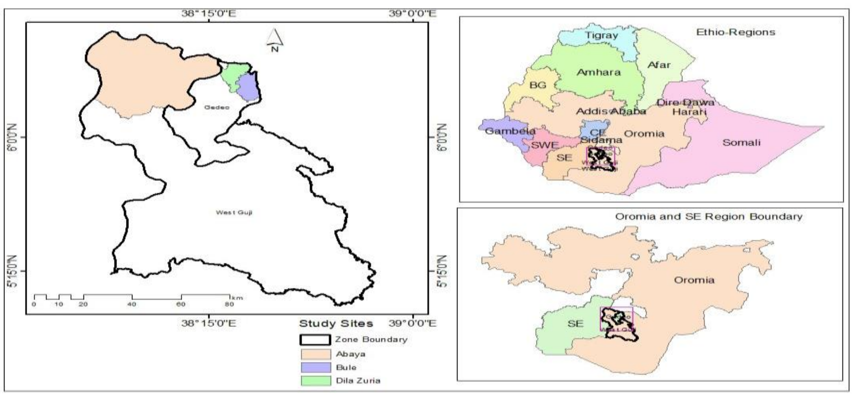

Figure 1. Map of study site

Sampling Techniques and Sample Size Determination

Sampling Techniques

A multi-stage sampling procedure was employed in the study to choose samples that fairly represented rural households in the study area. In order to select samples that accurately reflected rural homes in the study area, a multistage sampling approach was used. Three districts; Abaya, Dilla-zuria, and Bule were purposefully chosen to represent the low-land, mid-land, and highland agro-ecologies during the first phase. Highland agro-ecology was represented by Bule, midland by Dilla-zuria, and lowland by Abaya. Purposive sampling technique was used in the second stage to choose representative kebeles. Andida and Michile-sisota from Dilla-zuria district; Samaro and Bunata from Abaya district and Gubato and Ilalcha from Bule district were the selected kebeles. Three hundred seventy-six respondent households were selected at random on the third stage. The number of sample households in each kebele was allocated proportionately.

Data on household income, landholding, household adaptation measures to climate change, demography, and other household economic and socio-demographic information were collected. Respondent households were chosen at random for the third stage. Based on the number of households in each kebele, the 376 respondents that made up the overall sample size were allocated proportionately to each kebele. Systematic random sampling was used to assign the number of households in each kebele, which was received from the corresponding kebeles offices.

Sample Size Determination

To determine the required sample size, the formula developed by Yamane (1967) was applied at 95% confidence level.

$n= N/ (1+N (e)^2)$………………….. 1

Where: n is the required sample size for the research

N= population size

e = is level of precision (= 0.05)

As a result, 376 sample homes in all were chosen at random from a total of six kebeles, or in accordance with the population size of the kebeles that were chosen (Table 1).

Table 1. Distribution of sampled households

District	Kebele	Agro-ecology	Male headed HH	Female headed HH	Total HH	Sample HH
Abaya	Hasegola	Low-land	874	203	1077	65
	Samaro	Low-land	848	157	1005	60
Bule	Sika	High-land	522	63	585	35
	Suko	High-land	403	59	462	28
Dilla-zuria	Andida	Mid-land	1080	120	1200	72
	Sisota	Mid-land	1622	317	1939	116
Total			**5349**	**919**	**6268**	**376**

HH= household write the source

Data Type and Collection Methods

For this study, both quantitative and qualitative data were collected. Qualitative data was gathered at the community level through focus groups and key informant interviews. To collect information at the household level, a home survey was also conducted using structured questions. Three focus groups with 10 participants each were held with different groups of old aged farmers who had resided in each kebele for a considerable amount of time. The participants were selected from the kebele as per recommended by keble DAs and admiration. The researcher has developed checklist and translated to Amharic and in the Amharic version of the checklist was also translated to Gedeuffa (for Bule and Dilla zuria districts) and to Afaan oromo (for Abaya district). DAs has played facilitation role in conducting the survey and key FGD. Similar to this, key informant interviews were carried out with capable members of the community, including agricultural staff, government office officials, and senior farmers with a wealth of farming expertise for about an hour. The issue regarding climate change trend, impact of climate change on agriculture and common climate change adaptation strategies implemented by the farmers has been raised.

Method of Data Analysis

In this study, descriptive statistics including frequency, percentage, figures, and tables were used to summarize and illustrate socioeconomic and demographic data. In order to compare the differences across different agro-ecologies for various socioeconomic and demographic characteristics, the t test and Chi-square tests were also employed. The primary purpose of this test is to determine if the difference is statistically significant. The analysis was carried out using SPSS and STATA software.

Empirical Specification of the Model (MNL)

We tested the null hypothesis: independent variables have no impact on the choice of dependent variables (crop diversification, drought-resistant varieties, early maturing varieties, and soil and water conservation). Hence, farmers chose an adaptation strategy if the expected utility from it exceeded that of other adaptation strategies such that:

$$Yi = \begin{matrix} Yi \; if \; Vi > Vj \\ Yi \; if \leq Vj \end{matrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where, Yi represents the strategy type i, Yj an alternative strategy type j, Vi and Vj the corresponding expected indirect utility values of strategy type i and its alternative j, while Y* represents the strategy type chosen. Therefore, we can view farmers' decisions on the adaptation strategy within a random utility discrete choice model. This is particularly appropriate for modeling discrete choice decisions, such as between adaptation strategies, because it is an indirect utility function where an individual with specific characteristics associates an average utility level with each alternative adaptation strategy in a choice set. In this framework, the utility function is assumed to be known for each farmer, but some of its components are unobserved by the researcher. This unobserved part of the utility is treated as a random variable. For the i strategy decision, the expected indirect utility was then modeled as the sum of the observed variables and non-observed random component:

$Vi = \beta 1iXi+\varepsilon i$…………….. (3)

As in Eq. (1), we can write the choice utility of implementing any alternatives as follows:

$Vj = \beta 1jXj+\varepsilon j$……………… (4)

Where, β1i and β1j are vectors of parameters. Hence, farmers can decide simultaneously whether to choose one or more adaptation strategies conditional upon the vectors of explanatory variables XJ and XJ. In this approach; we can use a multivariate logit model to study the farmers' joint decisions to adaptation strategy. The empirical specification of the model takes the form:

$Y^*ij=Vi=\beta 1iXi+\varepsilon 1$………….. (6)

with j = 1, 2, 3, 4, 5

$Yi=1$ if $Yi^* >0$ and 0 otherwise….. (7)

where, Yi* is an unobservable latent variable denoting the probability of choosing j type of adaptation strategy, for i = 1 (Agroforestry), i = 2 (crop diversification), i = 3 (irrigation) i = 4 (improved variety) i = 5 (compost) i = 6 (Shifting cropping time) i = 7 (Migration) i = 8 (Grain storage) i = 9 (Enset) i = 10 (Soil and water conservation) i = 11 (Tree planting) i = 12 (Fertilizer). Thus, empirically the model can be specified as follows:

$YI1=\beta 1Xij1+\varepsilon i1$………… (8)

$YI2=\beta 2Xij2+\varepsilon i2$………… (9)

$YI3=\beta 3Xij3+\varepsilon i3$………….. (10)

$YI4=\beta 4Xij4+\varepsilon i$…………… (11)

$YI5=\beta 5Xij5+\varepsilon i5$……………….. (12)

$YI6=\beta 6Xij6+\varepsilon i6$ ………………. (13)

$YI7=\beta 7Xij7+\varepsilon i7$……………….. (14)

$YI8=\beta 8Xij8+\varepsilon i8$ ……………… (15)

$YI9=\beta 9Xij9+\varepsilon i9$ ……………… (16)

$YI10=\beta 10Xij10+\varepsilon i10$ ……….. (17)

$YI11=\beta 11Xij11+\varepsilon i11$…………… (18)

$YI11=\beta 12Xij11+\varepsilon i12$ …………… (19)

where, YI1 = 1, if a farmer chooses Agroforestry (0 other wise), YI2 = 1, if the farmer chooses crop diversification (0 otherwise), YI3 = 1, if the farmer chooses irrigation (0 otherwise), YI4 = 1 if the farmer chooses improved variety (0 otherwise), YI5 = 1 if the farmer chooses compost (0 otherwise), YI6 = 1 if the farmer chooses Shifting cropping time (0 otherwise), YI7 = 1 if the farmer chooses Migration (0 otherwise), YI8 = 1 if the farmer chooses Grain storage (0 otherwise), YI9 = 1 if the farmer chooses Enset (0 otherwise), YI10 = 1 if the farmer chooses Soil and water conservation (0 otherwise), YI11 = 1 if the farmer chooses Tree planting (0 otherwise), YI12 = 1 if the farmer chooses Fertilizer (0 otherwise); Xi = vector of factors influencing the choice of coping strategy (age, gender, Education, Land holding size, Farming experience, Income, Extension service and Altitude), βj = vector of unknown parameters (j = 1,2,3,4,5,6,7,8,9,10,11,12), and ε = is the error term.

RESULT AND DISCUSSION

Demographic and Socioeconomic Characteristics of Households

Most of the respondent in Abaya and Bule district had access to irrigation while only 28.3% of the respondents in Dilla-zuria district had access to irrigation. The result also showed that there was significant difference between districts in households' access to irrigation. This is may be due to the fact that Dillazuria district (the midland) is dominantly covered by perennial crop like coffee, fruit and enset while the lowland district (Abaya) is mainly covered by annual crop like teff and maize and Bule (the highland district) is mainly covered by annual crop like barely and Faba bean. Out of the total respondents, 96 %, 73.3% and 48.4% of the sampled household heads have an access to health service in their locality in Abaya, Dilla-zuria and Bule district respectively and there is significant difference between the districts in this regard. Regarding access to agricultural input, 97.6 %, 58.8% and 54.7% of the sampled household heads have an access in Abaya, Dilla-zuria and Bule district respectively and there is significant difference between the districts (Table 2).

Households' Adaptation Strategies

Farm households were asked regarding their main methods of adaptation to climatic variability and change. The findings were provided by smallholder farmers in the three districts that correspond to the agro-ecological zones of the lowlands, midlands, and highlands. Table 4 lists the twelve adaptation strategies that were found to be employed by the farmers in the research area. Agroforestry practices, crop diversification, irrigation, the use of better varieties, composting, harvesting water, changing cropping periods, fertilizer, grain storage, enset and soil conservation are some of these adaptation measures. The study's findings demonstrated that different districts employ different strategies for adapting to climate change. 95.3%, 90.6%, and 87.5% of the farmers who responded said that agroforestry, planting trees, and enset plants were the most prevalent adaptation practices used in the Bule district. As climate change adaptation measures, farmers in the Dilla-Zuria district plant trees, enset plants, and apply fertilizer to accelerate crop development. Of the total respondents, their percentages are 95.7%, 89.4%, and 88.3%, respectively. It was found that districts varied greatly in how they applied the following climate adaptation strategies. Agroforestry, fertilizer, irrigation, grain storage, enset plants, and mixed farming all had $P < 0.05$, $P < 0.01$, $P < 0.01$, and $P < 0.01$, respectively. This variation provides more proof that adaptation strategies are location-specific and differ from one locality to another (Dendir and Simane, 2021).

Determinants of Farmers' Choices of Adaptation Strategies to Climate Change

The factors influencing farmers' decisions to implement adaptation strategies against the effects of climate change were estimated using an MNL model. Although estimations do not accurately reflect the size of change or the probabilities, the MNL model's parameter estimates were utilized to indicate the direction of the independent variables' impact on the dependent (response) variable (Table 5). Probabilities and measures that are anticipated to change within the probabilities determine the marginal impacts of marginal probabilities. Specifically, adaption decisions are made by deviating from the mean in the independent variable (Greene, 2000). This study only interprets and discusses factors that were statistically significant at less than or equal to 10% probability levels.

Age of the Household Head

The study's findings indicated that while the age of the household head had a negative influence on the decision to implement irrigation, the use of improved crop varieties, composting, mixed farming, soil conservation and tree planting, and fertilizer application as climate change adaptation strategies, it had a positive influence on the decision to apply agroforestry practices and shifting cropping times (Table 5). In this sense, the decision to modify planting times and engage in agroforestry is favorably correlated with age. This indicates that the likelihood of agroforestry practice and crop time shifting increases by 23.7% and 8.8%, respectively, with the age of the household head. The indigenous expertise of the farmers in the research area may be the cause of the favorable influence of age on agroforestry adoption. The farmers in the study region are motivated to adopt agroforestry methods by indigenous knowledge and cultural beliefs, and older people are more inclined than younger people to accept these beliefs, according to a study by Getachew M. & Abiyot M (2017). In order to counteract the detrimental effects of climate change on agriculture, this study also discovered that age significantly and favorably correlated with changing the dates of planting. The rationale might be that farmers with more experience may be better able to evaluate the risks associated with investing in adaptation choices.

Table 2. Descriptive statistics of dummy variable on characteristics of the households

Dummy variable	District						P-value
	Abaya		Dilla zuria		Bule		
	N	%	N	%	N	%	
Irrigation (Yes)	66	52.8	53	28.3	35	54.7	.000
Credit access (Yes)	65	52.0	80	42.8	35	54.7	.143
Access to saving institutions (Yes)	64	51.2	78	41.7	34	53.1	.171
Access to extension service (Yes)	69	55.2	79	42.2	33	51.5	.057
Access to market (Yes)	125	100	187	100	64	100	1.00
Access to health service (Yes)	120	96.0	137	73.3	31	48.4	.000
Access to agricultural input (Yes)	122	97.6	110	58.8	35	54.7	.000

Table 3: Descriptive statistics of continues variable on characteristics of the households

Variable	District												P-value
	Abaya				Dilla zuria				Bule				
	Mean	S. dev.	Min.	Max.	Mean	S. dev.	Min.	Max.	Mean	S. dev.	Min.	Max.	
Age	52	11.75	32	75	55	11.10	32	75	53	9.046	38	70	.024
Education	4	3.64	0	12	4	3.35	0	12	4	3.743	0	12	.656
Family size	8	3.81	2	15	8	3.17	2.0	14.0	8	3.091	3	15	.416
Ratio	1.0	1.78	0	13	0.8	0.96	0	3.7	0.5	0.463	0	2.3	.032
Road distance	3.8	2.04	2	10	5	2.25	2	8	4	1.816	2	8	.000
Total Income	30008	54051	8000	600,000	38267	29516	5000	150000	34609	20993	20000	150000	.179
Land size	2.1	1.11	0.5	5.0	0.3	0.36	0.2	1.5	0.6	0.592	0.3	3	.000
No of livestock	15	13.66	0	50	1	1.05	0	6	1	1.07	0	5	.000

Table 4. Climate change adaptation strategies by district

Adaptation strategy	Abaya		Bule		Dilla-zuria		P-Value
	Yes		Yes		Yes		
	Frequency	%	Frequency	%	Frequency	%	
Agroforestry *	49	39.5	56	87.5	148	78.7	.017
Crop diversification	106	85.5	53	82.8	117	62.2	.853
Irrigation ***	65	52.4	20	31.2	69	36.7	.000
Improved variety	105	84.7	52	81.2	160	85.1	1.000
Compost	37	29.8	56	87.5	135	71.8	.092
Shifting cropping time	107	86.3	45	70.3	132	70.2	1.000
Fertilizer ***	106	85.5	46	71.9	166	88.3	.000
Grain storage **	116	93.5	16	25.0	1	0.5	.003
Enset ***	33	26.6	56	87.5	168	89.4	.000
Soil and water conservation	117	94.4	61	95.3	165	87.8	.999
Tree planting	117	94.4	58	90.6	180	95.7	1.000

***, **, * Significant at 1, 5, and 10% probability level, respectively

The results of the work of (Destaw & Fenta, 2021; Molla E. & Desta G., 2023) support the finding who observed that older agricultural households are better able to forecast crop production trends than younger ones. The application of compost, irrigation, improved crop varieties, soil conservation, and tree planting, on the other hand, are negatively correlated with age. In this regard, there is a negative correlation between age and the decision to utilize irrigation, better crop varieties, compost, mixed farming, soil conservation, and tree planting. The results show that the likelihood of applying irrigation, using an improved crop variety, applying compost, mixed farming, planting trees for soil conservation, and applying fertilizer decreases with increasing household age by 21.7%, 5.1%, 17.4%, 6.9%, 5.8%, and 8.1%, respectively. The likelihood of employing irrigation decreases with age, maybe because farmers become less likely to engage in labor-intensive tasks like irrigation agriculture as they get older. The findings of this study are in agreement with the findings of a study by Gemeda, D. O., & Garedew, W. (2023). In other words, younger farmers are more likely than older farmers to employ enhanced crop varieties, as the likelihood of doing so decreases with household age.

In contrast to older farmers, younger farmers are more interested in managing risk and are more flexible in their decision-making process. They also seek information and support from governmental and non-governmental organizations and are less inclined to stick to older local varieties. This finding is consistent with Obayelu et al. (2014), who concur that younger farmers are more likely to seek out new information and technologies. However, it contradicts the findings of Gebre et al. (2015) and Ayalnesh B. (2020), who discovered that the likelihood of utilizing an improved variety rises as household age increases. The labor-intensive nature of the composite preparation activity may be the cause of the 17.4% decline in farmers' likelihood of using composite application as a climate change adaptation technique, as indicated in table 6. Older farmers may not be able to perform this task due to its labor-intensive nature. The findings also indicate that farmers were less likely to use soil conservation techniques as adaptation strategies as they became older. This suggests that elderly farmers are less likely than younger farmers to adopt adaptation strategies for soil and water conservation. Therefore, when it comes to using soil and water conservation techniques, younger households are more proactive than older ones. Because it takes more work to conserve soil and water.

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Table 5. Parameter estimates of multinomial logit model for climate change adaptation decision

Adaptation	Age	Gender	Education	Land holding size	Farm experience	Income	Extension service	Altitude
Agroforestry	1.718*** (0.000)	3.293*** (0.000)	0.087 (0.483)	-0.609*** (0.000)	0.484* (0.006)	2.572** (0.001)	-1.454* (0.034)	0.306 (0.312)
Crop diversification	-1.898*** (0.000)	-.314 (.604)	.852*** (.000)	-.356* (.021)	-.183 (.368)	-.469 (.349)	1.371* (.034)	.253 (.422)
Irrigation	-1.521*** (.000)	1.915** (.003)	.450** (.001)	-.139 (.327)	.270 (.161)	17.76*** (.000)	2.342** (.001)	-1.637*** (.000)
Improved variety	-.411* (.022)	.987 (.053)	.268 (.046)	.478** (.002)	-.259 (.190)	.570 (.386)	2.134*** (.000)	.661* (.031)
Compost	-1.459*** (.000)	-.050 (.930)	.334* (.012)	.431* (.005)	-.351 (.095)	4.633*** (.000)	1.877** (.001)	1.690*** (.000)
Shifting cropping time	.477** (.004)	.820 (.108)	-.135 (.271)	.207 (.101)	1.338** * (.000)	-.143 (.765)**	1.047* (.035)	-.563* (.021)
Grain storage	.457 (.060)	-.390 (.589)	-.078 (.685)	.336 (.075)	-.007 (.975)	.351 (.546)	-.151 (.833)	-5.845*** (.000)
Enset	-.435 (.241)	.184 (.846)	-.078 (.685)	-.230 (.303)	.189 (.582)	.675 (.280)	-.167 (.850)	32.213 (.989)
Soil and water conservation	-1.970*** (.000)	3.826** (.001)	1.141** (.001)	-.644 (.075)	.385 (.403)	-.588 (.557)	-.009 (.995)	-.145 (.832)
Tree planting	-1.470*** (.000)	-17.188 (.998)	.003 (.992)	.391 (.139)	.060 (.884)	.343 (.741)	1.823* (.019)	.459 (.405)
Fertilizer	-.803*** (0.000)	-.469 (.565)	.277 (.057)	.386* (.022)	.465* (.024)	.032 (.951)	1.649* (.002)	.176 (.057)

***, **, * Significant at 1, 5, and 10% probability level, respectively

The findings concur with those of Atinkut & Mebrat (2016), Esubalew & Getnet (2023), and Obayelu et al. (2014), who pointed out that younger households are more likely than older ones to implement adaptation strategies for soil and water conservation. The outcome, however, runs counter to the findings of Gebre et al. (2015) and Ayalnesh B. (2020), who discovered that the likelihood of using soil conservation practices as a strategy for adapting to climate change rises as household age increases. Tree planting is a labor-intensive activity, which may be the reason why farmers are less likely to plant trees as a climate change adaptation strategy as they get older. However, several research findings contradict the results of this study. Research by Ayalnesh B. (2020), Oo et al. (2017), and Belay et al. (2017) has demonstrated that the likelihood of a home planting trees increases with the age of the household head.

Sex of the Household Head

Table 5's findings indicate that, in comparison to the base category, the likelihood of adopting agroforestry practices, irrigation, and soil conservation as adaptation methods was considerably higher for households led by men. According to the findings, the likelihood of implementing agroforestry, irrigation, and soil and water conservation as climate change adaptation techniques increased by 45.6%, 25.6%, and 12%, respectively, for households led by men (Table 6). Male-headed households were more likely than female-headed households to practice adaptive methods, as predicted. Male-headed households may have greater access to technologies and climate change information than female-headed households, according to a study by Deressa et al. (2008) that examined farmers' choices of climate change adaptation strategies in another region of Ethiopia. They were therefore better equipped than the female-headed ones to employ a variety of adaptation techniques (Demetriades & Esplen, 2010). This outcome is consistent with the findings of Abayineh and Belay (2017) and Ayalnesh B. (2020). On the other hand, Wondimagegn and Lemma (2016) argued that women engaged in a greater number of agricultural tasks and gained more knowledge and expertise in a variety of adaptation techniques.

Educational status of the household

The findings in Table 5 demonstrate that farmers' adoption of crop diversification, irrigation, composting, soil and water conservation, and fertilizer application as climate change adaptation techniques are all significantly improved by education. According to Table 6's marginal effect, the likelihood of implementing crop diversification, irrigation, composting, soil and water conservation, and fertilizer application practices as climate change adaptation strategies could rise by 11%, 6.6%, 4.3%, 4.7%, and 3.7%, respectively, with higher educational attainment. Because they are aware of the potential advantages of the suggested climate change adaptation measures, educated farmers are expected to embrace new technologies (Hassan & Nhemachena, 2008). The findings indicate that households with higher levels of education are more likely than those with lower levels of education to adopt irrigation technology as a method for adapting to climate change. According to Gebre et al. (2015) and Khan et al. (2021), education is one of the socioeconomic elements that affect adaptation strategy at the farm level. The findings also showed that farmers are more likely to use crop diversity as a climate change adaptation strategy as their educational attainment rises. The findings of the study by Fadina and Barjolle (2018) corroborated this conclusion. The findings indicate that the likelihood of using soil and water conservation measures as a strategy for adapting to climate change increases as educational attainment rises. This result was also supported by Tagel and Veen (2013).

Landholding Size

The uses of improved variety, compost and fertilizer application are positively and significantly correlated with landholding size. Nonetheless, it has a strong negative correlation with crop diversification and agroforestry practices. According to Table 6, the likelihood of adopting better varieties, grain storage movement, and fertilizer application as climate change adaptation strategies increases by 5.8%, 5.4%, 3%, and 4.8%, respectively, with an increase in landholding. Additionally, as landholding size increased, the likelihood of using enset plants, crop diversification, and agroforestry as climate change adaptation decreased by 11.1%, 4.6%, and 5%, respectively, according to the same data. According to Abdi et al. (2015), there is a favorable correlation between the size of a landholding and the utilization of better crop varieties as adaptation strategies. Because it requires significant expenditure, there may be a negative correlation between the amount of land holdings and the use of climate change adaptation measures. According to a 2017 study by Abayineh and Belay, farmers who own a lot of land are more inclined to take on the risk of climate change or use adaption strategies that may require significant financial outlays. They have a big plot, which allows them the confidence to not worry about adaptation strategies to lessen the effects of climate change.

Farm Experience

The findings in Table 5 demonstrated that adjusting cropping times as a method for adapting to climate change is positively impacted by Farm experience. This is because a farmer's knowledge of the detrimental impacts of climate change on agriculture in the past is supported by their experience on the field. This is due to the presumption that more seasoned farmers are more knowledgeable about weather data and how it affects farming methods. Compared to farmers with less agricultural expertise, farmers with more years of experience are more likely to apply fertilizer and modify cropping times as climate change adaptation strategies by 5.3% and 7.7%, respectively. This finding is consistent with Hossain et al. (2022) and Tanti et al. (2022) and suggests that more seasoned farmers possess information and expertise about climate change than less seasoned ones. In addition to suggesting that more seasoned farms typically have more knowledge of crop varieties, crop rotation, and farmers' decisions to either increase or decrease farm cultivated area in order to survive farming in the face of climate change, the findings also conclude that farmers with more agricultural practices have a greater chance of implementing adaptation strategies. According to a study by Amare et al. (2018), the likelihood of implementing better farming methods rises with farm experience.

Income

The study's findings showed that, income significantly influences the use of agroforestry, irrigation, and composite applications as strategies for adapting to climate change. According to Table 6's marginal effect result, a rise in household income can raise the probability of using irrigation, agroforestry, and composite applications as strategies for adapting to climate change by 43.9%, 45%, and 41.8%, respectively. This suggests that farmers with higher incomes are more likely than those with lower incomes to implement climate change adaptation strategies. This is due to the fact that farmers who earn more money may buy more agricultural inputs. This makes it easier for individuals to get over financial obstacles and better adapt to the effects of climate change. The work of Marie et al. (2020), which found that wealth significantly positively influenced households' adaption tactics, supports this finding. It does, however, run counter to the findings of Feleke et al. (2016), who found that households' adaption tactics were significantly impacted negatively by income.

Extension Service

Farmers' decisions to adopt crop diversification, irrigation, improved variety compost application, tree planting, and fertilizer application as climate change adaptation strategies were positively and significantly impacted by the frequency of extension visits, while farmers' decisions to engage in agroforestry as a climate change adaptation strategy were negatively impacted. In comparison to farmers without access to extension services, Table 6 shows that farmers who have contact with extension agents are more likely to use crop diversification, irrigation, improved variety compost application, tree planting, and fertilizer application by 23.1%, 32%, 25.8, 23.4, 26.1%, 9.7%, and 20%, respectively. However, the likelihood of using agroforestry as a climate change adaptation method drops by 34.1% as extension contact increases. A farmer with more extension contact will be better able to comprehend the negative effects of climate change on their farming activities as well as how to counteract these effects. This is implied by the positive effect of extension contact in adopting climate change adaptation strategies. Numerous authors endorsed the study's findings. This outcome is in line with the findings of Stefanović (2015) regarding tree planting, Nhemachena et al. (2014) regarding irrigation, Abrahm et al. (2017) regarding crop diversity, and Atube et al. (2021) with the use of better crop varieties.

According to research by Alemayehu & Bewket (2017), Asrat & Simane (2018), Ahmed et al. (2016), Belay et al. (2017), and Molla et al. (2023), farmers' adoption of climate change adaptation measures is significantly aided by extension access. However, this finding deviates from previous research by Wondimagegn and Lemma (2016) who shown that extension contacts on crop cultivation might be more focused on profitability and less on climate change risk adaption strategies.

Altitude

The agro-ecology of the study area is represented in this study by the variation in altitude gradients. According to the study's findings, households in various agro-ecologies employ various climate adaptation strategies because of variations in soil types, farming methods, slope, and climate. The findings in Table 5 showed that, using composite applications as a method for climate change adaptation is positively impacted by an increase in attitude gradient or by living in a highland area. As a climate change adaptation method, it has detrimental effects on off-season grain storage and irrigation application.

Table 6 Marginal effect due to independent variables

Adaptation	Age	sex	Education	Land holding size	Farm experience	Income	Extension service	Altitude
Agroforestry	0.237***	0.456***	-0.003	-0.111***	0.040	0.439**	-0.341***	-0.016
	(0.000)	(0.000)	(0.850)	(0.000)	(0.083)	(0.000)	(0.000)	(0.690)
Crop	-0.215***	-0.021	0.110***	-0.046**	0.000	-0.008	0.231**	0.008
diversification	(0.000)	(0.773)	(0.000)	(0.005)	(1.000)	(0.878)	(0.001)	(0.826)
Irrigation	-0.217***	0.256 **	0.066***	-0.012	0.047	0.450***	0.320	-0.228***
	(0.000)	(0.003)	(0.000)	(0.515)	(0.058)	(0.000)	(0.000)	(0.000)
Improved	-0.051*	0.149	0.023	0.058**	-0.057	0.002	0.258***	0.069
variety	(0.025)	(0.029)	(0.189)	(0.002)	(0.029)	(0.976)	(0.000)	(0.077)
Compost	-0.174***	0.020	0.041*	0.033	-0.056	0.418*	0.234**	0.155***
	(0.000)	(0.788)	(0.013)	(0.072)	(0.033)	(0.000)	(0.001)	(0.000)
Shifting	0.088**	0.143	-0.006	0.052	0.070***	0.077	0.261**	-0.082
cropping time	(0.002)	(0.125)	(0.758)	(0.016)	(0.000)	(0.377)	(0.002)	(0.053)
Grain storage	0.021	-0.034	0.004	0.054***	0.025	0.083	0.040	-0.329***
	(0.284)	(0.569)	(0.791)	(0.000)	(0.209)	(0.046)	(0.455)	(0.000)
Enset	-0.007	0.063	-0.014	-0.050***	-0.004	-0.021	-0.066	0.278***
	(0.729)	(0.279)	(0.229)	(0.000)	(0.846)	(0.577)	(0.165)	(0.000)
Soil and water	-0.069***	0.120***	0.047***	-0.009	0.016	-0.012	0.034	0.014
conservation	(0.000)	(0.000)	(0.000)	(0.472)	(0.271)	(0.723)	(0.406)	(0.534)
Tree planting	-0.058***	-0.084	0.008	0.029*	0.004	0.045	0.097**	0.042
	(0.000)	(0.390)	(0.443)	(0.012)	(0.799)	(0.363)	(0.002)	(0.059)
Fertilizer	-0.081***	-0.055	0.037*	0.048*	0.053*	0.012	0.200***	0.021
	(0.000)	(0.538)	(0.019)	(0.011)	(0.016)	(0.839)	(0.000)	(0.540)

***, **, * Significant at 1, 5, and 10% probability level, respectively

As altitude gradient increases, the likelihood of applying composite and planting enset crops as climate change adaptation increases by 15.5% and 27.8%, respectively, according to table 6's marginal effect of the variable. However, the likelihood of using irrigation, moving to a different location, and storing grain for the off-season decreases by 28.8%, 34.6%, and 32.9%, respectively. As stated in the study area description section of this work, the community in the lowland area is mostly agro-pastoralist, and the area is known for producing livestock by planting cereals like maize, which may be the cause for irrigation in the lowland altitude of the study area. These kebeles experience droughts more frequently than the highland portion of the research, and farmers there frequently stockpile grain out of concern about the upcoming season's climate shift. In contrast, farmers in higher altitudes are known to plant enset plants to stop soil erosion and mitigate the harmful effects of climate change. The research area's highland region is characterized by a steep slope that is prone to soil erosion. Farmers in the region frequently use enset plants to stop soil erosion, especially during unpredictable rainstorms. Highland farmers are also known for using composites to preserve soil and moisture. The study's findings generally demonstrated that farmers in various agro-ecologies employ various methods for adapting to climate change. The usage of various climate change adaptation measures differs by agrological zone, as verified by the work of Atinkut & Mebrat (2016) and Legese et al., (2013).

CONCLUSIONS

This study provides an extensive analysis of climate variability adaptation strategies employed by smallholder farmers across three agro-ecological zones in southern Ethiopia. The findings reveal that farmers adopt a range of strategies, including Agroforestry, crop diversification, irrigation, improved variety, compost, shifting cropping time, Migration, Grain storage, Enset, Soil and water conservation, Tree planting Fertilizer and often combining them to enhance effectiveness. These choices are influenced by factors such; Age of household, sex of household, educational status, land holding size, farm experience, income of the household, access to extension service and altitude. This study highlights that successful climate adaptation depends on prioritizing farmers' needs, as top-down policies often overlook crucial factors like market demand and cultural preferences. This sentiment underscores the critical need for participatory and context-sensitive approaches in adaptation planning to enhance policy effectiveness and enhance success in combating adverse impact of climate change on small holders' livelihood. The findings of this study provide a roadmap for designing inclusive, context-specific policies that address the multifaceted challenges of climate adaptation, ultimately supporting the broader goals of food security and climate resilience.

RECOMMENDATIONS

From the research we can recommend that area specific adaptation measures are critical, as agro-ecological conditions and socio-economic factors significantly affects farmers' decisions. Policies should prioritize gender-sensitive approaches to ensure female-headed households have equal access to resources and decision-making opportunities.

Various socioeconomic and demographic factors in the research area influenced farmers' decisions to select effective adaptation techniques. It is imperative that policymakers in the agriculture sector give adequate consideration to interventions that increase access to adult education, extension services, training for female farmers, and information on climate change adaptation strategies. In order to complement existing adaptation activities and give farmers up-to-date knowledge on climate change, development agents will expand their interactions with farmers. To improve farmers' ability to adapt to climate-related extremes, this would be crucial. It is recommended that studies on the gender-specific effects of climate change be carried out in order to provide inclusive and efficient solutions. By implementing these recommendations, policymakers and development practitioners can strengthen smallholder farmers' adaptive capacity and resilience to climate variability. This, in turn, will contribute to sustainable agricultural development and improved livelihoods in vulnerable regions like southern Ethiopia.

AUTHOR CONTRIBUTIONS

T.F.B conceptualized the study; collected the data; entered the data, analyzed and interpreted the data, and drafted the manuscript; Z.M and G.H. Conceptualization, data analysis, critically reviewed and approved the final version of the manuscript.

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The authors declare no competing interests.

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Original Research Article||

Assessment of Genetic Variability, Heritability, and Genetic Advance in Sugarcane (Saccharum spp.L) Genotypes, at Kessem and Metahara Sugar Estates, Ethiopia

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Abstract

The presences of genetic variation in the germplasm provide a better opportunity for trait enhancement through selection. The study aimed to assess the extent of genetic variability, heritability, and genetic advance for sixteen agro-morphological traits and to identify promising genotypes for future sugarcane breeding programs. A total of 187 sugarcane genotypes were evaluated at Kessem and Metahara Sugar Estates in Ethiopia, using an alpha-lattice design with two replications. The analysis of variance (ANOVA) revealed highly significant variation ($p<0.001$) among the genotypes for all measured traits, indicating that the genotypes are genetically diverse.The estimates of genetic variability, heritability, and genetic advance indicated the presence of notable genetic diversity in sugarcane genotypes and the extent of selection response for these traits in the population to develop superior genotypes for sugarcane improvement. Several traits had high to moderately high broad-sense heritability (h^2_β) and moderate genetic advance as a percent of mean (GAM): number of sprouted buds (h^2_β = 63.55; GAM = 19.00), number of tillers (h^2_β = 75.80; GAM = 14.55), cane yield (h^2_β = 52.66; GAM = 13.04), millable cane count (h^2_β = 70.15; GAM = 12.09), internode length (h^2_β = 72.73; GAM = 10.86), single cane weight (h^2_β = 66.67; GAM = 11.73), and estimable recoverable sugar % (h^2_β = 84.51; GAM = 10.11). These results indicate that these traits are influenced by additive gene, and selection based on these traits could effectively achieve the desired genetic improvements. The sugarcane genotypes with the highest sugar yields are B630-5, B58230, B57150, FG06787, FG08533, FG05414, 26-Wonji, C132/81, and B516-60. Thus, these genotypes require additional multi-location and multi-season testing to verify their stability, and suitability for breeding and commercial release at the Metahara and Kessem sugar estates in Ethiopia.

Key words: Agronomy; Heritability; Genotypes; Selection; Sugarcane; Variability

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INTRODUCTION

Modern sugarcane (*Saccharum spp.*) cultivars have been emerged from the interspecific hybridization of the wild species *Saccharum spontaneum* and the cultivated species *Saccharum officinarum*. This process, which began in the early 1900s (D'Hont et al. 1996; Cuadrado et al. 2004, and Lu et al. 2024), initially involved backcrossing the first interspecific hybrids with *S. officinarum* using the "nobilization" technique. This technique was aimed to enhance the desirable high sugar-producing characteristics of *S. officinarum* while mitigating the negative traits associated with *S. spontaneum* (Sreenivasan and Ahloowalia, 1987). This process improved cane yields, ratooning capacity, and resistance to biotic and abiotic stressors (Anna et al. 2015, and Govindaraj et al. 2014).

Sugarcane is geographically distributed and cultivated in tropical and subtropical climate regions (Flack-Prain et al. 2021; Cordeiro et al. 2007), and it plays a pivotal role in the global economy (Ali et al. 2024). It ranks third among the plant-based calorie sources for human consumption, following wheat and rice (Rathna et al. 2019). Moreover, sustainable sugarcane cultivation can promote ecosystem health (Filoso et al. 2015). Its high yield per area makes it an efficient crop for land use, eco-friendly farming practices can enhance soil fertility and reduce erosion (Tabriz et al. 2021; Adeel and Jadhav, 2025). In Ethiopia, sugarcane was utilized as a food source for humans and as fodder for livestock before the establishment of commercial sugar production (Tena et al. 2016; Coote, 1987).

Commercial sugar production in Ethiopia commenced in 1951 after a concession agreement between the Ethiopian Empire and the Dutch company Handels Vereeniging Amsterdam, which led to the establishment of a sugar estate at Wonji (Kassie, 2022). This initiative began with the development of a 5,000-hectare sugarcane plantation, laying the foundation for the country's modern sugar industry. In 1962, a second sugar factory was commissioned at Wonji Shoa, supported by an additional 2,000 ha sugarcane plantation (Mohammed, 1969; Kebede et al. 2011). Subsequent expansions included >10,000 ha at Metahara (1969) and >8,000 ha at Finchaa (1998) (Tafesse & Haile-Michael, 1970). In 2009, the Arjo Diddessa Sugar Factory manages over 16,000 ha. Omo-Kuraz II and III exceed 40,000 ha, at present, Kesem Sugar Factory (20,000 ha) is suspended because of the earthquake (Lewi et al. 2025). Tana Beles Sugar Factory covers 20,000 ha, and Welkait Sugar Factory planned~20,000 ha close due to war (Zikargie et al. 2022). Generally, Ethiopia cultivates 105,000 ha of sugarcane and produces 400,000 tons of sugar annually (Tena et al., 2023).

In Ethiopia, the average annual sugar consumption has increased from 3.6 kg to 10 kg per person. However, only 7 kilograms are produced locally per person; therefore, the remaining amount of sugar must be imported from abroad to satisfy national demand (Hamza et al. 2017). The sugar industry in Ethiopia is currently facing several challenges, among which declining cane yield represents a major challenge. A major factor contributing to this issue is the lack of improved sugarcane varieties that are better suited to the various agro-ecologies and growing conditions of the country's sugar plantations (Kebede et al. 2011). Evidence from major sugar estates indicates a substantial reduction in cane yield per hectare over time. Between the 1998 and 2019 harvesting seasons, productivity at Finchaa Sugar Estate declined from 166 to 84 t ha^{-1}, at Wonji from 140 to 101 t ha^{-1}, and at Metahara from 165 to 157 t ha^{-1} (Tolera et al. 2023). Therefore, improving sugarcane productivity through the development of high-yielding varieties is essential for mitigating sugar shortages by maximizing sugarcane yield per unit area.

Sugarcane yield is a complex quantitative trait governed by multiple genes and strongly influenced by both genetic and environmental factors (Hoarau et al. 2022). Because yield represents the cumulative expression of several yield-related traits and generally exhibits low heritability, direct selection for high yield alone may be inefficient for genetic improvement (Singh, 2000). In contrast, yield-contributing traits in sugarcane typically display simpler inheritance and less affected by environmental variation; therefore, selection based on these component traits can be more effective (Gatti et al. 2005). Thus, improvement in sugarcane yield can be achieved through indirect selection for traits with high heritability and strong associations with cane and sugar yield (Jackson, 2005).

Assessment of genetic variability, broad-sense heritability (h^2_β), and genetic advance as a percent of mean (GAM) provides a reliable basis to determine the extent of exploitable genetic diversity in populations, which is crucial for effective breeding, crop enhancement, and selecting superior genotypes (Sandhu et al. 2022, Xu et al. 2023). An estimate of phenotypic and genotypic coefficients of variation (PCV and GCV) also helps to identify genetically diverse parents for hybridization, thereby maximizing variability in successive generations (Ram et al. 1990; Singh and Singh, 1999). Breeding success depends on the magnitude of genetic variability, as greater variation increases the possibility of selecting superior genotypes (Cobb et al. 2013). Selection efficiency is primarily determined by heritability and expected genetic advance, while sustained genetic variability supports long-term genetic improvement (Fasoula and Fasoula, 2002).

Previous studies have reported promising outcomes where broad-sense heritability is high, accompanied by considerable genotypic coefficients of variation and high estimates of genetic advance expressed as a percentage of the mean (Tolera et al. 2023). Such conditions indicate that selection for traits such as millable cane number and single-cane weight can lead to significant improvements in cane yield (Jamoza et al. 2014; Gilles et al., 2022). For effective single-trait selection, genotypes should be prioritized based on traits exhibiting moderate to high heritability coupled with considerable genetic advance (Gallais, 1984; Yin et al. 1996; Merrick et al. 2022).

The heritability of various agro-morphological traits in sugarcane has been extensively quantified in previous studies. For example, Tena et al. (2023); Tolera et al. (2023) estimated heritability coupled with genetic advance expressed as a percent of mean using 400, and 196 sugarcane genotypes, respectively, originating from diverse geographic regions. Morphological markers, as simple and direct indicators of phenotypic expression, facilitate rapid and cost-effective assessment of genetic diversity and thereby support large-scale screening and selection in breeding programs (Kumar et al. 2024).

The present study examined 187 sugarcane genotypes introduced from various countries, including 102 newly imported hybrid seeds (Fuzz) from Barbados, 39 genotypes from CIRAD, 12 local landraces, and 34 older collections of uncharacterized genotypes. The main objective of this study was to estimate the phenotypic variability, heritability, and genetic advance as a percentage of the mean for various agro-morphological quantitative traits for effectively selecting sugarcane varieties for commercial purposes and identifying potential sugarcane genotypes for future breeding programs.

MATERIALS AND METHODS

Experimental Sites

The experiments were conducted during 2021-2022 cropping season at the Kessem and Metahara Sugar Estates of Ethiopian. Kessem Sugar Estate is located in Awash Fentale and Dullecha districts, zone three of the Afar Regional Government State, 250 km from Addis Ababa and 52 km from Metahara town. Its latitude and longitude are 9o 26 'N and 40o 30 'E, respectively, at an elevation of 700-150 masl. The maximum and minimum temperatures are 38 °C and 15 °C, respectively, and the average annual rainfall is 569 mm. Metahara Sugar Estate is located 8 km south of Metehara Town, in the Eastern Shewa Zone of the Oromia Regional Government State, 200 km from Addis Ababa. Its latitude and longitude are 8° 51'N and 39° 52'E, respectively, and its elevation is 950 masl. The maximum and minimum temperatures are 32.6°C and 17.5°C, respectively, and the average annual rainfall is 554 mm (Ambachew, 2005).

Experimental Materials

The study involved 187 sugarcane genotypes, of which 175 were introduced genotypes from many countries, including F1 hybrid genotypes derived from true botanical seed (fuzz), 12 genotypes were local landraces. The experimental materials were selected through random sampling techniques from the existing germplasm pool, taking into account their year of introduction, countries of origin, and seed types. All the experimental materials were sourced from the germplasm collections at the conservation garden of the Ethiopian Sugar Industry Group Research Centre. The commercial standard varieties NCo-334 and B52-298 were used as controls. Comprehensive details about genotypes, including their origins of country and years of introduction, are presented in the Table 1.

Table 1. List of 187 sugarcane genotypes based on country of origin and year of introduction grown at the Metahara and Kessem Sugar Estate in Ethiopia during 2021/22 cropping season.

Name of the genotypes	Number of genotypes	Country of origin	Year of introduction
FG03104, FG05088, FG05221, FG05404, FG05405, FG06-87,FG06790, FG07320, FG03447, FG05045, FG05-256, FG05-387, FG05414, FG06680, FG07004, FG07252, FG04356, FG05300, FG05360, FG05450, FG04333, FG06787, FG07210, FG03097, FG08109, FG07018, FG08971, FG08755, FG08758, FG07188, FG06544, FG06691, FG07338, FG08096, FG08177, FG08355, FG08533, FG08747, FG08-763	39	France	2014
5-Yhabesha shenkora, 8-Kay Shenkora, 13-Kay Shenkora, 19-BUS, 26-Wonji, 3-Kay Shenkora, 42-kay Ageda Shenkora, 46-Wotete, 92-YE Bako Shenkora, 158-Ancha, 183-Alaa,189 Erero	12	Ethiopia	2011
B153-5, B154-1, B358-1, B358-2, B489-5, B489-6, B491-2, B491-12, B491-13, B498-4, B498-5, B498-14, B516-1, B516-10, B516-11, B516-20, B516-21, B516-31, B516-40, B516-41, B516-50, B516-51, B516-60, B516-61, B517-6, B517-15, B517-16, B517-25, B517-26, B517-35, B517-36, B517-45, B517-46, B519-5, B519-6, B519-16, B527-5, B527-6, B527-15, B527-16, B528-5, B528-15, B528-16, B528-26, B528-5, B528-6, B528-15, B528-16, B546-5, B546-6, B546-15, B546-16, B549-5, B549-6, B549-15, B549-25, B552-16, B552-25, B556-5, B556-6, B556-15, B556-16, B558-15, B558-16, B563-6, B563-15, B563-16, B563-25, B56326, B564-5, B564-6, B566-5, B566-6, B566-15, B566-16, B566-26, B568-5, B568-6, B572-5, B572-15, B572-16, B594-5, B628-5, B630-5, B635-5, B635-6B651-5, B658-15, B658-16, B658-25, B644-5, B644-6, B644-15, B644-16, B688-5, B688-6,B690-6, B691-5, B691-6, B694-5, B694-6, B694-15	102	Barbados	2011
B52-298, B53164, B60-267, B49224, B41227, B59212, B52290, B49388, B52158, B4425, B58230, B50210, B60191, B52313, B51410, B5490, B4906, B39250, B4681, B522107,B5116, B5736, B57371, B51131, B57150	25	Barbados	1962
NCO-334, N 14	2	South Africa	1968
CP961029	1	USA	NA
C132/81	1	Cuba	NA
Co680	1	India	NA
Mex54/245	1	Mexico	NA
MPT96261, MPT97004, MPT981832	3	Philippines	NA

Experimental Design

The experiments were arranged in an alpha lattice design with two replications across 11 blocks, each block comprising 17 plots. Each plot constituted an area of 21.75 m². The planting materials, which come from seven-month-old canes, are cut into two-budded sets and planted in an end-to-end arrangement within three furrows, each plot measuring 5 m in length and 1.45 m in width. The plots were spaced 1.45 m apart, with 2 m between blocks and 3 m between replications. All trial entries were managed according to the standard crop management practices of the respective sugar estates. Urea was applied two months after planting at rates of 400 kg/ha at Metehara Sugar Estate (Tena et al., 2018) and 200 kg/ha at Kessem Sugar Estate (Ayele et al., 2023).

Data Collection

Agro-morphological traits were assessed according to USDA-ARS descriptor protocols (GRIN, 2004). Sixteen quantitative traits were recorded at different growth stages. The number of sprouted buds (NSB) was counted 45 days after primary shoot emergence. Tiller counts were recorded at three (TC3MAP) and five (TC5MAP) months after planting, while hand-refractometer Brix (HR-Brix7MAP) was measured at seven months after planting. At harvest, data were collected on the number of millable cane (MC), single-cane weight (kg), number of internodes per stalk, internode length (cm), stalk diameter (cm), and stalk length (m). Stalk diameter was measured using a vernier caliper and stalk length using a tape measure. Cane yield per hectare (CYPH) was calculated as follows:

$$\text{Cane yield t/ha} = \text{Number of millable cane per hectare} \times \text{single-cane weight (kg)} \quad (1)$$

Juice quality traits, including Brix%, pol%, purity%, and ERS%, were evaluated from composite juice samples collected 21 months after planting at the Metahara and Kessem Research Stations. Juice was extracted from ten randomly selected stalks per genotype using a Jeffco cane crusher. Brix% was determined as total soluble solids using a precision refractometer calibrated at 20°C following the method of Meade and Chen (1977). Filtered composite juice samples (Whatman No. 91 filter paper with Kieselguhr) were used for Brix determination. Pol% was measured using Horne's dry lead acetate method, in which a 300 mL juice sample treated with lead acetate (1 g per 100 mL) was filtered and polarized at 20°C. Purity% was calculated as the ratio of pol% to Brix%, while ERS% was estimated using the Winter–Carp formula (Sukhchain et al., 1997):

$$\text{ERS\% of cane} = [\text{Pol\%} - (\text{Brix\%} - \text{Pol \%}) \times 0.7] \times 0.75 \quad (2)$$

Where 0.75 represents the correction factor between theoretical yields of molasses mixed juice as established by milling test at Metahara and Kessem sugar factories, and 0.7 designates the quantity of sucrose lost in the final processing. Finally, sugar yield per hectare was calculated by multiplying cane yield per hectare by the estimated recoverable sucrose percentage, following the method described by Tesfa and Ayele (2018).

$$\text{SY (t/ha)} = \text{Cane yield (t/ha)} \times \text{ERS\% of cane} \quad (3)$$

STATISTICAL ANALYSIS

Analysis of Variance (ANOVA)

Data were screened to verify compliance with ANOVA assumptions for each quantitative trait across locations. Homogeneity of error variances among locations was tested using Bartlett's test, and normality was evaluated using the Shapiro - Wilk test. For combined analysis, variance homogeneity was further evaluated using Hartley's F-max test by comparing the largest and smallest mean square errors (MSE) from individual-location analyses. Error variances were considered homogeneous when the MSE ratio was ≤ 3. Upon satisfying these assumptions, combined ANOVA across locations was performed using PROC GLM in SAS version 9.4 under a linear model, treating locations as random. Mean squares for blocks, replications, genotype × location interaction, and residuals were appropriately pooled. Genotype effects were tested against the genotype × location interaction mean square, and interaction effects against the residual mean square. The statistical model used for the analysis of variance (ANOVA) in an alpha lattice design is as follows:

$$Yijkm = \mu + \tau i + \lambda j + (\tau\lambda)ij + \rho k(j) + \beta m(jk) + eijkm \quad (4)$$

Where; Yijkm: The phenotypic observation of the i-th genotype, in the m-th incomplete block, of the k-th replication, at the j-th location. μ: The overall population mean. τi (or gi): The random effect of the i-th genotype (i=1,2,…,187). λj: The random effect of the j-th location (j=1,2 [Kessem and Metahara]). (τλ)ij: The random interaction effect of the i-th genotype and the j-th location (G×L). ρk(j): The random effect of the k-th replication nested within the j-th location (k=1,2). The (j) in the subscript mathematically denotes this nesting. βm(jk): The random effect of the m-th incomplete block nested within the k-th replication at the j-th location. The (jk) demonstrates it is nested inside both layers. eijkm: The residual of intra-block experimental error.

Estimation of variance components

Variability among 187 sugarcane genotypes was estimated using rang, and an average values, as well as phenotypic (δ2p), genotypic (δ2g), genotype × location (δ2gl), and error (δ2e) variances. The results of the variance component were used to compute the phenotypic and genotypic coefficient of variation as well as heritability in a broad-sense (h^2b), and genetic advance as a percent of mean. The phenotypic, genotypic, genotype × location interaction and error variances were estimated following the method described by Falconer and Mackay (1996) using the following formulas:

$$\sigma^2 p = \sigma^2 g + (\sigma^2 gl)/l + (\sigma^2 e)/rl \quad (5)$$

$$\sigma^2 g = (MSg - MSgl)/r \quad (6)$$

$$\sigma^2 gl = (MSgl - MSe)/r \quad (7)$$

$$\sigma^2 e = MSe \ \ s \quad (8)$$

Where; σ2p is phenotypic variance; σ2g refers to genotypic variance; σ2gl is genotype by location interaction variance; σ2e is environmental variance; MSg is the mean square for genotype; MSgl is the mean square for genotype by location interaction; MSe is the mean square for error; l is the number of locations; g denotes the number of genotypes; and r indicates the number of replications.

Estimation of Genotypic and phenotypic coefficient of variation

The genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV), were calculated using the formula described by Singh and Chaudhury (1985). The estimations of variations were classified as low when values were less than 10%, medium when values were between 10 and 20%, and high when values were greater than 20% (Allard, 1960).

$$\text{Phenotypic coefficient of Variation: PCV (\%)} = \sqrt{\sigma^2 p}/\bar{X} * 100 \quad (9)$$

$$\text{Genotypic Coefficient of Variation: GCV (\%)} = \sqrt{\sigma^2 g}/\bar{X} * 100 \quad (10)$$

Where $\bar{x}$ represents the trait mean, σ2p is the phenotypic variance, σ2g is the genotypic variance, and σ2e is the environmental variance. PCV and GCV are the phenotypic and genotypic coefficients of variation, respectively.

Estimation of Heritability

Broad-sense heritability (h^2b) is estimated as the ratio of genotypic variance to phenotypic variance and expressed as a percentage, following the procedure described by Falconer (1989). Heritability estimates were classified according to the criteria proposed by Allard (1960) as low (0–30%), moderate (30–60%), and high (>60%). The broad-sense heritability was calculated using the following formula:

$$h^2b=(\sigma^2 g)/(\sigma^2 g+ (\sigma^2 gl)/l + (\sigma^2 e)/rl)\times 100 \quad (11)$$

Where; h^2b is heritability in a broad sense; σ^2g is genotypic variance; σ^2gl is the genotype by location interaction variance; l is the number of locations; r is the number of replications; and σ^2e is environmental variance.

Estimation of Genetic Advance

The expected genetic advance (GA) for each trait at 5% selection intensity (k = 2.06) was estimated following the method of Allard (1960). Genetic advance as a percentage of the mean (GAM) was calculated to compare predicted selection responses among traits using the formula of Comstock and Robinson (1952). According to Johnson et al. (1955), GAM values are classified as low (0–10%), moderate (10–20%), and high (≥20%). GA was also expressed as a proportion of the overall mean to facilitate comparison of traits for potential improvement through selection, following Johnson et al. (1955). The genetic advance (GA) is calculated as:

$$GA = k\times(\sqrt{(\sigma^2 p)} \times (\sigma^2g / \sigma^2p) = k\times (\sqrt{(\sigma^2 p)} \times h^2b = k \times \sigma\times h^2b \quad (12)$$

The genetic advance as a percent of mean (GAM) is calculated using the following formula:

$$GAM= GA/\bar{X} * 100 \quad (13)$$

Where GA = is the genetic advance; K = is the standardized selection differential at 5% selection intensity (k = 2.06); $\sqrt{\sigma^2p}$ is the square root of phenotypic variance; h^2b is heritability in a broad sense; GAM is the genetic advance as a percent of mean; and $\bar{x}$ is the mean of the population in which selection is employed.

RESULTS AND DISCUSSIONS

Analysis of Variance (ANOVA)

The combined analysis of variance (ANOVA) is presented in Table 2. The studied genotypes showed very highly significant ($P \leq 0.001$) variation for all measured traits. This indicated that the existence of genetic variation among the tested sugarcane genotypes. This marked variability suggests excellent opportunities for further genetic enhancement through selective breeding. These findings align with previous reports of significant variation among sugarcane genotypes by Tesfa et al. (2024), Todd et al. (2016), and Tolera et al. (2024).

Similarly, most traits, including NSB TC3MAP, TC5MAP, HR-Brix10MAP, IN. IL, SL, NMC, SCW, SD, CYPH, Brix%, pol%, purity%, ERS%, and SYPH, showed highly significant ($P \leq 0.001$) location effects. Of the 16 traits evaluated, 15 were significantly influenced by location, indicating substantial environmental differences between the two locations, likely due to variations in soil and climatic conditions. These results highlight the importance of multi-location testing for identifying stable and high-performing genotypes (Khan et al., 2004; Chang, 1996). Similar findings were reported by Ftwi et al. (2017) and Tena et al. (2016).

The genotype × location (G×L) interaction was highly significant ($P < 0.001$) for all measured traits except stalk length (SL). Significant G×L effects were observed for NSB, TC3MAP, TC5MAP, HR-Brix7MAP, IN, IL, NMC, SCW, SD, CYPH, Brix%, pol%, purity%, ERS, and SYPH. These results indicate that genotype performance varied across locations, reflecting differences in environmental responses. Such interactions hinder the identification of consistently superior genotypes, highlighting the importance of multi-location testing to identify stable and widely adapted genotypes. Similar findings have been reported by Ftwi et al. (2016) and Seife and Tena (2020).

Table 2. Combined analyses of variances (ANOVA) for 16 Agro-morphological traits of 187 sugarcane genotypes grown at the Kessem and Metahara Sugar Estates of Ethiopia.

Traits	Replication (1)	Block(Rep) (10)	Location (1)	Genotype (186)	G x L (186)	Error (363)	CV (%)	R^2
NSB45DAP	43.31*	7.25 ns	187.00***	81.07***	34.64***	8.65	14.03	0.89
TC3MAP	225.83 ns	129.06 ns	1318.24***	506.72***	175.66***	73.80	11.74	0.85
TC5MAP	3.61 ns	54.33 ns	3396.83***	690.77***	308.83***	83.83	12.31	0.87
HR-Brix7MAP	0.048*	0.017 ns	1.187***	0.010***	0.001***	0.004	8.16	0.73
NMC	2.95 ns	51.68*	13.63 ns	341.96***	123.50***	23.49	6.78	0.92
IN (count)	9.20 ns	15.79 ns	4630.10***	48.46***	15.85***	10.14	11.08	0.82
SD (cm)	0.001 ns	0.074*	0.603***	0.113***	0.055***	0.029	6.13	0.76
IL (cm)	0.190 ns	0.943 ns	25.214***	5.494***	1.658***	0.971	9.85	0.80
SL (m)	0.011 ns	0.108*	9.240***	0.123***	0.051 ns	0.046	8.07	0.71
SCW(kg)	0.243 ns	0.017 ns	8.458***	0.266***	0.175***	0.086	16.84	0.75
CY t/ha	2515.27ns	452.2397ns	76823.70***	3397.81***	1756.41***	913.83	18.34	0.76
Brix %	0.043 ns	0.878 ns	16.992***	7.889***	1.394***	0.567	4.00	0.90
Pol %	0.049 ns	0.870 ns	17.07***	7.855***	1.390***	0.557	4.46	0.90
Purity %	0.019 ns	0.392 ns	5.414***	3.266***	0.601***	0.247	0.56	0.89
ERS %	0.028 ns	0.481 ns	9.615***	4.408***	0.782***	0.310	4.81	0.90
SY t/ha	61.98 *	9.304 ns	2048.98***	56.08***	31.53***	14.18	20.18	0.78

NSB = number sprouted buds per plot; TC3MAP and TC5MAP = Tiller count 3 and 5 months after planting per plot; NMC10MAP/P = number of millable cane 10 months after planting per plot; HR-Brix7MAP = Hand refractometer Brix reading 7 months after planting; SCW = Single cane weight (Kg); NI = Number of internode; IL = Internode length (cm); SL= Stalk length (cm); SD = Stalk diameter (cm); = CY t/ha = Cane yield ton per hectare; SY t/ha = Sugar yield ton per hectare; Brix% = Brix percent; Pol % = Pol percent; Purity% = Purity percent; SR% = Sugar percent; G x L = genotype-by-location interaction; Block(Rep) = Block nested under Replication; Rep (Loca) = Replication nested under location; DF = Degree of freedom; *** = $p < 0.001$ Very highly Significant; ** = $p < 0.01$: Highly Significant; * = $P < 0.05$ significant; ns = $p > 0.05$ non-significant.

Range and Mean performance analysis

The minimum and maximum mean values, along with the range of sixteen quantitative traits evaluated across 187 sugarcane genotypes, are presented in Table 3. The mean number of sprouted buds per plot at 45 days after planting was 21.00, ranging from 7.00 in genotype FG08755 to 35.00 in genotype B635-6, indicating substantial phenotypic variability. Higher sprouted bud counts were predominantly observed in genotypes derived from Barbados (fuzz), reflecting considerable genetic diversity for this trait. This suggests that germplasm from France and Barbados (fuzz) possesses broad variability in sprouted bud number. Therefore, by selecting the best genotypes, such as B635-6, from the tested fuzz genotypes, it is feasible to develop sugarcane genotypes with improved potential for sprouted bud counts. In alignment with the current findings, Tolera et al. (2023) evaluated 196 sugarcane genotypes and found that the average number of sprouted buds per plot was 20.86, with a range of values from 4.74 to 48.85. Three months after planting, the average tiller count per plot was 72.87, with recorded values ranging from 42.75 for genotype FG05360 to 103.00 for genotype C0680. Five months after planting, the average tiller count per plot was 77.00, with recorded values ranging from 42.75 for genotype 158-Ancha to a maximum of 103.00 for genotype B546-15. Higher tiller counts were observed in genotypes derived from Barbados and USA, considerable genetic diversity for this trait.

Table 3. Estimates of range and mean performance for 16 Agro-morphological traits of 187 sugarcane genotypes grown at the Kessem and Metahara Sugar Estates of Ethiopia during 2021/22 cropping season.

Trait	Range		Mean
	Minimum	Maximum	
Number of sprouted buds 45 days after planting	7.00	35.00	21.00
Tiller number at four months after planting	42.75	103.00	72.87
Tiller number at five months after planting	40.75	113.25	77.00
Hand Refracto-meter Brix reading 7 months after planting	0.73	1.00	0.87
Number of millable cane per hectare	45.75	97.25	71.50
Internode number per stalk	19.00	43.00	31.00
Stalk diameter (cm)	2.10	3.30	2.70
Internode length (cm)	7.51	13.66	10.58
Stalk length (m)	2.04	3.14	2.59
Single cane weight (kg)	1.14	2.44	1.79
Cane yield (t/ha)	122.02	241.66	181.89
Brix %	14.46	21.61	18.03
Pol %	12.35	19.47	15.91
Purity %	84.21	90.92	87.56
Estimable recoverable sugar percent (%)	8.30	13.65	10.97
Sugar yield (t/ha)	9.94	30.12	20.03

Genotype from USA and Barbados possesses a broad variability in tiller count. Genotypes C0680 and B546-15, which produced the highest tiller counts, are promising candidates for tiller improving ability through selection. These findings are consistent with reports by Tena et al. (2018) and Tolera et al. (2023).

Hand Refractometer Brix (HR-Brix) is a convenient tool for estimating sugar content at the early growth stage of sugarcane. In this study, HR-Brix values ranged from 0.73 in genotype 5-YE Habsha Shenkora to 1.00 in genotype B527-6, with a mean of 0.87, indicating variation among genotypes during the early maturation stage. However, HR-Brix is an indirect measure of sugar content and is influenced by environmental factors such as soil conditions, climate, and crop management practices (Swapna et al., 2012). Therefore, while the observed variation may reflect genetic differences, definitive conclusions regarding genetic variability require additional sugar quality assessments and consideration of environmental effects, as noted by Ram et al. (2022) and Senthilkumar et al. (2022).

The tested sugarcane genotypes exhibited a mean millable cane count of 72.87, with values ranging from 45.75 in genotype B690-6 to 97.25 in genotype B154-1. Both the minimum and maximum millable cane counts were recorded among the fuzz genotypes introduced from Barbados. This wide range of variation indicates substantial genetic diversity in stalk production capacity among the evaluated genotypes. Such variability provides considerable opportunities for the genetic improvement of sugarcane through the selection and breeding of high-performing genotypes with superior stalk populations, such as B154-1. These findings are consistent with Tena et al. (2016), further reinforcing the potential for enhancing sugarcane breeding programs.

Stalk diameter (SD) were varied significantly among genotypes, ranging from 2.10 cm in B154-1 (thinnest) to 3.30 cm in FG05-25 (thickest), with a mean of 2.70 cm. The thinnest and thickest genotypes originated from Barbados (fuzz) and France, respectively. Sugarcane stalk diameters are categorized into five categories, according to Abdul et al. (2017): thin (2.0 cm), medium thin (2-2.5 cm), medium (2.5-3.0 cm), medium thick (3.0-3.5 cm), and thick (>3.5 cm). Based on these criteria, the FG0669 genotype from CRAD, with diameters of 3.30 cm, was categorized as medium-thick. By selecting the best genotypes for this trait, it may be possible to develop thicker-stalked cultivars, as there is significant variability among different sugarcane genotypes. In line with this finding, (Tolera et al., 2023), noted that sugarcane stalk diameters ranged from 1.93 to 3.42 cm with a mean value of 2.65 cm.

A wide range of genetic diversity was observed in internode length (IL) and stalk length (SL) among the tested genotypes. The mean value recorded for IL was 10.58 cm, while the mean value recorded for SL 2.59 m. For IL, 5-YE Habsha Shenkora had the smallest value at 7.51 cm, whereas 46-Wotete exhibited the largest value at 13.66 cm. Both the shortest and longest internode lengths were found in Ethiopia. Regarding SL, genotype B564-6 had the shortest value at 2.04 m, while genotype FG05-256 had the longest value at 3.14 m. The shortest stalk length was registered from Barbados, while the longest originated from France. Therefore, the study confirmed substantial variation in internode length among genotypes at Barbados and France, while stalk length variation was noted in Ethiopian landrace genotypes. Prior studies by Tolera et al. (2023) emphasized variability in internode and stalk length; however, (Tena et al. 2016) also observed variability in internode length.

Single cane weight (SCW) was varied considerably among the evaluated genotypes, ranging from 1.14 kg in genotype B39250 to 2.44 kg in genotype 183-Alaa, with a mean value of 1.79 kg. The lowest SCW was recorded in a genotype originating from Barbados, whereas the highest SCW was observed in a genotype derived from Ethiopian landraces. This pronounced variation among genotypes highlights the potential for improving single cane weight through the selection of superior genotypes, particularly 183-Alaa, from Ethiopian sugarcane landraces. Comparable ranges and mean values for SCW have been reported by Tolera et al. (2023) and Tena et al. (2016), who documented SCW values ranging from 0.95 to 2.86 kg, with an average of 1.67 kg.

Cane yield (CY, t/ha) exhibited substantial variation among the evaluated genotypes, ranging from 122.02 t/ha in genotype FG05045 to 241.66 t/ha in genotype B630-5, with a mean value of 181.79 t/ha. The lowest-yielding genotypes were introduced from France, whereas the highest-yielding genotype originated from Barbados, indicating marked differences in cane yield among genotypes from different countries of origin. This variability underscores the potential for yield improvement through the selection of superior genotypes, particularly B630-5. Similar variability in cane yield has been reported in previous studies (Tolera et al., 2023; Kumar et al., 2018), corroborating the results of the present study.

Brix% ranged from 14.46% (B52313) to 21.61% (CP961029), with a mean of 18.03%, while pol% varied from 12.35% (B52313) to 19.49% (MPT96261), averaging 16.73%. Juice purity% ranged between 84.21% (FG05360) and 90.92% (C0680), with a mean of 87.56%, and ERS% varied from 8.35% (B52313) to 13.64% (MPT96261), averaging 10.99%. The pronounced variability observed in Brix%, pol%, purity%, and ERS% demonstrates significant potential for genetic improvement through selection. Identifying genotypes with superior mean performance for these traits offers valuable prospects for developing sugarcane varieties with enhanced sugar quality and yield. Genotype MPT96261, exhibited high pol% and recoverable sucrose%, can be considered a promising parental line for future breeding programs. These findings are consistent with earlier reports (Ashagre and Khan, 2020; Abu-Ellail et al., 2020; Tena et al., 2018; Tolera et al. 2023).

Estimated sugar yield (t/ha) showed substantial variation among the evaluated genotypes, ranging from 9.94 t/ha in genotype B549-6 to 30.12 t/ha in genotype B4425, with a mean value of 20.03 t/ha. Both the lowest and highest sugar yield values among Barbados-introduced fuzz genotypes reflect a wide genetic base and pronounced variability for this trait. Such variability is highly desirable in breeding programs, as it provides opportunities for effective selection and genetic gain. The superior performance of genotype B4425 highlights its potential as an elite parent or candidate variety for enhancing sugar yield in future sugarcane improvement. These findings are consistent with earlier reports of variability in sugar yield among fuzz genotypes (Tolera et al., 2023), further emphasizing the value of exploiting this genetic diversity for yield-focused breeding program.

Estimation of variance components

Genetic variance is a critical parameter, as it quantifies the extent of genetic variability present for a specified trait and reinforces the potential for genetic improvement through selection (Houle, 1998). The study revealed that phenotypic variance (σ^2p) was higher than the corresponding genotypic variance (σ^2g), and G × L interaction variance (σ^2gl), for all measured traits (Table 4). The greater magnitude of phenotypic variance indicates a substantial contribution of environmental factors to the total observed variation and reflects the influence of environmental conditions on trait expression. These findings are consistent with Tena et al. (2016), who reported that phenotypic variance exceeded both genotypic and interaction variances for all evaluated traits in sugarcane genotypes. However, genetic variance (σ^2g) was highest for NMC, ERS %, SY t/ha (Table 4), indicating lower environmental influence on these traits. Similarly, Tesfa et al. (2026) reported the highest genetic variance for NMC.

Table 4 Variance Components, Coefficients of Variation, Heritability, and Genetic Advance as a Percent of the mean for 16 Quantitative Traits evaluated in 187 Sugarcane Genotypes

Trait	σ^2p	σ^2g	σ^2gl	σ^2e	GCV	PCV	H^2 (%)	GA	GAM
NSB45MAP	17.28	11.61	13	8.65	16.23	19.79	67.18	7.23	34.43
TC3MAP	126.68	82.77	50.93	73.8	12.48	15.45	65.34	15.18	20.83
TC5MAP	172.69	95.49	112.5	83.83	12.69	17.04	55.29	14.97	19.45
HR-Brix7MAP	0.003	0.002	0.001	0.005	5.43	6.4	72.11	0.085	9.69
NMC	85.5	54.62	50.01	23.49	10.34	12.94	63.88	12.22	17.09
IN	11.4	8.15	2.86	10.14	9.21	10.9	71.48	4.99	16.1
SD (cm)	0.027	0.015	0.010	0.029	4.54	6.08	55.56	0.188	6.98
IL (cm)	1.37	0.96	0.34	0.971	9.26	11.08	69.92	1.68	15.89
SL (m)	0.038	0.018	0.002	0.046	5.22	6.78	59.35	0.215	8.29
SCW(kg)	0.066	0.024	0.042	0.086	8.66	14.42	36.09	0.193	10.76
CY t/ha	849.7	410.35	421.29	913.83	11.14	16.03	48.29	41.59	22.87
Brix %	1.97	1.62	0.412	0.567	7.04	7.79	82.10	2.38	13.2
Pol %	1.97	1.62	0.417	0.557	8.00	8.81	81.94	2.43	15.25
Purity %	0.815	0.665	0.177	0.247	0.93	1.03	81.60	1.51	1.72
ERS %	1.04	0.90	0.23	0.31	8.68	9.3	86.79	1.82	16.63
SY t/ha	11.83	6.14	8.68	14.18	12.37	17.18	51.91	17.18	51.91

σ^2g = Genotypic variance; σ^2p = Phenotypic variance; σ^2e = Environmental variance; σ^2gl = Genotypic by location interaction variance; PCV = Phenotypic coefficient of variation; GCV = Genotypic coefficient of variation; h^2b=heritability in broad sense; GA=Genetic advance; GAM=Genetic advance as percent of mean

Estimation of Genotypic, and Phenotypic Coefficients of Variation

Estimates of phenotypic (PCV) and genotypic coefficient of variation (GCV) for 16 quantitative traits are presented in Table 4. PCV values were higher than the corresponding GCV values for all traits, indicating that the observed variation was influenced not only by genetic factors but also by environmental effects. The GCV ranged from 0.93% to 16.23%, and PCV varied from 1.03% to 19.79%. The purity percentage was exhibited the lowest GCV (0.93%), while the number of sprouted buds per plot showed moderate GCV (16.23%). These results indicate differences in the magnitude of genetic variability and environmental influence among traits. Similar findings were reported by Tolera et al. (2023) and Tena et al. (2016) who observed low GCV and PCV values for purity percentage.

Moderate genotypic (GCV) and phenotypic (PCV) coefficients of variation were observed for sprouted buds, tiller counts (3 and 5 months), millable canes, cane yield, and sugar yield. While the higher PCVs reveal environmental influence on these traits, the moderate GCV values indicate sufficient genetic variability to allow for effective improvement through selection. These results revealed considerable genetic variability among the evaluated genotypes, indicating good potential for improvement through selection.

Sprouted buds (GCV = 16.23%, PCV = 19.79%), tiller count at 3 months (GCV = 12.48%, PCV = 15.45%) and 5 months (GCV = 12.69%, PCV = 17.04%), millable canes (GCV = 10.34%, PCV = 12.94%), cane yield (GCV = 11.14%, PCV = 16.03%), sugar yield (GCV = 12.37%, PCV = 17.18%), and internode length (GCV = 15.38%, PCV = 19.03%) exhibited moderate GCV and PCV values, indicating substantial genetic variability and good potential for selection. Similar moderate variability for millable canes, cane yield, and sugar yield was reported by Tena et al. (2016) while comparable results for stalk length were reported by Tesfa et al. (2026).

Number of internodes (GCV = 9.21%, PCV = 10.90%), single cane weight (GCV = 8.66%, PCV = 14.42%), exhibited low GCV and moderate PCV values. However, internode length (GCV = 5.22%, PCV = 6.78%), HR-Brix (GCV = 5.43%, PCV = 6.40%), and stalk diameter (GCV = 4.54%, PCV = 6.08%), Brix % (GCV = 7.04%, PCV = 7.79%), Pol % (GCV = 8.00%, PCV = 8.89%), purity% (GCV = 0.93%, PCV = 1.03%), exhibited low GCV and PCV values, indicating limited genetic variability. The relatively low GCV and higher PCV indicate that environmental factors had a greater influence on the expression of these traits than genetic factors, limiting their potential for improvement through direct selection. Enhancing these traits may therefore require broadening the genetic base through the introduction of diverse germplasm or other breeding approaches that increase genetic variation. Similar findings for Pol%, purity%, and Brix% were reported by Belwal and Ahmad, (2020) for Brix% and purity% by Tesfa et al. (2023) and for purity% by Shimelis (2018).

Estimation of heritability in broad sense (h^2b)

According to Wright (1921), the integration of the genotypic coefficient of variation (GCV) with heritability provides a more reliable prediction of expected genetic gain under phenotypic selection. Heritability, in this context, represents the proportion of total phenotypic variation that is attributable to genetic factors and is therefore fundamental in predicting the response to selection (Vidadala et al., 2024). Based on the classification proposed by Allard, broad-sense heritability (H^2) is categorized as high (>60%), moderate (30–60%), and low (<30%). In the present study, broad-sense heritability (H^2) ranged from 7.09% to 82.00%, with HR-Brix% exhibiting the lowest estimate and ERS% the highest. The estimates of broad-sense heritability for the evaluated sugarcane traits are presented in Table 4.

High heritability estimates (> 60%) were observed in most juice quality traits, such as brix (82.10%), pol (81.94%),), purity (81.60%),), and estimable recoverable sugar (86.79%). In addition, yield component traits, such as the NSB (67.18%), TC3MAP (65.34%), NMC (63.88%), NI (65.34%), and IL (71.48%), also confirmed high heritability values. This suggests that environmental or non-genetic factors have a limited impact on these trait expressions, making these traits suitable for selection. High heritability values for all juice quality (biochemical) traits such as brix%, pol, purity %, and estimable recoverable sugar % and NSB, TC3MAP, NMC, NI, and IL were reported by Tena et al. (2016), Abu-Ellail et al. (2020).

Moderately high heritability estimates (30–60%) were observed for several traits, including SL (59.35%), SD (55.56%), SCW (36.09), CYPH (48.29%), and SYPH (51.91%). These values suggest that, although genetic factors contribute substantially to the variation observed, environmental or other non-genetic factors also play a considerable role in the expression of these traits compared with traits exhibiting higher heritability. The moderate heritability levels further imply that the phenotypic expression of these traits is influenced by non-additive genetic effect. Thus, genetic improvement through direct selection for these traits may occur at a relatively slower rate than for traits with higher heritability estimates. Moderate heritability estimate for NI, SD, SCW, CYPH, and SYPH was reported by Tolera et al. (2024)

Juice quality traits generally exhibited high heritability, indicating strong genetic control and suitability for improvement through phenotypic selection. As noted by Johnson et al. (1955), knowledge of genetic variability and heritability is essential for effective trait selection. In this study, Brix%, Pol%, purity%, estimable recoverable sugar%, NSB, TC3MAP, NMC, NI, and IL showed high heritability and substantial potential for genetic gain. Likewise, the number of sprouted buds, tillers, stalks, and internode length emerged as reliable selection criteria due to their genetic stability and breeding value for improving sugarcane yield and juice quality.

Estimation of Genetic Advance

Effective crop selection relies heavily on a combination of high heritability and genetic advance as a percent of mean (GAM) (Alam et al. 2017), with the latter predicting the expected genetic gain per selection cycle (Hodge, 1992). Here, estimated GAM values showed considerable diversity, ranging from 1.72% (purity) to 51.91% (SYPH) (Table 4). This wide variation indicates excellent potential for improving specific traits in these sugarcane genotypes. Following the classification by Johnson et al. (1955) where GAM is partitioned into high (>20%), moderate (10–20%), and low (<10%) categories these findings provide a reliable indicator of the genetic progress achievable through future breeding efforts.

High genetic advance as percentage of the mean (>20%) was observed for NSB (34.43%), TC3MAP (20.83%), SYPH (22.87%), and SYPH (51.91%). These High GAM values indicate considerable genetic gain and the predominance of additive gene action, suggesting that phenotypic selection can effectively improve these traits. Similar results have been reported for NSB, TC3MAP CYPH, and SYPH Tolera et al. (2023), Shimelis (2018).

Moderate genetic advance as percentage of the mean (10–20%) values for the traits TC5MAP (19.45%), NMC (17.09%), NI (16.10%), IL (15.89%), SCW (10.76%), Brix % (13.20%) ERS % (16.63), were recorded (Table 4). This suggests that these traits can be improved through selection across successive generations; however, the expected rate of genetic gain is relatively lower than that of traits exhibiting high genetic advance. Similar moderate GAM estimates were reported by Tesfa et al. (2026) for stalk diameter, single cane weight, and internode number and by Tolera et al. (2023) for internode length, Brix% (13.20%), and estimated recoverable sugar% (16.63%). These shared findings indicate moderate expected genetic gains, suggesting these traits can be effectively improved through selection.

Low genetic advance as percentage of the mean (<10%) was observed for HR-Brix7MAP (9.69), SD (6.98), SL (8.29), and Purity % (1.72), indicating limited potential for genetic improvement through selection. The low GAM values suggest a greater influence of non-additive gene action and/or environmental factors on trait expression. Similarly, low GAM estimates for purity% have been reported by Tena et al. (2016), Tolera et al. (2023), and Jamoza et al. (2019). In contrast, the low GAM observed for stalk length (SL) in the present study differs from the moderate values reported by Tena et al. (2016) and Tolera et al. (2023).

Following Johnson et al. (1955), combining high heritability in broad sense (h^2b), GCV, and GAM allows for accurate genetic gain predictions. In this study, cane yield, sugar yield, and early bud/tiller traits (NSB, TC3MAP) showed high heritability paired with high GAM and moderate GCV. Meanwhile, later tillers (TC5MAP), millable cane (NMC), and remaining quality/yield traits (NI, SCW, CYPH, Brix%, Pol%, and ERS%) displayed moderate-to-high heritability and GAM alongside moderate GCV. Finally, these joint metrics reveal that additive gene actions largely regulate the expression of all these evaluated traits. Because the phenotypes directly reflect their genetic potential, breeders can reliably develop improved genotypes using simple, straightforward phenotypic selection techniques aligning with previous findings by Tolera et al. (2023) and Abu-Ellail et al. (2017).

CONCLUSION

The research findings showed a wide range of genetic variability in the different genotypes of sugarcane that were evaluated. The values for GCV, h^2_β, and GAM, which measure genetic variability, ranged from 0.93% to 16.23%, 36.09% to 86.79%, and 1.72% to 51.91%, respectively. Several traits, such as the number of sprouted buds, number of tillers at three months after planting, cane yield (t/ha), sugar yield (t/ha), exhibited moderate to high values for GCV, h^2_β, and GAM. The results indicate that additive genetic effects play a substantial role in these traits, and phenotypic selection may improve them. Consequently, the top 5% of sugarcane genotypes with the highest sugar yields (t/ha) are B630-5, B58230, B57150, FG06787, FG08533, FG05414, 26-Wonji, C132/81, and B516-60. These sugarcane genotypes could be selected as potential parent genotypes for crossbreeding and further enhancement of these specific traits. Additionally, the sugarcane genotypes with high sugar yield (t/ha) should undergo testing at multiple seasons and locations to evaluate their stability and suitability for commercial use at the Metahara and Kessem sugar estates and similar agro-ecological zones.

DISCLOSURE STATEMENT

The authors declare that they have no conflicts of interest.

AUTHORS' CONTRIBUTIONS

Gezahagn Terefe: Writing-review; editing, Writing-original draft, Visualization, Validation, Software, Methodology, Investigation, Formal Analysis, Data curation, Conceptualization. Esayas Tena: Writing-review; and editing, Methodology, Validation, Visualization, Supervision, Conceptualization. Bezuayhu Tesfaye: Writing-review and editing, Methodology, Validation, Visualization, Supervision, Conceptualization. Andargachew Gedebo: Writing-review & editing, Methodology, Validation, Visualization, Supervision, Funding acquisition, Conceptualization.

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Journal of Science and Development

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The structure of these articles will largely be determined by their subject-matter. However, they should be clearly
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Journal article

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Books

Whitmore T.C. 1996. *An introduction to tropical rain forests*. Clarendon Press, Oxford, 226pp.

Steel R.G.D. and Torrie J.H. 1980. *Principles and procedures of statistics*. 2nd ed. McGraw-Hill Book Co., New
York. 633 pp.

Contribution as a chapter in books (Book chapter)

Dubin H.J. and Grinkel M. 1991.The status of wheat disease and disease research in warmer areas. In: Lange L.O., Nose1 P.S. and Zeigler H. (eds.) *Encyclopedia of plant physiology. Vol. 2A Physiological plant ecology*. Springer- Verlag, Berlin. pp. 57-107.

Conference/workshop/seminar proceedings

Demel Teketay 2001. Ecological effects of eucalyptus: ground for making wise and informed decision. Proceedings of a national workshop on the eucalyptus dilemma, 15 November 2000, Part II: 1-45, Addis Ababa.

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Publications of organizations

WHO (World Health Organization) 2005. Make every mother and child count: The 2005 World Health Report. WHO,
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Wageningen, The Netherlands. 108 pp.

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Publications from websites (URLs)

FAO 2000. Crop and Food Supply Assessment Mission to Ethiopia. FAOIWFP. Rome. (http://www. fao.or~/GIE
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