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Mixed teff (*Eragrostis tef,* Poaceae) cultivation and consumption among smallholder farmers in South Wollo Zone, Ethiopia

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Abstract

Background Indigenous cropping systems were often developed with a focus on resilience. For example, farmers in many parts of the world have traditionally grown crop varietal mixtures to mitigate risks of crop failure due to drought, pests, and disease. However, crop varietal mixtures are threatened by policies encouraging farmers to plant homogenous, single-variety cropping systems, which are more vulnerable to increasing climate variability. Teff is one of the indigenous staple crops of Ethiopian origin cultivated throughout the country for multiple purposes. Farmers continue to cultivate diverse varieties of teff, as well as a varietal mixture known as SERGEGNA teff. We assessed farmers' knowledge and practices related to SERGEGNA teff in the northern highlands of Ethiopia to understand its advantages as well as threats to its continued use.

Methods Research was conducted in six kebeles (sub-districts) of Kalu and Tehuledere districts of South Wollo Zone, Ethiopia, situated in warm moist lowlands and tepid and cool mid-highlands. Data were collected through structured surveys with 304 randomly sampled interviewees, semi-structured interviews with 36 purposively sampled key informants, six focus group discussions, guided field tours and market surveys. Varieties of teff in standing crop fields were assessed within 5 m × 5 m random plots at the seed-setting stage. Data analysis included cross-tabulation of survey and interview data, descriptive statistics, and hierarchical clustering.

Results Teff dominates the farm fields in the six study kebeles. Altogether, 13 distinct varieties, including farmers' varieties (landraces) and breeders' varieties, were recorded. Fifty-three percent of survey respondents reported active cultivation of SERGEGNA teff variety mixtures. The same proportion asserted preference for varietal mixtures over pure brown or white varieties on account of nutritional benefits and non-food domestic functions. The varietal mixture was also top-ranked by key informants for drought and disease resistance, resilience, and ecological elasticity. Households reported utilizing the varietal mixture in various types of food and selling at local markets. Most respondents (53% of those who reported cultivating SERGEGNA teff in 2023) indicated using SERGEGNA teff to prepare leavened and unleavened foods, including INJERA, DIMESO, KITA, ANEBABERO, SEREBAT, porridge and gruel.

Conclusion Farmers express that the ongoing cultivation and use of SERGEGNA teff boost production and enhance resilience and economic returns. These perspectives should be considered in initiatives promoting single breeder's varieties, which risk supplanting traditional crop varietal mixtures. Further study, alongside proactive conservation,

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and scaled-up efforts of institutions concerned with food security, biodiversity conservation, and inclusion of ILK are needed.

Keywords Agroecological zones, Drought and disease resistance, Kalu, Local mixed teff varieties, Sergegna teff, Tehuledere

Introduction

Agriculture plays a crucial role in ensuring human health and well-being. To meet the food demands of the rapidly growing global population, agricultural productivity may need to double by 2050 [1]. This increase is vital for preventing food shortages and ensuring that everyone has access to adequate nutrition. Addressing this challenge will require innovations in farming practices, advancements in agricultural technology, and sustainable resource management to enhance crop yields while minimizing negative environmental impacts. Farming practices such as intensive tillage and increased input of synthetic fertilizers have helped drive high agricultural outputs but at the cost of widespread environmental degradation [2]. The intensive approach to agriculture has negatively affected biodiversity and associated ecosystem service provision, reducing the stability and resilience of agricultural systems [3].

Investigations into traditional and indigenous farming practices and associated knowledge offer new insights to address these challenges [4]. Around the world, farmers have traditionally mixed multiple crop varieties in the same fields as a strategy to increase yield stability, reduce disease pressure, and increase productivity [5]. In Ethiopia, varietal mixtures are a part of many traditional farming systems and have survived to date despite newly introduced crops and farming methods. For example, sorghum varietal mixtures are commonly planted [6, 7] to enhance yield, satisfy different needs, and mitigate risk.

In southern Ethiopia, enset (*Ensete ventricosum*) is frequently planted in highly diverse stands with sometimes dozens of named varieties together, providing diverse uses and balancing tradeoffs such as resilience and taste [8]. Similarly, teff (*Eragrostis tef*) varietal mixtures are widely planted across the country and are readily available for purchase at local and regional markets [9]. Teff, a self-pollinated, annual, warm-season grass, is primarily cultivated as a grain for human consumption in Ethiopia and, to a limited extent, as forage and food in other countries. Endemic to Ethiopia, teff exhibits its greatest diversity there [10]. As with other crops, the exact time of its domestication remains unknown, but it was likely cultivated in Ethiopia well before the Semitic expansion of 1000 to 4000 BC [11].

Today, teff is cultivated by over 6.3 million smallholder farmers [12] and supports 70–75% of Ethiopia's population as a staple food. Traditional landraces are widely grown across the country. Although teff can be produced under a wide range of agroecological conditions, it performs exceptionally well at an altitude of 1800 to 2100 m above sea level, where average temperatures range between 10 °C and 27 °C, and in areas with annual rainfall between 750 and 850 mm, with rainfall during the main growing season between 450 and 550 mm [13]. Teff has extensive varietal diversity, with numerous landraces adapted to specific growing conditions [9]. Broadly, farmers' tef crops are classified into three main types: white, brown, and mixed. The mixed type, known as sergegna teff (All words in small caps throughout this paper are local names), translates to "the people at a wedding"—a name that reflects the diversity seen at wedding ceremonies, where different colors, genders, ages, and clothing come together.

Teff is associated with numerous health benefits, including the prevention and management of conditions such as diabetes and anemia [14]. It has a lower glycemic load due to its slowly digesting starch content, and it contains relatively higher lysine concentrations than commonly consumed cereals like wheat, maize, and sorghum. Additionally, teff serves as a good source of fiber, minerals (especially calcium and iron), and phytochemicals such as polyphenols and phytates [15] While its vitamin content is similar to other cereals, the fermentation process used in making injera (a flat, thin, crepe-like preparation) generates additional vitamins, further enhancing its nutritional value [16]. Teff is naturally gluten-free, making it a promising alternative for individuals with coeliac disease or gluten intolerance [17]. Furthermore, teff exhibits antioxidant activity due to its phytochemical content, which functions as direct antioxidants and modulators of antioxidant-response genes, suggesting its potential role in alleviating diseases triggered by oxidative stress [18, 19].

Despite the extensive cultivation and nutritional importance of teff in Ethiopia, the widespread indigenous practice of mixing teff varieties—sergegna—has not been the focus of prior ethnobotanical or agroecological studies. Like other traditional varietal mixtures, these mixtures may offer farmers enhanced yield stability, improved nutrition, and other benefits. Due to the lack

of knowledge about the value of this and other varietal mixtures, the practice is threatened by the introduction of homogeneous varieties and other agricultural technologies, risking its replacement before it is fully understood. To better understand the benefits, drawbacks, and threats to SERGEGNA teff, we conducted interviews, focus group discussions, field observations, and a market survey in the South Wollo Zone to explore farmers' perceptions, attitudes, and traditional knowledge related to SERGEGNA teff.

In response to these gaps, this study characterizes the teff varieties found in different agroecological zones based on their morphological traits, examining variations across altitudinal gradients, traditional knowledge differences across gender and age groups, agronomic practices related to teff cultivation—with a focus on SERGEGNA—and the potential benefits of varietal mixtures of teff compared to sole teff varieties.

Material and methods

Description of the study area

The Kalu and Tehuledere Districts (Weredas) of South Wollo Zone, Amhara Region, Ethiopia, were selected for this research due to their diversity of agroclimatic zones, the importance of teff cultivation, and the presence of SERGEGNA teff varietal mixtures. Kalu is located 378 km north of Addis Ababa, the capital of Ethiopia, and 23 km south of the city of Dessie. The area is situated between 11.25°N to 11.40°N latitude and 39.65°E to 39.85°E longitude. It has 30 rural and 4 urban kebeles (The kebele or sub-district is the smallest administrative unit, corresponding to a neighborhood in urban areas and a larger geographic area in rural areas). Kalu wereda lies within the altitude range between 1450 and 2680 m above sea level. The Wereda encompasses three agroclimatic zones, namely lowlands (KOLLA, 43%), mid-temperate highlands (WEYNA DEGA, 38%), and extreme highlands (DEGA, 19%). The major soil types include Cambisols, Phaeozems, and Lithosols. Both crop production and animal husbandry are typically practiced under traditional agricultural production systems [20]. The main cereals produced in Kalu District include teff, wheat, millet, sorghum, and barley.

Tehuledere wereda is located northwest of Kalu. The capital of Tehuledere, Haik, is located 430 km north of Addis Ababa and 30 km south of Dessie city. The area is situated between 11.18° N to 11.25° N latitude and 39.68° E to 39.75° E longitude. There are 23 kebeles within the Wereda, including 19 rural kebeles, 2 urban and 2 semi-urban towns. The altitude of the Wereda ranges from 1500 to 2928 m.a.s.l and includes KOLLA (15%), WEYNA DEGA (72%), and DEGA (13%) agroclimatic zones. As in Kalu, Cambisols, Phaeozems, Vertisols, and Lithosols are the major soil classes, and agriculture is the primary economic activity in Tehuledere. Teff, sorghum, and wheat are the most common cereals grown.

Specifically, this study was done in Abecho, Addis Mender, and Choresa sub-districts (kebeles) in Kalu District and Hitecha, Qorkie, and Wolde Lulu in Tehuledere District. All six kebeles were selected based on information obtained from district offices indicating widespread cultivation and use of SERGEGNA teff. Kebeles were also chosen to represent different agroecological zones, including M2 (warm moist lowlands), M3 (tepid moist mid-highlands), and M4 (cool moist mid-highlands) which are approximately equivalent to KOLLA, WEYNA DEGA, and DEGA agroclimatic zones [21, 22] (Fig. 1).

Data collection

Random sampling was used to select general informants, while purposive sampling was used to select key informants. There were 50 or more participants from each kebele, totaling 304 participants from the six kebeles. The sample sizes for the structured surveys were calculated by assuming 50% availability using the 95% confidence

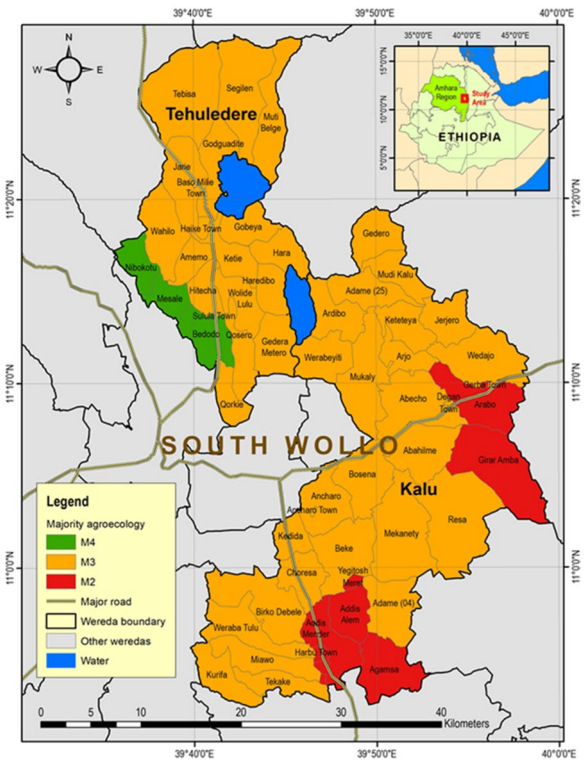

Fig. 1 Map of Ethiopia showing the location of Amhara Region, South Wollo Zone and Kalu and Tehuledere districts with kebeles and the majority agroecological zones

interval at 5% absolute precision by applying the formula for estimating a single population proportion [23]

$$n = \frac{(Z_{\alpha/2})2p(1-p)2}{d^2} \quad (1)$$

where n = the required sample size, $Z_{\alpha/2}$ = critical value of the standard normal distribution, p = proportion, q = complement of the proportion, and d = margin of error.

Additionally, six key informants—elders and other knowledgeable male and female farmers—were identified from each kebele using purposive sampling [24]. Key informants were selected based on recommendations from elders, farmers, students, religious leaders, and the researcher's observations within community groups and were individually interviewed.

This project was reviewed for ethical acceptability by the Department of Plant Biology and Biodiversity Management of Addis Ababa University, which produced a letter that was presented to each of the two district administrators. Data collection was undertaken upon permission of Kalu and Tehuledere district administrative offices and the informed consent of each participant. After obtaining permission to conduct the research in the respective districts, discussions were held with the administrators and agricultural development agents (DAs).

Focus group discussions were organized in each of the six kebeles, with 5–10 participants, including community leaders, elders, and farmers, facilitated by the principal researcher. Participants were purposively selected based on recommendations from local authorities, considering their knowledge and community acceptance. A total of six discussions were held, each lasting two to three hours. Discussions followed a participatory approach, where all participants were encouraged to share their views, and the facilitator ensured engagement from less active individuals. At the beginning of each discussion, we explained the aim of the study to the participants before proceeding with the main discussion topics. The main topics discussed included the advantages and disadvantages of SERGEGNA teff, trends over the past ten years, reasons for any increase or decrease in its cultivation—including changes in farming practices, input availability, and climate conditions—the foods prepared from teff varietal mixtures, differences in taste or health benefits, and seasonal factors influencing these teff types.

Structured interviews with farming households were comprised of closed questions focused on the use and production of teff, and whether or not the farmer had experience planting varietal mixtures. The structured survey was administered using the Kobo Toolbox application on a smartphone, which enabled rapid data collection in an area with limited internet service. Semi-structured interviews and guided field walks were conducted with key informants who were determined to be especially knowledgeable about teff varietal mixtures, as well as kebele and wereda officials and development agents, specifically those affiliated with agriculture and natural resource management. These interviews, particularly those with key informants, provided deeper insights into crop varietal mixtures of teff, their advantages, and disadvantages when compared to sole cropping of pure white or brown varieties, and associated indigenous knowledge (Table 1).

Guided field walks and farm tours played a crucial role in specimen collection and the on-the-spot recording of teff characteristics during ongoing interviews. Market surveys were conducted at each kebele market to assess the marketability, pricing, and distribution of mixed teff varieties (Fig. 2). The survey involved farmers, traders, and consumers, who were questioned about the price, availability, and demand for SERGEGNA teff. Additionally, stakeholders, including local market coordinators, provided insights into market trends.

We first identified farmlands containing diverse teff varieties to ensure wide representation of varieties in the study, followed by the selection of sampling plots. Data on teff variety mixtures were then collected from 45 randomly placed 5 m × 5 m plots within these farm fields, where the crop had reached the seed-setting stage. Morphological identification and characterization of the constituent varieties were conducted on-site with the help of farmers. Samples of each variety were subsequently collected and transported to the National Herbarium (ETH) for further identification by comparison with previous collections. Additionally, seed samples from each field were purchased from farmers to facilitate further characterization, identification, and documentation. This process included analyzing seed color and size as part of this study, while nutritional analysis was considered an additional aspect of the project. Altitudinal data were recorded to compare varietal differences across elevation ranges.

Data analysis

Ethnobotanical data collected during interviews and focus groups were analyzed using recommended tools for ethnobotanical studies as outlined by Martin [25] and Alexiades [24]. Descriptive statistics, including

Table 1 Summary of structured and semi-structured questions

Main questions on teff and SERGEGNA teff: characteristics, farming, use, harvest, and market value	
Structured Survey of Farming Households (Questionnaire)	Frequency of planting SERGEGNA teff Farmer's plan to plant SERGEGNA teff in the future Reason for planting SERGEGNA teff
	Season and Time of planting and harvest SERGEGNA teff
	Soil type recommended for planting SERGEGNA teff
	Application of fertilizer to [SERGEGNA teff]? Types of fertilizer used?
	Rotation of SERGEGNA teff with other field crops? Crops rotated
	Use of irrigation for SERGEGNA teff?
	Foods prepared with SERGEGNA teff
	Marketing of SERGEGNA teff, market value of SERGEGNA teff compared with its components as mono crops
Semi-Structured Interview of Key informants (Knowledgeable farmers or farmer experts)	Reasons for growing SERGEGNA teff
	Place of usual planting [SERGEGNA teff] and reasons and reasons why do they plant it there?
	Soil type that preferred to plant [SERGEGNA teff] and reason why they select?
	Comparison of [SERGEGNA teff] to [teff varieties] in terms of its yield? Does it tend to have higher or lower yields than [teff varieties] planted separately? Reasons
	Comparison of [SERGEGNA teff] to [teff varieties] in terms of its yield stability? Does it more reliably produce grain when the weather is unusually dry or there is too much rain?
	Comparison of [SERGEGNA teff] to [teff varieties] in terms of its susceptibility to weeds, disease resistance, insect pest tolerance? Would you say it usually requires more or less weeding than [teff varieties] planted separately? Why?
	Comparison of [SERGEGNA teff] to [teff varieties] in terms of its disease resistance? Would you say it is more or less likely to be affected by disease than [teff varieties] planted separately? Why? Comparison of [SERGEGNA teff] to [teff varieties] in terms of foods prepared? Taste? Nutrition status?
	Different about the way to harvest [SERGEGNA teff] compared to the way to harvest [teff varieties] when you plant them separately?
	Use the residues of [SERGEGNA teff] for fodder? How does it compare to [teff varieties] used separately? Are there any other uses for the residues of [SERGEGNA teff]?

percentages and frequencies were calculated in MS Excel and visualized using the 'ggplot2' package in R [26].

Cluster analysis was performed using 10 standardized phenotypic morphological traits (Table 2), clustered into three groups based on dissimilarity ratio:

$$1-\left[\frac{\sum\left(x_{k,i}*x_{k,j}\right)}{\left(\sum x_{k,i}^{2}+\sum x_{k,j}^{2}\right)-\sum\left(x_{k,i}*x_{k,j}\right)}\right] \quad (2)$$

where X is the standardized value of the morphological trait *k* for the varieties *i* or *j* that are being compared. Each trait was binary coded (1 for present, 0 for absent) and analyzed using R software (R Core Team, 2024). The number of clusters was determined using the Elbow method with 'factoextra' [27] and 'cluster' [28] packages' and relationships between teff varieties were visually represented with a dendrogram.

Pearson's Chi-square test was used to test for differences between teff varieties observed in Kalu and Tehuledere districts. Post hoc pairwise comparisons using the false discovery rate (FDR) were employed to determine the significance of differences among varieties observed in the study Kebeles. Residuals from the Chi-squared test for teff varieties across study Kebeles were visualized using the 'corrplot' package in R [29].

The association between altitude and the distribution of each teff variety was analyzed using a generalized additive model (GAM), with altitude as the predictor variable and the presence of the varieties as the response [30].

Fig. 2 Data collection methods; A and C focus group discussion; B, D, and F field observation & semi-structured interview; E and G market survey; H specimen collection of teff varieties in Kalu & Tehuledere districts, Ethiopia, 2023 (Photo by first author). The individuals depicted in the images have provided full consent for their images to be published

Table 2 Morphological traits of teff (*Eragrostis tef)*

Morphological traits	Descriptions
Seed color	Teff has different seed color types, including white, creamy white, and brown, which help distinguish different teff varieties morphologically [13, 50]
Seed size	Teff seeds vary in size depending on the variety [13]
Lemma color	The pigmentation of the outer bract varies among teff varieties and is an important trait for classification. It includes colors such as white, brown, and reddish [13, 50]
Panicle form	Teff exhibits different panicle forms, including very loose, loose, semi-loose, semi-compact, and compact [13, 50]
Spikelet number	Refers to the total number of spikelets on a panicle, which varies among teff varieties and is an important agronomic trait influencing grain yield [13, 50]
Panicle length	The panicle length varies among teff varieties, with some having short panicles and others large or intermediate-sized panicles. This trait serves as an important morphological feature for classification [13, 50]
Glume color	The glume is the small, leaf-like bract at the base of a spikelet, which helps enclose and protect the developing seeds. Glume color varies across different teff varieties and is an important morphological trait often used in teff classification[13, 50]
Height	Teff height varies, with some varieties being tall, medium-sized, or short, which helps distinguish different teff varieties [13]
Stem thickness	Teff varieties differ in stem thickness; some have thick stems, while others have medium-sized or thin stems [13]
Stem color	The color of the stem varies among teff varieties; some have white stems, while others have brown or pink stems [13]

Ethnobotanical indices, including *RFC* relative frequency of citation, *UV* use value, *FL* fidelity level , were computed

Traditional knowledge dynamics were examined by comparing the use of teff varieties reported by men and women, young to middle-aged (18–40 years), and elderly (41–80 years); agricultural experts' guidance (fully guided by agricultural experts, mainly using breeder varieties, and partially guided by agricultural experts, using both local and improved varieties); and experience level (experienced: growing mixed teff varieties for more than 5 years; less experienced: growing mixed teff varieties for less than 5 years) were compared using a t-test.

$$\text{Relative frequency of citation (RFC)} = \frac{\text{FC}}{\text{N}} (0 < \text{RFC} < 1) \quad (3)$$

where FC is the frequency of citation, which is the number of informants who mention the use of the plant, and N is the total number of informants participating in the study.

$$\text{Use value (UV)} = \frac{\sum U_i}{N} \quad (4)$$

where U is the number of uses mentioned by informant *i* and N is the total number of informants.

$$\text{Fidelity level } (FL) = \frac{I_p}{I_u} \times 100 \quad (5)$$

where I_p indicates the number of informants who mention a specific use of plant *p* and I is the number of informants who mention any use of plant *p*.

Furthermore, preference ranking and direct matrix ranking were conducted with key informants to identify teff varieties based on attributes such as drought and disease resistance. The values assigned by key informants in these rankings were aggregated to determine community preferences for teff varieties in the study area [25]. A summary of the statistical methods, their purposes, and corresponding research questions is presented in (Table 3).

Results

Demographic features of the informants

Of the total of 304 general informants who participated in the structured survey, the majority (251, 83%) were male and 53 were female. Only 38 respondents (were in the youngest age group (18–30), 129 (42%) in the 31–45 age range, 110 (36%) in the 46–60 age range, and 27 (9%) more than 60 years old. Most of the respondents (291, 96%) were heads of households (Table 4).

Crops grown in Kalu and Tehuledere districts

Thirty-seven crop species were reportedly planted by general informants (Table S1). The most commonly grown species were teff (*Eragrostis tef*, 47%) wheat (*Triticum aestivum*, 53%), sorghum (*Sorghum bicolor*, 43%), chickpea (*Cicer arietinum*, 49%), and mung bean (*Vigna radiata*, 28%). Teff and sorghum are planted both as single varieties and in varietal mixtures. Less frequently reported crops included common bean (*Phaseolus vulgaris*, 1.7%), garlic (*Allium sativum*, 1.3%), black mustard (*Brassica nigra*, 0.99%), emmer wheat (*Triticum dicoccum*, 0.66%) and ground nut (*Arachis hypogaea*, 0.66%). Regarding plant parts used for food and other purposes, seeds/grains constituted the largest proportion at 68%, followed by leaves at 15% (Table S1).

Varieties of teff in Kalu and Tehuledere districts

A total of thirteen distinct teff varieties (including two varieties with sub-types) were recorded within the study area (Table 10). Seven of these varieties were documented and collected only from Kalu district, five only from Tehuledere district and one from both districts. The varieties include both local farmers' varieties and breeders' varieties. Local varieties are known as ABSH LEMNE,

Table 3 Summary of statistical methods, their purposes, and corresponding research questions

Statistical methods	Purpose	Corresponding research questions
Cluster analysis	To assess morphological similarities among different teff varieties	Do morphological similarities exist among teff varieties?
Pearson's Chi-square test	To assess whether teff varieties grown across districts and kebeles are similar	Are teff varieties grown similar across districts?
Post hoc pairwise comparisons	To determine whether the similarity in teff varieties grown across districts and kebeles is statistically significant	Is the similarity in teff varieties between kebeles statistically significant?
Residuals from the Chi-squared	To determine whether teff varieties across different kebeles are similar	How do the observed teff variety distributions deviate from the expected values?
Generalized additive model (GAM)	To assess the effect of altitudinal differences on teff varieties	Does altitudinal difference affect teff varieties?
t-test	To examine differences in traditional knowledge among respondents	Is there a significant difference in traditional knowledge among respondents?
Ethnobotanical indices (RFC, UV, FL)	To compare the different uses of varietal mixture of teff (SEREGEGNA teff)	How do the different uses of SEREGEGNA compare?
Preference ranking	To compare the different uses of varietal mixture of teff with sole varieties	How do the advantages of SEREGEGNA compare to those of sole teff varieties?
Direct matrix ranking	To compare teff with other crops and SEREGEGNA (varietal mixture of teff) with other teff varieties	How do the attributes of teff compare to those of other crops, and how does SEREGEGNA compare to different teff types?

RFC relative frequency citation, *UV* use value, *FL* fidelity level

Table 4 Demographic characteristics of general informants in the Kalu and Tehuledere districts (Wereda)

Attr/Resp	Wereda/Kebele						Total by Wereda		Overall Study Area Total
	Kalu			Tehuledere					
	Abecho	Addis Mender	Choresa	Hitecha	Korke	Welde Lulu	Kalu	Tehuledere	
Gender									
M	50	39	48	38	38	38	137	114	251
F	0	11	2	14	14	12	13	40	53
	50	50	50	52	52	50	150	154	304
Head of HH									
Yes	48	48	50	50	48	47	146	145	291
No	2	2	0	2	4	3	4	9	13
	50	50	50	52	52	50	150	154	304
Age									
18–40	16	27	27	27	34	26	70	97	167
41–80	34	23	23	25	18	14	80	57	137
	50	50	50	52	52	50	150	154	304

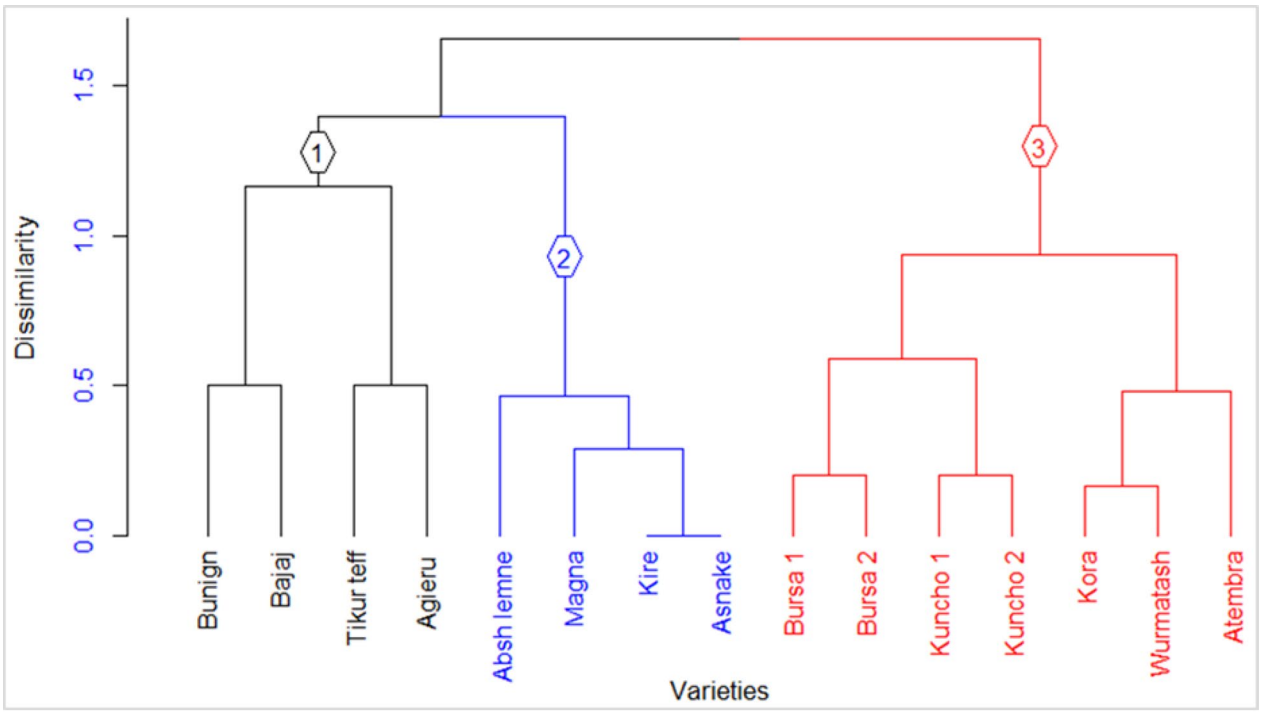

Fig. 3 Dendrogram of teff varieties based on morphological similarity

TIKUR teff, BUNIGN, MAGNA, KIRE, ASNAKE, and AGIERU, while two sub-types of BURSA, BAJAJ (TSEDEY), ATEMBRA, KORA, two sub-types of KUNCHO and WURMATASH are breeder's varieties. TIKUR teff and AGIERU were both considered to be 'red teff' (locally called KEY or TIKUR teff) and the others were considered 'white' varieties. All teff varieties, both local and breeder's, have mixed forms (SERGEGNA). The hierarchical classification based on morphological characteristics classified the teff varieties into three main groups (Fig. 3). The major morphological characteristics distinguishing the three groups were seed color and size, lemma color, stem thickness and color, panicle form and length, glume color, and number of spikelets.

Group I: consists of teff types characterized by thin, short stems and short panicles. This group is known for its shorter maturation period, and one of its varieties, BAJAJ, is named after the fast three-wheeled transportation vehicle commonly used in rural areas. The seed colors in this group range from brown (TIKUR teff and AGEIRU) to white (BUNIGN and BAJAJ).

Group II: includes teff types with very white seeds and bright white lemma color. These varieties have medium stem thickness, with MAGNA being the characteristic variety.

Group III: is characterized by medium white seed color, tall and thick stems, and large panicles. Some varieties in this group, such as WURMATASH, ATEMBRA, and KORA, ook like brown teff superficially but are actually white teff. These varieties have pink stems and glume colors with white seeds, while others have white stems and glumes.

The variation in teff varieties across kebeles within the study districts was assessed using the Pearson Chi-square test, yielding an overall significance value of $p = 0.00138$. A post hoc pairwise comparison of kebeles based on teff varieties was conducted to determine whether the variability between kebeles was statistically significant. The results indicated that differences in teff varieties among all kebeles were significant ($p < 0.05$, Table S2).

Residuals from the Chi-square test provided insights into the extent to which observed frequencies in each cell of the contingency table (formed by crossing teff varieties with kebeles) deviated from expected frequencies. In Abecho Kebele, the variety ABSH LEMNE was planted more frequently than expected based on its overall distribution across the districts, whereas the variety KUNCHO was less commonly cultivated. Additionally, certain varieties, such as KORA, BAJAJ, and MAGNA, were absent in this kebele despite their presence in other kebeles (Fig. 4).

Blue symbols (> 0, light and dark) indicate that a teff variety is used more frequently than expected. Larger blue symbols represent a greater deviation, meaning the

Fig. 4 Residuals of the Chi-squared test, showing how the observed frequency of teff varieties in each kebele compares to the expected frequency

variety is strongly preferred and widely used by farmers in that kebele. Smaller blue symbols suggest a moderate increase in usage, indicating that the variety is still used more than expected, but to a lesser extent.

Red symbols (< 0, light and dark) indicate that a teff variety is used less frequently than expected. Larger red symbols represent a greater deviation, meaning the variety is rarely or not used by farmers. Smaller red symbols indicate a milder underuse, suggesting the variety is used less than expected but with a smaller difference.

Variety occurrence of teff across altitudinal gradient

Teff variety response curves, based on presence-absence data, revealed that altitude significantly influences the distribution of teff varieties. Among the commonly cultivated varieties, ATEMBRA, TIKUR teff, and AGIERU are more frequently planted at higher altitudes (above 2200 m), whereas ABSH LEMNE, BURSA, and WURMATASH are typically found at lower elevations, ranging from 1400 to 1800 m. KUNCHO and to some extent, MAGNA are widespread, with peak occurrences around 2000 m (Fig. 5). Additionally, varietal mixtures of teff (SERGEGNA teff) occur across all altitudinal ranges, with notable prominence in ABSH LEMNE, KUNCHO, ASNAKE, and ATEMBRA.

Indigenous knowledge of the community

The majority of respondents (162, 53.3%) reported planting mixtures of teff varieties (SERGEGNA teff), while the remaining (142, 46.7%) plant one variety per field. More respondents in Kalu (56.2%) practiced mixed teff variety cultivation compared to Tehuledere district (43.8%). Among the farmers who planted SERGEGNA teff in the 2023 cropping year, 11.73% of respondents have been planting SERGEGNA teff for more than 35 years in the study districts, 25% reported having planted it for 20 to 25 years, 15.43% for 5 to 10 years, and 14.2% for 1 to 5 years.

Most of the respondents (60.5%) agreed that currently there is a decrease in the practice of planting SERGEGNA teff compared to 10 years ago (Fig. 6).

In the 2023 cropping season, 142 respondents did not grow SERGEGNA teff. Among these farmers, 78.8% (112 respondents) had previously grown mixed varieties of teff, while 21.2% (30 respondents) had never done so. Of those who had grown varietal mixtures, 58.0% did so in the previous year (2022), 23.2% did so in the past five years, 17.9% did so 6–10 years ago, and 0.89% did so 11–20 years ago.

Indigenous knowledge differed within age, gender, experience, and the influences of agricultural development agents (DAs) in the use and citation of different varieties of teff mixture. As respondents' ages increased, they tended to grow more varieties of teff, with a significant difference between age categories ($P < 0.05$). The 18–40-year-old category used and

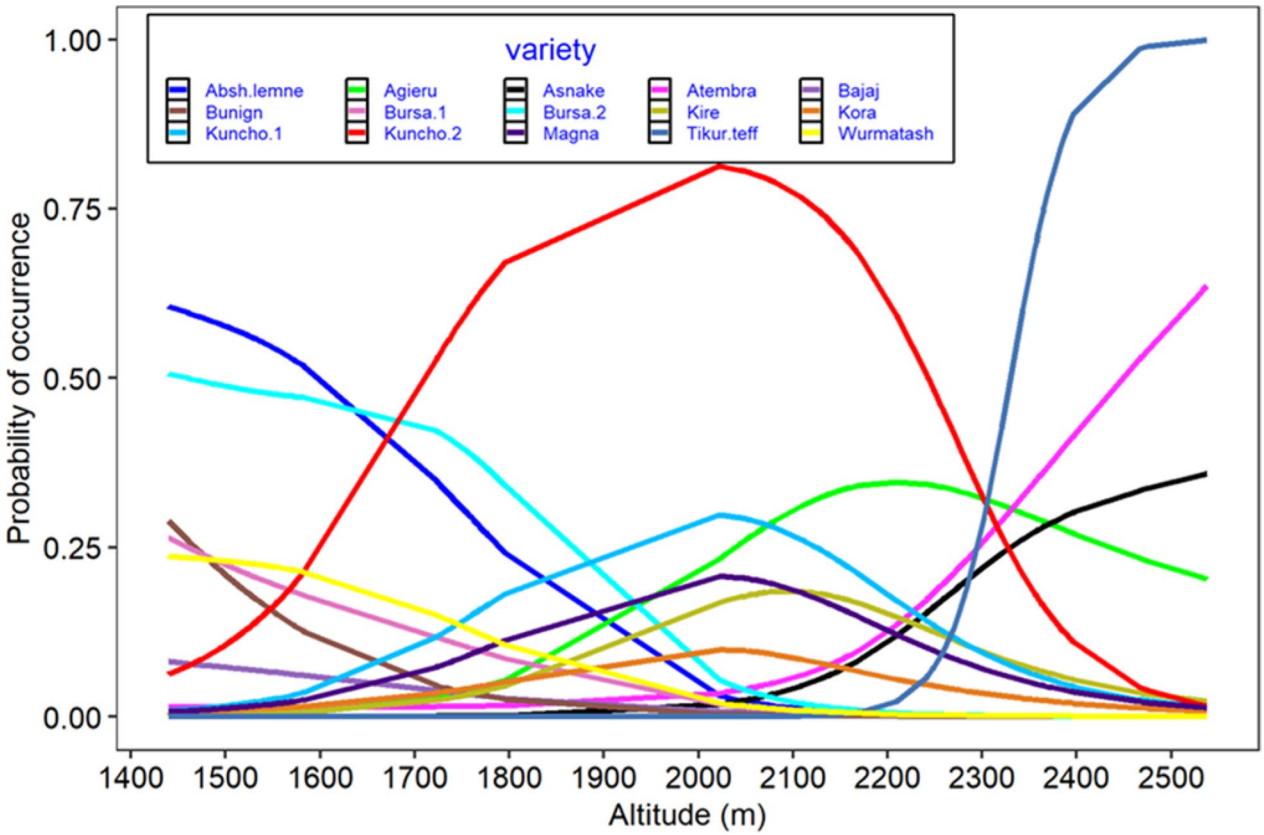

Fig. 5 Teff variety response curves as a function of altitude

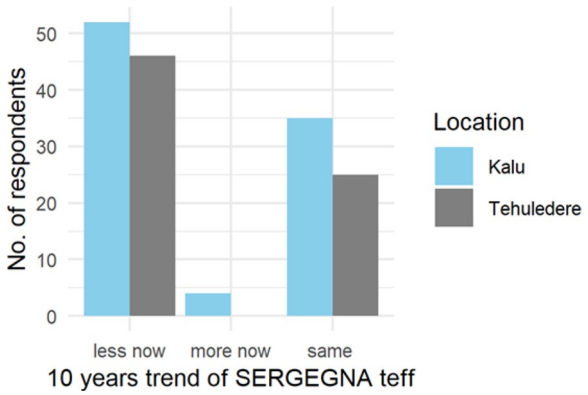

Fig. 6 Trends in teff varietal mixture cultivation during the last ten years in the study districts

cited a smaller number of teff varieties compared to the older age cohorts, both planted in fields or in storage for another year or cropping season. Male headed households used and mentioned different teff varietal mixture than female headed households, with a significant difference ($P < 0.05$). More teff varietal mixture were used and reported by experienced SERGEGNA farmers (planted SERGEGNA teff > 5 years) including the key informants, compared with less experienced SERGEGNA farmers (planted SERGEGNA teff < 5 years). Farmers who were guided fully by development/extension agents used and mentioned fewer number of teff varieties than those guided partially (Table 5). These farmers used and followed the recommendation from the expert's only rather than using their indigenous knowledge; however, these farmers who were influenced partially used both their indigenous knowledge and the expert's knowledge to select and use the varieties of teff.

Planting and harvesting time of mixed varieties of teff

There were similarities and differences in the timing for growing and harvesting mixed varieties of teff in the two districts. The planting time for SERGEGNA teff varieties depended on their maturation period. Two planting seasons were noted: summer (KIREMT) and autumn (BELG),

Table 5 Statistical analysis of the number of teff varieties reported according to gender, age, interactions with DAs, and experience in Kalu and Tehuledere Districts

Attributes	Group of informants	n	Average ± SD	t-value	P-value
Gender	Male	283	2.01 ± 1.004	2.8665	0.0044*
	Female	57	1.59 ± 0.99		
Age	18–40 y/o	169	1.58 ± 0.998	7.042	0.00001*
	41–80 y/o	171	2.29 ± 1.006		
Development agents' guidance	Fully guided by DA	177	1.63 ± 1.00	-2.9105	0.00001*
	Partially guided by DA	163	2.28 ± 1.006		
Informant category	Experienced (> 5 years of growing SERGEGNA)	218	2.31 ± 1.005	10.263	0.00001*
	Less Experienced (< 5 years of growing SERGEGNA)	122	1.29 ± 0.84		
Total number of informants (N)		340			

*Significant difference ($p < 0.05$); ** t (0.05) (two-tailed), df = 338, DA = agricultural development agents

with most planting occurring in mid-July (93.83%), followed by late July (75.93%), early July (40.74%), and early August (6.17%). The less common BELG season, due to unreliable rain, included mid-February (1.23%), late February (1.23%), and early March (3.70%). Harvesting periods for SERGEGNA teff were also similar across the districts with some variations. No respondents in Tehuledere harvested in October, while 43.21% did so in Kalu. Most respondents harvested in early November (59.88%), followed by mid-November (57.41%), late November (55.56%), early December (6.17%), mid-October (6.79%), early June (3.70%), mid-June (1.85%), and late June (1.23%).

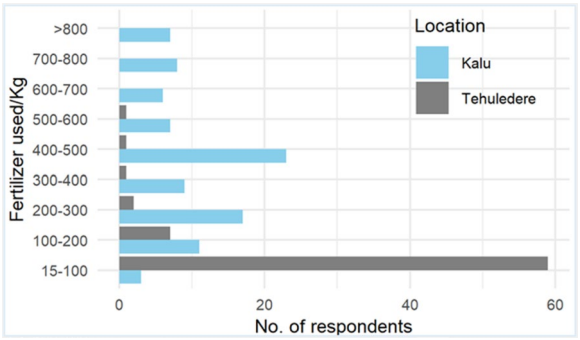

Fig. 7 Amount of fertilizers used by farmers in Kalu and Tehuledere districts

Source of seed, soil type, and fertilizer usage of SERGEGNA teff

Several ways of obtaining SERGEGNA teff seed for planting were reported in the study districts such as personally saved seed, family members, local markets, and neighbors. Of the total respondents who planted SERGEGNA teff in the 2023 cropping season, 69.75% used their own seed stored from a previous year (Table S3).

The soil types where SERGEGNA teff is grown varied across the study districts. Farmers in different kebeles identified suitable soils for planting SERGEGNA teff, including red soil, black soil (WALKA AFER), and clay loam/sandy loam (locally called TASMIMA, BODAM, or KEYATE). Most respondents preferred clay loam/sandy loam soils for a varietal mixture of teff, while others specifically growing mono-cropped breeder's varieties such as KUNCHO frequently grew in black soil types (Table S3). The farm sizes in the Kalu and Tehuledere districts ranged from 0.25 ha to over 1 ha. The majority (72.22%) planted on 0.25 ha to 0.5 ha (traditionally called 1 TIMAJE and 2 TIMAJE, respectively), followed by 0.5–0.75 ha (16.67%), 0.75-1 ha (6.79%), and more than 1 ha (4.32%).

Table 6 Main crops rotated with SERGEGNA teff

Crops rotated with SERGEGNA teff	No. Kalu	No. Tehuledere	Total	%
Sorghum bicolor	82	28	110	67.90
Cicer arietinum	35	23	58	35.80
Vicia faba	-	20	20	12.35
Pisum sativum	-	2	2	1.23
Vigna radiata	42	-	42	25.93
Triticum aestivum	11	58	69	42.59
Phaseolus vulgaris	8	5	13	8.02
Hordeum vulgare	1	2	3	1.85
Eleusine coracana	7	-	7	4.32
Zea mays	7	27	34	20.99
Allium cepa	3	22	25	15.43
Solanum tuberosum	-	7	7	4.32
Ipomoea batatas	-	1	1	0.62
Lathyrus sativus	-	26	26	16.05
Vicia lens	-	5	5	3.09
Avena sativa	1	-	1	0.62
Solanum lycopersicum	1	-	1	0.62
Sesamum indicum	2	-	2	1.23

More than 95% of respondents who grew mixed varieties of teff managed fertility by adding either natural or artificial fertilizers. The types of fertilizers used varied across the study districts. In Kalu district, 94.51% of respondents who planted SERGEGNA teff used natural fertilizer, specifically compost, which is significantly higher compared to Tehuledere district (11.27%) (Table S3). The quantities of fertilizer used varied between the two districts, with farmers noting that the amount of fertilizer applied depended more on soil types than on the variety of teff grown. For instance, farmers reported applying more artificial fertilizer in black soils compared to other soil types. In Kalu district, the majority of respondents applied 400–500 kg, while in Tehuledere district, most used 15–100 kg of fertilizer (Fig. 7).

Crop rotation of SERGEGNA teff with other crops

In the two study districts, nearly all (97.53%; 158) of the respondents who planted varietal mixtures of teff practiced crop rotation every cropping season. Farmers stated that they practiced crop rotation for teff regardless of whether they grew SERGEGNA or sole variety teff. The most commonly rotated crops with SERGEGNA teff were sorghum, wheat, and chickpea (Table 6). Irrigation was rarely used for teff cultivation, including varietal mixtures, with over 95% (155) of respondents from both districts indicating they did not use irrigation. Only 4.32% (7) of respondents practiced irrigation for mixed varieties of teff, with six respondents from Kalu district and one from Tehuledere district employing this practice.

Advantage of mixed varieties of teff

Farmers in the Kalu and Tehuledere districts have several common reasons for growing varietal mixtures of teff. The most frequently cited reasons include stable productivity, food preference; and resistance to disease, pests, and drought. The majority of respondents preferably used SERGEGNA teff to prepare a variety of dishes, such as porridge, DIMESO, INJERA, KITA, ANEBABERO, SEREBAT, and gruel (MUK/ATIMET). INJERA was a common dish, while SEREBAT was typically served after a funeral. KITA and ANEBABERO were used as snacks. Gruel and porridge

Table 7 Advantages of SERGEGNA varietal mixtures of teff in Kalu and Tehuledere Districts

Use categories	Use report of each category	Details of use report	Total No. of citations	Total No. of informants	RFC	FL	UV
Production and productivity	Stable	Use lasts long performs for long period of time	125	162	0.77	10.27	0.77
Climate resilience	Drought resistant	Performs under low rainfall	45	162	0.28	3.70	0.43
	Disease resistant	Not damaged by diseases	19	162	0.12	1.56	
	Tolerates off-season rainfall	Performs under irregular rainfall	5	162	0.03	0.41	
Food	INJERA	Leavened thin spongy flat bread	162	162	1.00	13.31	2.78
	SEREBAT/SETETO	Unleavened bread/thinner	134	162	0.83	11.01	
	KITA	Unleavened bread/ thicker	111	162	0.69	9.12	
	MUK	Gruel	12	162	0.07	0.99	
	ANEBABERO	Two-layered injera	5	162	0.03	0.41	
	GENFO	Porridge	8	162	0.05	0.66	
	DEMISO	Pieces of unleavened bread with sesame	4	162	0.02	0.33	
Residue	Fodder for domestic animals	Animal feed	121	162	0.75	9.94	1.27
	Construction	Residue mixed with mud and other materials to reinforce walls, providing structural support	85	162	0.52	6.98	
Health (nutritional) benefit	Gruel for newborns and delivered mothers	High food value/ restorative	21	162	0.13	1.73	0.60
	Injury	Healing broken bones/ recovery	15	162	0.09	1.23	
	Injera suitable for the body	Benefits the body	61	162	0.38	5.01	
Weed control	Crop protection	Management	145	162	0.90	11.91	0.90
Seed conservation	Traditional seed-banking	Household seed bank	6	162	0.04	0.49	0.04
Generate income	Cash income	Source of money	119	162	0.73	9.78	0.73

RFC relative frequency citation, *FL* fidelity level, *UV* use value

Table 8 Preference ranking of teff varieties for drought resistance

Varieties of teff in Kalu district	Key informants								Total	Rank
	1	2	3	4	5	6	7	8		
WURMATASH	4	3	5	6	8	4	3	4	37	5th
KUNCHO	2	4	1	3	2	1	5	3	21	6th
ABSH LEMINE	6	7	6	8	7	8	6	5	53	2nd
BURSA/DEBELBELIE	1	2	3	1	3	2	2	1	15	8th
BUNIGN	7	6	8	5	6	5	8	7	52	3rd
SERGEGNA	8	8	7	7	5	7	7	6	55	1st
BAJAJ	5	5	4	2	5	6	4	8	39	4th
MAGNA	3	1	2	4	1	3	1	2	17	7th

are commonly eaten by new mothers and can also be consumed by individuals who have sustained injuries, such as broken bones. DEMISO is prepared by mixing it with sesame, with the option of adding sugar and pepper to improve its taste. It is also enjoyed by guests and relatives from various places (Table 7).

Conversely, the 30 farmers who practiced sole cropping of teff provided various reasons for not using mixed varieties, viewing them as a threat to the cultivation of SERGEGNA teff and other local varieties (Fig. S1). The most commonly cited reason was pressure from development agents to adopt breeders' varieties, which was reinforced through support packages such as fertilizer assistance. Farmers growing breeders' varieties receive incentives, including artificial fertilizer. In this system, new breeders' varieties are cultivated as sole crops rather than being mixed with other varieties, as they are replaced annually.

Farmer rankings of teff variety traits

Preference ranking of different sole varieties of teff and SERGEGNA for drought resistance was performed in Kalu district. Key informants ranked SERGEGNA teff as the preferred crop for its drought resistance compared to any of the sole varieties. The least preferred teff variety for drought resistance was BURSA (Table 8).

In Tehuledere district, where teff disease infestations (locally known as MECHI and KEK) are more prevalent, SERGEGNA teff is regarded as the most disease-resistant, with ATEMBIRA and TIKUR teff following closely behind (Table 9).

Various crop types were compared with teff using direct matrix ranking to evaluate their multiple uses in the study districts. Key informants identified teff as the top multipurpose crop, followed by wheat and sorghum (Table S4).

Additional direct matrix ranking was conducted to assess the multiple uses of different teff varieties in the study districts. Key informants agreed that the SERGEGNA varietal mixture offers more advantages than sole-cropped teff varieties (Table S5).

Marketability of SERGEGNA teff

Nearly all respondents in Kalu and Tehuledere districts acknowledged the significance of various teff varieties for the market, although not all sold mixed teff. Among those who produced SERGEGNA teff in 2023 cropping season, most (73.5%, 119) reported selling it in the local market, while 26.5% (43) used it solely for household

Table 9 Preference ranking of teff varieties for disease resistance

Varieties of teff in Tehuledere district	Key informants								Total	Rank
	1	2	3	4	5	6	7	8		
KUNCHO	3	1	2	1	3	4	1	2	17	6th
KORA	1	2	3	3	1	1	4	1	16	7th
ASNAKE	4	3	5	7	2	3	6	4	34	4th
SERGEGNA	5	7	6	5	4	7	5	6	45	1st
ATEMBIRA	6	6	7	2	7	5	3	7	43	2nd
TIKUR TEFF	4	4	5	7	2	3	6	4	35	3rd
KIRE	7	3	4	4	2	6	2	5	33	5th

Table 10 Teff varieties in Kalu and Tehuledere districts

Common name	General category	Varietal types	(Longitude, Latitude)	Altitude	Seed color	Lemma color	Panicle form	Spikelet/ panicle	Panicle length(cm)	Glume color
BURSA 1/ DEBELBELIE/	White	Breeder	10.99, 39.75	1726.85	White	Pink variegated with white	Compact	300	30–36	Dull white
BURSA 2	White	Breeder	11.13, 39.96	1502.4	White	White	Compact	350	30–38	Light white
TIKUR teff	Red	Local	11.17, 39.68	2408.3	Brown	Light gray	Very loose	152	25–30	Black
BUNIGH	White	Local	11.13, 39.9	1502.9	Pale white	Silver white	Very loose	104	20–25	White
BAJAJI (TSEDEY)	White	Breeder	10.9, 39.79	1469.87	Creamy white	Greenish white	Very loose	140	25–35	White
ATEMBRA	White	Breeder	11.17, 39.69	2262.4	Pale white	Red violet	Fairly loose	196	25–36	Purplish red
KORA	White	Breeder	11.26, 39.68	2054.34	Pale white	Red violet	Fairly loose	465	36–40	Dark
KUNCHO 1	White	Breeder	11.17, 39.68	2262.3	Pale white	Pink variegated with white	Very loose	416	25–48	Purple black
KUNCHO 2	White	Breeder	10.99, 39.75	1726.85	White	White	Very loose	375	30–52	Light white
MAGNA (BORENA)	White	Local	10.99, 39.75	1726.85	Very white	Very white	Loose	510	40–50	Bright white
KIRE	White	Local	11.27, 39.68	2210.27	Very white	White	Very loose	375	25–38	Bright white
ASNAKE	White	Local	11.17, 39.69	2262.4	White	White	Loose	325	35–45	Light white
ABSH LEMNE	White	Local	11.13, 39.90	1511.34	White	White	Fairly loose	428	26–37	Light white
WURMATASH	White	Breeder	11.13,39.90	1502.4	Pale white	Light paler red violet	Fairly loose	440	30–48	Dark
AGIERU	Red	Local	11.27, 39.68	2210.27	Brown	Light white (livid)	Very loose	120	20–25	Dull white

Common name	Height (cm)	Seed size	Stem thickness	Stem color	Days to mature
BURSA 1	55–88	Large (dull white glumes)	Thick	Light white	90–100
BURSA 2	60–92	Large (light glumes)	Thick	Light white	90–100
TIKUR TEFF	50–80	Small	Thin	Dull green	65–80
BUNIGH	40–72	Small	Thin	Light white	50–65
BAJAJ	45–73	Medium	Thin-Medium	Greenish white	70–90
ATEMBRA	45–84	Large	Medium	Dark pink	120–135
KORA	50–90	Large	Very thick	Pink	110–120
KUNCHO 1	60–110	Large	Very Thick	Dull white	90–115
KUNCHO 2	53–120	Large	Very thick	White	90–115
MAGNA (BORENA)	65–90	Medium	Thick	Bright white	90–100
KIRE	50–93	Medium	Medium	Bright white	120–130
ASNAKE	56–87	Medium	Medium	Bright white	100–129
ABSH LEMNE	75–83	Medium	Medium	Bright white	90–95
WURMATASH	90–102	Large	Very thick	Light pink	90–100
AGIERU	42–70	Small	Thin	Silvery white	95–120

TIKUR indicates brown

Bursa 1and Bursa 2-sub-types of Bursa

KUNCHO 1 and KUNCHO 2- sub-types of KUNCHO

Altitude- in m.a.s.l

Range in length and days of maturity indicates—the minimum and maximum values of the character

consumption. A comparison between the districts shows that more respondents in Kalu district (78, 65.5%) sold SERGEGNA teff compared to Tehuledere district (41, 34.5%). SERGEGNA teff was abundantly available in all local markets of the study kebeles and was priced intermediately compared to other teff varieties (Table 10).

Most respondents (82.1%) reported a price of 120 birr per WOLDIA (traditional weight measure equivalent to 1.25 kg, with 17.9% citing a higher price of 130–140 birr per WOLDIA. In comparison, white teff was priced at 150 birr per WOLDIA and TIKUR teff (red/brown teff) at 110 birr per WOLDIA in the study districts. Farmers attributed the price differences among teff varieties to seed color, with white teff commanding the highest market price.

Discussion

Various local and improved teff varieties were identified in Kalu and Tehuledere districts, comparable to the 15 varieties found in East and West Gojjam (Northwestern Ethiopia) [31]. Significant variation in teff cultivars was observed across the study kebeles, influenced by agroecological factors, particularly rainfall and altitude. Certain cultivars were dominant in specific agroecological zones, with farmers classifying teff varieties as highland "DEGA" and lowland "KOLLA." "DEGA" highland varieties thrive in areas with high rainfall and are resistant to waterlogging, while "KOLLA" lowland varieties are more drought-tolerant. In Kalu district, varieties such as ABSH LEMNE, WURMATASH, BURSA, and BAJAJ were dominant in KOLLA agroclimatic zones, while in Tehuledere district, varieties like KIRE, ASNAKE, KORA, and ATEMBIRA were more common. Specifically, TIKUR teff, ATEMBIRA, and ASNAKE were predominantly found in high-altitude DEGA agroclimatic zones.

Even though the percentage of varietal mixture in teff varied, all thirteen teff varieties (including 6 breeder's varieties and 7 local varieties) exhibited mixed forms, with white varieties containing brown (red) interiors and brown (red) varieties containing white interiors. SERGEGNA teff, in particular, is predominantly a mixture of white and brown (red) types. Farmers sometimes intentionally mixed white varieties when specific varieties failed to fully grow. In these cases, underperforming varieties were mixed with others such as WURMATASH and ABSH LEMNE, or KUNCHO and BURSA. The varietal mixtures (SERGEGNA) typically resulted from seed mixing between different varieties grown on separate plots, in nearby farmers' fields, due to flood-mediated seed dispersal, or via shared threshing floors during harvest. The long-term use of local varieties in fields seemed to increase the likelihood of mixing, as these varieties had more opportunities to cross with others. Although SERGEGNA teff is primarily composed of local varieties, new breeder's varieties, after being cultivated for two to three years, also became part of the mixture through the same mechanisms. Given teff's low outcrossing ability (0.2–1%) [13, 32], cross-pollination plays a minimal role in these mixtures compared to seed mixing via threshing floors and flood dispersal.

Farmers in both districts conserve local teff varieties, though faced with pressures from new breeder's varieties introduced by agricultural development agents. This is consistent with broader tradeoffs between the use of improved varieties and agrobiodiversity conservation in the Sahel, as seen in pearl millet cultivation—where breeder's varieties reduce diversity in Niger [33]. Therefore, managing these tradeoffs is essential to sustain both productivity and biodiversity. Farmers' seed choices were also influenced by market demand and institutional factors, affecting the diversity and adaptation of local varieties over time. This dynamic contributes to the genetic erosion of local teff varieties, reflecting similar patterns observed in the genetic erosion of tetraploid wheat [34]. Even though these factors push farmers to adopt breeders' varieties, they also maintain the traditional practice of saving their local varieties. This is evidenced by 70% of respondents, who believe that conserving local varieties is essential when improved varieties fail or result in decreased productivity. Farmers play a crucial role in keeping the genetic resource of local varieties of different crops [35].

Another traditional agricultural practice employed by farmers to increase the productivity of teff or SERGEGNA teff was crop rotation. The main crops used in this practice were categorized as legumes and cereals, including chickpea, sorghum, grass pea, mung bean, and faba bean. This practice, when involving legumes, is known as 'MAKER,' which translates to farmland soil improvement through legume cultivation. Crop rotation can enhance productivity by enriching the soil with plant growth-promoting microbes [36, 37]. These microbes include species such as *Acinetobacter*, *Agrobacterium*, *Bacillus*, *Burkholderia*, *Chryseomonas*, *Enterobacter*, *Pseudomonas*, and *Rhizobium*, which contribute to nitrogen fixation, phosphate solubilization, phytohormone production, siderophore synthesis, and antibiotic production [38, 39].

Additionally, respondents mentioned that crop rotation helps reduce harmful insect pests that cause significant

crop losses. This result aligns with findings reported in other studies, as a means of insect control by disrupting the life cycle of pests [40, 41]. Interestingly, some of the crops rotated with SERGEGNA teff are frequently planted as variety mixtures themselves, such as sorghum which may be planted as WAJERA (mixed) sorghum, with up to 24 named varieties in a single plot [42]. Rotating mixtures of species are also planted in the northern highlands of Ethiopia. For example, wheat-barley mixtures are rotated with faba bean-field pea mixtures in North Gondar Zone [43].

Despite a perceived decline in the cultivation and use of teff varietal mixtures compared to the past, advantages cited by respondents may explain its continuation. Respondents cited environmental challenges such as drought and diseases, with sustainability and enhanced productivity being major motivations in both districts. As observed in other crop varietal mixtures, SERGEGNA teff may optimize land use by leveraging differences in tiller count, panicle length, stem thickness, and spikelet numbers to maximize productivity. This effective land use has been supported by a study conducted on rice cultivars [44]. The stable production of SERGEGNA teff may be also attributed to beneficial interactions among varieties. Some teff varieties have sturdier stems that support weaker ones, reducing lodging. Differences in tolerance, one variety may be resistant to drought and the other resistant to waterlogging, meaning the yield is more stable from season to season [45].

In Kalu district, which is predominantly covered in the lowland KOLLA agroclimatic zone susceptible to drought, respondents noted reduced rainfall in the 2023 cropping season. According to farmers, teff varietal mixtures provided some yield under these conditions, along with straw for livestock. Competition and resource utilization within and between crops during mixed cropping contribute to effective water use in times of scarcity, as observed in studies on wheat cultivars [46] and barley-durum wheat mixtures in dry lands [47]. These findings indicate that yield stability can be enhanced through mixed cropping of complementary varieties or species by optimizing resource use and improving resilience to moisture stress. This resilience is achieved through better water use efficiency, reduced competition at critical growth stages, and adaptation to variable moisture conditions, particularly in drought-prone regions.

Farmers also highlighted the disease resistance of SERGEGNA teff, particularly against diseases locally known as KEK and MECHI, prevalent in the Tehuledere district. While these diseases affect productivity, the impact was mitigated by mixed teff varieties compared to improved varieties. Planting mixed varieties can reduce the effects of pathogenic microorganisms, due to changes in microbial communities and slowed disease spread through mixed cropping [48].

Another advantage of SERGEGNA teff highlighted by farmers is its suitability for making INJERA, a traditional Ethiopian fermented pancake. Its ability to hold water, long shelf life, slightly unique sour flavor, pliability, and smooth texture made it preferred over other varieties for these purposes. Respondents also mentioned higher flour yield from mixed teff compared to other varieties, which is in line with other studies [49]. The straw of mixed teff varieties is valuable for feeding livestock during the dry season and for reinforcing mud walls in construction, contributing to the economic and structural strength of houses.

Generally, cultivating mixed teff varieties aligns with global trends in varietal and mixed cropping systems, where genetic diversity enhances resilience, productivity, and adaptation to changing environmental conditions [51, 52]. Similar methods are observed in wheat and rice underscoring the ecological and agronomic benefits of diversity within crop species. Moreover, this practice reflects farmers' indigenous knowledge, as they intentionally maintain diversity to buffer against environmental challenges and ensure long-term yield stability. However, as seen in many traditional farming systems worldwide, institutional and market forces are influencing the continuity of these practices. Supporting policies that preserve farmers' varietal mixtures, promote local seed-saving initiatives, and incentivize diverse cropping systems through subsidies or research funding could contribute to more resilient and sustainable food production systems globally.

Conclusion

A total of thirteen teff varieties, including two with subtypes, both local and improved, were documented within the study area. Varietal mixtures, known as SERGEGNA teff, were also observed. The varieties cultivated differed significantly across districts and kebeles. Knowledge and practice related to SERGEGNA teff varied among respondents based on age, gender, experience, and expert guidance. Approximately 53.3% of respondents cultivated mixtures of teff varieties, while 46.7% practiced sole cropping. Respondents in the study districts have been planting teff varietal mixtures for over 35 years. However, most acknowledged a decline in this practice compared to the past. A significant majority (69.75%) of respondents used their seeds for SERGEGNA teff. Additionally, over

95% of those cultivating mixed teff applied fertilizers and practiced crop rotation with other crops.

The primary reasons for cultivating SERGEGNA teff included stable productivity, drought resistance, and culinary preference. However, factors such as lower market value and the availability of improved teff varieties deterred some farmers from planting mixed varieties. SERGEGNA teff was favored for its superior drought and disease resistance. In direct matrix ranking, teff emerged as the most preferred crop compared to five other crops, with SERGEGNA teff ranking above pure white and red teff varieties. Mixed teff varieties were highly marketable across all study kebeles, commanding a medium price.

Given these findings, strategic efforts are necessary to sustain and enhance the cultivation of mixed teff varieties. Institutions should establish local seed banks and conduct genetic studies to assess diversity and resilience. Extensive field trials are essential to identify and promote the most suitable mixed varieties for different agroecological zones. Further analysis of nutritional and microbiological properties will help determine potential health benefits, such as complementary nutritional profiles or altered fermentation. Additionally, market potential and value chain analyses will enhance the economic value and competitiveness of mixed teff varieties. Expanding this study across Ethiopia to include diverse varietal mixtures and indigenous knowledge will provide broader insights. These efforts will help sustain local teff varieties, particularly SERGEGNA teff. Furthermore, this approach can serve as a global model for preserving traditional grain diversity, supporting food security, and enhancing resilience to climate change through the sustainable use of genetic resources.

Glossary of local terms

Belg	The short rainy season in Ethiopia, usually from February to May, supporting crop cultivation in some regions.
Dega	A high-altitude agroecological zone in Ethiopia, ranging from 2,400 to 3,200 m above sea level, characterized by cooler temperatures.
Kek	A crop disease in South Wollo caused by cold temperatures during the flowering stage, especially in teff, leading to crop damage and reduced yields.
Kiremt	The main rainy season in Ethiopia, typically occurring from June to September, crucial for agricultural production.
Kolla	A lowland agroecological zone in Ethiopia, characterized by hot and dry conditions, typically below 1,500 m above sea level.
Mechi	A crop disease in South Wollo caused by fluctuating weather conditions and unseasonal rainfall during the flowering stage of crops like teff, leading to crop failure.
Sergegna teff	A varietal mixture of teff, resembling "the people at a wedding" in diversity, consisting of local and breeder's teff with both white and brown varieties, known across Ethiopia.
Weyna Dega	A mid-altitude agroecological zone in Ethiopia, typically ranging from 1,500 to 2,400 m (or 2,500 m) above sea level, known for moderate temperatures and favorable conditions for crop production.
Woldia	A traditional weight measuring unit used in South Wollo, equivalent to 1.25 kg, commonly used for measuring grains and other agricultural products.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13002-025-00776-2.

Supplementary file1

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Author contributions
DA designed the project, conduct the fieldwork, the data analysis, wrote the first draft, and prepared the final manuscript of this paper. ZA, ZW and BW supervised the research work, participated in design and monitoring, data analyses, and reviewed the manuscript, EA, AMC, MLR, ZA participated in the initial design and development of the Traditional Grain Mixtures Project and reviewed the draft manuscript. All authors read and approved the final manuscript for submission.

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Availability of data and materials
All the data have been included in the main paper and the appended supplementary material.

Declarations

Ethics approval and consent to participate
Prior to data collection, permission letters were obtained from the Department of Plant Biology and Biodiversity Management, the Ethiopian Biodiversity Institute, and the Agriculture and Administration Offices of Kalu and Tehuledere districts. Consent was also obtained from district officers, Kebele leaders, and agricultural development agents. Informed oral consent was secured from each respondent after explaining the research objectives, underlining that the findings would be used for academic purposes. Data were collected only after voluntary consent was unequivocally granted. At the end of the interview, the participants signed a declaration of consent, and the researchers published the data according to the principle of prior consent.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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