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Distribution, conservation, and indigenous knowledge of finger millet germplasm in different agroecologies in Uganda

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Introduction: Crop improvement is crucial in addressing food and nutritional security, as it requires a wide range of genetic diversity to serve as germplasm during breeding. Finger millet is an underutilized yet climate-resilient crop with valuable genetic variation that can be leveraged to enhance food security and improve nutritional quality.

Methods: This study examines varietal diversity, farmers' preferred attributes, varietal distribution, production environments, and traditional conservation practices of finger millet germplasm across six agroecological regions (Mid-Northern, Northern, West Nile farmlands; Southern dryland and highlands, Western highlands, and Karamoja drylands) in Uganda. Data was collected between June 2020 and February 2021 through household surveys, key informant interviews, and field observations.

Results: Most agroecologies were highly to moderately suitable for finger millet production, and farmers utilized traditional knowledge to select and conserve millet germplasm for present and future purposes. Over 90% of the varieties collected were landraces exhibiting wide variability, providing desirable traits necessary for improving finger millet. A total of 460 landrace accessions were collected, and 198 distinct local names were documented across ethnic groups, depending on morphology, maturity, and cultural significance. Farmer selection and conservation of finger millet focused on taste (38.6%), drought tolerance (31.9%), pest and disease tolerance (14.1%), and early maturity (12.4%), confirming the role of preferential traits in addressing food and nutrition security. Conservation practices include sharing seeds with neighbors or relatives, replanting stored seeds, and selecting and storing seeds in designated areas, such as farm stores or rooftops. Over 72.1% of the seed was from farmer-saved sources, underscoring the important role of farmers in maintaining varietal diversity. Correlation analysis showed significant associations between soil characteristics, agroecology, seed sources, and farmer preference. PCA grouped varietal adoption drivers into environment factors, market/consumption attributes, and seed system/conservation practices. However, threats such as labor demands, drought, pests, diseases, aging farmers, and the replacement of millet with maize and rice pose a risk of genetic erosion.

Conclusion: The abundance of landraces presents a rich genetic pool for breeding and conservation. Integrating both *in situ* and ex situ conservation strategies is recommended to safeguard finger millet diversity to support food and nutrition security.

KEYWORDS

diversity, finger millet varieties, land use, landraces, selection, traditional knowledge

1 Introduction

Climate variability, including increasing temperature, changing precipitation patterns, increased levels of CO_2 and ozone, increased acidity of agricultural soil, and drought, remains one of the major challenges affecting food security, not only by affecting crop yields directly but also by reducing the available agricultural land, water, and genetic diversity (Holleman et al., 2020; Khoury et al., 2022; Yadesa and Chalchisa, 2022; Meza-Joya et al., 2023). This is further exacerbated by the global population increase, which is anticipated to reach 10 billion by 2050, according to the United Nations Department of Economic and Social Affairs, Population Division (2022), underscoring the need for increased food production. To meet the global demand for food supply, a wide genetic diversity is required to develop better, high-yielding varieties that are tolerant to biotic and abiotic stresses (Yadesa and Chalchisa, 2022). However, crop domestication, which involves the selection of desirable traits, has led to a narrow genetic base in most commercially grown crops, exposing them to the impact of climate change (Smỳkal et al., 2018). Traditional landraces and their weedy relatives are a rich reservoir of useful genetic diversity for coping with biotic and abiotic stresses, and their conservation is necessary for future crop improvement to ensure food and nutrition security (Tamiru and Abdela, 2021). These traditional crops play a major role in the sustainability of the agroecosystems and the conservation of indigenous knowledge for generations (Bisht et al., 2022). Unfortunately, traditional crops are often neglected, receiving minimal research effort and conservation measures, which makes them prone to genetic erosion despite being an important source of food, nutrition, and income security for farmers living in marginal environments.

Finger millet, {*Eleusine coracana* (L.) Gaertn; $2n = 4\times = 36$}, is an important traditional and underutilized crop that farmers have conserved for decades (Hamba et al., 2024). Considered one of the oldest cereals to be domesticated in Africa, about 5,000 years ago (Joshi et al., 2021), the crop is believed to have originated from Uganda and Ethiopia in East Africa (National Research Council, 1996; Joshi et al., 2021; Joshi et al., 2023). Due to its wide adaptability, finger millet is grown in all the agroecologies of Uganda, mainly on a subsistence scale by smallholder farmers (Wanyera, 2005; Owere et al., 2014; Adikini et al., 2021). The crop holds strong cultural significance among different ethnic groups in Uganda, thereby embodying rich indigenous knowledge (Wanyera, 2005; Hamba et al., 2024). However, a lack of information on land suitability limits the expansion of crop production across agroecologies, with most farmers utilizing marginal land, thereby impacting the yield harvested. Analyzing land suitability across Ugandan agroecologies would help identify the limiting factors for finger millet production and guide the development of crop management practices that increase land productivity (Narayanaswamy et al., 2017).

Being an ancient crop, finger millet is thought to harbor a diversity of useful genes with the potential to address biotic, abiotic, and nutritional challenges in the face of climate change (Priyanka et al., 2021). Nutritionally, finger millet is a rich source of protein, especially methionine and lysine, which are lacking in most starchy diets like cassava (*Manihot esculenta* Crantz), maize (*Zea mays* L.), and banana (*Musa acuminata*; Chandra et al., 2016; Pandian et al., 2017; Wambi et al., 2021). The crop is a rich source of micronutrients, particularly calcium, iron, and zinc, and has a low glycemic index, making it suitable for individuals with diabetes and anemia. Therefore, it plays an important role in the diet of ordinary farmers (Mbithi-Mwikya et al., 2000; Kumar et al., 2016; Wambi et al., 2021). Further, the crop has almost no storage pests and can be kept for more than 10 years, making it a traditional component of farmers' risk avoidance strategy during drought periods (Sakamma et al., 2018; Adikini et al., 2021). The presence of useful genes in finger millet has also been demonstrated in other studies; for example, the presence of genotypes with early and vigorous growth, large panicle size, increased finger number and branching, as well as high-density grain, was reported (Gupta et al., 2017). Hatfield and Dold (2019) reported finger millet varieties with high water use efficiency (WUE), elevated carbon dioxide fixation rates, and minimal leaf area, which could make them perform extraordinarily well in semi-arid climates. While Gupta et al. (2014) and Gupta et al. (2017) reported varieties with high nitrogen use efficiency (NUE), the above genetic diversity of finger millet enables farmers to cope with the complex agricultural challenges that exist in their environment (Tsehaye et al., 2006). However, this rich genetic diversity is largely in the hands of ordinary farmers, whose priorities and farming interests are constantly changing, thereby increasing the risk of losing genetic material.

Despite being the primary center of finger millet diversity, Uganda conserves only a handful (approximately 1,000) of finger millet accessions at the Uganda National Gene Bank, and very few accessions are held in global gene banks (Upadhyaya et al., 2006; Wambi et al., 2021; Kasule et al., 2023). Most finger millet collections in the international gene bank are primarily comprised of landraces from India. The low level of collection and conservation of Ugandan germplasm is attributed to limited research investment and a lack of funding support from donors and the national government, leaving finger millet as an orphan crop (Kasule et al., 2023). This has increased the risk of genetic erosion (Priyanka et al., 2021) as well as loss of indigenous knowledge since farmers are shifting away from finger millet production to cultivation of crops that have better production technologies, like maize (Smỳkal et al., 2018; Tamiru and Abdela, 2021; Hamba et al., 2024; Khoury et al., 2022).

This situation is further worsened by the outbreak of finger millet blast disease and parasitic weed in most fields where finger millet is grown in Uganda, thereby accelerating the rate of genetic erosion (Takan et al., 2012; Mbinda et al., 2021). This calls for urgent strategies and efforts to ensure the proper conservation of diverse genetic material for future use in crop improvement, addressing food and nutritional security in the face of climate change.

Successful germplasm conservation requires knowledge of the crop's geographical distribution and diversity in each agroecology (Priyanka et al., 2021). According to Li et al. (2010)The geographical distribution of crop diversity is correlated with genes that enable adaptation to various areas, their ecological conditions, and different uses. In maize, for example, eco-geographical data associated with the origin of the accessions have proved useful in germplasm classification (Vilaró et al., 2020). However, no effort has been made to understand the distribution of finger millet landraces across agroecologies in Uganda. Other studies have found that topography, soil type, and water availability directly influence the choice of crops and farming techniques. According to Schmid and Schöb (2023), areas with fertile soils and ample rainfall tend to favor diverse crop cultivation, while arid regions favor drought-tolerant crops that can withstand harsh climatic conditions. This implies the need to collect and conserve finger millet germplasm in all agroecologies to diversify the sources of useful genes for future crop improvement.

Additionally, the socio-economic and cultural knowledge that guides the selection and retention of a given variety is a prerequisite for conserving germplasm. Studies have shown that farmers continue to grow specific landraces due to their special attributes, like taste, adaptability to environments, easy access to seeds, and overall resilience to shocks (Swiderska et al., 2011; Nakabonge et al., 2018; Hamba et al., 2024), and improved risk management (Swiderska et al., 2011; Mburu et al., 2016). The precious indigenous knowledge from local communities that traditionally cultivated this crop in Uganda has never been adequately captured. Through indigenous knowledge, farmers recognize the need for a constant and diverse supply of germplasm to meet their household needs and livelihoods. Such knowledge will not only give ideas about the best ways of maintaining the genetic diversity of the crops, but also the potential utilization options (Salgotra and Gupta, 2016). In addition, through indigenous knowledge, farmers have developed systems for naming and classifying local varieties (Tsehaye et al., 2006; Nakabonge et al., 2018; Bernis-Fonteneau et al., 2023). Varietal naming may reflect the cultural values, the place of origin, the person who introduced the variety, or the special agronomic attributes of the variety (Tsehaye et al., 2006; Nakabonge et al., 2018; Bernis-Fonteneau et al., 2023). Knowledge of local nomenclature and folk taxonomy is essential for systemic germplasm collection and helps develop an ex-situ conservation scheme for farmers' varieties. Ex-situ conservation refers to the preservation of genetic resources outside their natural habitats, typically in seed banks, seed vaults, or botanical collections (Engelmann and Engels, 2002).

This study was therefore designed to understand the suitability of land for finger millet production, the distribution and diversity of landraces, the indigenous knowledge that guides the production and retention of landraces by farmers, and the threats to germplasm conservation in different agroecologies in Uganda. The findings from this study will guide genetic diversity studies on this crop and help formulate sustainable production and conservation strategies, both *in situ* (on-farm) and ex situ.

2 Materials and methods

2.1 Study area

The study was conducted in Uganda, located between latitudes 4°12′N and 12°9′S and longitudes 29°34′W and 35°0′E. Six agroecological zones were selected based on their history of finger millet production in the country, and these included: (i) Southern dryland and highlands agr-ecology, also known as the Albertine region. Four districts from this agro-ecology, including Masindi, Kikuube, Kagadi, and Kakumiro, were surveyed. (ii) Mid-Northern farmland agroecology, also called the Acholi subregion. Three districts, which included Gulu, Pader, and Kitgum, were selected. (iii) Northern farmland agro-ecology, also known as the Lango subregion. In this region, a total of four districts were selected, including Kole, Lira, Dokolo, and Alebtong. (iv) West Nile farmlands, also called the West Nile region. The study was conducted in the districts of Nebbi, Zombo, Arua, Madi-Okollo, Pakwach, Yumbe, Koboko, Maracha, Moyo, and Adjumani in this region. (v) In the Western highlands, sometimes called the Ankole region, sampling was done in the districts of Mbarara, Isingiro, Bushenyi, Ibanda, Mitooma, Sheema, and Rubirizi. (vi) Karamoja dry land agrocologies, where sampling was done in the districts of Abim, Nakapiripirit, and Napak (Figure 1). The eastern agroecological zone was excluded from the study because previous studies have already been conducted in this region. Finger millet accessions from this region have been characterized and are available at the NaSARRI gene bank, Serere, Uganda (Adikini et al., 2021). The respective districts were selected because they are among the districts with the highest finger millet production in the given agroecologies.

2.2 Study design

The study employed mixed-methods research, incorporating both qualitative and quantitative methods to capture the local varieties grown and traditional practices employed in the cultivation, use, and conservation of finger millet by farmers. The qualitative method involved key informant interviews and field observation, while the quantitative method involved the use of semi-structured questionnaires. Data collection was between June 2020 and February 2021.

2.3 Sampling strategy and data collection

Districts from the six agroecological zones were purposively selected based on the track record of growing finger millet. In each district, sub-counties were purposively selected based on their performance and history of millet cultivation, as obtained from the district production and marketing officers. In each of the chosen sub-counties, purposive simple random sampling was used to select farmers growing millet, employing the snowball method with the assistance of agricultural extension workers at each district who were familiar with the farmers and their fields. To minimize bias from purposive and snowball sampling, we ensured broad geographic coverage by sampling 5 to 7 sub-counties per district and selecting 4 to 6 villages per sub-county, each approximately 3 to 5 km apart. Farmers were chosen randomly to minimize bias and improve data representativeness. Respondents with experience in finger millet production were identified from a list of households compiled by village heads and interviewed using a semi-structured questionnaire. Finger millet farmers were informed about the purpose of the study and the use of their responses in a language they understood, and

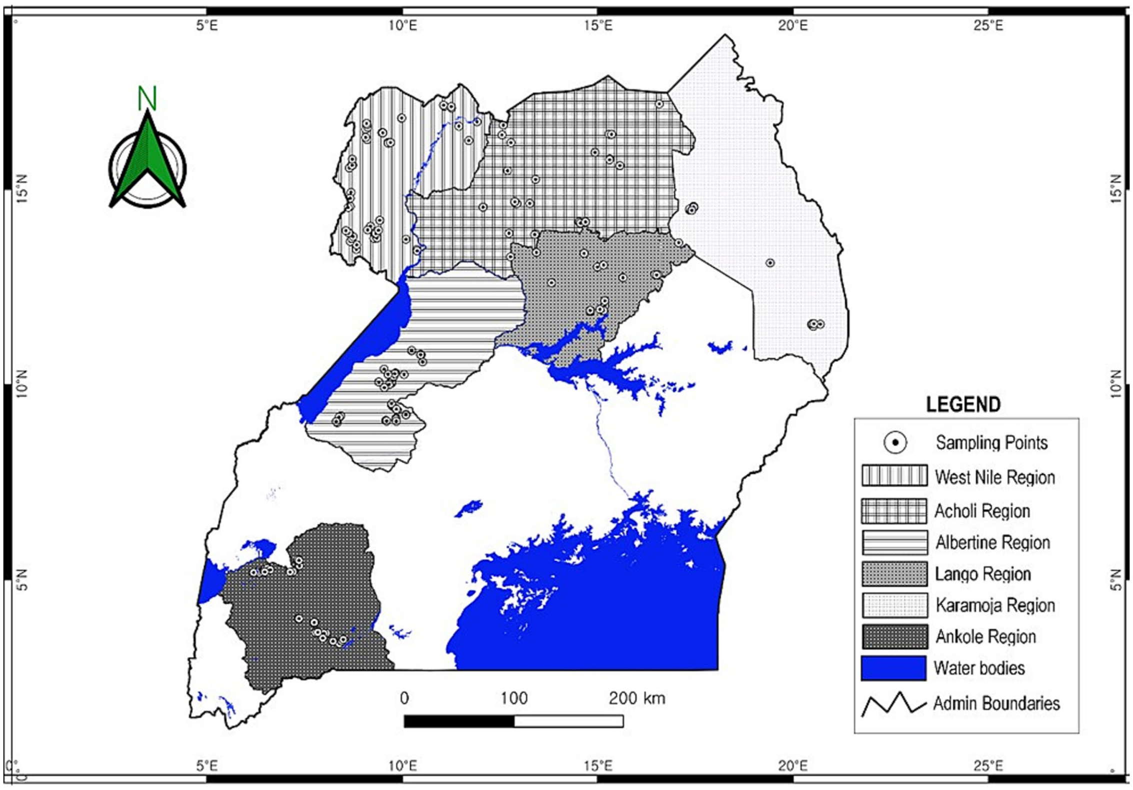

FIGURE 1
Location of the 6 agroecological zones of Uganda where the study was conducted.

they provided their consent willingly before data collection. Furthermore, for the participants who could not read and write, informed consent was sought verbally. A total of 428 farmers were interviewed using a semi-structured questionnaire across all the selected agroecological zones to record variables, which included: finger millet overall production, location coordinates, suitable areas, finger millet germplasm collections per region, local naming of finger millet and their meaning, farmer-preferred attributes per region, source of seed, and threats to finger millet production. Finger millet land races/varieties were recorded as named by farmers in their native languages, along with the meanings of these names for the different ethnic groups across all the selected agroecological zones. The survey team visited the fields where finger millet was grown and recorded attributes such as the physical properties of the soil (soil drainage, texture, stoniness, and topography) to identify the different soils used by farmers to grow this crop. In addition, the hand-texturing or feel method, adopted from Ritchey et al. (2015), was used to quickly assess and classify the textural characteristics of the soil samples from the surveyed farmers' fields (Opole et al., 2018). Laboratory validation of soils in the study areas was not conducted, as this study aimed to capture field-level observations of soils that support the cultivation of finger millet varieties in Uganda's diverse agroecologies. In farmer fields where finger millet had reached physiological maturity, we collected distinct panicles directly from the plants. In cases where farmers had already harvested their crops, we obtained dry panicles or clean seeds from them. These samples were obtained exclusively for conservation and documentation of landrace diversity.

2.4 Weather data extraction

The study utilized online satellite-based weather datasets accessed from the NASA Giovanni (Beaudoing et al., 2020) platform. First, the region of interest, i.e., the six agroecological zones of Uganda and the study period (June 2020–February 2021), was verified within the Giovanni interface as a basis for extracting specific weather parameters (precipitation, temperature, relative humidity, and wind speed) that contribute to finger millet production. Data in GeoTIFF raster format was generated and imported into QGIS (version 3.42.0) for geospatial processing. The coordinate reference system was reprojected to WGS 84 (EPSG: 4326) to ensure spatial coverage of all regions within Uganda and enhance data accuracy. Thereafter, raster files were converted to a vector format using the vector creation tool in QGIS. This process converted each raster cell into a polygon feature, with the corresponding raster value stored as an attribute in the output vector layer. The shapefiles of the 6 agroecological zones were spatially overlaid to extract weather attribute values corresponding to each region. All weather attribute values falling within each region were extracted using the field calculator tool. The extracted weather statistics were exported from QGIS as CSV files, which were subsequently compiled to generate the observed datasets (Table 1).

2.5 Assessment of land suitability

GIS-based mapping utilized historical weather and soil data to generate finger millet land suitability maps, incorporating topographic, climatic, and edaphic data sets (FAO, 1976, 2007). Soil data included raster files for soil pH, nitrogen, organic carbon, and topsoil texture at 0–15 cm from the SoilGrid version 2.0 program (Poggio et al., 2021); Topographic data was extracted from the Digital Elevation Model to determine slope and erosion potential (Reuter et al., 2009) as well as the Giovanni spatial database (Fick and Hijmans, 2017) was used to extract total annual rainfall and temperature raster files for the period 2021. The FAO (2022) Ecocrop model critical values were adopted and assigned weights based on crop requirements (Simard et al., 2024). In accordance with the FAO (1976) land suitability classification system, crop requirements were matched with topography, climate, and land attributes using a multicriteria decision-making process (FAO, 2007). The computed values for each parameter provided potential land units for finger millet production, enabling the generation of suitability maps (FAO, 1976).

2.6 Data analysis

The collected data was exported into Microsoft Excel (Microsoft Corporation 2016) for cleaning. The data were coded and analyzed using the Statistical Package for the Social Sciences (IBM SPSS version 29.0, 2022), employing descriptive statistics. Multiple response data for finger millet farmer-preferred attributes per region were grouped using the multiple response command in SPSS. Data were presented as frequencies, percentages, and crosstabs, while finger millet local varieties were listed using ethnic names provided by the farmers. Pearson chi-square tests were used to analyze relationships between variables to make statistical inferences at a 0.05 significance level. The varietal diversity of the collected finger millet germplasm was estimated using the Shannon-Weaver diversity index (H; Jain et al., 1975). A generalized linear model (GLM) was employed to investigate the factors influencing farmers' adoption decisions. The model was expressed as: $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon$.

Where:

Y: Variety Adoption is the dependent variable representing the adoption level of finger millet landraces by farmers in different agroecologies.

β_0: Intercept (baseline adoption level when all predictors are zero).

$\beta_1, \beta_2, \ldots, \beta_n$: Coefficients representing the effect of each predictor on variety adoption.

$X_1, X_2, \ldots, X_n$: Predictor variables like Special variety attributes, Soil Texture, Source of Seed, Soil Drainage, Soil Topography, among others.

ε: Error term accounting for unexplained variability.

Additionally, Pearson Correlation analysis was conducted using JMP Student Edition 19 to determine the relationships among the factors that drive finger millet adoption, at a significance level of $p < 0.05$. Principal Component Analysis (PCA) was also performed in JMP, retaining principal components with eigenvalues equal to or greater than 1.

3 Results

3.1 Weather parameters across agroecological zones

The weather conditions varied across the six agroecological zones during the June 2020 and February 2021 data collection period (Table 1). The total precipitation was highest in the West Nile farmland (690 mm) and lowest in the Karamoja drylands (411 mm). The Southern drylands and highlands, as well as the Western highlands, received moderate rainfall, at 533 mm and 535 mm, respectively. The average monthly wind speed also differed among agroecological zones, ranging from 3.60 m/s to 4.38 m/s in the Karamoja drylands. Average monthly surface air temperatures varied from 20.5 °C in the Western highlands to 23.5 °C in West Nile farmland. Relative humidity showed notable diurnal variations, with daytime humidity reported to be lowest in the Karamoja drylands (45%) and highest in the southern drylands and highlands (63.7%), while nighttime humidity increased across all the agroecological zones, from 72.4% in Karamoja drylands to 83.9% in southern drylands and highlands (Table 1).

3.2 Land suitability for finger millet production in different agroecologies in Uganda

A total of 167,583 km² of land was analyzed for finger millet production across all zones, using the established criteria. Out of this, the information generated showed that most of the land areas in the Southern highlands (92.0%), Northern farmland (96.4%), and mid-Northern agro-ecological zones (99.4%) are highly suitable for finger millet production (Table 2). Most of the land areas in Karamoja drylands (45.9%), Western highland (35.6%), and West Nile farmlands (23.0%) agro-ecological zones are moderately suitable for finger millet production. Marginally suitable land for finger millet production was slightly higher for Western agroecologies (1.7%), followed by

TABLE 1 Summary of weather parameters recorded across six agroecological zones of Uganda between June 2020 and February 2021.

Regions	Total precipitation (mm)	Av. monthly wind speed (m/s)	Av. monthly surface air temperature (°C)	Av. daily day relative humidity (%)	Av. daily night relative humidity (%)
Mid-Northern farmland (Acholi)	638	3.68	23.35	49.01	73.17
Southern dryland and highlands (Albertine)	533	4.03	23.41	63.73	83.85
Western highlands (Ankole)	535	3.79	20.52	58.92	79.50
Karamoja drylands	411	4.38	21.73	45.02	72.40
Northern farmlands (Lango)	608	4.20	23.27	46.89	73.71
West Nile farmland	690	3.60	23.47	51.35	75.59

Karamoja dry land (0.6%). At the same time, Southern, mid-Northern, and Northern farmland did not have any marginal land (Table 2). These results are further illustrated in Figure 2, which utilizes the GIS map for all six agroecologies.

3.3 Soil characteristics of the finger millet production environment across agroecologies

Three physical properties (drainage, soil types, and soil stoniness) were used to characterize the environment in which finger millet is grown in farmers' fields across six agroecologies. The observations from farmers' fields growing finger millet showed significant differences ($p < 0.001$) in soil characteristics across the different agroecological zones, including drainage ($\chi^2 = 266.32$), texture ($\chi^2 = 457.59$), stoniness ($\chi^2 = 192.8$), and topography ($\chi^2 = 188.24$; Table 3). In terms of soil drainage, most finger millet fields had good drainage except for the mid-northern and northern agroecologies that had moderate soil drainage (Table 3). A smaller proportion of fields in the southern (3.9%), Karamoja (5.7%), Northern (4.3%), and West Nile (1.3%) regions had very poor soil drainage systems. Overall, soil from the Western region had the best drainage, followed by West Nile farmlands, Southern drylands and highlands, and Mid-northern agroecological zones.

In terms of soil texture, finger millet was found to grow well in a diverse range of soil environments. In Karamoja, the southern highlands, West Nile, and western agroecologies, finger millet was predominantly grown in loam soil. In contrast, in mid-northern and northern agroecologies, the crop was grown mainly in sandy loam soil. The soil texture profile revealed that Karamoja drylands, Southern drylands and highlands, and West Nile farmlands have loam soils. In contrast, the Northern, mid-Northern, and Western agroecological zones have sandy loam soils. For the case of West Nile and western agroecologies, finger millet was also found to grow in various soil types, including clay, sandy clay, sandy loam, and silty loam, to a lesser extent (Table 3). The fields were also assessed for stoniness, and most fields across the six agroecologies had no or very low levels of stoniness (Table 3). Lower proportions of fields <9% across agroecologies were observed with a medium level of stones, while only 2.6% of fields in the West Nile were rocky. In terms of topography, most finger millet fields across agroecologies had a plain type of topography, except for southern, West Nile, and western agroecologies, where diverse topographies were observed. In the southern, western Nile, and western agroecologies, in addition to plains, finger millet was observed to grow on hills, undulating land, floodplains, and low topography (Table 3). The plain level was the major topography property for all the sampled agroecological regions (Table 3).

3.4 Farmer experience in finger millet cultivation

This study found that most farmers (over 52%) in the Northern, Mid-Northern, and West Nile regions have over 50 years of experience in finger millet cultivation, while in the southern and western agroecologies, most farmers have between 31 and 50 years of experience (Figure 3). Very few farmers have less than 10 years of experience in most agroecologies, except in Karamoja, where the majority of farmers fall into this category (Figure 3).

3.5 Distribution and diversity of finger millet varieties from farmers in different agroecologies in Uganda

A total of 460 finger millet accessions were reported by farmers and seeds collected for conservation at the National Semi-Arid Resources Research Institute (NaSARRI), Serere, Uganda (Table 4), and subsequently duplicated at the Uganda National Gene Bank (UNGB) in Entebbe. Of these, 147 were collected from Western, 35 from Karamoja, 47 from Northern (Lango), 86 from West Nile, 82 from Southern (Albertine), and 63 from mid-northern (Acholi) agroecologies/regions (Table 4; Figure 1). Variety diversity varies with agroecologies based on the names shared by farmers. The highest variety diversity was recorded in western agroecologies (53), followed by West Nile (52), and the least was Karamoja (17) (Table 4). Across the surveyed agroecological zones, significant differences ($\chi^2 = 159.41$, $p < 0.001$) were observed in the distribution of germplasm types (Table 5). Over 96% of diverse finger millet varieties across agroecologies were landraces, except in Karamoja, where landraces contributed only 47%. The rest were commercial varieties, a small proportion of breeding lines, and wild relatives (Table 5).

3.6 Finger millet variety naming by farmers and their meaning

Out of 460 finger millet varieties collected from farmers, 77.6% (357) of finger millet varieties had distinct local names, while the

TABLE 2 Land suitability for finger millet production in different agroecologies of Uganda.

Agroecologies	Total land area (km^2)	Land suitability (%)		
		Highly suitable	Moderately suitable	Marginally suitable
Mid northern	12,780	99.4	0.6	0.0
Western	39,266	62.8	35.6	1.7
Southern	16,594	92.0	8.0	0.0
Karamoja	27,341	53.5	45.9	0.6
Northern	56,118	96.4	3.6	0.0
West Nile	15,484	76.2	23.5	0.3

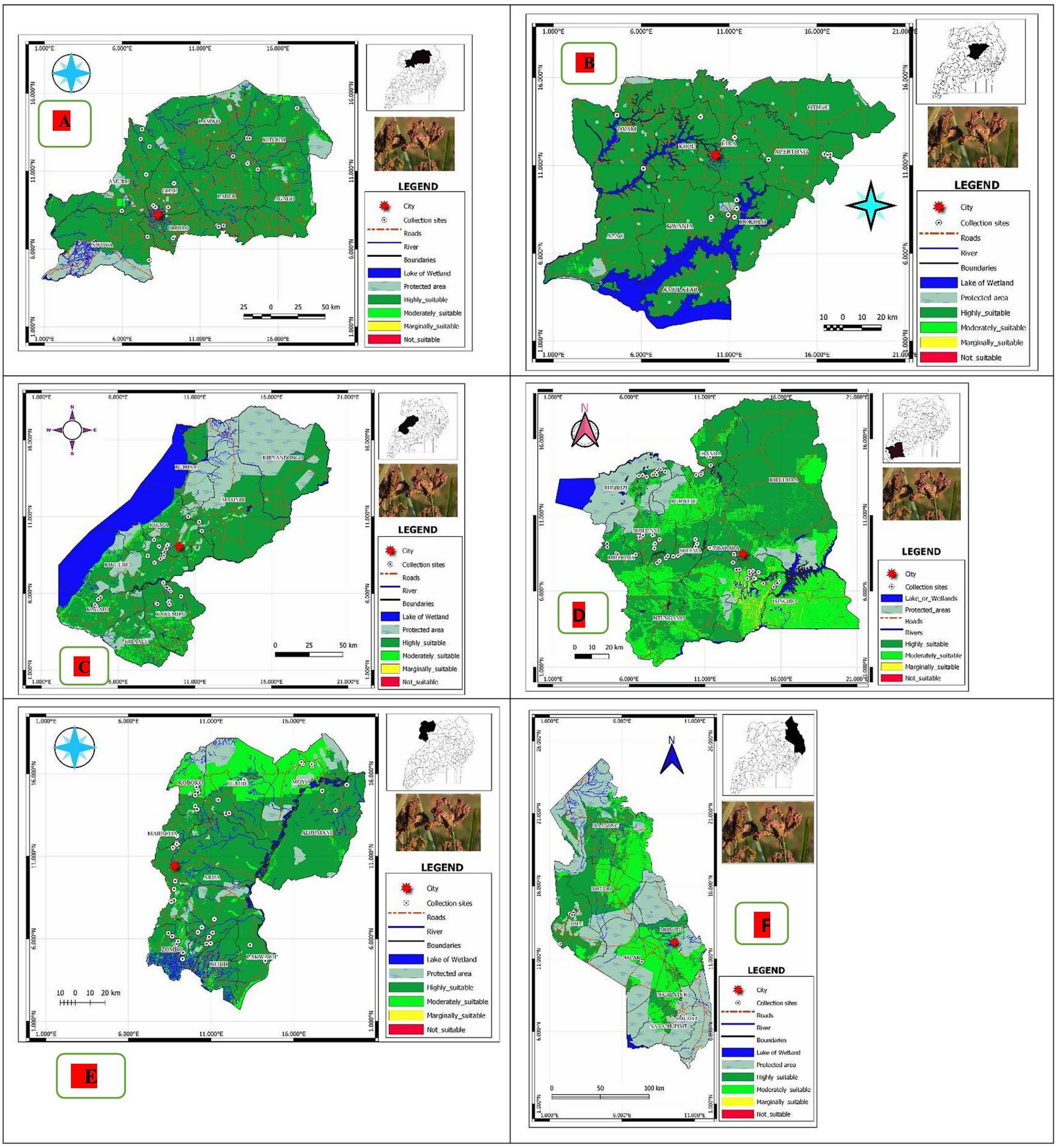

FIGURE 2
Potential production areas and sample collection points for finger millet in the selected region of Uganda: Mid-Northern **(A)**, Northern **(B)**, Southern drylands and highlands **(C)**, Western highland and drylands **(D)**, West Nile **(E)**, and Karamoja **(F)**.

remaining 22.4% (103) millet varieties did not have specific local names; instead, they were generalized as millet, but in the local dialect of different ethnic groups (Supplementary Table S1). Among the Banyankole, Bakiga, and Banyoro, finger millet is called Oburo; among the Acholi, Lango, and Alur, it is called Kal; while among the Lugbara, Kakwa, and Madi, they call millet Anyaa. From this study, it was observed that farmers name finger millet varieties based on morphological traits, maturity periods, color, place of origin, person or organization that introduced the variety, taste, and cooking characteristics (Supplementary Table S1). The variety naming is very distinct and unique to each agroecology and among ethnic groups, except in a few cases where the variety name and meaning are shared across agroecologies, for example, variety Nyaemve (meaning white millet) in the West Nile and Albertine region, Adoke (meaning birds do not eat) in Acholi and Karamoja region, Lawatimia (meaning good to have relatives because they give things), and Odyera (meaning mixtures of friends) in Lango and Acholi region (Supplementary Table S1). On the other hand, some varieties were found to have similar names with different meanings in different agroecologies. For example, the variety Kabumbli, which means

TABLE 3 Properties of the soil used for finger millet cultivation in six agroecological zones of Uganda.

Soil property	Agroecological zone						Mean	Df	Chi-square	*p-value*
	Mid-northern (%)	Southern (%)	Karamoja (%)	Northern (%)	West Nile (%)	Western (%)				
Soil drainage										
Good	28.6	63.6	60	0	75	98.9	54.4	15	266.32	<0.001
Medium	0	11.7	0	0	0	0	2.0			
Moderate	71.4	20.8	34.3	95.7	23.7	1.1	41.2			
Poor	0	3.9	5.7	4.3	1.3	0	2.5			
Soil Texture										
Clay	0	0	0	0	2.6	21.5	4.0	35	457.59	<0.001
Loam	7.9	84.2	100	0	81.6	49.5	53.9			
Sand	0	0	0	0	0	1.1	0.2			
Clay Loam	0	0	0	0	1.4	0	0.2			
Sandy Clay	0	0	0	0	10.5	0	1.8			
Sandy Loam	92.1	15.8	0	100	3.9	24.7	39.4			
Silty Loam	0	0	0	0	0	3.2	0.5			
Stoniness										
Low	74.6	80.8	77.1	72.3	64.5	29	66.4	20	192.8	<0.001
Medium	6.3	5.1	0	6.4	21.1	9.7	8.1			
Moderate	0	7.7	0	0	0	0	1.3			
None	19.1	6.4	22.9	21.3	11.8	61.3	23.8			
Rocky	0	0	0	0	2.6	0	0.4			
Topography										
Flood plain	0	0	0	0	1.3	3.2	0.8	25	188.24	<0.001
Hilly	0	20.5	0	0	13.3	36.6	11.7			
Low	0	0	0	0	1.3	0	0.2			
Plain Level	100	76.9	100	100	72.1	49.5	83.1			
Undulating	0	2.6	0	0	12	10.7	4.2			

Df = Degrees of Freedom, and *p*-value indicates the probability of obtaining observed results, assuming the null hypothesis is true.

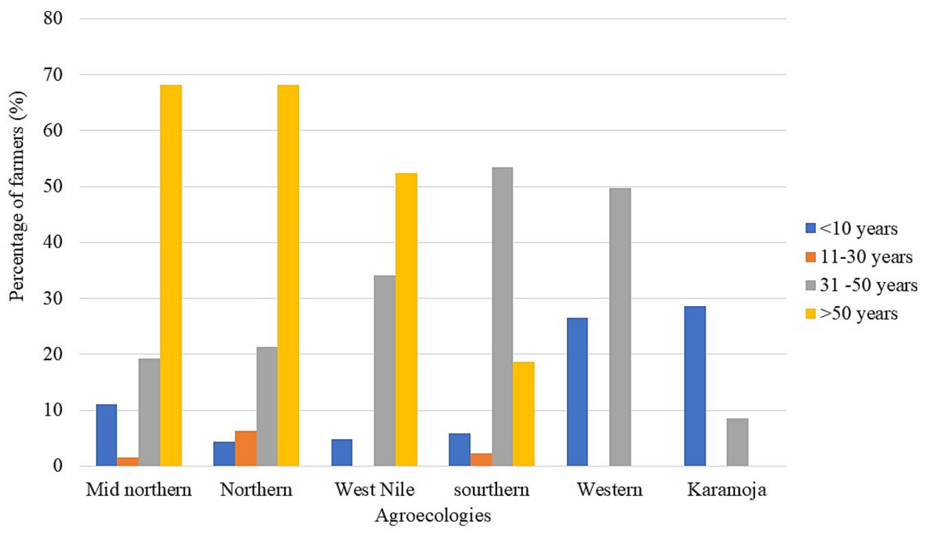

FIGURE 3
Farmer experience in finger millet cultivation across agroecologies in Uganda.

TABLE 4 Distribution and diversity of finger millet varieties across agroecologies.

Agroecologies	Total number of finger millet varieties collected	varieties with local names	Variety diversity index across agroeologgies
Western highland	147	119	3.64
Southern highland	82	41	3.42
Northern farmland	47	45	2.93
mid-Northern	63	61	2.43
West Nile farmlands	86	57	3.56
Karamoja dry land	35	34	3.23
Total	460	357 (77.6%)	

The Variety Diversity index across agroeologgies was calculated based on the Shannon-Wiener diversity index.

"compact head" in the western region, has a different meaning in Albertine, where it refers to "early maturing with compact head." Variety Okama in Karamoja refers to quick maturity, whereas in Lango, it denotes a white color (Supplementary Table S1).

3.7 Seed sources and conservation practices for finger millet among farmers in Uganda

Significant differences ($\chi^2 = 381.54$, $p < 0.001$) were observed in seed sources among farmers across the different agroecological zones (Table 6). Over 70% of farmers across agroecologies store their own seed, which they recycle every season, except in the Karamoja region, where only 20% use their own saved seed (Table 6). Some farmers, however, buy seed from the market or obtain seed from neighbors and relatives within the same village or neighboring villages. For the Karamoja region, over 60% of the finger millet seeds used by farmers were sourced and distributed by NGOs (Table 6). Very few farmers in the southern agroecology reported obtaining seed from a research station. In terms of seed conservation, the practices for conserving finger millet germplasm varied significantly ($\chi^2 = 126.94$, $p < 0.001$) among the different farmers in six agroecological zones (Table 7). Finger millet farmers have, over the years, developed innovative ways of conserving seeds. In this study, we found that farmers maintain their seeds through regular planting in the field or in their backyards, proper drying in the drying yard, and storage is done on rooftops and in stores, including traditional granaries (Table 7).

3.8 Varietal adoption and farmer preferences for cultivation and selection of finger millet across regions

The attributes that farmers consider when selecting finger millet germplasm varied significantly ($\chi^2 = 846.3$, $p < 0.001$) across agroecological zones (Table 8). Generally, the reasons driving farmers' adoption and cultivation of finger millet in the surveyed regions of Uganda include taste, drought resistance, pest/disease resistance, early maturity, cooking quality, richness in iron, less damage by birds, and aroma (Table 8). Drought resistance was the highest-ranked reason for adoption of finger millet accessions in the Southern drylands and highlands (Albertine) (98.5%) and Northern (Lango) regions (57.8%). In comparison, taste was the highest-ranked attribute for Western agroecologies (82.8%) and the West Nile region (77.6%) (Table 8). Pest and disease resistance is the preferred finger millet attribute in mid-northern agroecology, while early maturity ranked high in Karamoja dry lands (74.3%). Aroma, less damage by birds, and richness in iron were the least ranked attributes for the adoption of finger millet accessions in the surveyed regions. We employed a Generalized Linear Model (GLM) to assess the factors influencing farmers' adoption of finger millet (Table 9). The analysis revealed that soil texture ($F = 5.1$, $p < 0.001$), special varietal attributes ($F = 4.1$, $p < 0.001$), source of seed ($F = 4.8$, $p < 0.001$), soil topography ($F = 2.8$, $p = 0.017$), and soil drainage ($F = 3.1$, $p = 0.027$) significantly influence finger millet varietal adoption (Table 8). In contrast, stoniness ($F = 2.1$, $p > 0.05$), sample status ($F = 1.0$, $p > 0.05$), and collection source ($F = 0.77$, $p > 0.05$) did not significantly influence varietal adoption (Table 9).

3.9 Market segments and multivariate relationships influencing finger millet adoption

Finger millet was predominately grown for household food consumption (86.3%) while a smaller proportion was grown for beverage production (6.2%), brewing (5.2), or dual purposes (2.3%) (Figure 4). The correlation analysis showed significant associations among several factors influencing finger millet production and adoption across agroecologies in Uganda (Table 10). Agroecology showed positive significant correlations with collection source ($r = 0.48$, $p < 0.001$), soil stoniness ($r = 0.22$, $p < 0.001$), and seed source ($r = 0.19$, $p < 0.001$) while showing significant negative correlations with soil topography ($r = -0.21$, $p < 0.001$), soil texture ($r = -0.59$, $p < 0.001$), and soil drainage ($r = -0.48$, $p < 0.001$). Soil characteristics, including texture, drainage, and stoniness, were significantly interrelated ($p < 0.001$). Market segments were positively correlated with preferred varietal attributes ($r = 0.22$, $p < 0.001$) and negatively associated with seed source ($r = -0.1$, $p < 0.05$; Table 10).

The patterns of variation and relative importance of each factor that drive the adoption of finger millet in Uganda were assessed through principal component analysis (PCA). Each eigenvalue for the first four principal components (PC) was ≥1.0 and cumulatively contributed to 62.1% of the total variation (Table 11). PC1 accounted for 25.2% and was primarily associated with agroecology, soil texture, and soil drainage, while PC2 explained 14.5% of the total variation and was correlated to market segments and preferred varietal attributes. PC3 (12.5%) was associated with sample status, soil stoniness, and seed collection source, while PC4 (9.99%) was associated with Sample status and soil topography (Table 11). The first two PCs, PC1 and PC2, were plotted in a PCA biplot (Figure 5) to show the relative contributions of the different factors that drive the adoption of finger millet in Uganda.

TABLE 5 Profile of finger millet germplasm collected across the six agroecological zones of Uganda.

Sample status	Agroecological zone						Mean	Df	Chi-square	*p*-value
	Mid-northern (%)	Southern (%)	Karamoja (%)	Northern (%)	West Nile (%)	Western (%)				
Breeder's line	0	2.4	5.3	0	0	0	1.3	25	159.412	<0.001
Commercial variety	0	0	21.1	0	1.3	0	3.7			
Landrace	96.8	97.6	47.3	100	98.7	100	90.1			
NGO	0	0	26.3	0	0	0	4.4			
Wild	3.2	0	0	0	0	0	0.5			

Df, Degrees of Freedom, *p*-value indicates the probability of obtaining observed results, assuming the null hypothesis is true.

TABLE 6 Finger millet seed sources in the six agroecological zones of Uganda.

Seed source	Agroecological zone						Mean	Df	Chi-square	*p* value
	Mid-northern (%)	Southern (%)	Karamoja (%)	Northern (%)	West Nile (%)	Western (%)				
Bought	0	0	0	0	0	4.2	0.7	40	381.543	<0.001
Friends	0	0	0	0	1.4	0	0.2			
Local market	0	16.2	0	0	7	7.6	5.1			
Neighboring village	1.6	5.4	2.9	2.1	11.3	2.5	4.3			
NGO	0	1.4	68.6	0	0	0	11.7			
Own saved seeds	95.2	74.4	20	89.4	76.1	78.2	72.1			
Bulindi ZARDI	0	2.7	0	0	0	0	0.5			
Within the village	3.2	0	8.6	8.5	4.2	7.6	5.4			

Df, Degrees of Freedom, *p*-value indicates the probability of obtaining observed results, assuming the null hypothesis is true.

TABLE 7 Finger millet germplasm conservation practices for the different farmers in six agroecological zones of Uganda.

Collection source	Agroecological zone						Mean	Df	Chi-square	*p* value
	Mid-northern (%)	Southern (%)	Karamoja (%)	Northern (%)	West Nile (%)	Western (%)				
Backyard	0	1.3	0	0	0	0.7	0.3	35	126.938	<0.001
Drying yard	0	0	0	0	0	6.3	1.1			
Farmland	36.5	40.7	14.3	23.4	29.9	3.5	24.7			
Farm store	58.7	54.3	80	76.6	68.8	89.5	71.3			
Local market	0	3.7	0	0	1.3	0	0.8			
On the rooftop	0	0	5.7	0	0	0	1			
Village Market	1.6	0	0	0	0	0	0.3			
Wild/ Natural vegetation	3.2	0	0	0	0	0	0.5			

Df, Degrees of Freedom; *p*-value indicates the probability of obtaining observed results, assuming the null hypothesis is true.

3.10 Threats to finger millet germplasm conservation by farmers in different agroecologies

This study identified several threats to finger millet production and conservation among farmers in various agroecologies. In western highland agroecologies and West Nile farmland, the labor-intensive nature of finger millet, from land preparation to weeding, harvesting, and post-harvest handling processes, was identified as the number one major threat to the conservation of finger millet in both agroecologies (Figure 6). Farmers mentioned that they are shifting their focus to the production of crops like maize and rice that have better production

TABLE 8 Attributes that farmers put into consideration when selecting finger millet germplasm in six agroecological zones of Uganda.

Special Variety attributes	Agroecological zone						Mean	Df	Chi-square	*p.* value
	Mid-northern (%)	Southern (%)	Karamoja (%)	Northern (%)	West Nile (%)	Western (%)				
Aroma	0	0	0	0	1.5	0	0.3	40	846.299	<0.001
Cooking quality	0	0	0	0	6	5.7	2.0			
Drought tolerance	14.3	98.5	0	57.8	11.9	8.6	31.9			
Less damage from birds	0	0	0	0	0	2.9	0.5			
Pest/disease resistance	71.4	0	0	13.3	0	0	14.1			
Quick maturity	0	0	74.3	0	0	0	12.4			
Richness in Iron	0	0	0	0	3	0	0.5			
Taste	14.3	1.5	25.7	28.9	77.6	82.8	38.5			

Df, Degrees of Freedom; *p*-value indicates the probability of obtaining observed results, assuming the null hypothesis is true.

TABLE 9 Factors influencing varietal adoption in finger millet cultivation and conservation.

Source	SS	Df	MS	F	Sig.
Corrected model	887961.568	46	19303.51	5.726	<0.001
Intercept	47176.843	1	47176.84	13.995	<0.001
Sample status	13570.488	4	3392.622	1.006	0.404
Collection source	15508.055	6	2584.676	0.767	0.596
Topography	46883.955	5	9376.791	2.782	0.017
Soil texture	120747.243	7	17249.61	5.117	<0.001
Stoniness	28312.909	4	7078.227	2.1	0.08
Soil drainage	31148.736	3	10382.91	3.08	0.027
Special variety attributes	112762.192	8	14095.27	4.181	<0.001
Source of seed	128422.097	8	16052.76	4.762	<0.001
Error	1361880.693	404	3370.992		
Total	5,708,676	451			
Corrected total	2249842.262	450			

SS, Sum of Squares; Df, Degrees of Freedom; MS, Mean Square; F, F-statistic; Sig. = Significance indicates the probability of observing the obtained F-statistic.

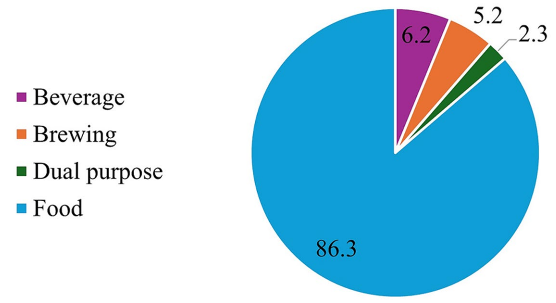

FIGURE 4
Primary purposes for growing finger millet among the surveyed areas.

technologies. Pests and drought ranked second, followed by flood, poor-yielding variety, poor soil fertility, and limited land availability (Figure 6). In Northern and mid-northern agroecologies, drought ranked number one threat to finger millet production and conservation. This was followed by the labor-intensive nature of finger millet production, the lack of improved seed, poor-yielding varieties, and limited land availability, particularly in the case of northern agroecologies. Additionally, in the mid-northern region, farmers cite *Striga* weed, labor intensiveness, floods, poor soil fertility, and the advanced age of most finger millet farmers, as well as the production of other crops, especially rice, as additional factors threatening the production of finger millet. In the Albertine region, pests are ranked as the number one threat to finger millet production. This is followed by the production of poor-yielding varieties, the cultivation of alternative crops, limited land availability, drought, and labor intensiveness (Figure 6).

4 Discussion

4.1 Implications of weather parameters across agroecological zones

The observed variation in weather conditions suggests that finger millet can grow in diverse environments across agroecologies in Uganda, ranging from semi-arid areas, such as the Karamoja drylands, to more subhumid regions (Table 1), including the southern drylands and highlands. The low rainfall and humidity recorded for the Karamoja drylands confirm the semi-arid nature of this region and the suitability of finger millet as a drought-tolerant crop, consistent with previous studies (Gupta et al., 2017; Rakkammal et al., 2023). By contrast, moderate rainfall and humidity in the West Nile farmland, southern drylands, and highlands, and the Western highlands are

TABLE 10 Correlation between several factors influencing finger millet adoption.

Factor	Agroecology	Collection Source	Sample Status	Soil Topography	Soil Texture	Soil Stoniness	Soil Drainage	Market Segments	Preferred Attributes	Seed Source
Agroecology	1.00									
Collection Source	0.48***	1.00								
Sample Status	−0.08	0.14**	1.00							
Soil Topography	−0.21***	−0.06	−0.01	1.00						
Soil Texture	−0.59***	−0.37***	0.10	0.15**	1.00					
Soil Stoniness	0.22***	0.20***	0.08	0.01	−0.11*	1.00				
Soil Drainage	−0.48***	−0.14**	0.08	0.23***	0.48***	−0.16**	1.00			
Market Segments	−0.09	−0.14**	−0.03	0.08	0.01	0.23***	−0.14**	1.00		
Preferred Attributes	0.01	−0.02	−0.11*	−0.07	−0.05	0.12*	−0.15**	0.22***	1.00	
Seed Source	0.19***	0.03	−0.05	−0.12*	−0.11*	−0.01	−0.15**	−0.10*	0.04	1.00

*Significant at the 0.05 probability level, **Significant at the 0.01 probability level, ***Significant at the 0.001 probability level.

TABLE 11 The proportion and variation explained for the factors influencing finger millet cultivation in Uganda.

Variable	PC1	PC2	PC3	PC4
Agroecology	**0.54**	−0.12	0.03	−0.13
Collection source	0.37	−0.26	**0.41**	−0.09
Sample status	−0.05	−0.19	**0.54**	**0.60**
Soil topography	−0.22	0.08	0.30	**−0.60**
Soil texture	**−0.50**	0.04	0.03	0.26
Soil stoniness	0.21	0.34	**0.48**	0.13
Soil drainage	**−0.44**	−0.20	0.16	−0.03
Market segments	−0.01	**0.66**	0.14	0.02
Preferred attributes	0.09	**0.51**	−0.17	0.19
Seed source	0.18	−0.12	−0.39	0.36
Eigenvalue	2.52	1.45	1.25	1.00
Proportion explained (%)	25.15	14.46	12.53	9.99
Cumulative proportion (%)	25.15	39.61	52.14	62.13

PC, principal component. Boldface values denote high score values, indicating the most relevant factors (>**0.40**) that contributed to the variation of the components.

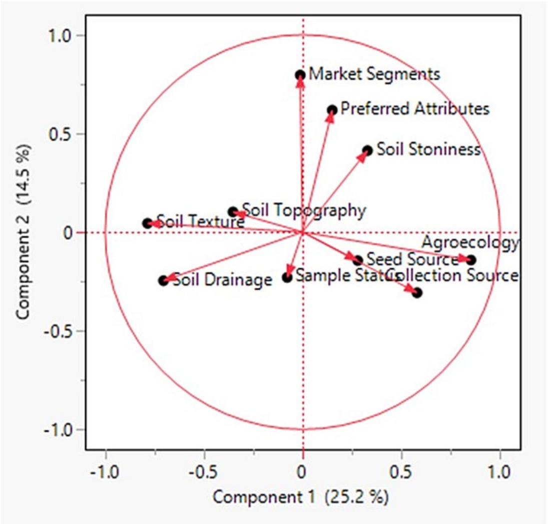

FIGURE 5
Principal component analysis (PCA) biplot showing the relative contributions of factors influencing finger millet adoption in Uganda.

consistent with studies indicating that these zones have more favorable conditions for growing finger millet (Kasule et al., 2023; Hamba et al., 2024). The temperature across agroecological zones fell within the optimal range for finger millet growth (20–24 °C), although the crop can withstand cooler or hotter conditions (Dida and Devos, 2006). The high wind speeds, coupled with low humidity, were observed in the Karamoja drylands, which increases evaporation and explains the available water stress often associated with this region, a pattern consistent with reports from other semi-arid finger millet-growing regions in East Africa (Opole et al., 2018). On the other hand,

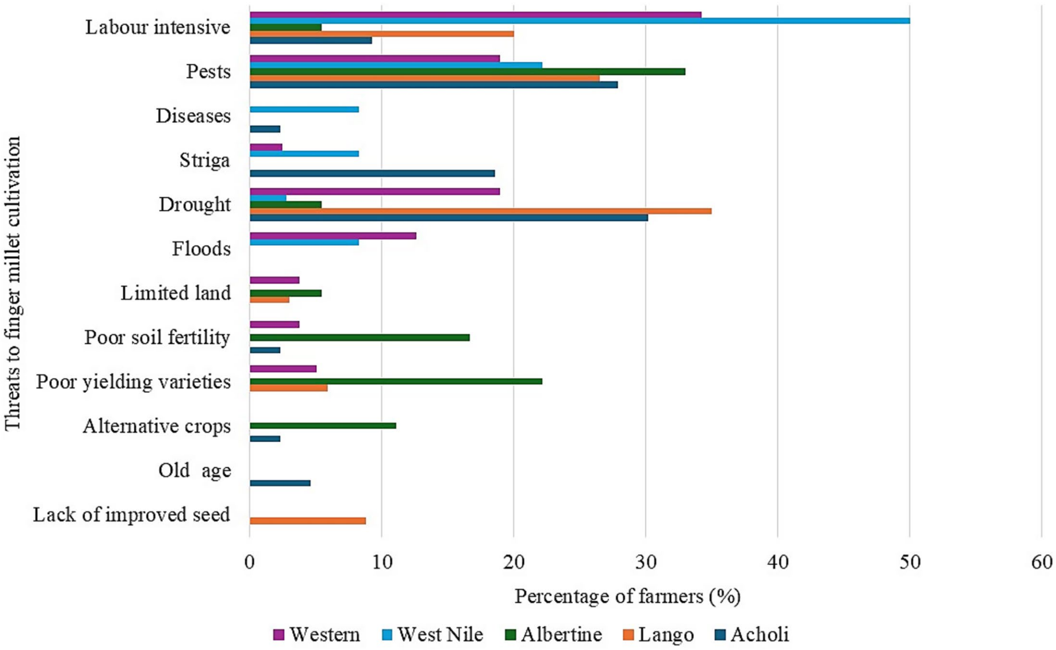

FIGURE 6
Threats to finger millet cultivation in Uganda.

moderate wet regions with higher nighttime humidity and low wind speeds may experience reduced moisture loss but potentially elevated disease pressure, such as finger millet blast (Takan et al., 2004). Overall, the weather conditions observed in this study agree with previous studies on the environmental requirements for finger millet (Dida and Devos, 2006; Gupta et al., 2017; Opole et al., 2018; Adikini et al., 2021). This reinforces the role of finger millet as a highly adaptable and climate-resilient crop capable of thriving in both dry and moderately humid agroecologies of Uganda.

4.2 Land suitability for finger millet production

Land suitability analysis enables the identification of the main limiting factors for agricultural production, allowing decision-makers to develop crop management strategies that increase land productivity (Narayanaswamy et al., 2017). According to this study, the suitability assessment revealed that most agroecologies are highly suitable for finger millet production, with the Southern Highlands, Northern farmland, and mid-Northern agroecological zones having a greater proportion of land that is highly suitable (Table 2). In comparison, the greater proportion of land areas in Karamoja drylands, Western highlands, and West Nile farmlands agroecological zones are moderately suitable for finger millet production. This implies that there is greater potential for increasing the production and conservation of finger millet across all agroecologies in Uganda. The small proportion of marginally suitable land in Western agroecologies and Karamoja dry land could be due to slopes, soil depth, soil erosion, and rainfall as the major limiting parameters for optimal growth of finger millet, as reported earlier by other researchers (Rabia, 2012; AbdelRahman et al., 2016; Narayanaswamy et al., 2017).

4.3 Soil and environmental adaptation of the finger millet

This study found that farmers cultivate finger millet in a wide range of environments, including various soil types, topographies, and levels of stoniness (Table 3). This confirms earlier reports that finger millet has wide adaptability to varying climatic conditions and soil characteristics (Upadhyaya et al., 2008; AbdelRahman et al., 2016; Adikini et al., 2021). Some of the finger millet varieties were found growing in rocky soils, hills, floodplains, and a wide range of soil textures, which further confirms the report that finger millet can develop and perform well in marginal soils with rainfall as low as 400 mm (Rabia, 2012; AbdelRahman et al., 2016; Narayanaswamy et al., 2017). Topography, soil types, and other soil characteristics have been found to influence the distribution and diversity of crops in each environment. Farmers have utilized this knowledge to select varieties that suit a given environment (Jarvis et al., 2000). The ability of finger millet varieties to grow in dynamic environments highlights the rich diversity of genetic materials, which, if well harnessed, can be utilized in the development of varieties with improved agronomic performance and greater adaptability. However, the variation in agroecological zones, such as regions with less favorable environments like Karamoja, calls for localized adaptation strategies to maximize the production potential of finger millet. Furthermore, laboratory validation is necessary for soils sampled from agroecologies to enhance the accuracy of soil characterization.

4.4 Farmer experience in finger millet cultivation

This study revealed that over 50% of farmers in the Northern, Mid-Northern, and West Nile regions had over 50 years of experience in finger millet cultivation, whereas in the southern and western agroecologies, most farmers had between 31 and 50 years of experience (Figure 3). Similar results were reported by Hamba et al. (2024), who attributed this to the accumulated knowledge of finger millet production over the years and increasing awareness of the economic importance of this crop, motivating farmers to cultivate it for many years. This extensive experience in finger millet production demonstrates that traditional knowledge and management practices are rich and well-preserved, which is crucial for maintaining landraces, on-farm seed systems, and conserving crop diversity. Very few farmers had less than 10 years of experience in most agroecologies, except in Karamoja, where the majority of farmers fell into this category. This is due to the recent adoption efforts driven by extension services and training programs aimed at improving farmer livelihoods by promoting finger millet production in the region.

4.5 Diversity of finger millet germplasm

The diversity of the finger millet germplasm is further evidence by the distinct varieties reported across agroecologies. Over 96% of the reported varieties were land races, with Western and West Nile agroecologies having the most diverse finger millet germplasm (Table 4). This finding confirms previous reports that Uganda is the primary Centre of finger millet diversity (National Research Council, 1996; Joshi et al., 2021; Joshi et al., 2023). Although landraces are often reported as not high-yielding, they have a wide varietal variability and the ability to survive under stress-prone conditions (Tsehaye et al., 2006). The rich diversity offers an opportunity for finger millet crop improvement to address food and nutritional security (Owere et al., 2015). The low diversity of finger millet observed in Karamoja agroecologies (Table 5), could be because farmers in this region began to grow finger millet in recent years following sensitization by government extension agents and non-governmental organizations (NGO) to promote the crop in the area, considering that it is suitable for finger millet production, but also to fight nutritional insecurity in the region. This was further evidenced in this study, where many farmers had less than 10 years' experience in finger millet production (Figure 3). Such a community needs to be retooled with improved production practices and more effective utilization of the crop to increase its productivity.

4.6 Farmer variety nomenclature and local knowledge

Farmers in Uganda were able to differentiate their varieties through local naming. A total of 198 distinct variety names were recorded among ethnic groups across the six agroecologies (Supplementary Table 1), indicating a long history of finger millet production in Uganda, as well as considerable diversity. Most of the names given to finger millet varieties had significant meaning reflecting the different morphological or agronomic attributes possessed by a given variety, for example, variety Katome, which, among the Banyakoles, means compact head, Obwengato, which means the variety has long fingers, and Kal atar among the Langi, meaning white seeded millet. Farmers name their varieties according to their maturity periods; for example, Otataka among the Banyakole, Okama among the Langos, and Padiyo among the Aringas, all meaning early maturing varieties (Supplementary Table 1). This study also found that farmers in Uganda name finger millet varieties according to the place where the variety was obtained (e.g., Kyambarara, meaning it's from Mbarara, or Busoga, meaning it's from the Busoga region) or according to the name of a person or organization that introduced the variety. The local nomenclature varied across different ethnic groups and agroecological regions. Similar findings have been reported in many crops, including cassava (Nakabonge et al., 2018), beans (Loko et al., 2018), sorghum (Dossou-Aminon et al., 2016), as well as barley and wheat (Bernis-Fonteneau et al., 2023). Some of the morphological criteria used by farmers in naming the variety are similar to the scientific descriptors used in characterizing finger millet, implying that a researcher can easily identify a given variety by understanding the name alone (Supplementary Table 1). Naming also reflects the extent to which varieties are shared within or across agroecologies. For example, in this study, the variety Anyaa Sudan indicates that it may have originated from Sudan. The shared names and meanings across agroecologies reflect germplasm exchange among communities, which can result from migration or the sharing of seeds with relatives. Farmer naming alone is not enough to differentiate a variety (Bernis-Fonteneau et al., 2023). This implies the need for improved methods, including phenotyping and the use of molecular tools, to further characterize farmer varieties and establish their genetic diversity and population structure, thereby guiding the breeding process (Kasule et al., 2024a; Kasule et al., 2024b).

4.7 Farmer varietal preference, adoption, and trait selection for finger millet across agroecologies

There were variations in finger millet landrace varieties preferred by farmers in different agroecologies. Interaction with farmers revealed that they grow more than one finger millet variety in their field to mitigate the risk of loss due to harsh weather and pest damage. Farmers further revealed that millet varieties serve different purposes, such as brewing, food, or for sale (Figure 4). Farmers' preference for local land races agrees with earlier findings that most land races are well adapted to low-input farming systems and possess essential quality traits (Orr et al., 2016; Hamba et al., 2024). Among the traits that farmers use for selecting and adopting varieties, drought resistance was ranked first as the most preferred trait in finger millet in the southern highlands and northern agroecologies (Table 8). This could be because the region tends to have long drought spells and unpredicted rainfall. Having a variety with such traits guarantees food security and mitigates the effects of climate change in the region (Kasule et al., 2023; Hamba et al., 2024; Kasule et al., 2024c). Similarly, in Karamoja, farmers prefer to grow those varieties that mature early. Early-maturing crop varieties can yield a positive harvest within a short period after planting, thereby protecting farmers in the event of low rainfall or drought. This means farmers are aware of climate change and the marginal environment where this crop is grown. In addition, multiple cropping can be achieved in a small piece of land to ensure food and nutrition security, as well as ecological balance (Hamba et al., 2024).

In western and West Nile agroecologies, taste ranked first, followed by drought, cooking quality, and pests and diseases (Table 8). This is because finger millet is a highly valued food among the communities living in those two regions. A similar result was reported by Hamba et al. (2024). Studies in other crops, such as maize, sorghum, and cassava, have similarly highlighted the influence of taste, marketability, and agronomic traits in shaping farmers' variety choices and trait preferences (Mwema et al., 2017; Kasule et al., 2020; Orr et al., 2020; Andiku et al., 2021; Habte et al., 2023). This implies the need for integrating consumer traits with agronomic traits during the breeding process. Lack of variety adoption has been linked to poor taste in some of the earlier-released finger millet varieties (Gierend et al., 2014). In mid-northern agroecologies, pests and disease resistance were ranked first, followed by drought and taste. The major pest mentioned by farmers was the grasshopper, which destroys finger millet at all growth stages, from seedling to maturity. Farmers also recognize blast disease and *Striga,* which significantly affect crop yields. Research has shown that finger millet blast disease can cause a yield loss of up to 90% in susceptible varieties. Therefore, farmers in this region select and adopt varieties that can tolerant pests and diseases. Land races from this region can be a potential source of resistance to pests and diseases if properly conserved.

The GLM analysis of finger millet cultivation in Uganda revealed the multifaceted nature of variety selection, with environmental conditions, soil characteristics, and seed quality emerging as significant factors influencing farmers' decisions (Table 9). These findings align with previous research emphasizing the importance of these variables in crop cultivation (Owere et al., 2014; Hamba et al., 2024). The significance of topography, soil texture, and drainage highlights the critical role of environmental factors in crop production (Li et al., 2021). Additionally, the importance of special attributes and sources of seed agrees with studies emphasizing the significance of varietal traits and seed quality in agricultural decision-making (Westengen et al., 2023). However, the non-significant effects of sample status and collection source suggest that other unexplored factors may influence variety selection, warranting further investigation. Understanding the complex interplay of these agronomic, environmental, and socio-economic factors is essential for promoting sustainable finger millet production and ensuring food security in Uganda. The implication of this for any finger millet breeding program is that it should emphasize developing varieties that combine both farmer-preferred traits with adaptation to local soils, and that the seeds of the variety must be easily accessible to farmers. This would significantly enhance finger millet production in Uganda.

4.8 Seed systems and on-farm conservation

Farmer preference for land race directly influences the nature of the seed system. In this study, most farmers across agroecology maintain their seed, which they reuse each season (Table 6). In places like Karamoja, where farmers cannot keep their own seed, they can obtain it from neighboring villages through seed exchange, from non-governmental organizations that supply seed, or occasionally from the market. Similar results have been reported by other scholars in earlier studies (Owere et al., 2014; Hamba et al., 2024). This implies that improving seed access through on-farm seed production is a viable option, which will also promote the conservation of diverse land races by communities (Opole, 2019). From this study, we further discovered that many farmers have developed innovative methods for seed storage and conservation, demonstrating their knowledge and resourcefulness in preserving this valuable crop. Some farmers preserved their finger millet seeds on the rooftop of their houses near the fire, while others used traditional granaries. Others ensured that the seeds were properly dried in the drying yard and stored in the house using sacks and drums (Table 7). These local storage systems can conserve finger millet seed in a viable state for more than 2 years, according to the farmers. This demonstrates the wealth of knowledge farmers possess in safeguarding their millet harvest for an extended period, thereby guaranteeing a food supply and seed sources for future use.

4.9 Market segments and multivariate relationships influencing finger millet adoption

The market segments indicated that finger millet is primarily cultivated for household food consumption (Figure 4), highlighting its role as an important crop for food security and income generation in Uganda. Surplus production is often sold in local markets, providing farmers with additional income and supporting their livelihoods. Smaller proportions of the crop are allocated to beverage production, such as local busheera products, brewing, and dual purposes, reflecting the diverse cultural and economic roles of finger millet (Hamba et al., 2024). Although the utilization of finger millet among smallholder farming communities for brewing and beverages is limited, these uses present an emerging opportunity that can be leveraged to enhance the value chain and promote alternative uses through value addition and market development, thereby increasing farmer incomes and incentivizing the wider adoption and cultivation of finger millet.

Correlation analysis revealed that environmental, socio-economic, and seed systems factors influence finger millet cultivation in Uganda (Table 10). Agroecology demonstrated significant associations with soil characteristics, including texture, drainage, and stoniness, confirming that environmental suitability remains a key determinant of where finger millet landraces thrive (Mukherjee et al., 2025). The positive and significant correlation between agroecology and seed sources confirms that local seed systems and region-specific practices play a crucial role in maintaining and adopting finger millet landraces (Hamba et al., 2024). Similarly, the relationship between market segments and preferred variety attributes demonstrates the influence of farmer preferences and end-use considerations on variety choice (Kasule et al., 2020; Hamba et al., 2024). The correlation findings are consistent with GLM findings from our study and align with previous studies emphasizing the combined role of environmental conditions, farmer priorities, and seed management in adoption decisions (Mwema et al., 2017; Kasule et al., 2020; Orr et al., 2020; Andiku et al., 2021; Habte et al., 2023).

PCA further supported correlation findings by separating drivers of finger millet adoption into distinct yet interrelated dimensions (Table 11). PC1 captured environmental factors, including agroecology and soil properties, while PC2 revealed socioeconomic influences, such as market segments and preferred varietal attributes, that affected the adoption of finger millet (Figure 5). PC3 and PC4 identified conservation and seed system management practices as important aspects for the adoption of finger millet, including sample status and seed collection sources. Previous studies have corroborated that ecological suitability, farmer-driven preferences, and seed system dynamics are important in maintaining genetic diversity for finger millet (Gierend et al., 2014; Hamba et al., 2024; Orr et al., 2020).

4.10 Threats to finger millet production and conservation in Uganda

Despite finger millet being a valued crop among many ethnic groups in Uganda, several threats to finger millet genetic diversity have been recognized by farmers in different agroecologies (Figure 6). The labor-intensive nature of finger millet production (land preparation, weeding, and harvesting) and post-harvest processes poses a significant threat to the conservation of finger millet diversity across all agroecologies. This is due to a lack of improved technologies resulting from research neglect on finger millet, which has led farmers to opt for crops with better production technologies, such as maize and rice, thereby endangering the diversity of finger millet. This is further worsened by the fact that most finger millet farmers are old, and many youths have not taken up the crop. According to Kidoido et al. (2002), the reported limiting factors to finger millet production were seeding rate, labor, tools and equipment, production experience, and weed management.

In mid-northern and northern agroecologies, most farmers recognize drought as a major threat to the conservation of diverse finger millet, followed by pests and diseases (Figure 6). These regions experience a monomodal type of rainfall, which typically occurs from May to October. However, this has become increasingly unpredictable, and most landraces that used to grow for more than 4 months, as well as those that cannot tolerate drought and heat, are likely to be lost; yet, they may harbor other important genes. Pests, mainly birds, damage, grasshoppers, and rodents, were identified by the farmers as a threat to finger millet conservation. Similarly, diseases (such as blast) and *Striga* were recognized by farmers in the West Nile and Acholi regions (Figure 6). Other threats mentioned by the farmers included floods, especially in Western and West Nile agroecologies, limited land availability, poor soil fertility, poor-yielding varieties, and a lack of improved seeds, all of which were identified as threats to finger millet conservation and production in Uganda.

4.11 Implications for conservation and breeding

This study reveals the on-farm conservation of finger millet germplasm through farmers' traditional and cultural preferences for landraces, utilizing traditional knowledge for on-farm conservation and future use of finger millet. The predominance of diverse landraces from different agroecologies in Uganda should be conserved through an integrated approach that combines *in situ* (on-farm) and ex situ (gene banks) methods. Given that farmers differentiate varieties and retain them for generations based on farmer-preferred traits such as taste, drought tolerance, and early maturity, among others, while considering their adaptability to soils and environment, similar breeding efforts should prioritize such traits to impact improved variety adoption. Strengthening local seed systems and seed exchange programs will support conservation of landraces and uptake of improved varieties. The rich genetic diversity observed in different agroecologies offers significant potential for crop improvement. Most agroecologies, such as the Southern Highlands, Northern farmland, and mid-Northern agroecological zones, are highly suitable for finger millet production, while Karamoja drylands, Western highlands, and West Nile farmlands agroecological zones are moderately suitable for finger millet production, which underscores the strategic importance of these regions for finger millet crop intensification to address food security. Participatory and community-based approaches that involve farmers in variety selection and advancement in breeding programs are crucial for ensuring adoption, conserving genetic diversity, and enhancing finger millet production.

5 Conclusions and recommendations

The study revealed the resilience of finger millet landraces in Uganda across diverse agroecological zones, with farmers continuing to cultivate and save seeds of these traditional varieties despite the availability of improved varieties. Farmers' selection of landraces is intricately linked to environmental factors, soil conditions, preferred attributes, and seed quality. Finger millet landraces are often preferred across Uganda's agroecologies due to their desirable traits, including drought tolerance, early maturity, taste, and resistance to pests and diseases. These traits ensure food security among finger millet farmers in the country. While there is a wealth of local finger millet germplasm, urgent action is needed to establish a formal seed and conservation system to prevent genetic erosion. Our findings reveal significant potential for local breeding and conservation efforts to harness the vast genetic diversity present in these landraces for future crop enhancement.

Threats such as threats such as labor-intensive production and the replacement of crops with maize and rice pose a significant risk to conservation, raising concerns about genetic erosion. A few farmers have adopted the use of mechanization for threshing finger millet, and we highly recommend its wider use. However, the use of mechanization for weeding is a bit complicated; first, most farmers do not plant millet in lines as most do broadcasting due to limited land availability and the need to intercrop with many other crops, second, the presence of weedy relatives for finger millet within landraces makes separation challenging for mechanization, third, smallholder farmers often complain on the high cost of these machines which limits uptake. Therefore, we propose government support for finger millet farmers through the development of affordable technologies and alternative methods that can distinguish true millet from weedy relatives, thereby improving the uptake of the crop in Uganda's diverse agroecologies.

We therefore recommend developing formal seed systems that integrate farmer preferences, promoting participatory plant breeding programs, and increasing awareness of the scientific conservation and management of improved seeds. The coordination between in situ and ex situ conservation strategies must be established to link on-farm varietal maintenance with institutional seed banks, while keeping proper documentation for the different landraces for future use in conservation and breeding programs. Concerted efforts involving breeders, policy makers, and farmers will be pivotal if the rich genetic diversity of finger millet from Uganda is to be preserved while improving crop productivity in the face of socioeconomic challenges and climate change.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

Ethical approval for this study was obtained for all participants involved, as required for studies involving humans. This research was authorized by the National Agricultural Research Organization (NARO), which, by its mandate, adheres to scientific and ethical processes during research. Informed consent was obtained from all participants involved in the study, and they provided written informed consent to participate. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

SA: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing, Data curation. RK: Investigation, Methodology, Validation, Writing – review & editing. SS: Methodology, Validation, Visualization, Writing – review & editing. JA: Conceptualization, Data curation, Methodology, Supervision, Validation, Writing – review & editing. DO: Data curation, Methodology, Writing – review & editing. AMA: Data curation, Methodology, Writing – review & editing. EZ: Conceptualization, Data curation, Methodology, Supervision, Validation, Writing – review & editing. HFO: Conceptualization, Project administration, Supervision, Writing – review & editing. DAO: Conceptualization, Project administration, Supervision, Writing – review & editing. FK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

During the conceptualization and execution of this research, FK held the position of Associate Plant Breeder with the National Semi-Arid Resources Research Institute.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer SP declared a shared affiliation with the author FK to the handling editor.

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References

AbdelRahman, M. A., Natarajan, A., and Hegde, R. (2016). Assessment of land suitability and capability by integrating remote sensing and GIS for agriculture in Chamarajanagar district, Karnataka, India. *Egypt. J. Remote Sens. Space Sci.* 19, 125–141. doi: 10.1016/j.ejrs.2016.02.001

Adikini, S., Roggers, G., Ojulong, H., Aita, A., Opie, H., Wandulu, J. A., et al. (2021). Finger millet production manual for Uganda. Entebbe, Uganda: National Agricultural Research Organization.

Andiku, C., Shimelis, H., Laing, M., Shayanowako, A. I. T., Adrogu Ugen, M., Manyasa, E., et al. (2021). Assessment of sorghum production constraints and farmer preferences for sorghum variety in Uganda: implications for nutritional quality breeding. *Acta Agric. Scand., Sect. B Soil Plant Sci.* 71, 620–632. doi: 10.1080/09064710.2021.1944297

Beaudoing, H., Rodell, M., et al. (2020). GLDAS Noah Land Surface Model L4 3 hourly 0.25 x 0.25 degree, Version 2.1 [Data set]. NASA Goddard Earth Sciences Data and Information Services Center. doi: 10.5067/E7TYRXPJKWOQ

Bernis-Fonteneau, A., Aakairi, M., Saadani-Hassani, O., Castangia, G., Ait Babahmad, R., Colangelo, P., et al. (2023). Farmers' variety naming and crop varietal diversity of two cereal and three legume species in the Moroccan high atlas, using DATAR. *Sustainability* 15:10411. doi: 10.3390/su151310411

Bisht, I. S., Rana, J. C., Jones, S., Estrada-Carmona, N., and Yadav, R. (2022). Agroecological approach to farming for sustainable development: the Indian scenario. *Biodivers. Ecosyst.* 107, 107–128. doi: 10.5772/intechopen.100281

Chandra, D., Chandra, S., Pallavi, and Sharma, A. K. (2016). Review of finger millet (*Eleusine coracana* (L.) Gaertn): a power house of health benefiting nutrients. *Food Sci. Human Wellness* 5, 149–155. doi: 10.1016/j.fshw.2016.05.004

Dida, M. M., and Devos, K. M. (2006). "Finger millet" in Cereals and millets. ed. C. Kole (Berlin, Heidelberg, Germany: Springer), 333–343.

Dossou-Aminon, I., Dansi, A., Ahissou, H., Cissé, N., Vodouhè, R., and Sanni, A. (2016). Climate variability and status of the production and diversity of sorghum (*Sorghum bicolor* (L.) Moench) in the arid zone of Northwest Benin. *Genet. Resour. Crop. Evol.* 63, 1181–1201. doi: 10.1007/s10722-015-0310-y

Engelmann, F., and Engels, J. M. M. (2002). Technologies and strategies for ex situ conservation.

FAO (1976). A framework for land evaluation, Rome, Italy: Food and agriculture organization of the united nations. vol. 32.

FAO (2007). Land evaluation towards a revised framework. *Land Water Discuss. Pap.* 3, 428–429. Available online at: https://edepot.wur.nl/488269

Fick, S. E., and Hijmans, R. J. (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* 37, 4302–4315. doi: 10.1002/joc.5086

Gierend, A., Ojulong, H., and Wanyera, N. (2014). A combined ex-post/ex-ante impact analysis for improved sorghum and finger millet varieties in Uganda, socioeconomics discussion paper series number 19.

Gupta, S. M., Arora, S., Mirza, N., Pande, A., Lata, C., Puranik, S., et al. (2017). Finger millet: a "certain" crop for an "uncertain" future and a solution to food insecurity and hidden hunger under stressful environments. *Front. Plant Sci.* 8:643. doi: 10.3389/fpls.2017.00643

Gupta, S., Gupta, S. M., Gupta, A. K., Gaur, V. S., and Kumar, A. (2014). Fluctuation of Dof1/Dof2 expression ratio under the influence of varying nitrogen and light conditions: involvement in differential regulation of nitrogen metabolism in two genotypes of finger millet (*Eleusine coracana* L.). *Gene* 546, 327–335. doi: 10.1016/j.gene.2014.05.057

Habte, E., Marenya, P., Beyene, F., and Bekele, A. (2023). Reducing susceptibility to drought under growing conditions as set by farmers: the impact of new generation drought tolerant maize varieties in Uganda. *Front. Sustain. Food Syst.* 6:854856. doi: 10.3389/fsufs.2022.854856

Hamba, S., Kasule, F., Mayanja, I., Biruma, M., Natabirwa, H., Sanya, L. N., et al. (2024). Farmer-preferred traits and variety choices for finger millet in Uganda. *Front. Sustain. Food Syst.* 8:1282268. doi: 10.3389/fsufs.2024.1282268

Hatfield, J. L., and Dold, C. (2019). Water-use efficiency: advances and challenges in a changing climate. *Front. Plant Sci.* 10:429990. doi: 10.3389/fpls.2019.00103

Holleman, C., Rembold, F., Crespo, O., and Conti, V. (2020). The impact of climate variability and extremes on agriculture and food security-an analysis of the evidence and case studies.

Jain, S. K., Qualset, C. O., Bhatt, G. M., and Wu, K. K. (1975). Geographical patterns of phenotypic diversity in a world collection of durum wheats 1. *Crop Sci.* 15, 700–704. doi: 10.2135/cropsci1975.0011183X001500050026x

Jarvis, D., Myer, L., Klemick, H., Guarino, L., Smale, M., Brown, A., et al. (2000). A training guide for. Situ, 4.

Joshi, P., Gupta, S., Ojulong, H., Sharma, R., Vetriventhan, M., Kudapa, H., et al. (2023). "Finger millet improvement in post-genomic era: hundred years of breeding and moving forward" in Smart plant breeding for field crops in post-genomics era. eds. D. Sharma, S. Singh, S. K. Sharma and R. Singh (Singapore Pte: Springer), 221–253.

Joshi, R., Jain, A., Malhotra, N., and Kumari, M. (2021). "Origin, domestication, and spread" in Millets and Pseudo cereals. eds. M. Singh and S. Sood (Duxford, United Kingdom: Elsevier), 33–38.

Kasule, F., Alladassi, B. M. E., Aru, C. J., Adikini, S., Biruma, M., Ugen, M. A., et al. (2024a). Genetic diversity, population structure, and a genome-wide association study of sorghum lines assembled for breeding in Uganda. *Front. Plant Sci.* 15:1458179. doi: 10.3389/fpls.2024.1458179

Kasule, F., Diack, O., Mbaye, M., Kakeeto, R., and Econopouly, B. F. (2024b). Genomic resources, opportunities, and prospects for accelerated improvement of millets. *Theor. Appl. Genet.* 137:273. doi: 10.1007/s00122-024-04777-9

Kasule, F., Kakeeto, R., Tippe, D. E., Okinong, D., Aru, C., Wasswa, P., et al. (2023). Insights into finger millet production: constraints, opportunities and implications for improving the crop in Uganda. *J. Plant Breed. Crop Sci.* 15, 143–164. doi: 10.5897/JPBCS2023.1018

Kasule, F., Ojulong, H. F., Wandulu, J. A., Kakeeto, R., and Adikini, S. (2024c). Pearl millet: a marginalized solution to climate change adaptation, nutrition and food security challenges in Uganda.

Kasule, F., Wasswa, P., Mukasa, S. B., Okiror, A., Nghituwamhata, S. N., Rono, E. C., et al. (2020). Farmer preference of cassava cultivars in eastern Uganda: a choice beyond disease resistance. *Agric. Sci.* 2, 169–p169. doi: 10.30560/as.v2n2p169

Khoury, C. K., Brush, S., Costich, D. E., Curry, H. A., De Haan, S., Engels, J. M., et al. (2022). Crop genetic erosion: understanding and responding to loss of crop diversity. *New Phytol.* 233, 84–118. doi: 10.1111/nph.17733

Kidoido, M., Kasenge, V., Mbowa, S., Tenywa, J., and Nyende, P. (2002). Socioeconomic factors associated with finger millet production in eastern Uganda.

Kumar, A., Metwal, M., Kaur, S., Gupta, A. K., Puranik, S., Singh, S., et al. (2016). Nutraceutical value of finger millet [*Eleusine coracana* (L.) Gaertn.], and their improvement using omics approaches. *Front. Plant Sci.* 7:934. doi: 10.3389/fpls.2016.00934

Li, Q., Gu, F., Zhou, Y., Xu, T., Wang, L., Zuo, Q., et al. (2021). Changes in the impacts of topographic factors, soil texture, and cropping systems on topsoil chemical properties in the mountainous areas of the subtropical monsoon region from 2007 to 2017: a case study in Hefeng, China. *Int. J. Environ. Res. Public Health* 18:832. doi: 10.3390/ijerph18020832

Li, Y.-H., Li, W., Zhang, C., Yang, L., Chang, R.-Z., Gaut, B. S., et al. (2010). Genetic diversity in domesticated soybean (*Glycine max*) and its wild progenitor (*Glycine soja*) for simple sequence repeat and single-nucleotide polymorphism loci. *New Phytol.* 188, 242–253. doi: 10.1111/j.1469-8137.2010.03344.x

Loko, L. E. Y., Toffa, J., Adjatin, A., Akpo, A. J., Orobiyi, A., and Dansi, A. (2018). Folk taxonomy and traditional uses of common bean (*Phaseolus vulgaris* L.) landraces by the sociolinguistic groups in the central region of the Republic of Benin. *J. Ethnobiol. Ethnomed.* 14:52. doi: 10.1186/s13002-018-0251-6

Mbinda, W., Kavoo, A., Maina, F., Odeph, M., Mweu, C., Nzilani, N., et al. (2021). Farmers' knowledge and perception of finger millet blast disease and its control practices in western Kenya. *CABI Agric. Biosci.* 2:13. doi: 10.1186/s43170-021-00033-y

Mbithi-Mwikya, S., Van Camp, J., Yiru, Y., and Huyghebaert, A. (2000). Nutrient and antinutrient changes in finger millet (*Eleusine coracana*) during sprouting. *LWT Food Sci. Technol.* 33, 9–14. doi: 10.1006/fstl.1999.0605

Mburu, S. W., Koskey, G., Kimiti, J. M., Ombori, O., Maingi, J. M., and Njeru, E. M. (2016). Agrobiodiversity conservation enhances food security in subsistence-based farming systems of eastern Kenya. *Agric. Food Secur.* 5, 1–10. doi: 10.1186/s40066-016-0068-2

Meza-Joya, F. L., Morgan-Richards, M., Koot, E. M., and Trewick, S. A. (2023). Global warming leads to habitat loss and genetic erosion of alpine biodiversity. *J. Biogeogr.* 50, 961–975. doi: 10.1111/jbi.14590

Mukherjee, B., Jha, R. K., Sattar, A., Dutta, S., Bhattacharya, U., Samanta, S., et al. (2025). Harnessing the potential of millets for climate-resilient and sustainable agriculture. *Front. Plant Sci.* 16:1574699. doi: 10.3389/fpls.2025.1574699

Mwema, C., Orr, A., Namazi, S., and Ongora, D. (2017). Harnessing opportunities for productivity enhancement for Sorghum & Millets (HOPE): Baseline survey, Uganda, series paper number 41.

Nakabonge, G., Samukoya, C., and Baguma, Y. (2018). Local varieties of cassava: conservation, cultivation and use in Uganda. *Environ. Dev. Sustain.* 20, 2427–2445. doi: 10.1007/s10668-017-9997-6

Narayanaswamy, Y., Inayathulla, M., Thabrez, M., and Shashishankar, A. (2017). Land suitability evaluation of soils for crop production. *Int. J. Innov. Res. Sci. Eng. Technol.* 6, 18187–18196. doi: 10.15680/IJIRSET.2017.0609083

National Research Council (1996). Finger millet lost crops of Africa 1 39 57.

Opole, R. (2019). Opportunities for enhancing production, utilization and marketing of finger millet in Africa. *Afr. J. Food Agric. Nutr. Dev.* 19, 13863–13882. doi: 10.18697/AJFAND.84.BLFB1004

Opole, R., Prasad, P., Djanaguiraman, M., Vimala, K., Kirkham, M., and Upadhyaya, H. (2018). Thresholds, sensitive stages and genetic variability of finger millet to high temperature stress. *J. Agron. Crop Sci.* 204, 477–492. doi: 10.1111/jac.12279

Orr, A., Mwema, C., Gierend, A., and Nedumaran, S. (2016). Sorghum and millets in Eastern and Southern Africa: Facts, trends and outlook. Available online at: https://core.ac.uk/download/pdf/219474328.pdf (Accessed July 3, 2025).

Orr, A., Schipmann-Schwarze, C., Gierend, A., Nedumaran, S., Mwema, C., Muange, E., et al. (2020). Why invest in Research & Development for sorghum and millets? The business case for east and southern Africa. *Glob. Food Sec.* 26:100458. doi: 10.1016/j.gfs.2020.100458

Owere, L., Tongoona, P., Derera, J., and Wanyera, N. (2014). Farmers' perceptions of finger millet production constraints, varietal preferences and their implications to finger millet breeding in Uganda. *J. Agric. Sci.* 6:126. doi: 10.5539/jas.v6n12p126

Owere, L., Tongoona, P., Derera, J., and Wanyera, N. (2015). Variability and trait relationships among finger millet accessions in Uganda. *Uganda J. Agric. Sci.* 16, 161–176. doi: 10.4314/ujas.v16i2.2

Pandian, S., Sivasankar, C., Muthuramalingam, P., and Ramesh, M. (2017). An amazing nutritional value in wonderful finger millet makes this "the most lovable food crop" to the world. *Sci. J. Food Sci. Nutr.* 3, 34–36. Available online at: https://www.sciresliterature.org/Nutrition/SJFSN-ID20.php

Poggio, L., De Sousa, L. M., Batjes, N. H., Heuvelink, G. B., Kempen, B., Ribeiro, E., et al. (2021). SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. *Soil* 7, 217–240. doi: 10.5194/soil-7-217-2021

Priyanka, V., Kumar, R., Dhaliwal, I., and Kaushik, P. (2021). Germplasm conservation: instrumental in agricultural biodiversity—a review. *Sustainability* 13:6743. doi: 10.3390/su13126743

Rabia, A. H. (2012). "A GIS based land suitability assessment for agricultural planning in Kilte Awulaelo district, Ethiopia." in The 4th International Congress of ECSSS, EUROSOIL, 1257.

Rakkammal, K., Maharajan, T., Shriram, R. N., Ram, P. S. J., Ceasar, S. A., and Ramesh, M. (2023). Physiological, biochemical and molecular responses of finger millet (*Eleusine coracana*) genotypes exposed to short-term drought stress induced by PEG-6000. *S. Afr. J. Bot.* 155, 45–59. doi: 10.1016/j.sajb.2023.01.053

Reuter, H. I., Hengl, T., Gessler, P., and Soille, P. (2009). Preparation of DEMs for geomorphometric analysis. *Dev. Soil Sci.* 33, 87–120. doi: 10.1016/S0166-2481(08)00004-4

Ritchey, E. L., McGrath, J. M., and Gehring, D. (2015). Determining soil texture by feel. Agriculture and Natural Resources Publications. Kentucky, USA. 139, Available online at: https://uknowledge.uky.edu/anr_reports/139

Sakamma, S., Umesh, K., Girish, M., Ravi, S., Satishkumar, M., and Bellundagi, V. (2018). Finger millet (*Eleusine coracana* L. Gaertn.) production system: status, potential, constraints and implications for improving small farmer's welfare. *J. Agric. Sci.* 10, 162–179. doi: 10.5539/jas.v10n1p162

Salgotra, R. K., and Gupta, B. B. (2016). "Plant genetic resources and traditional/indigenous knowledge: potentials and challenges" in Plant genetic resources and traditional knowledge for food security, eds. R. K. Salgotra and B. B. Gupta Springer Nature: Berlin, Heidelberg, Germany. 1–21.

Schmid, B., and Schöb, C. (2023). Ecological intensification of agriculture through biodiversity management: introduction. *J. Plant Ecol.* 16:rtad018. doi: 10.1093/jpe/rtad018

Simard, M., Denbina, M., Marshak, C., and Neumann, M. (2024). A global evaluation of radar-derived digital elevation models: SRTM, NASADEM, and GLO-30. *J. Geophys. Res. Biogeosci.* 129:e2023JG007672. doi: 10.1029/2023JG007672

Smỳkal, P., Nelson, M. N., Berger, J. D., and Von Wettberg, E. J. (2018). The impact of genetic changes during crop domestication. *Agronomy* 8:119. doi: 10.3390/agronomy8070119

Swiderska, K., Reid, H., Song, Y., Li, J., Mutta, D., Ongugo, P., et al. (2011). The role of traditional knowledge and crop varieties in adaptation to climate change and food security in SW China, Bolivian Andes and coastal Kenya

Takan, J., Akello, B., Esele, P., Manyasa, E. O., Obilana, A. B., and Audi, P. O. (2004). Finger millet blast pathogen diversity and management in East Africa: a summary of project activities and outputs. *Int. Sorghum Millets Newsl.* 45, 66–69. Available online at: https://hdl.handle.net/10568/103292

Takan, J., Chipili, J., Muthumeenakshi, S., Talbot, N., Manyasa, E., Bandyopadhyay, R., et al. (2012). Magnaporthe oryzae populations adapted to finger millet and rice exhibit distinctive patterns of genetic diversity, sexuality and host interaction. *Mol. Biotechnol.* 50, 145–158. doi: 10.1007/s12033-011-9429-z

Tamiru, C., and Abdela, T. (2021). Assessment of on-farm diversity status and farmer's perception for landraces crops at eastern Hararghe, Ethiopia. *Agric. For. Fish.* 10, 152–159. doi: 10.11648/j.aff.20211004.15

Tsehaye, Y., Berg, T., Tsegaye, B., and Tanto, T. (2006). Farmers' management of finger millet (*Eleusine coracana* L.) diversity in Tigray, Ethiopia and implications for on-farm conservation. *Biodivers. Conserv.* 15, 4289–4308. doi: 10.1007/s10531-005-3581-3

Upadhyaya, H. D., Gowda, C. L. L., Pundir, R. P. S., Reddy, V. G., and Singh, S. (2006). Development of core subset of finger millet germplasm using geographical origin and data on 14 quantitative traits. *Genet. Resour. Crop. Evol.* 53, 679–685. doi: 10.1007/s10722-004-3228-3

Upadhyaya, H., Reddy, V. G., and Sastry, D. (2008). Regeneration guidelines finger millet.

Vilaró, M., Vidal, R., and Abadie, T. (2020). Diversity of maize landraces in germplasm collections from South America. *Agrociencia (Uruguay)* 24, 1–11. doi: 10.31285/agro.24.108

Wambi, W., Otienno, G., Tumwesigye, W., and Mulumba, J. (2021). Genetic and genomic resources for finger millet improvement: opportunities for advancing climate-smart agriculture. *J. Crop Improv.* 35, 204–233. doi: 10.1080/15427528.2020.1808133

Wanyera, N. (2005). Finger millet (*Eleusine coracana*)(L.) Gaertn) in Uganda. Finger millet blast Management in East Africa. Creating opportunities for improving production and utilization of finger millet, 1.

Westengen, O. T., Dalle, S. P., and Mulesa, T. H. (2023). Navigating toward resilient and inclusive seed systems. *Proc. Natl. Acad. Sci.* 120:e2218777120. doi: 10.1073/pnas.2218777120

Yadesa, L., and Chalchisa, D. (2022). The impact of climate change on crops genetic resources diversity in Ethiopia consequence for conservation. *Adv. Biosci. Bioeng.* 10, 24–32. doi: 10.11648/j.abb.20221002.12