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Review

Insights into finger millet production: constraints, opportunities and implications for improving the crop in Uganda

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Finger millet [*Eleusine coracana* (L.) Gaertn.] is an important staple food crop cultivated by many smallholder farmers in drought prone areas of Africa for food, nutritional security and income generation. It serves as an important source of energy, proteins, minerals and calcium to many Ugandans. In addition, the sale of finger millet grain and value-added products like the different "busheera" beverages and local beer provide income to many households in Uganda. The crop is believed to have originated from the highlands of East African countries - Uganda and Ethiopia around 5000 years ago but its production is still low. Among the cereals grown in Uganda, finger millet ranks third after maize and sorghum and its production is on a decline with on farm average yield of less than 1 ton/hectare compared to its potential yield of 5 tons/ha. Some of the constraints to millet production include the subsistence nature employed by smallholder farmers, farmer neglect, use of low yielding varieties, poor agronomic practices, insect pests, diseases, declining soil fertility, poor post-harvest handling, and limited support by government and donor community, among others. Furthermore, the selfing nature, and the small floret size contributes to the low pace of genetic improvement of finger millet. The objective of this review paper is to present current status on production, constraints, opportunities, research gaps and implications for finger millet improvement in Uganda.

Key words: Finger millet, breeding, food security, seed systems, genetic improvement.

INTRODUCTION

Finger millet [*Eleusine coracana* (L.) Gaertn.], is an important staple food crop grown in the semi-arid tropics of Eastern and Southern Africa, and Southern Asia (FAOSTAT, 2022). The crop is highly self-fertilized with a tetraploid genome (2n = 4x = 36, AABB) and taxonomically belongs to Poaceae family and

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Chloridoideae sub-family (Srinivasachary et al., 2007). The crop is grown for subsistence by more than 400 million farmers worldwide in marginal lands (FAO, 2019; FAOSTAT, 2022). Among millets, finger millet ranks fourth worldwide in terms of production after sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* [L.] R. Br), and foxtail millet (*Setaria italic* L.) (FAO, 2019; Maharajan et al., 2019). An estimated total production area of 30934728 hectare (ha) is devoted to millets production worldwide (FAOSTAT, 2022). It is estimated that, the share of the global finger millet production area is about 12.5 % of the millet with approximately 3.7 tons of grain produced per annum globally where 2.5 and 1.2 million tons are produced in Africa and India, respectively (FAOSTAT, 2022).

Finger millet is mostly known by different local names by the different countries like *tokuso* or *dagusa* in Ethopia, *ragi* or *mandua* in India, *koddo* in Nepal, *koracan* in France, African millet or finger millet in England, *fingerhirse* in Germany, *wimbi* in Kenya, etc. (Fuller, 2014; Gebreyohannes et al., 2021). The crop can grow even in non-irrigated conditions better than the majorly consumed cereal grains like rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), and maize (*Zea mays* L.) and in very low rainfall regime between 200 and 500 mm (Gupta et al., 2017; Ruiz-Giralt et al., 2023). It is small-seeded minor cereal with light brown to brick red coloured or dark brown seed coat which is mainly rich in phytochemicals such as a polyphenol and dietary fibers (Abioye et al., 2022).

Finger millet is believed to have originated from Uganda and Ethiopia highlands in East Africa around 5000 years ago and it is one of the oldest cereals to be domesticated in Africa (National Research Council, 1996; Fuller, 2014). The name finger millet is derived from the appearance of spikes or fingers, which are arranged and appear like human fingers (Gebreyohannes et al., 2021). Finger millet is widely cultivated in eastern and central Africa, India, Sri Lanka, Himalayas, southern China, Taiwan, Indonesia, Guam, Australia (FAOSTAT, 2022). It grows better than many crops in soils with low fertility and can yield without the use of fertilizers; its stability in marginal environments especially drought prone areas makes finger millet an important staple food crop providing food security to millions of people (Owere et al., 2014; Adikini et al., 2021).

Among the cereals grown in Uganda, finger millet ranks third after maize and sorghum respectively, occupying a total area of 437,000 ha of land, with a production output estimated at 78,249.98 tons in 2021 (Adikini et al., 2021; FAOSTAT, 2022). Among the ethnic groups in Uganda, finger millet is locally known as “*Oburo*” by the Baganda, Banyoro and Banyankole, “*Kal*” by Luo tribes like Acholi, Lango, Japadola, kumam, Ethur, jaluo; “*buulo*” by the bamasaba tribes; “*Akima*” or “*Alos*” by Iteso tribes. It is naturally biofortified and nutritionally superior to the major food staples, as its grains constitute dietary energy, proteins, methionine, iron, calcium, and tryptophan; essential in addressing nutrition deficiencies like anemia and calcium deficiency (Sharma et al., 2017; Ojulong et al., 2021). Therefore, it is important to grow finger millet in order to contribute to dietary diversity for sustainable agriculture and healthy diets to ensure food and nutritional security (Vetriventhan and Upadhyaya, 2018). Finger millet grains are processed and converted into edible forms of food and brewing products through malting, fermentation, milling, cooking, roasting and popping or puffing (Mubiru et al., 2020).

Despite its importance, finger millet production in Uganda has remained low with on-farm average grain yield of <1 ton/ha (Adikini et al., 2021). The low yields are due to several finger millet production constraints, which can be categorized as biotic, abiotic, socio-economic and policy (low research consideration), among others. Major biotic constraints to finger millet production include blast disease; most destructive biotic constraint affecting finger millet production worldwide, followed by the parasitic weed *Striga*, stem borers, fall armyworm, armyworms and common bugs among others (Owere et al., 2014; Grovermann et al., 2018; Adikini et al., 2021). Abiotic factors include drought and low soil fertility (Ebanyat, 2009; Gupta et al., 2017), while socio-economic factors include difficulty in post-harvest handling, high labor costs associated with weeding, use of unimproved varieties, poor agronomic practices, low mechanization of operations and inadequate production knowledge and experience among others (Tenywa et al., 1999; Kidoido et al., 2002; Owere et al., 2014). Although many benefits are associated with the use of finger millet grain and products derived from it, there is little research and innovations to address its production constraints, seed systems and opportunities as compared to other cereals such as maize, sorghum, rice, and wheat. This study, therefore, critically reviews the different key concepts important in understanding finger millet benefits, constraints, preferential traits, breeding and prospects to address food and income insecurities in Uganda.

HISTORY AND RESEARCH OF FINGER MILLET IN UGANDA

From the archaeobotanical sampling of macroscopic plant remains, the history of finger millet domestication starts about 5000 years ago, where the crop was cultivated in western Uganda and later spread to Ethiopian highlands (Doggett, 1989; Fuller, 2014). Restricted archaeological evidence and ethno-graphic interviews among the Banyoro of western Uganda in pre-colonial times, finger millet was and still is an important cereal in this region (Esele, 1989; Young, 1999). Furthermore, ethnobotanical work carried out in 1995 in Uganda stressed the importance of finger millet in pre-colonial and historic times (Young, 1999; Fuller, 2014).

Through excavation in Uganda, scientists uncovered other archaeological indicators of agriculture, such as grinding stones (used for milling finger millet) and iron knife blades, similar to those used for harvesting finger millet today proving that finger millet production is age-old in Uganda, where farmers have been growing it for thousands of years (National Research Council, 1996; Young, 1999; Fuller, 2014). This is also evident in rural communities in Uganda who still process finger millet using ancient technologies like grinding stones. However, due to neglect, Uganda nearly lost the zeal for crop production and preservation of finger millet genetic resources especially due to the popularity of newer crops such as maize and potatoes in some regions of the country (Doggett, 1989; Young, 1999).

Finger millet research is based at the Serere Experimental Station (SES) under the umbrella of East African Agriculture and Forestry Research Organization (EAAFRO) which was mandated to undertake cereals research in Uganda (East African Agriculture and Forestry Research Organization, 1971). This regional research organization was established in 1948 and served in three East African countries namely Uganda, Kenya and Tanzania taking over the activities of the former East African Agricultural Research Institute established in Amani, Tanganyika in 1944 (Keen, 1951). EAAFRO derived its funding from the East African Community General fund, donations from the United Kingdom Government, United States Agency for International Development (USAID), Rockefeller and Ford Foundations, the Norwegian Agency for International Development Cooperation (NORAD) among others and the total budget for 1969-1970 was Uganda shillings 11, 492,450 (East African Agriculture and Forestry Research Organization, 1971). The British oversaw governing EAAFRO from 1948. Finger millet research at SES first focused on germplasm collection, cleaning and preservation for farmer-preferred landraces. However, many scientists at SES at that time did not have the required research facilities to handle finger millet breeding (Keen, 1951). With the help of existing collaborators like International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); capacity building was offered in terms of training of scientists, mentorship and germplasm conservation for finger millet breeding in 1960's-1970's in the Teso sub-region (East African Agriculture and Forestry Research Organization, 1971). Later, SES changed to Serere Research Station (SRS) headed by Officer-in-charge as a director working under the ministry of Agriculture in the Directorate of Research. ICRISAT administered population improvement for finger millet which started around 1970's with the help of the scientists they had trained in Uganda. Around the 1970's crosses for finger millet started in Uganda by using introduced cytoplasmic male sterile (CMS) lines from ICRISAT for use in the finger millet breeding program in Uganda. The institute back then had equipment for crossing, counting and selfing finger millet. Among the screened lines, male sterility was identified in GULU E, which provided a basis mechanism for enforcing out-crossing and establishing of a broad base population in the program to improve finger millet landraces (East African Agriculture and Forestry Research Organization, 1971).

Since 1968, a broad gene pool of the different collections has been developed via breeding under finger millet improvement program (Keen, 1951; East African Agriculture and Forestry Research Organization, 1971). Crossing of selected parents continued as well as selfing and double crosses were attempted. Back crossing program focused on blast and lodging resistance was started (East African Agriculture and Forestry Research Organization, 1971). Over 300 crosses were made with good straw strength and standability. It is important to note that hot water emasculation technique had not been fully mastered for crossing and therefore an attempt was made to introduce male sterility into some of the lines (East African Agriculture and Forestry Research Organization, 1971; Doggett, 1989). However, due to delayed planting, the CMS lines died due to an insect-transmitted virus. Attempts were made later in 1970 to do seed treatment for these lines and pursue the male sterility research further (East African Agriculture and Forestry Research Organization, 1971; Doggett, 1989; Esele, 1989). The finger millet breeding program released three varieties namely ENGENY, GULU E and Serere 1 during 1969-1971, which were multiplied and distributed to farmers by the seed multiplication scheme. Preferred traits included good malting and grain quality, lodging resistance, good yields and adaptable to different environments (Esele, 1989). This explains why some of these varieties are still conserved in the northern and eastern Uganda because they possess farmer-preferred attributes for making millet bread and thick porridge/ ugali referred to as "kalo" in Uganda. GULU E which produces a deep dark color of finger millet thick porridge, known as "Atapa" in Teso region and "kwon kal" for the Luo is from the eastern part of Gulu district.

The varieties like ENGENY, EDING, ENGOM, GULU E, ELABA, OKIRING, SERERE 1, 104, 358, 66, 116, 149, 12, 117, 312, 119, 91, 82, 101, 21, 152 among others were experimented in regional trials in different agro-ecologies of Uganda. Many local varieties like EMIROIT, OBEETE, and EMODINGOIT among others were yielding an average yield of 800 kg/ha (East African Agriculture and Forestry Research Organization, 1971). The testing locations included Teso district (Kaberamaido, Kuju, Arapai, Kumi, Bukedea, Serere, Katakwi); Busoga district (Vukula, Bugaya, Nakabango), Lango district (Ngetta and Aduku), Acholi district (Labora), West Nile district (Abbi, Nebbi, Pakelle), Madi district (Iriri), Karamoja district (Namalu, Kibale), Bukedi district (Iki-Iki and Tororo) and Buganda district (Namulonge) in the 1970's (East African Agriculture and Forestry Research Organization, 1971).

Important traits like grain yield, number of heads, days to anthesis, blast disease resistance, plant height at harvest, lodge resistance and head type among others were collected from the screening trials (Doggett, 1989; Esele, 1989). Some of the varieties released in 1980s includes PESE 1 (P224), SEREMI 1(P249), U15(SEREMI 2), SEREMI 3 (S x17-88), SERERE 14 and SEC 695 among others (Esele, 1989). Among the scientists' spear heading millet research at this time were; Mukuru, SZ who was appointed a breeder for finger millet in Uganda but later transferred to ICRISAT (Mukuru and King, 1992). Peter Esele, a pathologist who doubled as a finger millet breeder; advanced many finger millet progenies in Uganda but were later lost during the 1986-1990's insurgence in Teso region (Esele, 1989; Mukuru and King, 1992).

Networks like the Eastern Africa Regional Sorghum and Millet Network (EARSAM) (1982 to 1992) facilitated the exchange of research information and germplasm sharing as well capacity building and infrastructural development in Uganda (Esele, 1989). The EARSAM Network brought together National Agricultural Research Systems (NARS) of 8 countries in eastern Africa (Ethiopia, Burundi, Kenya. Rwanda, Somalia, Sudan, Tanzania, and Uganda) (Mukuru and King, 1992). All these NARS were given a comparative advantage through working together to find solutions to various constraints limiting finger millet production in the region (Esele, 1989). This network therefore, through its funding and infrastructural development boosted finger millet research in Uganda (Mukuru and King, 1992). Later, during 2003-2007, the Eastern and Central Africa Regional Sorghum and Millet Network (ECARSM) was formed and focused on market orientation and dealt with constraints in the production and consumption chains. However, EARSAM and ECARSM ceased to function owing to funding limitations (Mukuru and King, 1992). Other networks included the Sorghum, Millet and Other Grains Collaborative Research Support Program (INTSORMIL CRSP) funded by the USAID also facilitated institutional capacity building (Oryokot, 2001). The INTSORMIL agronomists, animal nutritionists, biotechnologists, plant breeders, cereal chemists, economists, entomologists, food scientists, plant pathologists and weed scientists, from the Land Grant universities of Kansas State University, University of Nebraska, Ohio State University, Purdue University, Texas A&M University, West Texas A&M University, and the USDA/ARS collaborated with national research programs in East Africa like the cereals breeding in Uganda (Dalton and Zereyesus, 2013). The International Board for Plant Genetic Resources Descriptors for finger millet (IBPGR) also provided germplasm from 1976 to 1980s (East African Agriculture and Forestry Research Organization, 1971). Furthermore, INTSORMIL facilitated germplasm exchange, knowledge sharing and Infrastructural development in Uganda (1970s-1980) (Esele, 1989). They facilitated the renovation of research facilities like the striga research facility and the protocol for striga extraction in the seed bank at SRS in Uganda (Doggett, 1989; Esele, 1989; Dalton and Zereyesus, 2013).

Finger millet breeding activities collapsed during the insurgence in 1986-1992, when rebel wars in eastern Uganda to counterattack the government National Resistance Army (NRA) led to the exodus of scientists from the Serere Research Station (SRS) to Namulonge Research Station (NRS) (Doggett, 1989). This caused money which was supposed to support cereals breeding to be re-allocated to cassava breeding at NRS (Esele, 1989). It led to the collapse of finger millet research at SRS. It is also important to note that the cold storage that was also preserving finger millet accessions collapsed due to infrastructural break down (Oryokot, 2001). This resulted in the loss of more than 1000 germplasm collections of finger millet; lucky enough this germplasm was also kept in the ICRISAT Gene bank and was later retrieved for use in Uganda (Esele, 1989). After the insurgence, the government rebranded agricultural research under the National Agricultural Research Organization (NARO), an agency of the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) with the mandate to coordinate and oversee all aspects of public-funded agricultural research in Uganda in 1993 where SRS was later renamed Serere Agricultural and Animal Research Institute (SAARI) and was mandated to carry out finger millet breeding under the cereals improvement program (Oryokot, 2001). Also, after the insurgence some scientists like Peter Esele were moved to SAARI to continue finger millet research (Mukuru and King, 1992). Key traits of focus were blast resistance, striga and drought tolerance (Wanyera, 2005). Varieties like SEREMI 1 and 2 from Ugandan advanced germplasm collections were released in TESO region to address hunger in this region (Wanyera, 2005; Owere et al., 2014). Pathologists like Dr. Takan helped to address the problem of blast disease in finger millet working hand in hand with Peter Esele (Oryokot, 2001).

The main focus of the finger millet breeding program from 1993 to 2002 was to; (1) develop improved varieties of finger millet through germplasm evaluation and breeding, (2) develop early maturing finger millet varieties resistant to lodging, diseases (blast), and for specific end-use quality, (3) evaluate local and introduced finger millet varieties for grain quality, malting potential and yield for local and industrial use, (4) improve finger millet yields through the use of integrated agronomic management practices, (5) promote post-harvest handling and storage technologies in finger millet and finally, and (6) establish strong partnerships with clients and other end-users (Esele and Odelle, 1995; Oryokot, 2001). Nelson Wanyera took over the finger millet breeding at now, the National Semi-Arid Resources Research Institute (NaSARRI) when Esele left the institute to join politics

(Owere et al., 2014; Wanyera, 2005). This time finger millet research concentrated on germplasm cleaning, collection and advancement for lines that were under national performance trials led to the release of five finger millet varieties in 2017 namely NAROMIL 1 (FMS383), NAROMIL 2 (FMS 376), NAROMIL 3 (FMS 72), NAROMIL 4 (SEC 915) and NAROMIL 5 (IE 2440) (Ministry of Agriculture, Animal Industry and Fisheries, 2017). Crosses were made during this time; however, selections were not managed well, and a lot of mixtures existed in the finger millet program. The poor storage facilities and drying yards also contributed to the loss of crosses for finger millet (Esele and Odelle, 1995; Oryokot, 2001). Germplasm exchange and enhancement with collaboration with ICRISAT continued to improve finger millet in Uganda. Finger millet breeding is now spear headed by Scovia Adikini, a plant breeder/ pathologist in charge of finger millet breeding scheme optimization, human and institutional capacity building among others. Under Scovia's leadership, current research focuses on improving finger millet productivity for food and nutritional security and income through breeding for varieties that are well adapted and with required market traits (Adikini et al., 2021). She is currently evaluating over 1000 lines of finger millet for various traits like malting quality, nutritional quality and blast/striga/drought/pest resistance among others (Adikini et al., 2021).

FINGER MILLET PRODUCTION AND PROSPECTIVE AREAS IN UGANDA

Finger millet is grown throughout Uganda, especially in the Eastern, Northern, and Western agro-ecologies (Uganda Bureau of Statistics, 2020). Iganga, Kamuli, Kumi, Soroti, Mbale, and Tororo districts are the highest producers of finger millet in the eastern region; Gulu, Kitgum, Lira, Apach, and Arua districts in the northern region; and Kabale, Hoima, Bushenyi, Masindi and Mbarara districts in the western region (Adikini et al., 2021; Owere et al., 2014; Uganda Bureau of Statistics, 2020). These districts are estimated to provide over 65% of the total finger millet produced in Uganda (Uganda Bureau of Statistics, 2020). Many of the areas in the southern dryland and highlands, mid-northern, northern, West Nile farmlands, Western highlands, and Karamoja dry lands of Uganda are highly suitable for finger millet production. Therefore, it is anticipated that the production of this crop is likely to increase significantly due to the expansion of production into non-finger millet growing areas (Adikini et al., 2021; Owere et al., 2014). This is partly due to the nutritional benefits of the crop, its ability to withstand and perform under adverse climatic conditions (FAO, 2019), and the growing beverage and brewing industry in Uganda.

In the major producing regions, finger millet is predominantly grown on sandy-loam soils, where planting is done mainly in the first or long rains. The farmers' preference to grow finger millet in the first rains is due to adequate moisture/precipitation during this season, which later translates into higher yields obtained during the first rains compared to the second rains (Owere et al., 2014). Furthermore, the high labor rates, damage by stem borer, webworms, shoot fly, and aphids which are highly prevalent during the second rains, make most Uganda finger millet growers prefer the first season over the latter (FAO, 2019). The crop can give yield in different soils, from poor to very fertile, and can tolerate alkalinity. However, the best soils are alluvial, loamy, and sandy soils with good drainage and 800-1500 mm annual rainfall (FAOSTAT, 2022; Uganda Bureau of Statistics, 2020). With these soil properties and sufficient annual rainfall, most regions in Uganda can support finger millet cultivation (Upadhyaya et al., 2008). Therefore, concerted promotion among smallholder farmers in these regions can lead to wider cultivation of finger millet.

FINGER MILLET USES AND NUTRITIONAL BENEFITS

Finger millet is a staple food crop that plays an important role in the livelihoods of many rural smallholder farmers and their families in Uganda (FAOSTAT, 2022). In Uganda, like in many countries in sub-Saharan Africa, most of the finger millet produced is consumed at the household level, and surplus grain sold in local markets (Owere et al., 2014). The sale of finger millet with the cost of one kilogram being between 2000 to 5000 Ugandan shillings contributes greatly to rural households' incomes, especially to women's income. Ugandan finger millet is also exported to Russia, Senegal and Nigeria among others to earn the country more revenue (Uganda Bureau of Statistics, 2020). Finger millet grain has an extended shelf life of several years without significant damage by storage pests hence an important famine reserve crop providing food security opportunities for many Ugandans (Tenywa et al., 1999).

Finger millet is processed into flour which is used to make porridge as food commonly eaten as breakfast in Uganda. Hot finger millet porridge is useful for some rheumatic and arthritic pains and it is a good food for balancing blood sugar (Ojulong et al., 2021). Finger millet porridge is often flavored by e.g., fermentation, adding sugar, lemon, milk or honey, etc. In addition, "kalo" or "Ugali" is a type of millet bread made from finger millet and is very common in western, eastern, and northern parts of Uganda (Mubiru et al., 2020). Pregnant women benefit from finger millet because of its phytonutrients and iron content, which is higher than any cereal grain (Ojulong et al., 2021). Finger millet is also a remedy for stopping vomiting, relieving diarrhoea and soothing morning sickness among others (Saleh et al., 2013). These grain of this crop can be processed into several value-added products like busheera, malwa and kwete beverages, among others (Mubiru et al., 2020; Owere et al., 2014); all of these provide income to many households in Uganda. The flour from finger millet is used to bake bread and muffins, cookies and cakes. Busheera is a common traditional beverage produced in southwestern Uganda, while malwa is a local alcoholic beverage made from finger millet, whose preparation process takes about seven days to mature. Kwete is a local alcoholic beverage mainly consumed by the Lugbara people from the West Nile region in Uganda, whose entire production process takes about six days (Mubiru et al., 2020). Commercialization of these traditional products has, however, been limited due to poor quality, safety and short shelf life.

Finger millet is often neglected and underutilized, however, in terms of nutritional composition, it ranks higher than the majorly consumed cereal grains like rice (*O. sativa* L.), wheat (*T. aestivum* L.), and maize (*Z. mays* L.) (Abioye et al., 2022). The crop is one of the minor cereals known for its several health benefits which are attributed to its polyphenol and dietary fiber contents (FAOSTAT, 2022; Saleh et al., 2013). Finger millet serves as a major food in resource-poor countries of Asia and Africa by providing 75% of total calorie intake next to fine cereal grains (Longvah et al., 2017). The presence of five layered testa in finger millet makes it unique compared to other millets accounting for a higher dietary fiber content (Abioye et al., 2022). The grains of finger millet are nutritious and constitute important sources of protein (7-12%), fat (2-5%), carbohydrates (65-75%) and dietary fiber (15-20%) among others (Longvah et al., 2017; Saleh et al., 2013). Finger millet carbohydrate has unique property of slower digestibility making it a food for long sustenance (Ojulong et al., 2021).

Most people depending on wheat, rice and maize have poor diet intake of iron (Fe), zinc (Zn) and protein is the major cause of micronutrient and protein malnutrition (FAOSTAT, 2022). Finger millet has high levels of calcium, manganese, phosphorus, zinc, and iron compared to other cereals, thus when consumed, this millet has health benefits such as preventing calcium deficiency, anemia, constipation, and diabetes (Longvah et al., 2017; Saleh et al., 2013). The calcium content of entire finger millet seeds is 0.34%, compared to 0.01 to 0.06% for other major grains (Abioye et al., 2022). Finger millet has iron and zinc content of 1.9 - 4.65 mg/100 g and 1.95-4.27 mg/100 g, respectively (Sharma et al., 2017). Finger millet also possesses more lysine (2.2 g/100 g), threonine (3.4-4.2 g/100 g), and valine (480-630 mg/100 g) than other millets (Jagati et al., 2021). The ash concentration in finger millet is between 1.7 and 4.13%, which is higher than that of the other major cereal grains (Vetriventhan and Upadhyaya, 2018). Breastfeeding mothers who consume finger millet can produce sufficient breast milk for their babies (Saleh et al., 2013). Furthermore, because of its high nutrient contents, finger millet is gaining importance in Uganda for its potential use in the preparation of a variety of foods such as porridge, bread, biscuits, pastas, instant baby food, and composite flour (Ojulong et al., 2021). Therefore, with the aforementioned benefits, finger millet is an ideal crop for poverty alleviation, food, income, and nutritional security for many Ugandans, especially women and children residing in drought-prone areas of the country.

COMMON FINGER MILLET VARIETIES, PREFERRED ATTRIBUTES AND DISSEMINATION IN UGANDA

Despite the availability of high-yielding improved finger millet varieties, more than 60% of farmers in Uganda grow finger millet landraces that are low-yielding (Adikini et al., 2021). Commonly grown local varieties include ESERAIT, ETIYO, OTUNDURU, EMIROIT, OBEET, and OKWANGAPEL, among others. SEREMI 2 and PESE 1 are the most commonly grown improved finger millet varieties (Owere et al., 2014). The attributes like high yields, pest and disease tolerance, early maturity, compact head shape, grain size, high marketability, tolerance to shattering, long storage life, brewing quality, aroma, and taste in food are used by Ugandan farmers to select which varieties to cultivate (Owere et al., 2014; Wanyera, 2005). Through participatory interaction with farmers, desirable attributes were identified, leading to the development of finger millet varieties with the attributes desired on the market (Table 1) (Owere et al., 2014).

Through the National Agricultural Research Organization (NARO) and non-government organizations, the government has put some measures in place to help finger millet achieve its full utilization potential in Uganda. Some research projects like the cluster granary seed (CGS) project, launched in 2016 to be implemented in Amuria, Kumi and Kitgum districts of Uganda, led by the National Semi-Arid Resources Research Institute (NaSARRI) in partnership with World Vision Uganda, led to a small adoption of released finger millet varieties such as SEREMI 2 (FAO, 2019). However, the project reached out to a few farmer groups and farmers who directly benefited from it; this is relatively small compared to the number of finger millet farmers in eastern and northern Uganda. These farmer/farmer groups are now producing and conserving quality seeds (in both dryland cereals and legumes) for their communities. However, establishing an effective and sustainable seed delivery model for increased access to quality seeds is still lacking. Also, the capacity of farming communities to produce and conserve millet seeds has not been fully built, especially for finger millet. Another project; the Accelerated Varietal Improvement and Seed Delivery of Legumes and Cereals in Africa (AVISA) was launched in February 2019 to supplement the work done by Harnessing Opportunities for Productivity Enhancement for Sorghum and Millets

Table 1. Available improved finger millet varieties and their special attributes in Uganda.

Release Name/Designation	Breeding code	Popular Name	Parents	Source of breeding line	Year of release
NAROMIL1	FMS 383	-	IE 1010' / 'U 12' // 'P 277'	ICRISAT/Uganda germplasm collection	2017
NAROMIL2	FMS 376	-	('P 318' / 'OKRING') // 'IE-882'	Uganda Germplasm collection/ ICRISAT	2017
NAROMIL3	FMS72	-	P 248' / 'SX 8'	Uganda germplasm collection	2017
NAROMIL4	SEC915	-	Selection from world germplasm Collection	World collection	2017
NAROMIL5	IE2440	-	Selection from ICRISAT germplasm collection	ICRISAT	2017
SEREMI 1	(P249)/(Pese11)P	SEREMI 1	(P249)/(PESE 11)	Uganda germplasm collection	1999
SEREMI 2	U15	SEREMI 2	Selection from landrace	Uganda landrace	1999
SEREMI 3	Sx 17-88	SEREMI 3	(Sx 17/88)	Uganda germplasm collection	1999
PESE 1	P224	PESE 1	Selection from Uganda germplasm	Uganda germplasm collection	1989
GULU E	GULU E	GULU E	Selection from landrace	Uganda landrace	1970
SERERE 1	SERERE 1	SERERE 1	Selection from landrace	Uganda germplasm collection	1970
ENGENY	ENGENY	ENGENY	Selection from landrace	Uganda landrace	1969

All varieties are of self-pollinating type and adaptable to all agro-ecologies in Uganda.
Source: Adikini et al., 2021

(HOPE) by modernizing breeding, release and dissemination of NAROMIL 1-5 varieties, renovation of cereals seed store and increasing incomes for smallholders in Africa (Ojiewo et al., 2020). The delays brought on by COVID-19 restrictions, the AVISA project has not been able to fulfil all its objectives yet. Recent communications from the 2023 dry land Legumes and Cereals Review and Planning meeting in Accra, Ghana; International Maize and Wheat Improvement Center (CIMMYT) promised to provide continuous support to finger millet breeding and seed systems in Uganda through its AVISA project. (HOPE) by modernizing breeding, release and dissemination of NAROMIL 1-5 varieties, renovation of cereals seed store and increasing incomes for smallholders in Africa (Ojiewo et al., 2020). The delays brought on by COVID-19 restrictions, the AVISA project has not been able to fulfil all its objectives yet. Recent communications from the 2023 dry land Legumes and Cereals Review and Planning meeting in Accra, Ghana; International Maize and Wheat Improvement Center (CIMMYT) promised to provide continuous support to finger millet breeding and seed systems in Uganda through its AVISA project.

Major constraints to finger millet production

Socio-economic constraints

Although finger millet is among the top three cereal crops in Uganda, its production is still low, with on-farm average yields of <1000 kg/ha compared to on-station yields of 5000 kg/ha (Adikini et al., 2021; FAOSTAT, 2022). The yield gap between on-farm and on-station productivity is due to many socio-economic, abiotic and biotic factors. The socio-economic factors causing low millet yields mainly include the use of low-yielding unimproved varieties, poor agronomic practices, poor post-harvest handling and low research input coupled with reducing farm size threaten food and income security of smallholder farmers who rely on finger millet production. Besides, the lack of innovations for reducing drudgery in farming operations for finger millet remains a significant challenge to finger millet production in Uganda (Kidoido et al., 2002; Tenywa et al., 1999; Wanyera, 2005). Others include the labor-intensive nature of finger millet production in relation to other crops which limits expansion in acreage per household in Uganda (Kidoido et al., 2002). Finger millet production is still labor- intensive, especially during weeding, and the small seed size has constrained many farmers in Uganda in expanding its cultivation (Wanyera, 2005). Furthermore, improved varieties of finger millet that have been released have not been accessed by the farmers in Uganda due to inadequate information on improved varieties and poor seed dissemination practices resulting in greater grain quality and quantity losses (Ojiewo et al., 2020). Commercial production of finger millet in Uganda is halted by the lack of machinery for drying the grain which has left many processors to incur a lot of costs in drying the finger millet manually (Owere et al., 2014).

Finger millet being among the “underutilized cereals” in Uganda makes the crop to receive less attention from the research community and other practitioners and often priority goes to other cereals such as maize, rice and sorghum among others resulting in low productivity and limited area under cultivation for finger millet (Padulosi et al., 2013). However, finger millet particularly performs better than the prior crops in adverse agro-ecological and marginal soil conditions (Onyango, 2016). Therefore addressing the above socio-economic factors can boost the productivity of finger millet, thereby reducing poverty and hunger, the number one and two targets of the Sustainable Development Goals (SDGs) of the United Nations (Dawson et al., 2019). Furthermore, with the expansion of arid and semi-arid lands and vulnerability to climate change, policy considerations that allow funding for finger millet to be put in place (Wanyera, 2005).

Biotic and abiotic constraints

The biotic constraints include diseases, weeds (*Striga*), insects, pests, etc (Adikini et al., 2021; Owere et al., 2014). Blast is the most important disease that attacks finger millet in Uganda (Grovermann et al., 2018), while the abiotic factors include drought and low soil fertility (Owere et al., 2014).

Blast disease

Blast disease caused by the fungus, *Pyricularia grisea* (teleomorph: *Magnaporthe grisea*) is the most economically important biotic constraint to finger millet production, causing severe yield losses of 50 to 90%, thereby persistently threatening food and income security in Uganda (Adipala, 1989; Babu et al., 2013; Takan, 2004). *P. grisea* infects other cereals, such as wheat (*T. aestivum* L.), rice (Oryza sativa L.), and pearl millet (*Pennisetum glaucum* [L.] R. Br) and foxtail millet (*Setaria italic* L.) causing significant yield losses in Africa and Asia (Takan et al., 2012). Despite the wide host range of the pathogen, *M. grisea* populations mainly exist as host-specific (adapted) forms, capable of infecting a single host (Babu et al., 2013). The blast pathogen attacks all the aerial parts of the crop and at all growth stages; from seedlings to flowering stage, causing leaf, neck, and finger blasts (Figure 1), which result in the reduction of physiological maturity, yield, and biomass of the crop (Lenne et al., 2007; Takan et al., 2012). The neck and finger blast are the most destructive forms of the disease, leading to severe yield losses of up to 90% (Adipala, 1989; Babu et al., 2013). Infected leaves have grey elliptical or diamond-shaped lesions, and during the flowering stage, symptoms appear on the peduncle and fingers, causing neck and finger blasts (Adipala, 1989; Babu et al., 2013; Takan, 2004).

The pathogen is seed-borne, transmitted through the movement of infected seed from reservoirs/sources contracted from crop debris, weeds and finger millet wild relatives, such as *Eleusine indica, Digitaria* species, *Epimyrma africana, Doctylocterium* species and *Setaria* species (Takan, 2004). *P. grisea* transmission is exacerbated by the virtue that most subsistence smallholder farmers are not aware of the disease and have continued to use owned saved seed of susceptible varieties from season to season (Adikini et al., 2021; Takan, 2004), thus unknowingly facilitating disease spread. Several phytosanitary measures like the use of chemicals, disease-free seed, early planting, crop rotation, weed management and intercropping, among others, have been employed to reduce the effect of blast (Adipala, 1989; Owere et al., 2014). These cultural practices have not been fully effective, and the disease has continued to spread. Chemical control methods using fungicides like pyroquilon, tricyclazone, mancozeb, and carbofuran have effectively controlled the blast disease (Mgonja et al., 2007). However, these chemicals are not only expensive for the resource-limited smallholder farmers to acquire every season but also environmentally non-friendly. The most efficient, economical, and feasible way to manage blast is by developing and deploying resistant/tolerant finger millet varieties like NAROMIL 1-5 and SEREMI 2 combined with agronomic practices (Adikini et al., 2021; Takan et al., 2012).

Earlier studies reported that variations in *P. grisea* were associated with morphology, pathogenicity and genetic diversity (Tracyline et al., 2021). *P. grisea* evolution has often led to resistance breakdown overtime due to pathogen variability and therefore, interferes with the breeding objective of developing finger millet resistant genotypes (Kariaga et al., 2016). Therefore, understanding the variations in the morphological and genetic diversity of *P. grisea* population overtime is pivotal in untangling durable resistance to the losses caused by these pathogens (Takan et al., 2012; Tracyline et al., 2021). Studies on the genetic variability of *M. grisea*, using RAPD, RFLP, AFLP and SSR markers confirmed the variability and virulence complexity of the pathogen. These studies also revealed the presence of genetic diversity among different *M. grisea* strains collected from different environments (Takan et al., 2012; Tracyline et al., 2021; Yadav et al., 2019). The phylogenetic analysis of *P. grisea* isolates from Kenya grouped the samples into two main clusters and six sub-

Figure 1. Leaf blast (a) and Neck and finger blast (b) attacking finger millet.
Source: Faizo Kasule

clusters revealing that isolates from the studied regions were genetically diverse within the isolate population as opposed to geographical differentiation (Tracyline et al., 2021). Therefore, it is important to study virulence changes in the pathogen populations to anticipate resistance breakdown in existing finger millet cultivars such as NAROMIL 2 variety in Uganda; and to design strategies to sustain the cultivation of high-yielding, farmer and consumer preferred cultivar (Babu et al., 2013b). Genetic diversity to characterize the pathogen populations in Uganda was done more than 10 years ago, (Takan et al., 2012) and with the rapid evolution in *M. grisea*, there is need for a new characterization of this pathogen so as to use this information as a basis for epidemiological studies.

Lack of knowledge on the pathogen adapted to finger millet in Uganda overtime hinders efforts towards the identification and development of resistant cultivars adapted to local agro-ecological conditions. The East African Center of Innovation for Finger Millet and Sorghum (CIFMS) at NaSARRI has embarked on understanding the *P. grisea* population structure by employing both traditional microbiology and modern biotechnology assays in plant breeding to accelerate the development and adoption of new blast-resistant varieties of finger millet with the potential to substantially control blast and increase productivity in Uganda and Africa. In addition, about 2000 local landraces are being preserved and conserved at NaSARRI, Serere, and these are being used as sources of genetic variation for plant breeding experiments (Adikini et al., 2021).

Striga

Striga, infamously known as witch weed affects over 300 million farmers, thereby persistently threatening food and income security in sub-Saharan Africa (SSA) (Ejeta, 2007). Cereals such as maize, sorghum, finger millet and pearl millet among others are majorly attacked by *Striga* species, *Striga hermonthica* (Del.) Benth. and *Striga asiatica* (L.) Kuntze (Spallek et al., 2013). These are obligate root hemiparasitic plants which belong to the family Orobanchaceae (Ejeta, 2007). *S. hermonthica* (Del.) Benth is the most widespread and destructive witchweed affecting finger millet (Figure 2) contributing to low yields and intensive labor requirements in the eradication of this weed (Ejeta, 2007; Midega et al., 2010). The severity of *Striga* depends upon degree of infestation, seed viability, ecotypes, virulence, host crop susceptibility, climatic conditions, and cultural practices (Rodenburg et al., 2015).

Figure 2. Finger millet trials hit by *Striga hermonthica* at Bukedea, Uganda in 2022A season (A) and in farmers' fields in Pallisa (B).
Source: Faizo Kasule

Several phyto-sanitation strategies have been recommended for *S. hermonthica* control in SSA. These include crop rotations, the use of manure, quarantine imposed on infested areas, control of the movement of farm equipment between infected and uninfected areas, intensive herbicide application, hand weeding, uprooting and burning of *Striga* plants in infected fields (Haussmann et al., 2000; Hearne, 2009). However, the use of a single control method has proved to be ineffective in managing *Striga* infestation once well-established in the field (Badu-Apraku, 2010). This is exacerbated by the virtue that *Striga* produces many seeds with vast genetic variability and complex life cycle that can remain viable in the soil for up to 20 years (Huang et al., 2012). In addition, *Striga* seeds are very tiny and light and therefore, are easily dispersible in nearby fields through wind, animals, and agricultural tools, thereby gradually enriching seed reserve in the soil (Ejeta, 2007).

Furthermore, these strategies are expensive and are not generally available to small farmers in *Striga*-prone zones of Africa and Asia, therefore, prevention of *Striga* through breeding for resistance is the most sustainable strategy for the resource-poor farmers in SSA (Adewale et al., 2020; Ejeta, 2007).The development of improved varieties with *Striga* resistance depends on the identification of good sources of resistance and exploitation of these sources (Ejeta, 2007). Reports of genetic resistance to *Striga* have been documented in maize (Adewale et al., 2020), sorghum (Haussmann et al., 2000), rice (Rodenburg et al., 2015) and pearl millet (Kountche et al., 2013). Therefore, the Identification of source germplasm with differential resistance mechanisms can facilitate combining several resistance genes to obtain more durable and stable polygenic resistance to *Striga* in cereals (Adewale et al., 2020; Kountche et al., 2013).

To select for *Striga* resistance in host plants, screening at the field and laboratory conditions are essential. In vitro methods of screening for resistance are useful for identification of better breeding materials (Rodenburg et al., 2015). The search for resistance or tolerance often begins with the recognition of plants around which fewer or less vigorous *Striga* plants are observed or the crop yield is less affected relative to other plants growing around them in fields deliberately infested with parasitic weed seeds (Adewale et al., 2020; Ejeta, 2007; Rodenburg et al., 2015). Screening in field conditions is preferred when targeting complex traits like *Striga* that are influenced by different environmental conditions (Haussmann et al., 2000). Screening of cereals basing on visible host plant symptoms and *Striga* emergence counts is a common way to investigate the inheritance of genes controlling resistance and tolerance to *S. hermonthica* (Adewale et al., 2020; Haussmann et al., 2000; Kountche et al., 2013). However, similar research on identification of sources of resistance to *Striga* in finger millet has not been fully exploited yet finger millet has potential as a smart crop to provide alternative solutions in the context of climate change (Adikini et al., 2021; Kountche et al., 2013). Therefore, there is still a need for further research to characterize and identify new sources of resistance to *Striga* in finger millet for future exploitation.

Insects and pests

Important finger millet pests in Uganda include armyworms, cutworms, leaf aphids, stem borers, ear head caterpillars, and the fall armyworm (Adikini et al., 2021; Grovermann et al., 2018; Kidoido et al., 2002; Tenywa et al., 1999). Common bugs that feed on millet are; green bug (*Schizaphis graminum*) and chinch bug (*Blissus leucopterus leucopterus*) by sucking sap from young leaves and whorls hence causing yellowing and distortion of leaves, and wilting or death of plants (Akhtar et al., 2012; Maiga et al., 2008). Chemical control has

Figure 3. Stem borer effects on finger millet planted in 2022A season at NaSARRI, Uganda.
Source: Faizo Kasule

also proven effective for the control of bugs, however, it is not cost-effective for resource-poor farmers of SSA (Buntin et al., 2007). Through resistance breeding and screening, some finger millet varieties have been developed with resistance to bug species (Akhtar et al., 2012).

The two common species, *Kraussaria angulifera* Krauss and *Oedaleus senegalensis* of grasshoppers are potential regular pests of finger millet in Africa, and pest outbreaks are common in arid and semi-arid areas causing yield losses of 50-90% in finger millet (Maiga et al., 2008). Adopted control measures for grasshoppers include the planting of neem trees in finger millet fields which produce metabolites that adversely affect the grasshopper development phases (Amatobi et al., 1988). (Jago et al., 1993) reported that natural enemies like tenebrionid beetle *Pimelia senegalensis* Olivier and a *Eurombidium* species mite attack grasshoppers and can cause 40 and 51% mortality, respectively.

Lepidopteran stem borers are also major pests attacking finger millet in Africa (Gahukar and Reddy, 2019). These include the sorghum stem borer (*Chilo partellus* [Swinhoe]) (Pyralidae), finger millet stem borer or pink borer (*Sesamia inferens* Wlk.) (Noctuidae), white stem borer (*Saluria inficita* Wlk.) (Pyralidae) and the and maize stalk borer (*Busseola fusca* Fuller) (Noctuidae cause damage to millet) (Kalaisekar et al., 2016; Nwanze and Harris, 1992). Stem borers attack finger millet from the seedling stage (about 4 weeks after planting) to grain maturity (Figure 3). Their larvae enter the leaf whorl and feed on soft tissues; affected leaves show pinhole damage after they unfold forming tunnels into millet stems. This leads to the drying or wilting of the central shoot or growing point during the vegetative stage (Gahukar and Reddy, 2019; Kalaisekar et al., 2016). Stem borer infestation can cause yield losses of up to 100% in millets and this is dependent on cultivar and crop age, plant density and environment among other factors (Sasmal, 2018). Different management strategies are recommended to control stem borers including cultural practices, biological control agents, synthetic pesticides, use of resistant varieties among others (Gahukar and Reddy, 2019). However, most of these cultural methods and chemicals of pest control are not cost-effective for the majority of subsistence resource-constrained smallholder farmers of SSA (Kalaisekar et al., 2016; Sasmal, 2018). Therefore, the use of pest-resistant millet genotypes is the best alternative to manage stem borers.

Stem borers are becoming a major problem for finger millet farmers in Uganda and this is exacerbated by virtue that these insect pests also feed on other cereals like maize, sorghum and pearl millet, making their control strategies harder (Adikini et al., 2021; Badji et al., 2020). Stem borer rising populations are also attributed to the fact that these are observed to oviposit on non-host plants such as cowpea and cassava which are common

Figure 4. Finger millet lines hit by drought stress at NaSARRI, Serere in 2022B season.
Source: Faizo Kasule

crops intercropped with cereals in Uganda (Tefera, 2010). Different authors have screened millet by utilizing artificial infestation and genotypes with varying levels of resistance identified (Adikini et al., 2021; Kalaisekar et al., 2016). However, there is limited information on the resistance of finger millet to stem borer, yet it is a common pest on this crop in Uganda. This, therefore, calls for serious research regarding resistance of millet genotypes to these insect pests. The recently released varieties like the NAROMIL 1-5, PESE 1 and SEREMI 2 among others are high yielding, tolerant to major diseases but their susceptibility to major pests like stem borers is unknown. Improving resistance to stem borer requires identification of sources of resistance to increase the bases of resistance to this pest (Adikini et al., 2021; Badji et al., 2020; Owere et al., 2014; Wanyera, 2005).

Drought

In semi-arid and arid environments where finger millet is a dominant crop, drought or inadequate moisture is the major abiotic stress affecting its productivity (Anitha et al., 2019). Although finger millet is more drought resilient as compared to other cereals such as maize, simulation models predict that drought stress reduces the grain yield of finger millet to the extent of 40% on a global scale (Sakamma et al., 2018). Terminal drought adversely affects this crop (Figure 4), especially in areas it is grown by subsistence farmers who rely on rain-fed agriculture, hence prone to the risk of economic yield loss due to drought (Mwangoe et al., 2022). Drought stress leads to a reduction in plant height, panicle length, biomass, grain number and grain weight among others in finger millet. There is also a significant reduction in leaf area, dry matter accumulation, seed weight, chlorophyll content, radiation use efficiency and yield as a result of drought (Mude et al., 2020). Prolonged drought causes a reduction in protein, carbohydrate, amylase and relative water content (Gupta et al., 2017). Drought stress effects on finger millet are further exacerbated by changing weather and climatic conditions. The frequency and intensity of drought has increased in recent times (Selvaraju and Baas, 2007). However, a high degree of tolerance to high temperatures during the early and reproductive stages in some finger millet landraces offer a promising genetic resource for isolation of candidate genes governing adaptation to drought conditions (Gupta et al., 2017; Mwangoe et al., 2022).

Finger millet adaptation to drought is a result of biochemical adaptation to water stress leading to a change in chlorophyll content, production of antioxidant scavenging enzymes, increase in proline content, production of secondary metabolites such as alkaloids, terpenes, flavonoids, mevalonic acid and shikimic acid among others (Tiwari et al., 2019, 2020). Finger millet improvement in Uganda in the past has emphasized selecting for high-yielding lines with little regard for drought tolerance traits (Adikini et al., 2021; Esele and Odelle, 1995; Takan, 2004). The breeding program in Uganda now focuses on developing high-yielding, nutritious finger millet varieties with higher adaptable traits in water-limited environments or drought-prone areas in the country. Genetic improvement research for finger millet is on course by exploiting different mechanisms of drought resistance for advancement of drought-tolerant cultivars.

Low soil fertility

Among the abiotic constraints, poor soil fertility is a major problem constraining crop productivity in smallholder farmers due to inadequate nutrient replenishment which in turn limits finger millet productivity in Uganda (Ebanyat, 2009). This is furthermore exacerbated by the presence of parasitic *Striga* weeds (Kountche et al., 2013). Most soils where finger millet is grown are deficient in major and micro nutrients mainly due to continuous cropping, limited or no use of mineral fertilizers, poor recycling of residues and low rates of organic matter application among others which limits the crop’s yield potential (Ebanyat et al., 2021). Fertilizer use by finger millet smallholder farmers is low in Uganda because of high fertilizer costs and limited access as a result of poor infrastructure and a weak private crop input sector. The area covered by poor fertility fields in smallholder Ugandan communities is substantial and will increase if no action is taken to replenish and sustain soil fertility (Ebanyat, 2009; Ebanyat et al., 2021). Despite the presence of improved finger millet varieties in Uganda, soil fertility depletion affects the crop’s productivity (Kidoido et al., 2002; Owere et al., 2014). Potential options to restore soil fertility include the use of inorganic fertilizers to optimize locally available organic inputs and addressing site-specific constraints to restore and improve soil fertility as guided by an integrated soil fertility management paradigm (Rurinda et al., 2014). Therefore, measures for improving/restoring fertility in degraded soils are needed for smallholders to sustain finger millet production and close yield differences within farms in Uganda (Ebanyat et al., 2021).

Nitrogen, phosphorus and potassium are important for early establishment of finger millet. The effects of co-applying N, P and K fertilizers on crop performance have been reported, and it is assumed that N, P and K interactions improve yield and fertilizer use efficiency (Kang et al., 2020). Tenywa et al. (1999) and Rurinda et al. (2014) reported that finger millet establishment and grain yield were improved more with a combined nitrogen, phosphorus and potassium application compared to either nitrogen or phosphorus application alone. Therefore, to obtain better yields in the marginal soils where finger millet is grown, there is need to optimize nutrient application and management practices to ensure proper nutrient uptake by the crop, which can be achieved through the use of mineral fertilizers, application of organic fertilizers (farmyard and green manure), bio-fertilizers (like arbuscular mycorrhizal fungi) or combination of all (Rurinda et al., 2014; Ebanyat et al., 2021).

FINGER MILLET SEED SYSTEMS IN UGANDA

The finger millet seed system in Uganda is both formal and informal. The informal sector is characterized by farmers who produce, obtain, maintain, develop and distribute seed resources from one growing season to the next (Muhhuku, 2002; Mastenbroek et al., 2021). The formal sector involves breeding, evaluating improved varieties, and producing and selling seed certified by the National Seed Certification Services under the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) (Mabaya, 2016; Mabaya et al., 2018). The informal sector dominates the finger millet seed system in Uganda due to limited access and exposure to certified seed, inadequate funds to purchase seed, and few seed agro-dealers, among others (Mabaya et al., 2018). This makes many finger millet farmers rely on this informal seed system that lacks seed certification and quality assurance (FAO, 2019; Mabaya, 2016; Mabaya et al., 2018). The informal seed is preserved for long periods through practices such as drying on yards and rooftops. The use of uncertified seed has contributed to the spread of pests and diseases in the country (Adikini et al., 2021; Takan, 2004). Under the formal finger millet seed system in Uganda, the dry land cereals at NaSARRI can only produce 10% of the 250 tons finger millet certified seed, which cannot cater for majority of the millet farmers in the country (Mabaya et al., 2018). In this sector, few seed multipliers and companies often source certified finger millet seed (foundation or basic) from NaSARRI or National Agricultural Research Organization (NARO) holdings.

Under CIFMS, seed multipliers under KULIKA Uganda were trained on the standard operating procedures for millet seed multiplication to fill the gap. Although this center is training many seed multipliers in eastern and northern, they are constrained, especially with the lack of funds to carry out such activities. Furthermore, NARO has one millet breeder based at NaSARRI; this, coupled with insufficient funds, makes it difficult to maintain a comprehensive millet breeding and seed multiplication to meet the seed demand. The center hopes to employ research associates, seed scientists, and inventory managers, among others, to work with the millet breeder to have a vibrant millet seed system in Uganda (Mabaya et al., 2018). Furthermore, CIFMS has training to equip millet farmers on the importance of using certified seed. The center is currently working with extension workers in eastern Uganda to act as a liaison between NaSARRI and finger millet farmers to improve the uptake of improved millet varieties and certified seed. In addition, finger millet farmers and extension staff are equipped with knowledge of agronomic practices, post-harvest handling processes, pests, and disease control strategies to improve millet yields and crop competitiveness in Uganda. There is, however, a need for sensitization of more farmers, research officers, extension staff, and policy regulators for the realization of improved millet production.

Lack of or inaccessibility to improved seed is one of the constraining factors to increased finger millet production in East Africa (Mabaya, 2016; Mabaya et al., 2018). The current effort under CIFMS focuses on cutting edge problem-oriented development, testing and deployment of tools, technologies and methods that lead to genetic gain and stability of finger millet. The proposed finger millet seed systems will start with sharing of improved finger millet varieties among the partners in Uganda, Kenya and Tanzania (https://www.feedthefuture.gov/feed-the-future-innovation-labs/). This is ongoing work by CIFMS that will allow learning for potential impact since it will involve relevant private sector, formal and informal partners interested and in need of accessing new technology. The proposed seed systems initiative will improve the efficiency and effectiveness of getting good genes and genotypes into the hands of the stakeholders by providing a clear feedback loop between the research and the broader agricultural community (Feed the future innovation lab for crop improvement, 2023). It will allow CIFMS to develop delivery channels for future outputs of its research at a relatively low cost. This seed systems work is coordinated by NaSARRI, KALRO, and TARI in collaboration with the cross-cutting team and the seed systems group from Cornell University (https://www.feedthefuture.gov/feed-the-future-innovation-labs/).

ADVANCES IN FINGER MILLET GENETIC IMPROVEMENT, ASSOCIATION MAPPING, CANDIDATE GENE IDENTIFICATION AND TRANSCRIPTOMICS

Improvement to finger millet in Uganda involves exploiting of the existing genetic variability in the desired traits, and the nature as well as degree of their association among them (Dramadri, 2015; Owere et al., 2015). Conventional breeding has been successful in the past decades in developing finger millet varieties (Table 1) in Uganda (Wanyera, 2005). Ugandan finger millet breeders use conventional breeding for improvement of agronomic and nutritional traits in order to develop high yielding, blast tolerant and highly nutritious finger millet varieties (Wanyera, 2005). This has been done traditionally by selecting advanced lines with improved performance using phenotypic traits (Violet, 2015). However, these approaches alone are not sufficient given the increasing population' demand for food and nutritional security (Bančič et al., 2021).

Genomics-assisted breeding could be exploited to speed up the variety development process. However, genomics-assisted breeding is limited in finger millet improvement in Uganda due to lack of human and infrastructural capacity building, and robust molecular markers until recently (Dramadri, 2015). Furthermore, limited information on genetic diversity of finger millet germplasm, genetic and genomic resources and lack of adequate marker-trait associations has hampered finger millet breeding (Devos et al., 2023). Exploration of genetic diversity using molecular markers unravels unique opportunities which are robust and accurate to assess variability in finger millet germplasm and populations (Brhane et al., 2022). Markers like Random Amplified Polymorphic DNA (RAPD) were utilize to characterize finger millet accessions for nutrition and mineral composition (Mundada et al., 2019); morphology and cytological origin (Prabhu et al., 2018). Other research focused on genetic diversity studies using Inter Simple Sequence Repeats (ISSRs); Amplified Fragment Length Polymorphisms (AFLPs) Random Fragment Length Polymorphisms (RFLPs) among others which laid a foundation for molecular breeding in finger millet (Ajeesh Krishna et al., 2022; Brhane et al., 2022).

The construction of a partial finger millet genetic map (Dida et al., 2007) from F_2 mapping population between *E. coracana* subsp. *coracana* (Okhale 1) and *E. coracana* subsp. *Africana* (MD-20) which contained 327 loci were mapped to either A or B genomes. This led to the development of more than 45 genomic single sequence repeats (SSR) markers to evaluate genotypic variation among a diverse panel of 79 finger millet accessions sourced from Africa and Asia (Dida et al., 2008). This explains why SSR markers are among the most used genetic markers for molecular analysis in finger millet (Dida et al., 2007, 2008). Expressed sequence tag-derived simple sequence repeats (EST-SSRs) have also been used to show polymorphisms across finger millet due to their high rate of transferability across species than SSRs (Brhane et al., 2021). Through genotype by sequencing of finger millet germplasm, thousands of Single Nucleotide Polymorphisms (SNPs) have been identified (Gimode et al., 2016; Devos et al., 2023). SNPs are co-dominant, highly polymorphic and reproducible, hence frequently used for genotyping large individuals in genetic diversity applications (Gimode et al., 2016; Brhane et al., 2022). A total of 92 SNPs were validated for genetic diversity in finger millet out of the 23285 SNPs generated by Gimode et al. (2016). Therefore, in order to capitalize the power of Next Generation Sequencing (NGS), there is need to develop additional SNPs, SSRs, EST-SSRs among others for finger millet (Devos et al., 2023).

Genome wide association studies (GWAS) is one of the genomics-assisted breeding approaches used in finger millet breeding. This is done by leveraging a combination of phenotypic traits and genetic markers to unravel genomic regions controlling traits of interest or quantitative trait loci (QTLs) associated with different agro-morphological, grain nutrition, pest and disease resistance traits (Sharma et al., 2018; Puranik et al., 2020; Sood et al., 2023). Sharma et al. (2018) used 109 SNP to conduct a genome-wide association mapping of major agro-morphological traits in finger millet. Puranik et al. (2020) performed a GWAS using linear and mixed model approaches and identified 418 SNP markers linked with mineral content (iron, zinc, calcium, magnesium, potassium and sodium) in an assembly of 190 finger millet genotypes. Sood et al. (2023) generated 2977 high quality SNP markers for agronomic traits and reaction to blast in 186 diverse finger millet genotypes. There are also reports of association mapping for blast disease resistance in finger millet (Dida et al., 2021).

Preliminary GWAS using linear model with principal component analysis let to identification of 19 SNPs associated with blast disease that could be developed into assays for genotype quality control and trait introgression; although, a low number of 101 finger millet genotypes was used limiting the power of a full GWAS (Dida et al., 2021). There is need to generate a large set of genome-wide markers especially SNPs through genotyping by sequencing (GBS) to demonstrate and capture genetic variations associated with agro-morphological, nutrition, pest and resistance traits in Ugandan germplasm through GWAS (Owere et al., 2015).

A number of probable candidate genes responsible for calcium accumulation in grains, days to maturity and grain yield have been identified in finger millet (Sharma et al., 2022). Genes *EcCBP* and *EcCIPK7* were highly expressed in high calcium finger millet genotypes (Sharma et al., 2022). A 4000+ marker genetic map by Katrien M. Devos (University of Georgia, Athens) (https://phytozome-next.jgi.doe.gov/info/Ecoracana_v1_1) for allotetraploid finger millet was used to identify causal gene candidates for quantitative locus (QTL) for anthocyanin production in stigma and anthers (Devos et al., 2023). Trait mapping, followed by variant analysis of gene candidates revealed that loss of purple coloration of anthers and stigma are associated with the loss-of-function mutations in the finger millet orthologs of the maize *R1/B1* and *Arabidopsis GL3/EGL3* anthocyanin regulatory genes (Devos et al., 2023).

Whole genome sequencing (WGS) of ML-365, a drought tolerant and blast resistant finger millet genotype using illumine and Sequencing by Oligonucleotide Ligation and Detection (SOLiD) technologies assembled 53,300 *unigenes* (Hittalmani et al., 2017). Overall, 2866 drought responsive genes were associated with major transcription factors across 19 Pfam domains (Hittalmani et al., 2017). In the same study, about 1766 *R-genes* for various diseases and 330 genes were found to be involved in calcium transportation and accumulation (Hittalmani et al., 2017). Comparative analysis of transcriptome data and validation of function of genes identified CIPK31 and TAF6 candidate genes responsible for drought adaptive mechanisms in finger millet under field conditions (Parvathi et al., 2019). However, gene discovery and advances in association mapping, transcriptomics, candidate gene identification and annotation in Ugandan finger millet germplasm has never been studied. Therefore, there is need for comparative differential gene expression analysis studies in Ugandan finger millet germplasm to unravel molecular mechanisms underlying biotic and abiotic tolerances/resistances. Also, there is need to use molecular tools in identification of important agronomic traits in Ugandan finger millet. This will fine-tune efforts for future finger millet improvement programs in Uganda.

FINGER MILLET BREEDING AND FUTURE PROSPECTS IN UGANDA

The CIFMS based at NaSARRI, Serere, Uganda, hopes to harness finger millet genetic resources for increased productivity and utilization in the arid and semi-arid regions of East Africa under the Feed the Future Innovation Lab for Crop Improvement (https://www.feedthefuture.gov/feed-the-future-innovation-labs/). To achieve this goal, there is a need to understand the farmer's perceptions about local finger millet germplasm, its diversity, on-farm conservation, and the different factors smallholder farmers employ in decision-making during selection, preference, and retention of this crop, a crucial step for the future conservation of finger millet accessions in Uganda (Owere et al., 2014). The CIFMS has set up networks and partnerships through research to understand the finger millet value chain, market analysis, drivers of adoption, gender, youth and capacity strengthening to boost finger millet research and production in Uganda. To breed resilient varieties, CIFMS targets to use advanced methodologies such as the use of gene and molecular marker discovery for novel traits (particularly, protein and micronutrients, and the resistance to biotic and abiotic stresses) and develop tools and methods for efficient phenotyping and rapid generation advancement of the desirable traits (https://www.feedthefuture.gov/feed-the-future-innovation-labs/) (Table 2).

Identifying genomic regions and candidate genes controlling yield under abiotic and biotic stresses will pave the way for marker-assisted selection and breeding

Table 2. Finger millet trait prioritization for Uganda.

Objective	Trait/purpose	Progress	Remarks
Optimizing the finger millet breeding pipeline	Climate adaptation (drought tolerance)	61 lines evaluated for drought tolerance	Identification of lines which can adapt to drought
	Grain Nutrition (Fe and Zn)	156 lines evaluated for Fe and Zn at Kawanda Food Biosciences Center	Breeding high-yielding millet with high levels of micronutrients and proteins
	Early maturity and grain quality	30 &64 lines evaluated for early maturity and grain quality respectively	Genetic improvement for widespread use of high-yielding, early maturing lines with good grain quality
	Performance trials	20 & 25 lines evaluated in National Performance & Multi-location Trials, respectively	Determine agronomic potential and adaptability of lines to different agro-ecologies
	Biotic stresses resistance	All 472 lines of millet are being evaluated for blast while 247 are for *Striga*	Disease management through Host plant resistance (HPR) involves a sound knowledge of biology and epidemiology of diseases
	Genomics-assisted Breeding	Genotyping is ongoing for 376 lines	Foundation for trait discovery, mapping, and deployment of QTLs/alleles/candidate genes linked to traits of economic interests

Source: Faizo Kasule

of superior finger millet varieties in Uganda. Currently, the research team at NaSARRI is generating knowledge on finger millet through the collection of farmer-preferred finger millet germplasm (Adikini et al., 2021; https://www.feedthefuture.gov/feed-the-future-innovation-labs/). This collection is done to identify additional sources of resistance to biotic and abiotic stresses, excellent nutritional quality, new commodity and priority setting, among others, to guide current and future breeding efforts. In addition, the center is developing/ optimizing tools and methods for efficient phenotyping and rapid generation advancement of desirable traits (https://www.feedthefuture.gov/feed-the-future-innovation-labs/). For instance, several local germplasm collections have been gathered from different agro-ecologies of Uganda and introductions from other countries (Bančič et al., 2021). These collections are being phenotyped for blast, striga, drought and nutritional quality among others (https://www.feedthefuture.gov/feed-the-future-innovation-labs/). Of this diverse panel, 600 finger millet accessions are being genotyped and, so far, eight markers have been validated throughout the genome (https://www.feedthefuture.gov/feed-the-future-innovation-labs/). These highly abundant SNPs will greatly facilitate high-resolution genome-wide genotyping for millet in Uganda.

Breeding for *Striga* resistance

Through, CIFMS a coalition was formed with plant breeders and weed scientists from the Tanzania Agriculture Research Institute and the Kenya Agricultural and Livestock Research Organization with a mission to defend farmers against *Striga* infestations across East Africa (https://www.feedthefuture.gov/feed-the-future-innovation-labs/). The digital tools are being deployed in innovative ways by the CIFMS), which aims to help scientists to breed improved varieties resistant to *Striga*, with the support from the Feed the Future Innovation Lab for Crop Improvement under the guidance of the breeding informatics and phenomics teams to screen a diverse panel of finger millet genotypes to *Striga* infestation under natural field conditions in Bukedea, a *Striga* hotspot in Uganda and also under controlled environments (Jamil et al., 2021; Bisikwa et al., 2022). CIFMS received 72 advanced lines targeting *Striga* resistance from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and together with 175 breeding lines from Uganda, Kenya and Tanzania, these have been screened for *Striga* resistance in *Striga* hotspots (Bukedea and Kaberamaido) and at NaSARRI (control environment) (https://www.feedthefuture.gov/feed-the-future-innovation-labs/). Through phenotyping our program has identified 80 lines that we suspect to possess *Striga* resistance genes. Determination of *Striga* genetic diversity based on molecular markers among these identified lines is underway (Jamil et al., 2021). Inheritance of traits associated with *Striga* resistance are currently being exploited in finger millet in Uganda (Bisikwa et al., 2022).CIFMS is now evaluating these 80 lines in Uganda, Kenya and Tanzania using *Striga* screening protocol which exploits the use of striga seed inoculation (Robert, 2011).

Secondly, since SNP markers in finger millet that are associated with resistance to *Striga* using genome-wide association study (GWAS) have not been identified for accessions from Uganda, a Genome-wide association studies (GWAS) population will be developed using these 80 accessions of finger millet with diverse geographic origins (Ejeta, 2007). High-throughput genotyping will be conducted using the DArTseq protocol (www.diversityarrays.com); details regarding DArT genotyping methods and procedures can be found at http://www. diversityarrays.com/dart-application and in (Kilian et al., 2012). Reads and tags found in each sequencing result will be aligned to the [*E. coracana* (L.) Gaertn.] and the resultant markers will be markers filtered to eliminate SNPs with missing rate greater than 10%, heterozygosity greater than 20% and minor allele frequency (MAF) less than 5% (Adewale et al., 2020).

SNPs with unknown or multiple chromosomes locations will be eliminated. After quality filtering, informative DArTseq markers distributed across the finger millet chromosomes will be used for the population structure, phylogenetic analysis and GWAS analyses (Badu-Apraku, 2010).

Breeding for blast resistance

One of the objectives of the finger millet breeding program in Uganda is to breed for blast resistance and most varieties were released based on resistance to blast (Owere et al., 2014). However, resistance break down remains high owing to the variability and evolution of the blast pathogen, *M. grisea* and as such most released cultivars have succumbed to disease (Aru et al., 2020; Babu et al., 2013). Little effort has been put in understanding the mechanism of blast resistance in finger millet and yet this is key in developing a strategy for breeding for resistance. Efforts need to be put to understand genetic basis of resistance in local and introduced germplasms. Currently, CIFMS has a mini core collection of 472 advanced lines targeting blast resistance, sourced from Uganda, Kenya, Tanzania and ICRISAT (Babu et al., 2013). Preliminary results from ongoing phenotyping work for blast resistance at NaSARRI indicated that 120 accessions seem to possess blast resistance genes. However, further screening of these accession with diverse pathotypes of *M. grisea* isolates from major finger millet producing agro-ecologies of Uganda is urgently needed (Takan et al., 2012). In addition, there is a need to determine the mode of inheritance governing resistance to blast disease among resistant finger millet genotypes (Kariaga et al., 2016). Concerted efforts to uncover the allelic relationship between broad-spectrum resistant genes and the segregation pattern of SSR markers in a population created from a resistant local source (ICRISAT) and susceptible adapted local genotypes is under way.

Breeding for drought stress resilience

Limited soil moisture content coupled with unpredicted weather is one of the key environmental stresses affecting grain yield and nutritional quality (Dramadri, 2015). Therefore, sustainable food and nutritional security requires breeding for cultivars with higher adaptation traits in water-limited environments. Although finger millet is known to be drought tolerant, its growth is adversely affected by both intermittent and terminal droughts (Assefa et al., 2013; Mwangoe et al., 2022; Selvaraju & Baas, 2007). An effort to breed for drought tolerance in finger millet in Uganda is limited and most of the released finger millet is based on stay-green traits.

Drought tolerance is a complex trait controlled by many genes and yet the underlying mechanism for drought tolerance is not fully known. Dramadri (2015) found significant variation for pre- and post-flowering drought tolerance among 15-finger millet lines implying the existence of genotypic variation. Over 1500 finger millet germplasm are currently conserved at NaSARRI but has not been characterized for drought hence limiting the potential for drought research.

Conventional plant breeding techniques such as the use of introductions, selections and hybridization are employed by the finger millet breeding program in Uganda to identify and develop tolerant varieties (Adikini et al., 2021; Assefa et al., 2013). To identify sources of tolerance to abiotic stresses such as drought, the finger millet breeding programs in Uganda has assembled millet accessions from Kenya, Tanzania, Uganda and ICRISAT. Together with the existing breeding lines and landraces at the NaSARRI Gene Banks, assembled germplasm is being screened for tolerance to drought. The assembled germplasm is also screened across drought-prone regions in East Africa to characterize accession response to drought (https://www.feedthefuture.gov/feed-the-future-innovation-labs/). More than 700 lines including breeding, introductions and Landraces for finger millet are being screened for drought tolerance in Uganda. Hybridization is being done in Uganda to introgress drought tolerance genes from landraces and stress tolerant genotypes into breeding lines to develop progenies with improved performance under water deficit conditions. These progenies are advanced and are now at F_3 generation.

The CIFMS is using the Innovation Lab genotyping facilities at Connell University, USA for gene and molecular marker discovery for novel traits such as drought tolerance. Working with the trait discovery team, CIFMS is on the verge of genotyping a panel of finger millet accessions comprising breeding lines, local landraces and more advanced varieties that are important among the East African breeding programs, including germplasm collections will be from breeding programs in Kenya and Tanzania and ICRISAT. The program hopes to do medium or high-density genotyping to analyze DArTseq single nucleotide polymorphisms (SNPs) to characterize a broad panel of finger millet accessions. The objectives involve characterization of finger millet's genomic and phenotypic variations to explore the diversification process by (i) understanding the diversity within millet accessions, which is essential to make sure that, in the NaSARRI Gene Bank, (ii) genetic integrity of a given accession is maintained with its innate variability, and (iii) diversity without losing any rare allele variants to provide insights for future breeding. Efforts to construct a cold room that can host more than 5000 finger millet accessions are underway in collaboration with the national gene bank. The team at NaSARRI, in collaboration with partners under CIFMS, is training students and research associates on how to use bioinformatics and artificial intelligence to explore the different finger millet phenotypic data through breeding informatics. Different digital data capture platforms are being explored to store and manage both phenotypic and genotypic data.

Breeding for nutritional quality

Micronutrient deficiencies of iron, vitamin A and zinc have been reported as a major cause of death among the children, especially in developing countries like Uganda (UBOS, 2012). Zinc deficiency is estimated to range between 20 to 69% while 20% are vitamin A deficient in Uganda (FANTA, 2010). Malnutrition occurs during the period of complementary feeding (6-18 months) because of inappropriate complementary foods (UBOS, 2012). Finger millet being a promising source of micronutrients and proteins and therefore, the most cost-effective approach for mitigating micronutrient and protein malnutrition is to introduce finger millet varieties selected and/or bred for increased calcium (Ca), Iron (Fe), Zinc (Zn) and protein contents (Ojulong et al., 2021). Cultivars rich in Ca, Fe, Zn and protein with farmer-preferred grain quality and adaptation traits are readily accepted in Uganda. Attempts to breed finger millet for enhanced grain micronutrient and protein contents are still in its infancy stage in Uganda. Exploitation of existing variability among germplasm accessions is the first step and short-term strategy for developing and delivering micronutrient and protein-dense finger millet cultivars to address the micronutrient and protein malnutrition in the target population (Ojulong et al., 2021; Vetriventhan and Upadhyaya, 2018). Since finger millet is rich in these micronutrients, concerted efforts are underway to breed varieties for increased Fe, Zn, and vitamin A content to contribute to the reduction in micronutrient deficiencies. CIFMS aims to untangle the nutritional quality of finger millet core collection assembled at NaSARRI sourced from Kenya, Tanzania, Uganda and ICRISAT for grain mineral content such as Ca, Fe, Zn and protein content. Research progress in Uganda is underway to identify high-Fe, Zn and Ca lines from a large set of germplasm and gene pools. A total of 156 finger millet accessions were sent to the Food Biosciences and Agribusiness Center, Kawanda, Uganda for nutrient profiling for protein content, Zn, Fe, Ca, phytates and phytate: Zinc molar ratios. So far, the preliminary results from 52 accessions shows that genotypes with high Fe content also presented with rich Zn content, and some with high protein level. The identified lines with high micronutrients interest the finger millet breeding program in Uganda towards biofortification.

CONCLUSIONS AND RECOMMENDATIONS

Finger millet has long been an important cash, food and nutritional security crop in Uganda. It helps alleviate food and income insecurity in Uganda due to its nutritional importance and ability to produce acceptable yields in wide environments, especially when improved varieties are used. However, continuous improvement efforts should incorporate local tastes and preferences in candidate varieties to guarantee adoption. Efforts should be tailored to collect, characterize, and conserve finger millet germplasm to identify, document, and incorporate farmer-preferred traits in improved varieties. Furthermore, there is need to develop varieties that are early maturing, resistant or tolerant to both abiotic and biotic stress factors, and with excellent nutritional qualities to meet the future demand. This can be achieved by expediting by utilizing multi-omics approaches, that is, phenomics, genomics, metabolomics and bioinformatics, which will help identify, validate, and incorporate important agronomic traits. In addition, concerted efforts are needed in areas like value addition and market analysis, gender and social inclusion, capacity building, and infrastructure development to ensure sustainable growth of the finger millet value chain in Uganda.

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CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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