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Pearl millet: A marginalized solution to climate change adaptation, nutrition and food security challenges in Uganda

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Pearl millet is an important climate-resilient crop in arid and semi-arid regions of Uganda. Its grains are used mainly for food, brewing, and feed; to a lesser extent, its stover is used as feed for livestock. Pearl millet research in Uganda started in the 1950s. However, over the past half a century, it has stalled and stagnated due to limited funding, insurgences, and human and infrastructural capacity, resulting in the loss of genetic diversity and low on-farm productivity. Pearl millet offers numerous advantages in the face of changing weather patterns and other agricultural constraints in Uganda, which pose significant challenges to agricultural productivity and food security. This review addresses the status of pearl millet research, identifies future prospects, and outlines extension priorities for semi-arid and drought-prone areas in Uganda. It emphasizes the crop's production environments, importance, constraints, nutritional value, health benefits, breeding status, and research priorities. Finally, we discuss pearl millet breeding, research priorities, production strategies, and its potential as a drought-tolerant crop for enhancing nutritional and food security in Uganda.

Key words: Pearl millet, drylands resilience, food and nutrition security, diversity, production.

INTRODUCTION

Pearl millet (*Pennisetum glaucum* [L.] R. Br, 2n = 2x = 14), belonging to the family Poaceae, ranks sixth in the world cereal production after wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.) and sorghum (*Sorghum bicolor* L.) (Yadav et al., 2012; Venkata Rao et al., 2018). Globally, pearl millet occupies more than 30 million (ha) from the continents of Africa, Asia, Australia, and North and South America (Yadav et al., 2012); of which Asia and Africa (Western and Central Africa) are the largest producers (FAOSTAT, 2022). On a country scale, India is the largest producer of pearl millet, both in terms of area

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(~8.5 million ha) and production (~9.0 million tons) (Anuradha et al., 2017). According to Jukanti et al. (2016), cereals such as pearl millet with high nutritional values and are resilient to various adverse climatic effects can significantly contribute to addressing food and nutritional security, especially in developing countries. Pearl millet is a major crop cultivated in drought-prone agroecologies because of its peculiar ability to respond to hot conditions due to its short developmental stages and capacity for a high growth rate. These characteristics make it an excellent crop for short growing seasons under improved crop management (Yadav et al., 2012; Nedumaran et al., 2014; Jukanti et al., 2016).

In Africa, pearl millet is among the top three cereals occupying a total area of 22 million ha (FAOSTAT, 2022). Pearl millet is adapted to environmentally marginalized conditions outperforming crops like maize and wheat. It is a multipurpose staple cereal for millions of poor rural households living in arid and semi-arid tropics (Lubadde et al., 2017; Lagat et al., 2018). It is mainly grown in Western, Central, Eastern, and Southern Africa (Nedumaran et al., 2014; FAOSTAT, 2022). Nigeria, Niger, Chad, Mali, Senegal, Sudan, Uganda, and Tanzania are the major producers of pearl millet in Africa (Nedumaran et al., 2014; Lubadde et al., 2016; FAOSTAT, 2022). The crop produces grain used as food by many resource-constrained smallholder farmers (FAOSTAT, 2022). Pearl millet is grown mainly as a fodder crop in the USA, South America, Australia, and Southern Africa (FAOSTAT, 2018). In addition to grain and forage uses, pearl millet crop residues are used as forage, building materials, and fuel for cooking, particularly in dryland areas (Lubadde et al., 2017; Lagat et al., 2018).

In East Africa, pearl millet is grown in Tanzania, Kenya, Rwanda, and Uganda and is an important staple food (Obilana, 2003). Among the countries in East Africa, Uganda is the major producer of pearl millet in the region (Obilana, 2003; Lubadde et al., 2016). Pearl millet, also known as bulrush millet, is an important food and cash crop for many people living in semi-arid areas in Uganda (Lubadde et al., 2014; Jukanti et al., 2016). The crop is grown on a subsistence scale throughout the country ranging from sub-humid environments, especially in the eastern, northern, northeastern, and to some extent northwestern regions (Lubadde et al., 2016, 2017). Pearl millet is called different names around agroecologies where it is grown in Uganda. In the Karamoja sub-region, it is known as "*Eraau*", in Acholi as "*Raa*" while in Ateso, it is known as "*Emawele*".

Pearl millet crop gives a stable grain and forage yield on poor, sandy soils under hot, arid, and dry environments in severe drought and intense heat agroecologies in northern and other drought-prone areas in Uganda (National Research Council, 1996; Winchell et al., 2018). In Uganda, the crop is cultivated either as a mono-crop, in intercrop, or mixed crop with legumes such as cowpea (*Vigna unguiculata* (L.) Walp.) and mungbean (*Vigna radiata* (L.) Wilczek) providing food and financial security to smallholder farmers (Lubadde et al., 2016; Nelson et al., 2018). The crop is used mainly as food, for brewing, and to a lesser extent as feed for livestock (National Research Council, 1996; Adebiyi et al., 2017). Pearl millet whole grain is ground to make flour mainly used for soft porridge and sometimes mixed with cassava flour to make composite flour for stiff porridge also called "*Atapa*" in Ateso, "*Kalo*" in Luganda, "*Kwon*" in Langi and Acholi, and "*ugali*" in Kiswahili (Lubadde et al., 2016). Pearl millet grains are highly nutritious with high levels of metabolizable energy and protein. It has high densities of iron and zinc, and more balanced amino acid profile than maize or sorghum (Taylor, 2016; Adebiyi et al., 2017). Furthermore, the grain is also rich in vitamin A, minerals like iron, zinc, magnesium and calcium, fiber, phenolics, antioxidants, and sulfur-containing amino acids, among others (Adebiyi et al., 2017). The pearl millet traits desired by Ugandans include stay-green, tallness, tillering ability, high yielding, early maturing, and tolerance to pests and diseases among others (Jukanti et al., 2016; Lubadde et al., 2016).

Pearl millet research in Uganda started in the 1950s with a collection of germplasm from farmers throughout the country. However, due to conflicts, wars, and lack of funding, pearl millet research stalled and stagnated especially in the 1970s-1980s, and this led to loss of more than 2000 pearl millet accessions at the East Africa Agriculture and Forest Research Organization (East African Agriculture and Forestry Research Organization [EAAFRO], 1971). Currently, pearl millet research is hosted at the National Semi-Arid Resources Research Institute (NaSARRI), located in Serere, Uganda. Enormous progress has been made to revamp and improve pearl millet research in Uganda since 2011, at NaSARRI (Lubadde et al., 2014, 2016, 2017). This paper presents an overview of the various aspects of pearl millet, including its production environments, importance, constraints, nutritional value, and various health benefits. We further provided strategies and approaches to increase pearl millet productivity. Finally, we discussed future prospects of pearl millet as an alternative crop for drought-prone and an option for providing nutritional and food security in Uganda.

LITERATURE REVIEW

Pearl millet history, production and conservation in Uganda

Pearl millet is believed to have been introduced in Uganda from Sudan around 3000 BC (Winchell et al., 2018). It was originally grown by pastoral communities in the northern region of the country, where it thrived in semi-arid and arid conditions (East African Agriculture

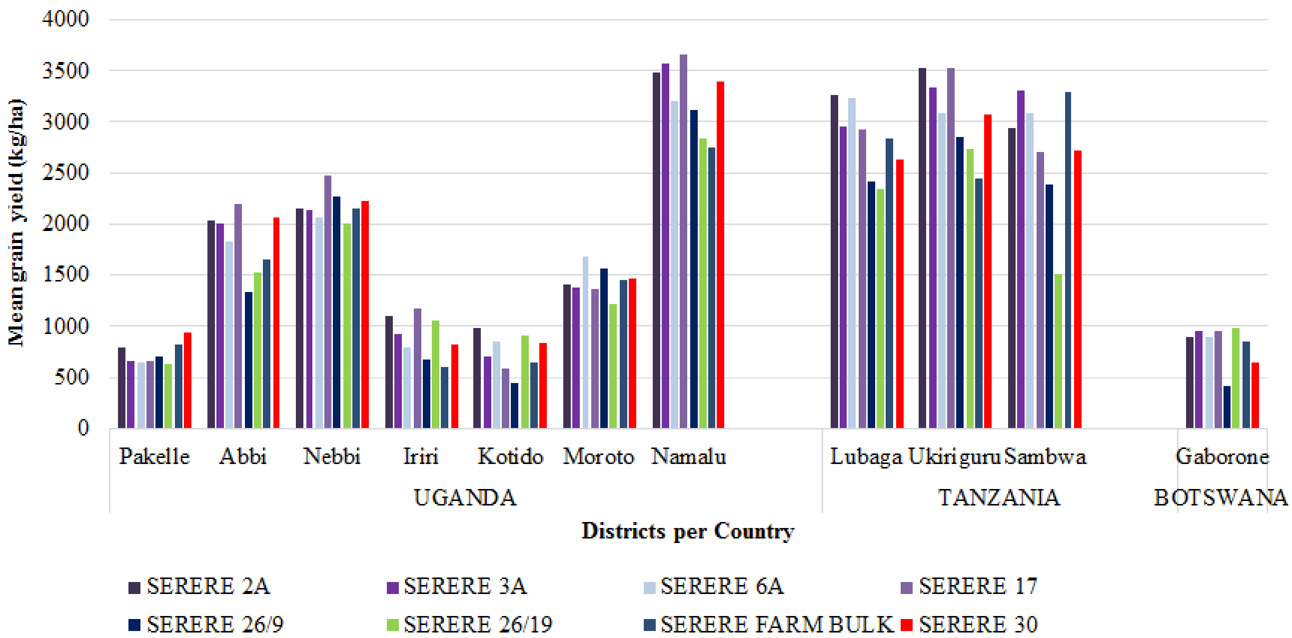

Figure 1. Mean grain yields from the Regional Field Pearl Millet Trials from Uganda, Tanzania and Botswana (1969-170). Source: East African Agriculture and Forestry Research Organization (1971).

and Forestry Research Organization, 1971). Pearl millet research in Uganda started in the 1950s at the East Africa Agriculture and Forest Research Organization which changed to Serere Agricultural and Animal Research Institute (SAARI) and now the National Semi-Arid Resources Research Institute (NaSARRI), located in Serere, Uganda (Kasule et al., 2023). This led to the collection of germplasm from pearl millet farmers from Uganda and this diversity panel served as a source of good traits for developing improved varieties. These improved lines were later adopted in Uganda (Figure 1) and other pearl millet-growing regions in Africa such as Tanzania, and Botswana, and in Asia, particularly India (East African Agriculture and Forestry Research Organization, 1971; Witcombe and Beckerman, 1987).

However, due to a number of reasons such as the breakdown of research services due to lack of funds, conflicts, and wars among others pearl millet research in Uganda stalled and stagnated in the 1970s-1980's. The enigma of such led to the loss of more than 2000 pearl millet accessions (both landraces and Improved varieties) (Witcombe and Beckerman, 1987). Pearl millet research resumed in Uganda at NaSARRI on a small scale with a focus on improving the crop to major biotic constraints like rust and ergot (Lubadde et al., 2014). Through activities like participatory rural appraisal and germplasm collection from pearl millet growing districts, scientists at NaSARRI aimed at identifying pearl millet populations that are early maturing, disease tolerant, high yielding, and drought tolerant among others, although still this research is being done on limited scale (Lubadde et al., 2016).

To date, pearl millet is mainly grown in semi-arid regions in northern (Acholi), northeastern (Karamoja) and eastern (Teso) regions (Figure 2). In northern its commonly grown in the districts of Kitgum, Lamwo, Agago, Yumbe and Moyo, northeastern in Kaabong, Karenga, Kotido and Abim while eastern in Katakwi, Amuria, Kumi and Ngora districts (Lubadde et al., 2014, 2016, 2017). These districts are characterized by moderate to high temperatures, low mean annual rainfall and widespread chronic food insecurity. Furthermore, in these regions other food crops meant to boost food security have seemingly failed to match the increased demand for food (Mottaleb et al., 2021). This has favored pearl millet production due to the crop's ability to grow under drought conditions (Serraj et al., 2005).

A study conducted in two semi-arid agro-ecological zones; the Teso and the Northern farming systems, in the 2011-2012 season showed that the average age of the household heads was 47 years for people growing pearl millet while the majority of the farmers in the range of 18-30 years were not growing pearl millet (Lubadde et al., 2014, 2016). This threatens the future of pearl millet crop production if the majority of the farmers cultivating the crop in the country are not youths. Furthermore, concerning the seed systems, the majority of the farmers in the northern region plant unimproved pearl millet seeds (landraces) while only 8% of those planted improved varieties. The seed source for pearl millet is mostly saved seed from previous harvests, from relatives, or bought from local markets with unknown genetic purity.

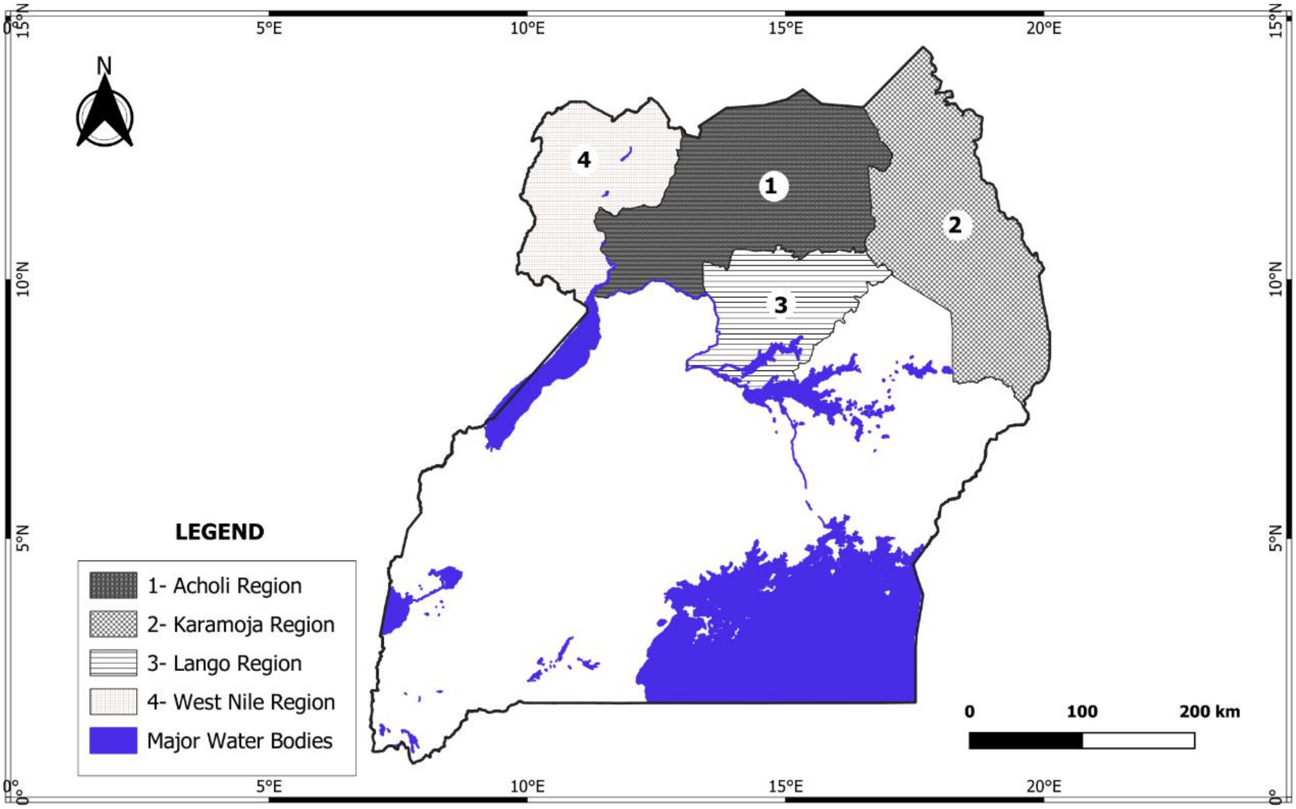

Figure 2. Map showing pearl millet productive regions in Uganda.

The most important reason for planting pearl millet landraces is the lack of quality seeds of improved varieties (Lubadde et al., 2016). Nevertheless, these farmers play an important role in pearl millet genetic resource conservation, hence, they aid in ensuring food and agricultural diversity, livelihoods, and food security in Uganda (Winchell et al., 2018; Olodo et al., 2020).

Most pearl millet farmers in Uganda do not utilize inputs like fertilizers, manure, herbicides, pesticides, and good agronomic practices like soil and water management measures among others to enhance pearl millet yields from the planted landraces. Furthermore, these farmers lack access to extension services or agricultural training on farming practices to enhance pearl millet productivity. They rely on the use of various practices passed on from their forefathers to ensure retention of pearl millet varieties (indigenous knowledge) (Lubadde et al., 2016; Olodo et al., 2020). Lubadde et al. (2016), reported that most pearl millet farmers in Uganda are not aware of the scientific importance of the conservation of pearl millet genetic resources but rather preserve varieties for the sake of supporting their current and future households' needs. However, this is an assumption that is not always right, most farmers do these practices for a reason, which they might not be able to explain scientifically but interacting and discussing with them you definitely get to fully grasp the importance of on-farm conservation of pearl millet genetic resources for future use.

A better understanding of gender differences in the adoption of pearl millet intensification strategies is crucial for designing effective policies to close the gender gap while sustainably enhancing farm productivity (Theriault et al., 2017). In pearl millet, men are mostly involved in land preparation and planting, women participate in weeding, harvesting, and threshing while bird scaring is done by children in Uganda (Lubadde et al., 2016). The pearl millet farmers in Uganda mainly practice the sole cropping system. Sole cropping without crop rotation with a legume does not promote optimal use of soil nutrients as it depletes the soil nitrogen and phosphorous resulting in low yields (Ebanyat et al., 2021). Broadcasting is the commonly adopted method by farmers in Uganda for sowing pearl millet. However, this method results in uneven plant stand, and seed wastage, and does not optimize yields, leading to reduced number and size of panicles due to large plant populations as opposed to row planting (B. Sharma et al., 2015).

Indeed, sowing methods also affect the pearl millet yield (Jan et al., 2015) and therefore, row planting should be adopted by farmers in Uganda if they are to minimize seed wastage during planting and also to obtain higher grain yield.

Broadcasting makes weeding difficult and labor-demanding compared to row planting (Lubadde et al., 2016). Weeds compete with pearl millet for water, nutrients, and light thus affecting plant growth and resulting in poor yields. This calls for timely and multiple weeding for effective control of weeds in pearl millet fields to maximize production (Girase et al., 2017). Pearl millet production is still labor-intensive, especially during weeding, and the small seed size has constrained many farmers in Uganda in expanding its cultivation (Lubadde et al., 2016). However, the high tillering ability of the crop and its fast growth, allows the crop to cover the ground fast smothering the weeds, compared to maize, and sorghum. The tillering also allows the crop to compensate for an uneven plant stand. For better pearl millet yields, effective weed control, narrow row spacing, and use of fertilizers are recommended especially at the pre-and early post-emergence stages in order to increase productivity in Uganda (Lubadde et al., 2016; Lagat et al., 2018). In conclusion, pearl millet has a rich history in Uganda, serving as a staple food crop for many communities. Its production is mainly rainfed with cultivation taking place in Acholi, Karamoja and Teso regions. Conservation efforts are underway to preserve the genetic diversity of pearl millet through farming communities and the National Agricultural Research Organization.

Uses of pearl millet in Uganda

Pearl millet is a versatile crop that has several prominent uses in Uganda (National Research Council, 1996), which include food, livestock feed, brewing, health benefits, crop rotation, and soil improvement among others (Sharma et al., 2015; Adebiyi et al., 2017). Farmers in northern and eastern Uganda were asked about the uses/importance of pearl millet in order to establish the significance of the crop to the farmers and results showed that most farmers cultivated pearl millet for food consumption (43.96%) followed by selling it as grain (35.53%) and brewing (17.22%) (Lubadde et al., 2016). To a lesser extent, some farmers barter the grain (1.47%) for other commodities while < 1% of the farmers feed grains to poultry (Lubadde et al., 2016; Olodo et al., 2020).

As food, the grain is ground to make flour which is used to make thin porridge called "*ugi*" and thick porridges known by different names as "*Atapa*" in the Teso region and "*Kwon*" in northern Uganda (Lubadde et al., 2014). Furthermore, some ethnic groups in Uganda mix millet with cassava flour to make composite flour, used mainly for thick porridge. In the Teso region, mixing with cassava flour is said to enhance the consistency of *atapa,* and *tamarind* is used to improve the taste.

However, in the northern and northeastern regions, pearl millet flour is not mixed with other food flour (Lubadde et al., 2016). Besides its importance as a staple food crop in the region, pearl millet contributes greatly to the incomes of rural households, particularly to women's income (Taylor, 2016; Olodo et al., 2020). Pearl millet grain and flour are sold in local markets where there is a high demand offering food and nutrition security and economic opportunities for many Ugandan smallholder farmers (Obilana, 2003).

For livestock feeding, pearl millet to a small extent, is used as a forage crop in Uganda (Lubadde et al., 2016). Pearl millet grain compares favorably with maize and sorghum as high-energy and high-protein ingredients in feed for poultry, pigs, cattle, and sheep (Masenya et al., 2021). According to Alonso et al. (2017), substituting maize with pearl millet in animal feed formulations may have advantages, such as higher protein content, lower incidence of mycotoxins, and similar lipid content although maize grain has higher energy compared to pearl millet grain. The crop residue after grain harvest is an additional valuable source of fodder for livestock. Currently, few smallholder farmers utilize pearl millet grain as feed for animals or poultry but in the future, it will be a crop of choice for animal and poultry feed according to current feed demand situations in Uganda due to its climate resilience and nutritive value (Alonso et al., 2017; Masenya et al., 2021). Stalks of the late maturing pearl millet types are used in roofing, fencing, and as firewood by farmers in northern Uganda (Lubadde et al., 2016). Traditional farming communities use pearl millet as yeast for local brewing(Olodo et al., 2020). Malting and fermentation processes result in malted and brewed products which are both non-alcoholic and alcoholic depending on the desired needs (Balli et al., 2023). Malted pearl millet is used in the brewing of traditional beer, consumed by locals in the northern and northeastern regions (Lubadde et al., 2014). It is an excellent source of yeast, however, some individuals in northern and eastern regions claim that some alcoholic drinks cause headaches after consumption which has resulted in a decline in the use of pearl millet as yeast (Lubadde et al., 2016).

Pearl millet nutritional value and preferred attributes

Over the years, there has been an increase in pearl millet grains and flour production and consumption in the northern and northeastern regions as these contain dietary fiber, carbohydrates, proteins, vitamins, minerals, micronutrients, and bioactive compounds, which are the most nutritional requirements for millions of poorest people in the regions of Uganda where it is cultivated (Adebiyi et al., 2017; Lubadde et al., 2014; Taylor, 2016). Pearl millet contains 9 to 13% protein, higher than rice (7.2%), maize (11.1%), sorghum (10.4), and barley (11.5%) (Adebiyi et al., 2017; Masenya et al., 2021).

The only cereals with a higher protein content than pearl millet are oats (16.7%), wheat (14.0%), and rye (13%), however, this crop also contains essential amino acids like lysine, threonine, methionine, and cysteine, higher than those found in sorghum and maize (Adebiyi et al., 2017; Dias-Martins et al., 2018). Pearl millet is also rich in unsaturated fatty acids with higher nutrient omega-3 fatty acid content which provide enough nutrition for an active and healthy life for poor men with low testosterone levels, (Dias-Martins et al., 2018). The crop has macronutrients and is considerably rich in resistant starch and soluble and insoluble dietary fiber and a higher digestibility of fat (8%) than most cereals like wheat, rice, barley, and sorghum (Adebiyi et al., 2017; Masenya et al., 2021).

Pearl millet is a good source of energy, with a calorific value of 361 Kcal/100 g and high in fiber content (1.2 g/100 g) (Dias-Martins et al., 2018). Pearl millet starches have amylase content ranging from 2.86 to 21.5% and higher swelling power and solubility. furthermore, the grains from this crop have a very high lipid content (6.4%), almost twice the amount in sorghum (3.4%) and maize (3.3%), but lower than oats (7.6%) (Taylor, 2016). Pearl millet is also gluten-free and a suitable choice for people with celiac disease or those following a gluten-free diet (Selladurai et al., 2023); plant chemicals like antioxidants, polyphenols, and phytochemicals, all of which are known for contributing to optimal human health in many ways (Adebiyi et al., 2017; Selladurai et al., 2023). The crop is also rich in vitamins such as thiamin, niacin, folic acid riboflavin, fat-soluble vitamin E, Vitamin A and B, minerals like calcium, zinc, iron, potassium, magnesium, phosphorus, copper, and manganese (Dias-Martins et al., 2018; Hassan et al., 2021). The total ash content of pearl millet (1.8%) is similar to wheat (1.9%), higher than maize (1.3%) and rice (0.9%), and lower than oats (2.5%) and barley (2.2%) (Hassan et al., 2021; Taylor, 2016). Pearl millet as a crop contains the highest amount of Fe content in cereals (80.0 mg/kg), compared to wheat with 35 mg/kg, corn with 27 mg/kg, brown rice with 18 mg/kg, and white rice with 7 mg/kg (Adebiyi et al., 2017). However, a lot of pearl millet varieties grown have low zinc and iron content, but the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in collaboration with national programs has developed biofortified pearl millet lines with high iron (≥80 mg/kg) and zinc contents and are currently under evaluation in Uganda (Ullah et al., 2016).

Pearl millet farmers in Uganda prefer varieties with attributes like stay green, medium height, high tillering ability, compact oval-shaped heads, high yielding, early maturity, and stay green due to its association to drought tolerance (Lubadde et al., 2016). In the Sahel and North-Sudan regions, farmers' most pearl millet preferred traits include compact and non-bristled panicle, large grain size, medium plant height, wide panicle diameter, early maturing, and very long panicle (Drabo et al., 2019), while in India, the order of importance differs; where high yield, drought tolerance, disease resistance, good taste, early maturity and large grains are the most important attributes for variety adoption (Yadav et al., 2016). White and gray-colored pearl millet grain is more preferred by farmers in West Africa than yellow and dark-colored grain (Drabo et al., 2019). Through participatory interaction with farmers, desirable attributes are identified, leading to the development of pearl millet genotypes with the attributes desired on the market (Lubadde et al., 2016; Drabo et al., 2019). Pearl millet is negatively affected by high air temperatures (up to 45°C) during flowering leading to high reproductive sterility which leads to drastic yield reduction. Therefore, breeding programs worldwide strive to improve desirable traits related to drought adaptability. This is also reflected in the observation made earlier by Yadav et al. (2016), where farmers selected varieties with stable yields under drought stress conditions rather than those with high grain yield under favorable conditions.

Constraints to pearl millet production

According to Lubadde et al. (2014), pearl millet production in Uganda is still low with on-farm average yields of less than 500 kg/ha compared to on-station yields of 5000 kg/ha. The yield gap between on-farm and on-station productivity is due to a number of abiotic and biotic factors and socio-economic challenges (Lubadde et al., 2016; Drabo et al., 2019).

Drought stress and declining soil fertility are the major abiotic constraints affecting pearl millet production (Yadav et al., 2012, 2016). In Uganda, pearl millet is mainly grown in semi-arid eastern, northern, and northeastern regions characterized by relatively moderate to high temperatures, low and erratic rainfall, and poor soils, which is exacerbated by the increasing climate change in the country justifying the need for climate resilient crops (Ebanyat et al., 2021; Mottaleb et al., 2021). The low amount and poor distribution of rainfall leads to less available soil moisture for crop utilization causing a reduction in seedling emergence, thus leading to poor growth, development, and establishment of the pearl millet and thus reducing productivity (Sharma et al., 2015). However, flowering and grain filling are the most sensitive stages to moisture deficits, and therefore, drought stress at these stages leads to a serious reduction in pearl millet grain productivity (Serraj et al., 2005). Furthermore, pearl millet cultivation in marginal soils with declining fertility coupled with high air and soil temperatures and heat stress results in poor yields of pear millet (Yadav et al., 2016).

Several diseases, insect pests, nematodes, birds, and weeds are the main biotic production constraints of pearl millet in many parts of Africa (Lubadde et al., 2016; Drabo et al., 2019; Gahukar and Reddy, 2019). Among the diseases, downy mildew (*Sclerospora graminicola*), smut (*Moesziomyces penicillariae*), rust (*Puccinia substriata* var. *indica*), blast (*Pyricularia grisea*) and ergot (*Claviceps fusiformis*) are most important constraints to

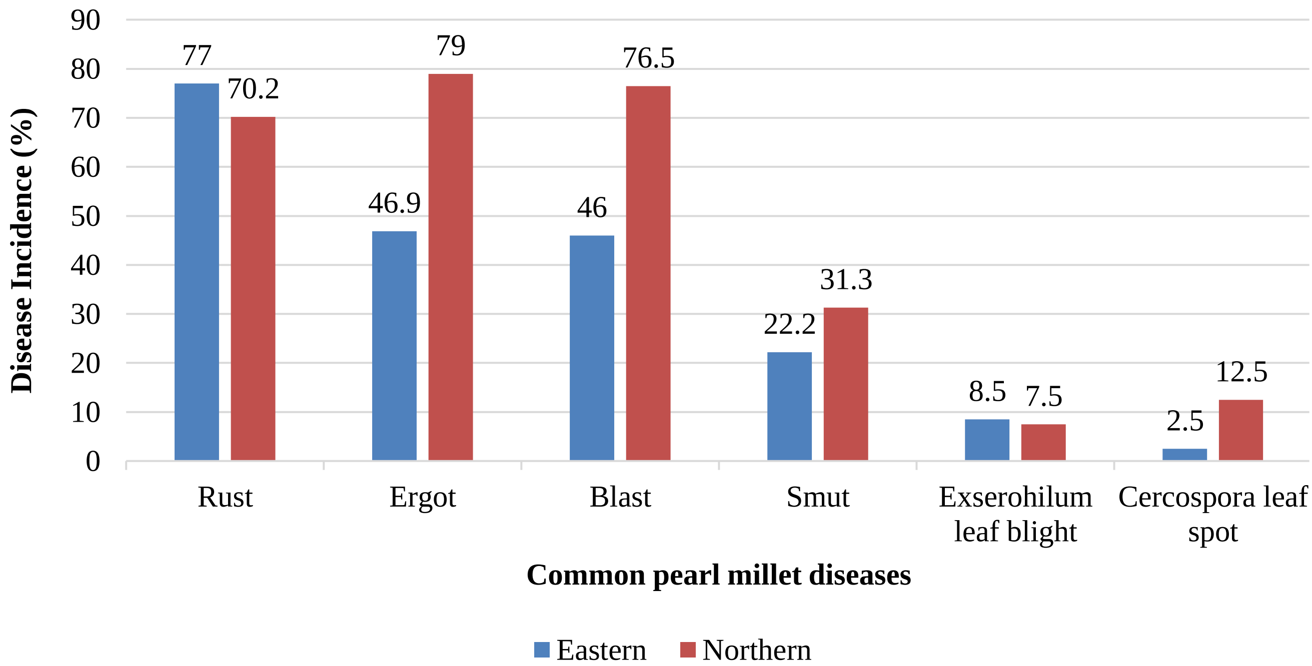

Figure 3. Occurrence of common pearl millet diseases from the eastern and northern regions of Uganda.
Source: Lubadde et al. (2014).

pearl millet production in Uganda (Thakur et al., 2011; Lubadde et al., 2014; Yadav et al., 2016). A disease survey conducted in 2012 in the farmers' fields in the predominantly pearl millet growing districts showed that the eastern region had the highest prevalence of rust (77%) while the northern region had the highest prevalence of ergot (79%), blast (76.5%) and smut (31.3%) (Figure 3) (Lubadde et al., 2014).

Low yields of 468 kg/ha were observed in the northern and eastern regions compared to the potential grain yield of 5000 kg/ha from research experiments due to the combined effect of common pearl millet diseases, unimproved varieties, and poor agronomic practices in farmers' fields (Esele, 1989; Lubadde et al., 2014). Rust is a destructive foliar disease in pearl millet growing regions in Uganda causing yield losses of above 50% and also lowering forage quality in susceptible pearl millet cultivars, which are the common cultivated lines in the country (Thakur et al., 2011). This disease affects pearl millet at growth and development stages but mostly occurs in severe form at/or after the soft dough stage (Yadav et al., 2016). When the rust strikes at the seedling stage, substantial reduction in grain and forage yield and quality is observed (Thakur et al., 2011).

Ergot is an important and widespread fungal disease in Uganda causing direct grain yield losses by replacing grains with toxic alkaloid-containing sclerotia, making the produce unfit for consumption (Miedaner and Geiger, 2015). This disease has been reported from India, Pakistan, and several countries in Africa including Botswana, Burkina Faso, Gambia, Ghana, Malawi, Senegal, Somalia, Tanzania, Uganda, and Zambia (Lubadde et al., 2014; Miedaner and Geiger, 2015; Drabo et al., 2019). Foliar blast (FB) disease is also an important disease in Uganda which has become a severe menace to successful pearl millet cultivation in the country causing severe yield losses (Lubadde et al., 2014).

Blast is widespread in the different pearl millet-growing ecologies of India, Sahel and North-Sudan regions (Drabo et al., 2019). Blast transmission is exacerbated by the virtue that most subsistence smallholder farmers are not aware of the disease and have continued to use owned saved seeds of susceptible varieties from season to season, thus unknowingly facilitating disease spread (Miedaner and Geiger, 2015; Drabo et al., 2019). Another disease affecting pearl millet in Uganda is smut, causing yield losses of 50 to 75% in the field, with damage of up to 100% in individual panicles (Lubadde et al., 2017). The disease has been reported in other countries like Pakistan, India, and the United States, and from many countries in Africa (Thakur et al., 2011).

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 diseases in pearl millet (Drabo et al., 2019). However, these cultural practices have not been fully effective, and the diseases have continued to spread.

Therefore, the use of host plant resistance is one approach that can significantly boost the integrated disease management method (Williams and Andrews, 1983). The development, screening, and evaluation of germplasm and breeding materials from a diverse panel of pearl millet lines with differential reactions to various diseases remain the most sustainable strategy especially for resource-poor farmers to manage diseases in pearl millet (Yadav et al., 2016).

According to Gahukar and Reddy (2019), pearl millet is attacked by at least 150 insect pests in its growth and development. The current pest status and crop damage are not yet known in the crop-growing agroecologies of Uganda. A number of these pests are considered economically important depending on the environment (Sharma and Davies, 1988; Nwanze and Harris, 1992; Gahukar and Reddy, 2019). Pests known to damage pearl millet include; stem borers (*Coniesta ignefusalis)* and pink stem borer *Sesamia inferens*, whose larvae feed on pearl millet leaves, also bores into the young stems causing dead-heart symptoms, as well as bores into the stem causing chaffy heads or stem breaking (Prasad and Babu, 2016; Gahukar and Reddy, 2019). Other pests like shoot flies *Atherigona approximate* whose larvae feed on the seedling growing tips cause dead-heart symptoms in pearl millet (Gahukar and Reddy, 2019).

Leaf-sucking pests such as the root aphids *Tetraneura nigriabdominalisi* remain at the base of the plants and suck the sap making infested plants turn pale yellow, stunted, and dry up (Sharma and Davies, 1988). The grain-sucking pests include the chinch bugs *Blissus leocopterus* and stink bugs *Nezara viridula* that suck the contents of the growing grain shrinking them and causing a chaffy appearance (Prasad and Babu, 2016; Gahukar and Reddy, 2019).The pearl millet head miners *Heliocheilus albipunctella* mine through the pearl millet head while eating the grain, millet grain midge *Geromyia penniseti,* whose larvae feed on the developing grains causing grain-less glumes having a white pupal case attached at the tip of the spikelets (Gahukar and Ba, 2019). The grain midge can cause up to 90% yield loss in some parts of Africa and India (Chandrashekar and Satyanarayana, 2006). Adult termites (diverse species) feed at the base of the pearl millet stems causing them to fall on the ground and dry up (Gahukar and Reddy, 2019). At the larvae growth stage, the white grubs *Holotrichia consanguinea* Blanch., feed on pearl millet roots and can be severe in arid and semi-arid agro-ecologies (Choudhary et al., 2018).

Fall armyworm *Sodoptera frugiperda*, whose larvae bore the stems and feed on stem contents including the growing tips—the African armyworm *Spodoptera exempta* whose larvae feed on the plant leaves also attack pearl millet (Gahukar and Reddy, 2019). Blister beetles, *Psylydolytta fusca*, are common pests in Africa and feed on pollen and grain. The nymphs and adults feed on developing grain causing it to shrink (Selander, 1988). The chafer beetle *Rhinyptia infuscata* can cause yield losses up to 37 to 57%. They feed on florets and stamens causing empty spikelets (Nwanze and Harris, 1992). Pearl millet in storage is also attacked by pests including the rice moth *Corcyra cephalonica*, grain mites, grain lice, flour beetle *Tribolium castaneum*, and rice weevil *Sitophilus oryzae,* and the saw-toothed beetle *Oryzaephilus surinamensis* (Sharma and Davies, 1988;Nwanze and Harris, 1992; Gahukar and Reddy, 2019).

Management of pearl millet pests is possible by application of synthetic pesticides (seed dressing, foliar sprays, fumigation), cultural practices such as the time of planting, crop rotation, field sanitation, host plant resistance (pest-resistant cultivars), biological control (natural enemies to destroy the pest), and a combination of pest control methods (Integrated pest management) (Drabo et al., 2019; Gahukar and Reddy, 2019).

Striga genus also infamously known as witchweed 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* spp., *Striga hermonthica* (Del.) Benth. and *Striga asiatica* (L.) Kuntze (Spallek et al., 2013; Drabo et al., 2019). These are obligate root hemiparasitic plants that belong to the family Orobanchaceae (Ejeta, 2007). *Striga* spp. especially *Striga hermonthica* (Del.) Benth is the most notorious parasitic weed affecting pearl millet production in SSA (Rouamba et al., 2021). Under drought conditions, *Striga* infestation can cause up to 100 % grain yield losses (Kountche et al., 2013). *Striga* weed invades the root system and directly competes with pearl millet for water and nutrients leading to low grain yield (Kountche et al., 2013; Rouamba et al., 2021). *Striga* control in pearl millet fields in Uganda is done through hand weeding, and crop rotation among others, however, these methods have high labor requirements that limit their implementation and use. Therefore, the use of host plant resistance against *S. hermonthica* to develop resistant varieties in combination with cultural control methods is required to reduce *S. hermonthica* on pearl millet production in SSA (Ejeta, 2007; Drabo et al., 2019; Rouamba et al., 2021). However, research on *Striga* infestations in pearl millet growing areas in Uganda has not been done and therefore, determining the magnitude, spatial distribution, and population dynamics of *Striga* infestation in pearl millet growing areas in Uganda remains a research gap to be undertaken. Birds are also a threat to pearl millet production in Uganda (Lubadde et al., 2016). This is constraining some farmers to abandon pearl millet production, especially in the first rainy season. Crop damage by birds was ranked as the second most important field constraint destroying pearl millet at all grain development stages in the northern and eastern regions of Uganda. The *Quelea quelea* birds are destructive at the milk stage while the weaver birds destroy pearl millet at all grain development stages. Most farmers have no control over the birds although some claim that planting in the second rains minimizes their effects (Lubadde et al., 2014, 2016). Early planting, many farmers planting the same variety at the same time has been demonstrated to reduce bird damage; bird scaring during the milking stage greatly reduces losses.

Exploiting pearl millet germplasm diversity in Uganda

Crop genetic resources are important in ensuring food security since they provide the raw materials needed for crop improvement (Mechlem, 2004). ICRISAT, in collaboration with the National Agricultural Research programs in Uganda, has in the past launched several expeditions where several pearl millet accessions were collected from Uganda and held at ICRISAT GeneBank (Upadhyaya and Gowda, 2009; Upadhyaya et al., 2012), and Uganda National GeneBank.

However, due to reasons related to management and lack of funds, the pearl millet lines conserved at the Uganda National GeneBank could not be properly maintained and thus this diversity was lost. Fortunately, the ICRISAT Genebank at Patancheru, India holds the world’s largest collection of over 22,000 pearl millet germplasm accessions from 50 countries, of 4,645 accessions were assembled from 16 East and Southern African countries (ESA) of which 48 accessions were collected funded by Rockefeller Foundation from Uganda in the 1980s (Upadhyaya and Gowda, 2009; Upadhyaya et al., 2012). ICRISAT launched a systematic germplasm collection in partnership with the International Board for Plant Genetic Resources, (IBPGR, now called Bioversity International), national and international institutes, National Agricultural Systems (NARS), universities, and NGOs. Under this arrangement, 119 accessions were collected from eastern and northern Uganda (Obilana et al., 1996; Upadhyaya et al., 2012).

Farmers over the years have cultivated a variety of crops like pearl millet on their farms that are adapted to particular needs and conditions (Williams and Andrews, 1983; Andrews et al., 1993; Upadhyaya and Gowda, 2009), and therefore form part of conserved germplasm. Pearl millet cultivation in Uganda has evolved over time and has undergone both environmental and human selection on farmers’ fields (Andrews et al., 1993; Venkata Rao et al., 2018). Ugandan smallholder farmers grow a diversity of pearl millet landraces which are consequently thought to be harboring important genes that will be of use in the future improvement of the crop (Lubadde et al., 2016). However, this crop's genetic diversity is threatened by diseases most notably ergot, rust, leaf blast, and smut that have resulted in reduced productivity and loss of germplasm (Baltensperger, 2002; Thakur et al., 2011).

Previous studies on the management and differentiation of local landraces of pearl millet grown by farmers in Uganda revealed that there could be variation in on-farm selection and cultivation of varieties influenced by cultural views (Upadhyaya and Gowda, 2009; Lubadde et al., 2016). This led to an attempt to assemble a collection of pearl millet accessions from the eastern, northern, and northeastern regions of Uganda.

METHODOLOGY

Between 2011 and 2015, a research team at NaSARRI, Serere, spearheaded an initiative under the Cluster Granary Seed Project to collect and assemble pearl millet accessions from major producing regions in Uganda. The sampling method employed was purposive simple random sampling, which involved the selection of accessions from major pearl millet cultivation districts in eastern and northern Uganda. These districts included Katakwi, Lamwo, Ngora, Serere, Kumi, and Kaberamaido. Approximately 60 different pearl millet accessions were collected and reposted in the NaSARRI gene bank. However, most of these accessions were mixed and therefore, needed cleaning and maintenance. Table 1 shows descriptors of pearl millet open-pollinated varieties (OPVs) collected from different semi-arid areas of Uganda. These were considered a store of valuable genetic diversity, which could be utilized in breeding programs.

Pearl millet is a highly cross-pollinated species, with outcrossing rates of more than 85%, because of its protogenos nature of flowering (Andrews et al., 1993; Upadhyaya and Gowda, 2009). The cereals program at NaSARRI had to properly control cross-pollination by wind and insects to maintain the genetic integrity of individual accessions collected from farmers’ fields, cluster bagging and sibbing were used for regenerating Ugandan landraces. The 60 accessions were planted at NaSARRI for three seasons for germplasm cleaning using a randomized complete block design with three replicates. The landrace collections were characterized as the program maintaining these OPVs at NaSARRI station. Each pearl millet genotype was planted in four rows, spaced 60 cm between rows and 20 cm within rows. Test materials were planted in a plot size of 4 by 2 m. Plots were separated by a distance of 1m from each other. Standard agronomic practices including planting in rows, timely weeding, thinning, gap filling, roughing of off-types and others were applied. No fertilizer or pesticide was applied at the time of characterizing these landraces.

The accessions were later reduced to 23 landrace varieties which were further evaluated at NaSARRI and data was collected from five randomly selected plants to record twelve traits which included plant height, panicle length, number of productive tillers, exertion Length, length of the fourth leaf, width of the fourth Leaf, Lodging, midrib color, overall disease score, overall pest score, stay green and a hundred seed weight (Table 2). At maturity, panicles from all plants from each plot were harvested, sun-dried, and threshed, and plot yield was established using hundred seed weight.

RESULTS AND DISCUSSION

Assessment of genetic diversity plays a vital role in evaluating, preserving, and using germplasm resources (Upadhyaya et al., 2012). Results from this study showed distinct variations among the 23 pearl millet accessions from different regions of Uganda (Table 2) tested, indicating the presence of genetic variability that can be exploited through selection. Lubadde et al. (2014) reported similar highly significant genetic variability in agronomic traits among pearl millet accessions from Uganda. These accessions have been entrusted to the

Table 1. Descriptors of pearl millet accessions collected form eastern, northern, and northeastern Uganda in 2011-2015.

Pearl millet accession ID	Local name	Panicle shape	Glum coverage	Glum color	Seed color
SPMGE/2017/001 KT	EMAWELE	Compact elliptic	1/2 Covered	Black	Grey
SPMGE/2017/002 KT	EMAWELE	Compact elliptic	1/2 Covered	Mahogony	Grey
SPMGE/2017/003 KT	EMAWELE	Compact elliptic	3/4 Covered	Grey	Grey
SPMGE/2017/005 LAM	RAA	Compact elliptic	1/2 Covered	Grey	Sienna (Yellow)
SPMGE/2017/007 NGR	EMAWELE	Compact elliptic	1/2 Covered	Mahogony	Grey
SPMGE/2017/008 KMI	EMAWELE	Compact elliptic	1/2 Covered	Mahogony	Grey
SPMGE/2017/009 KMI	EMAWELE	Compact elliptic	1/4 Covered	Grey	Grey
SPMGE/2017/010 SER	EMAWELE	Compact elliptic	1/2 Covered	Sienna (Yellow)	Purple
SPMGE/2017/011 KMU	-	Compact elliptic	1/4 Covered	Grey	Purple
SPMGE/2017/012 KMU	-	Compact elliptic	1/2 Covered	Grey	Grey
SPMGE/2017/013	OMODA	Compact elliptic	1/2 Covered	Black	Sienna (Yellow)
SPMGE/2017/014	ICMV 17	Compact elliptic	1/2 Covered	Grey	Purple
SPMGE/2017/015	ICMV 337	Compact elliptic	1/2 Covered	Black	Grey
SPMGE/2017/016	ICMV 221-2	Compact elliptic	1/2 Covered	Grey	Grey
SPMGE/2017/017	ICMV 94133	Compact elliptic	1/2 Covered	Purple	Grey
SPMGE/2017/018	GB 8735	Compact elliptic	1/2 Covered	Black	Grey
SPMGE/2017/019	SHIEBE	Compact elliptic	1/2 Covered	Grey	Grey
SPMGE/2017/020	NUP-23	Compact elliptic	1/2 Covered	Black	Grey
SPMGE/2017/021	S04-23	Compact elliptic	1/2 Covered	Purple	Grey
SPMGE/2017/022	SDMV 9400	Compact elliptic	1/2 Covered	Mahogony	Grey
SPMGE/2017/023	SOSAUK	Compact elliptic	1/2 Covered	Grey	Grey
SPMGE/2017/024	SDMU	Compact elliptic	3/4 Covered	Black	Grey
SPMGE/2017/025	SOSATC 88	Compact elliptic	1/2 Covered	Black	Sienna (Yellow)

SPMGE = Serere Pearl Millet Germplasm, Katakwi(KT), Lamwo (LAM), Ngora (NGR), Serere (SER), Kumi (KMU), and Kaberamaido (KMI).

Uganda National Gene Bank (UNGB) and ICRISAT, aiming for the development of composites and subsequent open-pollinated varieties (OPVs) through recurrent selection.

However, due to poor maintenance at UNGB and some genetic resources have been lost and to revive pearl millet breeding, the Ugandan research team had to acquire pearl millet germplasm from the ICRISAT GeneBank which is being maintained and experimented on at the dryland cereals program, NaSARRI, Uganda. Improved pearl millet lines developed by the NaSARRI cereals breeding program have not reached the vast number of smallholder farmers growing this crop in the country due to the limited financial support allocated to the crop and the absence of a functional seed system. Consequently, pearl millet lags behind other major grains such as maize and sorghum in yield improvement research. Furthermore, there is a need to collect more pearl millet accessions to supplement those collected by Upadhyaya et al. (2012). It is important to note that the 119 accessions were collected from a few districts in Uganda and therefore, emphasis should also be given to other pearl millet growing districts. In addition, in Uganda, the farmers' knowledge of pearl millet local varieties is not fully understood and there is a gap in that are acceptable and legitimate to the local communities. Therefore, understanding the socio-cultural integrating these into future on-farm conservation policies factors that influence farmer decision-making during the selection and retention of pearl millet varietal diversity is crucial for the future improvement of the crop. Documentation of farmer varieties based on farmers' knowledge and preferences for cultivation, utilization, selection, and conservation practices will generate knowledge on the conservation of food security crops like pearl millet, which is useful in the quest for attaining sustainable development goal 2 which focuses on ending hunger and all sorts of malnutrition by 2030.

Current pearl millet breeding and research prioritization

The national pearl millet breeding program is run by the dryland cereals program under the National Semi-Arid Resources Research Institute (NaSARRI) of the National Agricultural Research Organization (NARO), located in Serere, Uganda. To date, the main objective of the national pearl millet program is breeding advanced pearl millet technologies for multiple resistance, nutrition, and high yields. All the varieties in Uganda are improved open-pollinated varieties (OPVs) as hybrid breeding for

Table 2. Summary of 12 traits for 23 pear millet accessions.

Pearl millet accession ID	PH	PL	PT	EL	FLL	FLW	L	MC	OD	OP	SG	100SW
SPMGE/2017/001 KT	178.6	22.5	7.8	11.9	57.8	4.1	2	1	3	2	1	1.23
SPMGE/2017/002 KT	180.4	21	4.8	11.2	50.6	2.35	1	1	3	2	1	1.38
SPMGE/2017/003 KT	172	21.1	6.9	10.8	52.1	2.4	1	1	3	2	1	1.21
SPMGE/2017/005 LAM	166.8	21.1	4.7	11.6	56	3	1	2	3	3	1	1.49
SPMGE/2017/007 NGR	160.8	18.3	4.1	14.8	52	3.1	2	2	3	3	2	1.19
SPMGE/2017/008 KMI	163.2	18.5	6.1	16.5	49.7	3.1	1	2	3	2	2	2.37
SPMGE/2017/009 KMI	189.3	15.9	10.5	13.1	50.4	2.9	2	2	3	3	2	1.47
SPMGE/2017/010 SER	185.5	21.6	5.5	10	58.1	3.7	2	2	3	3	2	1.14
SPMGE/2017/011 KMU	186.6	21.6	3.3	9.9	50.5	2.6	2	2	3	2	2	1.44
SPMGE/2017/012 KMU	185.3	20.3	10.5	11.7	56.1	2.8	1	2	3	2	2	2.41
SPMGE/2017/013	180.5	20.3	3.8	12	54.1	2.9	1	2	3	2	2	1.98
SPMGE/2017/014	174.2	23.4	3.1	10.2	57	2.4	1	2	3	2	1	2.4
SPMGE/2017/015	151.1	26.7	39.3	12.4	56	2.55	1	1	3	2	2	1.78
SPMGE/2017/016	152.5	22.3	4.13	10.8	55.1	2.8	1	1	2	2	1	1.6
SPMGE/2017/017	142.4	22.9	3.7	12	58.7	2.9	1	2	2	1	1	1.86
SPMGE/2017/018	170.6	23.2	4.7	13.4	59.2	2.4	1	1	3	1	1	2.25
SPMGE/2017/019	148.7	23.9	3.9	10	49	2.5	1	1	2	2	1	1.68
SPMGE/2017/020	159.3	25.4	3.9	12.2	53.1	2.6	1	2	3	1	1	1.48
SPMGE/2017/021	147.9	27.5	3.4	10.9	54	2.5	1	1	3	1	1	1.48
SPMGE/2017/022	169.7	24.3	4.9	14.3	50	2.2	1	2	2	1	1	2.08
SPMGE/2017/023	156.7	23.9	2.8	9.3	49	2.6	1	1	3	1	1	1.92
SPMGE/2017/024	166.5	23.1	3.9	14.2	43.9	2.6	1	1	2	1	1	1.28
SPMGE/2017/025	142.5	24.9	2.9	13.9	49.5	2.4	1	2	2	1	1	1.66

PH = Plant height (cm), PL = Panicle Length, PT = Number of productive tillers, EL = Exertion Length, FLL = Length of the fourth leaf, FLW = Width of the Fourth Leaf, L = Lodging, MC = Midrib color, OD = Overall disease score, OP = Overall Pest Score, SG = Stay green and 100 SW = A hundred Seed Weight.
Source: NARO-NaSARRI.

pearl millet is yet to be initiated in Uganda due to lack of resources and lack of private breeding companies on seed value chains of staple crops like pearl millet. However, pearl millet hybrids have been introduced from ICRISAT-Nairobi for joint testing and are at advanced stages for possible release. The hybrids have shown a high yield potential of yield advantage of 40-60% over the improved OPV and show high potential for future pearl millet cultivation in the country (Venkata Rao et al., 2018). In other countries, pearl millet hybrids have been developed for example in India where they now have the biggest market share and are well-adopted by many Indian farmers (Matuschke and Qaim, 2008; Munasib et al., 2019).

The pearl millet maintained on station in NaSARRI, Uganda constitutes about 450 accessions which are maintained in response to the different production constraints in and differential requirements of various pearl millet growing regions therefore, prioritization of research has been conceptualized to address issues that are highly relevant to pearl millet cultivation in specific regions in Uganda (Figure 4). Drought is the primary abiotic constraint and it is caused by low and erratic distribution of rainfall (Lubadde et al., 2016). Hence, research related to the development of pearl millet cultivars suitable for rainfed and unpredictable low-rainfall situations has been a priority area in crop improvement in Uganda (Serraj et al., 2005; Yadav et al., 2016). A total of 25 pearl millet OPV lines are maintained (Figure 4) and evaluated for drought stress for climate adaptation focusing on drought tolerance in hot environments such as Serere, Moroto, Bukedea, and Nakapiripiriti. Screening of germplasm and introductions for increased adaptation to drought in Uganda has been a challenging task due to various complexities associated with drought adaptation mechanism and uncertainty in timing, intensity, and duration of stress coupled with the lack of funding to evaluate genotype by environment interactions for yield performance under drought and non-drought conditions are separate genetic entities (Yadav et al., 2012).

The pearl millet OPVs tested under the national performance trials (NPT) in 2023 in the drought hotspots of Uganda show promising results and the NaSARRI breeding program is yet to select the OPVs with inbuilt tolerance and resistance to climatic stresses such as

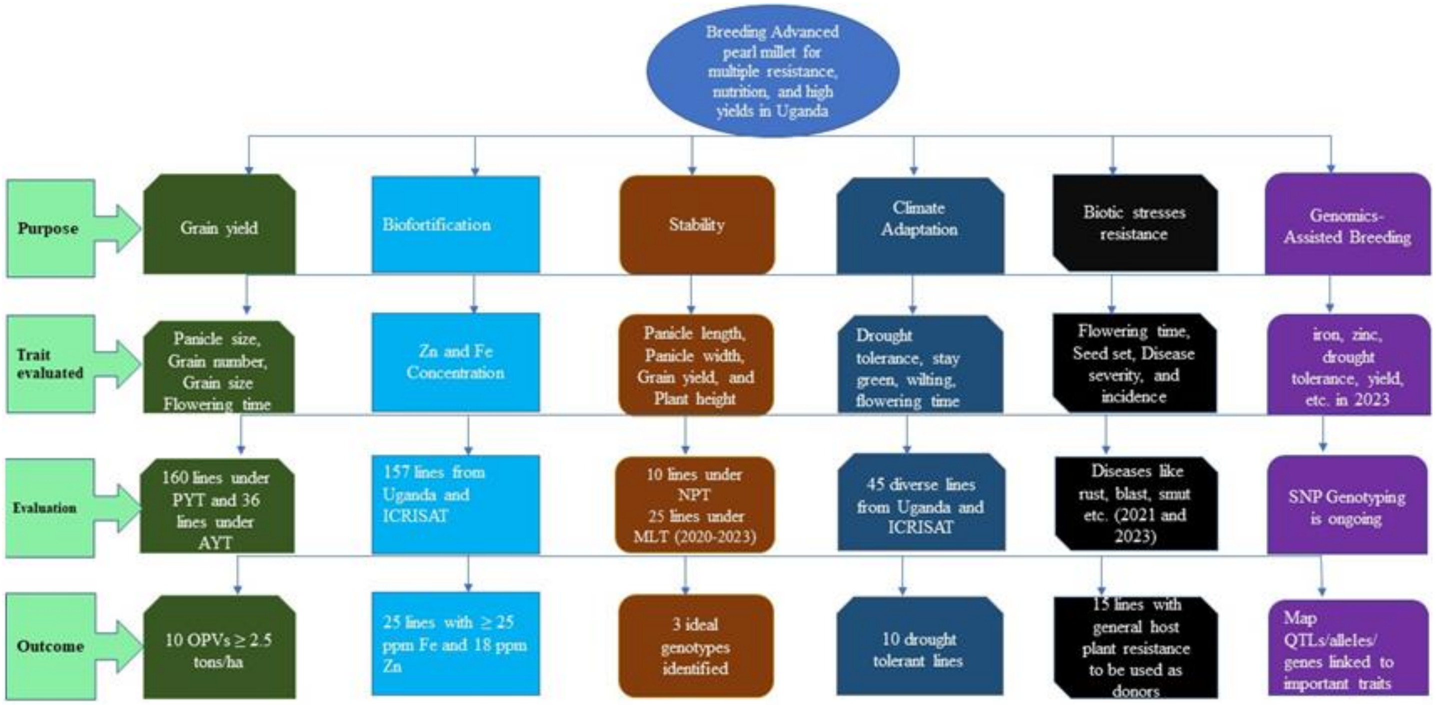

Figure 4. Pearl millet research progress in Uganda.
Source: Faizo Kasule.

drought and heat along with different diseases.

More than two billion people worldwide are affected by iron (Fe) and zinc (Zn) deficiencies, especially in developing countries (Webb et al., 2018; Mishra, 2023). In Uganda, micronutrient deficiencies related to Fe and Zn range from 20-70% in young children and 20 to 30% in adults (Buzigi et al., 2020). Since pearl millet is rich in these micronutrients, concerted efforts are underway to breed pearl millet varieties for increased Fe, Zn, and vitamin A content (Virk et al., 2021). This biofortification (agronomic or genetic enhancement of essential micronutrients and vitamins) collaboration involves germplasm sharing between ICRISAT and the National Agricultural Research System in Uganda (Yadav et al., 2012). Furthermore, there is research progress in Uganda to identify High-Fe/Zn lines from large sets of germplasm and gene pools. In most cases, pearl millet genotypes with high Fe content are also rich in Zn content, and therefore, breeding for both high Fe/Zn is underway in Uganda. ICRISAT-Nairobi is sharing Fe biofortified lines with values ranging from 70 to 240 mg/kg with National Agricultural Research Organization (NaSSARI and ZARDI-Nabuin) in different projects including HarvestPlus, which are at different stages of evaluation. Under the harvestplus project, 15 lines with Fe content ranging from 77.4 to 175.7 mg/kg have been selected for NPT in 2023. Currently, in the pearl millet breeding program in Uganda, a total of 157 lines evaluated for nutrition in the biofortified trial for Fe and Zn (Figure 4).

Challenges

Climate change and climate variability in Uganda have turned many arable areas in the country into semi-arid. This desertification has resulted in reduced arable land for agriculture; however, the effects of economic development and population increase have forced many farmers to cultivate in these marginalized semi-arid environments deemed not suitable for crop production (Lubadde et al., 2014, 2016; Drabo et al., 2019; Hamba et al., 2024). As a result, many crops, such as maize, increasingly fail to adapt to the changes and subsequently succumb to drought (Taylor, 2016).

Thus, one of the drought-tolerant crops that can withstand such extreme stress is pearl millet, which has increasingly become an important food security crop in Uganda (Yadav et al., 2016). Despite being an important food security crop, little research attention is paid to improving the locally adapted pearl millet materials in Uganda. Limited resources and scientists for pearl millet research in Uganda have led to the marginalization of this crop yet it is an important cereal.

However, Scientists at the National Semi-Arid Resources Research Institute (NaSARRI) have carried out numerous research activities on the crop, as a routine process to preserve, conserve, and improve pearl millet genetic resources amidst a constrained reality. The national pearl millet research has led to several breakthroughs including the submission of three candidate lines for release in Uganda although the government has not prioritized this cereal like maize, rice, and sorghum to sustainably finance research on pearl millet.

There is a need for immediate capacity building on pearl millet in public universities, and leading academic and research institutions in Uganda aimed at innovative teaching, learning, research, and services responsive to national and global needs. Student involvement in pearl millet research will drive the breeding goals of the National Agriculture Research Systems in Research, Capacity Building, and Community Development. The university collaboration is pivotal for driving millet research through training the young generation. Universities' role in graduate capacity building and optimization of phenotyping tools and methods will prove useful in reviving pearl millet research in Uganda. The limited capacity to produce pearl millet hybrids to attract private companies also is a result of a lack of capacity building and resources. Smallholder farmers in Uganda predominantly rely on landraces or open-pollinated varieties (OPVs), however, these are associated with low grain yields (648 kg/ha) as compared to 5000 to 7000 kg/ha yield potential from hybrids (Rao et al., 2018). Hybrid development requires capacity building in order to utilize diverse germplasm, critical in broadening the genetic base of cultivars (Yadav et al., 2016). Expertise is needed in the maintenance of both seed parents (A-lines) and restorer parents (R-lines), important in developing hybrids (Yadav et al., 2012).

Opportunities for variety release

The Uganda national pearl millet breeding program has evaluated pearl millet OPVs for years and has identified 3 candidate lines for release with a yield potential of 3500 to 4500kg/ha. The Distinctness Uniformity and Stability (DUS Testing) examination has been initiated on these 3 candidate lines for release and is currently at National Performance Trial (NPT). Before their release, these candidate lines will be profiled for the nutritional components such as crude fiber, proteins, carbohydrates, calcium, zinc, and iron. Furthermore, secondary metabolites such as anti-oxidants, tannins, phenolics, flavonoids, and alkaloids tests will be done. The above nutritional profiling will be done at the Nutrition and Biotechnology Laboratory at the National Crops Resources Research Institute (NaCRRI) and at the Uganda Virus Research Institute (UVRI).

For the DUS exercise, the Department of Variety Release and Seed Certification of the Ministry of Agriculture (MAAIF) at Entebbe, Uganda conducted three evaluations for; Distinctiveness, Uniformity, and Stability (DUS) on the three candidate pearl millet lines proposed for release. The team confirmed the stability of unique pearl millet cultivar descriptors to facilitate release, registration, and inclusion in the National Variety Catalogue. The DUS exercise was conducted at the seedling stage, dough stage, and maturity stage of the 2022 second season in four locations hosting pearl millet National performance trial Experimental Block at NaSARRI, Ngetta, Moroto, and Nakapiripiriti. A team was accompanied by breeders/scientists from the Dryland cereals program at NaSARRI. They identified three candidate lines which will be presented to the Variety release committee for recommendation for release to uptake pathways for increased production and productivity.

Efforts towards genomics-assisted breeding

The development of molecular markers using next-generation sequencing technology for breeding populations is a vital tool in championing pearl millet genetic improvement. High-density molecular markers are critical to quantitative trait loci (QTL) mapping to lay a foundation for marker-assisted breeding to improve the selection efficiency for faster development of pearl millet cultivars (Mohan et al., 1997; Singh and Nara, 2023). A number of QTLs for terminal drought resistance have been discovered using genetic maps of markers including microsatellite (SSR) and restriction fragment length polymorphism (RFLP) markers (Sehgal et al., 2012; Serraj et al., 2005). Association mapping is a powerful tool for identifying genetic variants associated with desirable traits (Saïdou et al., 2014; Pujar et al., 2020).

The genome sequencing of pearl millet in 2017 has provided valuable insights into the genetic makeup of this important cereal crop. The genome assembly consisted of approximately 1.79 billion base pairs covering about 91% of the estimated genome (Varshney et al., 2017). The sequencing and analysis of the pearl millet genome revealed an estimation of 38,579 genes and one of the key discoveries was the identification of genes involved in stress response (Varshney et al., 2017; Shinde et al., 2019). Stress responsive genes contribute to drought/heat tolerance and resistance in pearl millet and make the crop to thrive in arid and semi-arid environments (Chakraborty et al., 2022).

Candidate gene association studies and genetic-wide association studies are the two common approaches used in genetic research to identify relationships between genetic variations and specific traits or phenotypes in pearl millet (Pujar et al., 2020). Association mapping in pearl millet has been used to identify markers linked to traits such as drought tolerance, grain yield, disease resistance, grain iron, zinc, and protein content among others (Pujar et al., 2020; Saïdou et al., 2014; Shresthaet al., 2023). Pujar et al. (2020), identified four SNPs cosegregated for Fe and Zn, 18 SNPs associated with Fe, and 3 SNPs associated with Fe more than 7.5% of phenotypic variation.

In pearl millet, a candidate gene approach has been used to identify genes related to drought tolerance and seed dormancy. For example, the DREB gene family, which encodes transcription factors involved in stress response, has been identified as a potential candidate gene for drought tolerance in pearl millet (Lata and Prasad, 2011; Shinde et al., 2019). Similarly, genes involved in the abscisic acid (ABA) signaling pathway have been linked to seed dormancy and germination in pearl millet (Wu et al., 2021). Transcriptomics has been used in pearl millet to identify genes and molecular pathways involved in various physiological processes such as chlorophyll biosynthesis (Shinde et al., 2023), seed development (Varshney et al., 2017), and stress response (Lin et al., 2023). Transcriptomics analysis has also been used to identify differentially expressed genes (DEGs) between pearl millet varieties with contrasting traits such as drought tolerance or disease resistance (Ndiaye et al., 2022; S. Singh et al., 2022).

In Uganda, characterization of 431 pearl millet OPVs is underway to determine the genetic diversity and population structure of pearl millet germplasm and breeding populations in order to accelerate its genetic improvement for agronomic and nutritional traits. Toward this goal, leaf samples from a panel of 431 lines were obtained and sent to the genotyping-by-sequencing platform at Intertek for medium to high-density SNP genotyping. This approach will untangle the population genomic dynamics in order to understand the extent of genetic diversity of Ugandan pearl millet populations and later this can be pivotal for hybrid variety development. Association mapping, candidate gene approach, and transcriptomics are valuable techniques that can provide insights into the genetic basis of complex traits in pearl millet and accelerate the development of new varieties with improved agronomic performance in Uganda.

Conclusion

Pearl millet offers a marginalized yet powerful solution to address the challenges of climate change adaptation, nutrition, and food security in Uganda. The crop is sustainably important for food, nutrition, and income security for communities living in semi-arid and drought-prone areas in Uganda. The crop’s ability to grow under low rainfall with high temperatures and poor soil conditions ensures few crop failures resulting in assured food availability for people living in semi-arid and arid lands (ASALs). The crop’s high nutritional value is pivotal in improving nutritional quality and combating malnutrition hence overcoming the enigma of nutrition security and the available excess grain for sale ensures income insecurity among small-scale farmers living in the ASLs. There is an urgent need to improve pearl millet productivity and production stability in Uganda hence the focus should be on the development of pearl millet research in the country through improvement efforts tailored to incorporating local tastes and preferences in candidate varieties to guarantee adoption. In addition, concerted efforts are needed in areas like value addition and market analysis, gender and social inclusion, stakeholder engagement, capacity building (in the form of main staff like Breeders), and infrastructure development (phenotyping facilities, greenhouses, cold rooms, and labs among others). More funding especially from the government tailored to pearl millet research since this is a staple crop to ensure sustainable growth of the pearl millet value chain in Uganda. Efforts should be tailored to the collection, characterization, and conservation of pearl millet germplasm to identify, document, and incorporate farmer-preferred trait preferences in improved varieties. Furthermore, there is a need to develop varieties that are early maturing, resistant or tolerant to both abiotic and biotic stress factors, and with excellent nutritional qualities. There is a need to use genomic tools for screening and development of improved pearl millet genotypes in Uganda for faster and robust progress towards enhancing genetic gains for traits of interest thus, optimizing the breeding pipelines. This can be achieved by expediting phenomics, genomics, and bioinformatics which will help in the identification, validation, and incorporation of important agronomic traits.

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CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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