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Indigenous African cereal crops can contribute to mitigation of the impact of climate change on food security.

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Abstract

Zea mays L. (maize) is one of the top three cultivated cereals globally, along with wheat and rice. The United States, China, and Brazil are among the largest producers of maize, producing approximately 79% of the world's maize. Maize is used to produce human food and animal feed. It is also used to produce industrial products such as starch sweeteners, oil, beverages and bioethanol. South Africa produces maize as well. However, this production is relatively insignificant compared to the major producers. Furthermore, South Africa is a semi-arid country and as such receives less rainfall and has annual droughts. This has negative implications on maize production, which threatens food security. The sole reliance on a limited number of staple cereals is not a sustainable option. In order to truly improve food security, the diversification of staple cereals is necessary. Therefore, this review aims at discussing the diversification of staple cereals in southern Africa, specifically focusing on sorghum, pearl millet, finger millet and teff. These African indigenous cereals are known for their environmental resilience as well as having nutritional benefits. Southern Africa will experience more droughts in the future as a result of climate change, which will undoubtedly impact maize yields. Therefore, it is important that efforts are intensified to ensure that indigenous drought-adapted crops are fully exploited to improve future food security.

1. INTRODUCTION

Zea mays, commonly known as maize/corn, originated from the domestication of a wild grass known as teosinte (*Zea mays* ssp. *parviglumus*) around 9000 years ago in southern Mexico (Yang et al., 2019). Since its domestication, maize has grown to be a global crop with the largest producers being the United States, China and Brazil, producing approximately 79 % of the world's maize. Maize can be used to produce many food and industrial products such as starch sweeteners, oil, beverages and bioethanol, to name a few (Ranum et al., 2014). South Africa consumes about 10,5 million tons of maize per year. During the 2017/2018 season, 16.8 million tons were produced, with11.8 and 16.5 million tons produced during the 2018/2019 and 2019/2020 seasons, respectively. Nonetheless, consumption during 2019/2020 increased to 13 million tons, indicating that South Africa met its local consumption but had very little to export. South Africa is a semi-arid country which experiences frequent droughts. Drought is one of the major contributing factors to yield losses in maize (Wang et al., 2020). Furthermore, the frequency of these droughts is more likely to increase as a result of climate change. Significant research efforts have focused on producing drought tolerant maize varieties. Reliance on a limited number of staple cereals is not a sustainable option. In order to truly improve food security, the diversification of staple cereals is necessary. Hence, there is a need for the use of alternative African indigenous cereals which are better acclimated to the African environment. However, these indigenous cereals have no place in common agricultural practises today and as such are orphan cereals. Orphan crops are considered to be crops that have either originated or been domesticated in a geographical location over many years but have been neglected. These crops are often grossly underutilised and often neglected in terms of their development and potential (Mabhaudi et al., 2019). The use of these orphan cereals has major potential to become staple cereals along with maize. Therefore, this review focuses on four orphan cereals namely pearl millet, finger millet, sorghum and teff as potential future cereal staples for improving food security in Africa.

2. AFRICAN INDIGENOUS CEREALS

2.1 Sorghum

Sorghum bicolour (L.) Moench, commonly known as sorghum, is a grain crop that belongs to the grass family Poaceae. It is the fifth major staple cereal after maize, wheat, rice and barley. Sorghum was domesticated around 4000-6000 BC in Sudan (Winchell et al., 2017). This cereal crop still has many uses today as a source of food, animal fodder, the production of beverages and biofuels. Sorghum serves as a staple for more than 500 million people in more than 30 countries. Additionally, sorghum is known for its drought tolerance and as such has major potential in improving food security under persistent drought (Mwadalu and Mwangi, 2013). This is especially relevant to semi-arid countries in Sub-Saharan Africa.

2.2 Pearl millet

Pennisetum glaucum (pearl millet), belongs to the Poaceae grass family. This crop originated in central tropical Africa around 4000-5000 years ago. Pearl millet currently accounts for approximately 50 % of millet production globally. Millets can be used for human consumption and animal feed (Basavaraj et al., 2010). Pearl millet has been identified as one of the most resilient cereal grain crops owing to its development in semi-arid tropical regions. Pearl millet has traditionally been grown in hot arid/semi-arid regions, and thus, as a result of adaptive evolution, varieties with enhanced drought and heat stress tolerance have persisted because of natural selection (Serba and Yadav, 2016). A drought and heat tolerant cereal such as pearl millet could have major contributions to food security in semi-arid regions.

2.3 Finger millet

Eleusine coracana (L.) Gaertn, commonly known as finger millet, belongs to the Poaceae family of grasses. It was domesticated in eastern Africa and can be used for malting and beverage brewing, as well as human and animal feed. Just like pearl millet, finger millet is considered to be a drought-hardy crop as a result of its adaptation to semi-arid climates (Antony Ceasar et al., 2018). Furthermore, finger millet has a high calcium content as well as dietary fibre and antioxidant phenolic compounds (Thapliyal and Singh, 2015). Therefore, the exploitation of this crop would contribute significantly to improving food security as it is both nutritious and drought-hardy.

2.4 Teff

Eragrostis tef (Zuccagni) Trotter is commonly known as teff and originated in Ethiopia around 4000 BC. Teff is still significantly cultivated as a staple in Ethiopia today where it is grown for human consumption (mainly to make flat bread called injera) as well as animal fodder (Gebremariam et al., 2014). Furthermore, teff is a good source of fatty acids, minerals as well as a good source of the essential amino acid lysine which is low in other cereals.

It is important to note that the degree of drought tolerance may vary between genotypes in these indigenous cereal crops. However, unlike maize, these crops have not been extensively exploited and as such the potential of evaluating drought tolerance across genotypes could contribute significantly to the identification of the mechanisms that drive their drought tolerance. These mechanisms would allow for the breeding and development of superior, more resilient cereals and can be used as a molecular ‘compass’ for improvement of maize drought tolerance.

Table 1. Nutrient profile of African cereal crops as compared to maize (per 100 g edible portion; 12% moisture).

Nutrient	Sorghum	Finger millet	Pearl millet	Teff	Maize
Protein (g)	10.4	7.7	11.8	11	8.8
Carbohydrates (g)	70.7	72.6	67	70.2	73
Energy (kCal)	329	336	362	336	358
Fat (g)	3.1	1.5	4.2	2.5	4.6
Crude fibre (g)	2.0	3.6	3.0	3.0	2.8
Ash (g)	1.6	2.6	2.2	2.9	1.2
Calcium (mg)	25	350	42	165	26
Iron (mg)	5.4	9.9	11	15.7	2.7
Zinc (mg)	2.8	1.9	2.0	4.8	3.0
Magnesium (mg)	140	140	114	181	108
Potassium (mg)	220	314	418	401	324
Phosphorus (mg)	364	273	359	414	217
Vitamin A (RE)	21	0.6	22	8.0	0.19
Vitamin B1 (mg)	0.38	0.42	0.38	0.39	0.38
Vitamin B2 (mg)	0.15	0.19	0.21	0.27	0.2
Vitamin B3 (mg)	4.3	1.1	2.8	3.36	3.6
Vitamin B6 (mg)	0.5	NA	0.38	NA	0.62
Vitamin C (mg)	0.0	1.0	0.0	88	0.0
Essential Amino Acids (g/100 g)					
Histidine	0.19	0.23	0.25	0.3	0.31
Isoleucine	3.8	3.5	4.5	3.9	3.8
Leucine	12.8	7.0	11.6	7.5	11.9
Lysine	2.0	1.6	2.0	2.2	3.4
Methionine	1.0	3.3	1.6	3.0	1.9
Phenylalanine	4.1	3.8	5.6	4.9	4.8
Threonine	2.9	3.5	3.6	3.3	3.8
Tryptophan	1.0	1.6	1.3	1.2	0.8
Tyrosine	1.7	2.9	3.0	3.0	3.6
Valine	4.9	6.5	4.5	5.5	5.2
Cysteine	0.9	1.5	1.2	1.4	0.9

3. NUTRIENT PROFILE

Sorghum, finger millet, pearl millet and teff are important for millions of people in Africa. Large amounts of these cereals are used as food for humans in many of the African countries but their use is majorly limited to animal feeding in developed countries. The potential of these indigenous crops for improving and diversifying human nutrition, and adapting to climate change is great. The nutritional profile of these crops is presented in Table 1 and discussed below in comparison with maize. Like maize, sorghum grain mainly comprises starch followed by protein, fat and fibre. However, sorghum has about 1.5 g less fat and more waxes compared to maize. Sorghum grain is mainly made of complex carbohydrates (Kulamarva et al., 2009). Starch from sorghum is similar to that from maize. Sorghum starch can be used interchangeably with maize starch in various industrial applications (Barcelos et al., 2011). Compared to maize, protein contents of grain sorghum are more variable, ranging from 7 to 15 g/100 g (Afify et al., 2012). However, most sorghum cultivars contain about 10.4 g protein/100 g of dry grain, an amount that is approximately 1.6 g higher than maize. In its amino acid profile, sorghum protein is similar to maize as it is deficient in cysteine. However, some amino acids, including tryptophan and leucine, are slightly more in sorghum than in maize. Sorghum naturally contains no gluten (Marston et al., 2016) and thus it can be an excellent substitute for gluten-containing cereals such as wheat. Sorghum grain is packed with micronutrients, it is rich with minerals like potassium, phosphorus, magnesium, iron and zinc. It also contains higher levels of vitamin A than maize, an essential nutrient for healthy eyes and stronger immune system in humans (WHO, 2004).

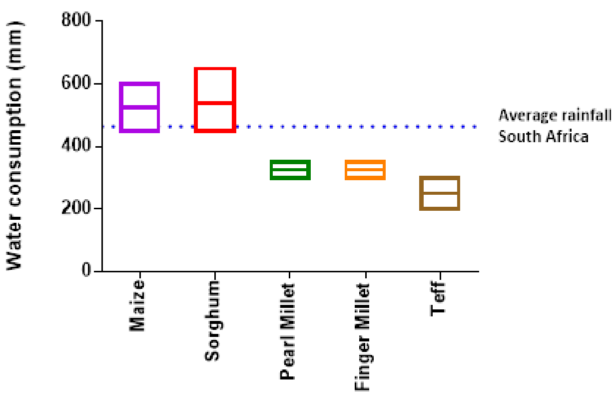

Fig. 1. Water consumption of maize compared to African indigenous cereals. Average water consumption of maize, sorghum, pearl millet, finger miller and teff relative to the average annual rainfall in South Africa.

In terms of nutrient composition, the grain of finger millet is the most variable, its protein content ranges from 6 to 13 percent (Chandra et al., 2016), and fat levels are much less than that in maize. The amino acid profile of finger millet grain is excellent as it represents good levels of tryptophan, methionine and aromatic amino acids. It also contains greater amounts of cysteine than maize. Finger millet is also rich in minerals like potassium, calcium, phosphorus, magnesium and iron. It contains 350 mg of calcium per 100 g of dry grain, which is approximately 40 times higher than maize and three times more than milk. Millet grains are also gluten free, making them a good alternative for gluten-containing grains (Niro et al., 2019).

Pearl millet is nutritious and is an excellent source of energy. Pearl millet grain contains higher amounts of protein than maize. The levels of fat and energy in pearl millet are close to those in maize. The amino acid profile of pearl millet grain is good, with decent amounts of tryptophan and threonine. Pearl millet grain is a very rich source of vitamins and minerals, it contains Vitamin A, potassium, phosphorus and calcium (Hassan et al., 2021).

Teff grain protein content averages about 11 g and has a high percentage of digestibility (Adebowale et al., 2011). Its amino acid profile is also excellent, with higher amounts of methionine, threonine and cysteine than maize. Teff is also rich in minerals, with about six times the calcium and iron, and nearly twice the amounts of phosphorus and magnesium, than maize has. Teff grain exhibits an extraordinary level of vitamin C compared to maize and other cereal crops.

One of the nutritional concerns is that the protein digestibility of the indigenous cereals mentioned above, except for teff, tends to be relatively lower than other cereals. Another concern is that sorghum grains are high in tannins, which inhibit the digestion and absorption of nutrients such as proteins. However, proper processing of these grains can improve the overall digestibility and reduce the levels of tannins as well (Joye, 2019). There is thus a need to recognize and value the importance of these neglected crops in ensuring food security and sustainability in the African continent.

4. ADAPTATION TO DROUGHT STRESS

4.1 Spending water wisely using climate-smart crops

South Africa receives an average rainfall of 460 mm, and given that it is a semi-arid country, it experiences seasonal droughts (Ndiritu et al., 2017). During times of drought, the country could receive well below the expected average rainfall. Furthermore, the frequency of drought is most likely to increase as a result of climate change. Drought has been identified as one of the key contributors to agricultural yield losses and its persistence undoubtedly poses a threat to the production of cereal staples such as maize. Under favourable conditions, maize requires 450-600 mm of water per growing season. African indigenous cereals such as sorghum, pearl millet, finger millet and teff require approximately 450-650 mm, 300-550 mm, 300-350 mm and 200-300 mm of water respectively to complete its life cycle (Sahet al., 2020; Elramlawi et al., 2018; Ullah, et al., 2017; Winch, 2018). Therefore, based on the water requirements, it is evident that a need for the diversification of staple cereals in southern Africa. Reliance on maize as a major staple crop in South Africa presents challenges for a semi-arid country. This is reflected in Fig. 1., which shows the water requirements of maize in contrast to average annual rainfall in South Africa. Cereal crop diversification should include the incorporation of sorghum, pearl millet, finger millet and teff as staple cereals alongside maize to ensure food security under drought. These indigenous cereals are well-known for their drought tolerance. This because they have been grown in sub-Saharan Africa for years and as such have adapted to arid/semi-arid environments

4.2 Plant adaptation to drought

The developmental stage of the plant greatly influences the effect of drought stress, as drought can occur at the seedling, vegetative, panicle development and grain filling stage. Crops that are better adapted to drought have evolved several adaptation mechanisms to minimise water loss, facilitate osmotic adjustment and maintain essential metabolic processes under water deficit (Basu et al., 2016). These adaptations include having elongated and denser roots for increased water uptake. Crop varieties with narrow leaves and decreased stomatal conductance are better adapted to drought stress (Taiwo et al., 2020). This is because the narrow leaves have a smaller surface area than wider leaves over which transpiration would occur. Additionally, some plants have developed a waxy cuticular coating on their leaves and stems. These adaptations allow the plant to maintain its water status during drought (Sevanto, 2020). Drought responses in plants can be at the physiological or morphological level. The investigation of these responses is usually the starting point for responses have not been investigated in African indigenous cereals as extensively as in maize. Therefore, these cereals are underexploited and remain to be a resource of untapped potential in improving food security under drought.

4.3 Physiological adaptation of African cereals to drought

Plants need to photosynthesize in order to grow and reproduce. This process is usually disrupted during drought as plants close their stomata in order to minimize water loss via transpiration (Li et al., 2017). During prolonged drought, CO2 assimilation is limited and as such the net photosynthetic rate decreases. Subsequently, this also leads to an increase in ROS production, which leads to leaf senescence and yield loss (Pintó-Marijuan and Munné-Bosch, 2014). Cereals such as sorghum have adapted physiological mechanisms such as the stay green trait, which includes delaying leaf senescence and elevating chlorophyll content. These collective adaptations allow sorghum to maintain photosynthesis under drought conditions, which sustains grain filling and yields under limited water supply (Hadebe et al., 2017). These physiological adaptive mechanisms give sorghum an advantage under water limited conditions, ensuring acceptable yields under drought. Pearl millet has also developed physiological mechanisms such as controlling transpiration during well-watered conditions prior to drought. Pearl millet has been shown to reduce its transpiration rate as a water-saving mechanism (Kholova et al., 2010). It has been suggested that this is to ensure water availability for grain filling, thereby ensuring good yields under water deficit (Kholova et al., 2010). Although some studies have been done on finger millet in response to drought, the physiological responses of finger millet to drought are still poorly understood and have not been as thoroughly investigated as in maize and sorghum.

4.4 Morphological adaptation of African cereals to drought

As a result of domestication in a semi-arid environment, cereals such as sorghum, finger millet, pearl millet and teff generally have narrower and smaller leaves than maize, resulting in a smaller surface area that minimizes the loss of water via transpiration. Furthermore, it has been suggested that plants that have over-invested in the development of larger leaves such as maize could have reduced seed yields (Srinivasan et al., 2017). Additionally, sorghum leaves and stems are covered with a waxy cuticle and epicuticular wax (EW), which minimises water loss (Busta et al., 2021). Epicuticular wax load is an effective component of abiotic stress tolerance. Studies done in pearl millet found a higher deposition of EW under stress conditions, and when coupled with stomata closure, this leads to reduction of cuticular permeability and as such better water retention (Makarana et al., 2019). Studies investigating the role of epicuticular wax in drought tolerance in finger millet and teff are still lacking. Therefore, research investigating EW deposition and the role thereof in providing drought tolerance in teff and finger millet remains to be investigated. One of the morphological characteristics that influence yields under water deficit is the formation of tillers. Unlike maize; sorghum, pearl millet and finger millet as well as teff have the ability to form tillers. This ability is commonly observed in sorghum landraces found in regions with limited rainfall. Tiller formation has been attributed to stable yield compensation, where the main panicle may have been damaged as a result of stress (Hadebe et al., 2017). Furthermore, sorghum has developed longer, denser roots, which improves drought tolerance as a result of improved water extraction efficiency. Deeper soil water capture has also been associated with better osmotic adjustment in sorghum. Pearl millet also has a deep rooting system, which contributes to its tolerance to drought (Talwar et al., 2020). Finger millet and teff, unlike pearl millet and sorghum, have a shallow but strong fibrous root system. Studies have shown that, under water stress, finger millet only extracts about 44 % of the total extractable moisture compared to 68% for sorghum, supporting the notion that it is not as deep rooted as sorghum (Kamenya et al., 2021).

4.5 Future trends for drought adaptation in African cereals

Changes in annual rainfall patterns as a result of climate change are prompting researchers to investigate the genetic basis of environmental resilience of orphan crops (Kamenya et al., 2017). Furthermore, the reduction in DNA sequencing costs has allowed for the sequencing of indigenous cereals such as sorghum, pearl millet, finger millet and teff. This allows for the genetic elucidation of drought tolerance mechanisms in these resilient cereals. These traits can then be targeted for the development of crops with improved drought tolerance. An example of the potential of using this approach was shown whereby the cloning of the SbER2-1 gene (a sorghum leucine-rich repeat kinase) into maize and Arabidopsis improved drought tolerance via improved maize and Arabidopsis water use efficiency, with improved net photosynthetic efficiency (Li et al., 2019). Therefore, there is a need to develop deeper understanding of the genetic basis of stress tolerance in indigenous African cereals. Genes associated with stress tolerance can then be used as molecular markers to improve the indigenous landraces as well as other cereals such as maize. In order to improve food security, the diversification of cereal staples is essential, which requires more extensive exploitation of African indigenous cereals in much the same way as popular cereals such as maize, wheat and rice.

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