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REVIEW

Bambara groundnut as a food, nutritional and income security crop in Sub-Saharan Africa

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Abstract

An over-reliance on the three major global food staples; maize, wheat, and rice, to continue feeding the world is a dangerous approach. Bambara groundnut originated in West-Africa, but was adopted in many African countries, and is produced almost exclusively by small-scale farmers. It has good levels of nutrients, particularly protein, carbohydrates and fat, as well as lysine, in such a balanced manner that it has been termed a "complete food". The long duration of cooking (hard-to-cook) of bambara groundnut, and the low number of uses in food preparation (in contrast to groundnut) are also factors responsible for lower levels of production and utilization compared to other legumes. Bambara groundnuts have more than 20% protein and can be used as a meat supplement or replacer. It also has high levels of iron and zinc. Landraces with dark-coloured seeds such as red or black, generally contain higher levels of nutrients and minerals than the cream-white or plain-white coloured landraces. The iron content of red bambara seeds was found to be double that of cream-coloured seeds. Antinutrients such as phytic acid can reduce the bioavailability of iron and zinc, but dehulling of the seed can reduce antinutrients significantly. Bambara groundnut has significant potential as a food security crop, but concerted efforts should be made by governments to market the crop, and to develop products and new uses for the seed and the plant. Plant breeding efforts can improve yield and cooking quality. This paper presents progress on the industrial application for food and nutritional security and genetic improvement of bambara groundnut through breeding.

1. Introduction

The importance of bambara groundnut in sub-Saharan Africa has been recognised for a long time (Anchirinah *et al.,* 2001). Bambara groundnut is a food security crop and is a rich and balanced source of nutrients (Anchirinah *et al.,* 2001; Goudoum *et al.,* 2016). It possesses good levels of nutrients, particularly protein, carbohydrates and fat in such a balanced manner that it has been termed a "complete food" (Amarteifio *et al.,* 2010; Koné *et al.,* 2011; Mazahib *et al.,* 2013; Murevanhema and Jideani, 2013; Ndidi *et al.,* 2014). Bambara groundnut is also important because of its relatively high lysine content (Ahmad *et al.,* 2015), which is low in cereals and other food legumes such as groundnuts and cowpeas (Massawe *et al.,* 2005; Klose and Arendt, 2012; Sharma *et al*., 2013a; Yao *et al.,* 2015; Katya *et al.,* 2017).

An over-reliance on the production of the three major global staples; maize, wheat and rice, to continue feeding the world is a dangerous approach and exposes food production to uncertainties, especially if one considers crop failure arising from biological and non-biological causes (Mayes *et al.,* 2012). Agriculture faces a two-pronged challenge: population increase and climate change (Ahmad *et al.,* 2015). In this regard, there is a need to increase the production of other crop species rather than depend on the small number of major crops. Bambara groundnut is one of the crop species that can be added to the list of crops to be grown to alleviate hunger and malnutrition (Mayes *et al.,* 2012; Ahmad *et al.,* 2015).

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Bambara groundnut originated in West Africa. However, this crop spread within Africa, eastwards up to Kenya and southwards up to South Africa and Madagascar (National Research Council, 2006; Eltayeb *et al.,* 2011; Emendu and Emendu, 2014). Arabs are thought to have taken bambara groundnut to Madagascar (Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa, 2016). But bambara groundnuts also spread to the Americas and to Asia, probably with the slave trade (Goli, 1997; Mohammed *et al.,* 2016).

The aim of this review was to evaluate the status of bambara groundnut in terms of nutritional value and traditional and non-traditional uses, as its status and potential as a food security crop in especially sub-Saharan Africa as well as the genetic improvement of bambara groundnut through breeding.

2. Bambara production

Bambara groundnut is currently produced almost exclusively by smallholder farmers (Chibarabada *et al.,* 2014; Muhammad, 2014; Ndidi *et al.,* 2014; Mayes *et al.,* 2015; Musa *et al.,* 2016) and mostly by women (Hillocks *et al.,* 2012; Molosiwa *et al.,* 2013; Ahmad *et al.,* 2013; Chibarabada *et al.,* 2014; Zenabou *et al.,* 2014; Forsythe *et al.,* 2015; Mabhaudhi *et al.,* 2016; Ibrahim *et al.,* 2018; Onwubiko *et al.,* 2018; Damfami and Oat, 2020). There are a number of reasons for this scenario. Some of these are stigma, lack of a developed value chain, lack of improved varieties, limited food preparation uses, and others. A number of studies have shown that bambara groundnut is grown mostly for home consumption, and to a lesser extent for sale (Abu and Saaka, 2011; Mwangwela *et al.,* 2012; Aliyu *et al.,* 2016; Mubaiwa *et al.,* 2018; Damfami and Oat, 2020).

Statistics on the production of bambara groundnuts are rare, both at national and global levels. This is because most countries do not include bambara groundnuts when they collect data on crop production and the crop is primarily grown for home use, and the surplus is sold locally (Brink *et al.,* 2006; Abu and Saaka, 2011; Mwangwela *et al.,* 2012; Mubaiwa *et al.,* 2018). Countries leading in the production of bambara groundnut are Burkina Faso, Chad, Côte d'Ivoire, Ghana, Mali, Niger and Nigeria. Outside of West Africa, the crop is also cultivated in East Africa, Southern Africa as well as Madagascar (Brink *et al.,* 2006).

Among food grain legumes, bambara groundnut has been widely reported to be third in production and utilisation after groundnuts (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* L. Walp.) (Ntundu *et al*., 2004; Basu *et al.,* 2007; Jonah *et al.,* 2010; Laary *et al.,* 2012; Olukolu *et al*., 2012; Pungulani *et al.,* 2012; Ogundele *et al.,* 2017; Wakhungu *et al.,* 2017).

The long duration of cooking (hard-to-cook) of bambara groundnut, which involves more time spent and more energy resources; low number of uses in food preparation (in contrast to groundnut which has several uses) are other factors responsible for the relegation of the bambara groundnut to a lower position.

2.1 Utilization

Bambara groundnut can be used as a stand-alone food or as a component of certain food preparations (Bonny *et al.,* 2019). Freshly harvested pods are boiled and eaten as a snack. When harvested and dried, the shelled nuts are very hard. They can be roasted to be eaten as a snack, or boiled to be eaten on their own or with maize. Sometimes after boiling, bambara groundnuts can be made into a paste and used as a sauce. In some communities, the leaves of bambara groundnut are also cooked and eaten as a vegetable (Mabika and Mafongoya, 1997; Ngugi, 1997).

Haulms of bambara groundnut, also rich in nitrogen and phosphorus, are fed to domestic ruminants (Drabo *et al.,* 1997; Bonny *et al.,* 2019). The seed is also used in traditional ceremonies, such as weddings, where it is cooked to be eaten specifically during such functions (Madamba, 1997). In Malawi, Forsythe *et al*. (2015) found from their survey that bambara groundnut is cooked to be eaten at initiation ceremonies and to celebrate the first child birth by young mothers. This is in agreement with an earlier finding in the same country by Mwangwela *et al.* (2012), who even listed initiation ceremonies as factors that raised the demand for bambara groundnut. To the list of ceremonies during which bambara groundnut is cooked and eaten, Mwangwela *et al.* (2012) also added funerals, initiation ceremonies of the youth and initiation into traditional cults. The black-coloured bambara groundnut is the most used.

In their extensive review of the difficulties of, and options for preparing bambara groundnut grain for food, Mubaiwa *et al.* (2017) considered the difficulty in cooking the grain, which they termed the “hard-to-cook phenomenon”, as the principal element discouraging the utilization of bambara groundnut for food. Linked to the “hard-to-cook” factor is the lack of processing techniques for the harvested crop, which in turn, reduces utilization. The lack of a solution to the “hard-to-cook” phenomenon in bambara groundnut has impacted utilisation and hence led to low production (Mazahib *et al.,* 2013) in spite of the immense benefits the crop confers as human food (Mubaiwa *et al.,* 2018; Tsamo *et al.,* 2018). The unavailability of a wide range of recipes has limited the utilization and hence adoption of the crop, with the exception of Zimbabwe where recipe books are reported to be in place (Plahar *et al*. 2002). Finding different recipes and various alternative uses for a crop, besides human consumption or soil health improvement, increases acceptability and adoption of a crop. This is what Carver Washington did for groundnuts at the beginning of the 20th century. Carver developed several recipes for groundnuts and a myriad of alternative uses of the crop, and that is how production of groundnuts rose in the USA from obscurity to prominence (Ginsberg, 2005; Boriss and Kreith, 2006).

In some individuals, the consumption of bambara groundnut causes flatulence which lowers the demand for the crop as a food material (Brough *et al.,* 1993; Graham and Vance, 2014; Adeleke *et al.,* 2017; Halimi *et al.,* 2019). Oligosaccharides, such as verbascose raffinose, as well as stachyose (Khattak *et al.,* 2007; Sreerama *et al.,* 2012) are considered the principle causes of flatulence from legume consumption (Brough *et al.,* 1993).

Anti-nutritional factors, such as tannins and oxalate, which are known to reduce seed quality and protein availability (Mongomaké *et al.,* 2009) have also been associated with the low adoption of bambara groundnut.

2.2 Non-traditional uses of bambara groundnut

Bambara groundnut has been tested for use in infant feeding formulations. Akaninwor and Okechukwu (2004) formulated and evaluated six weaning foods, with Nutrend (a commercial maize-soya bean weaning formula) as a positive reference diet and maize starch flour (protein-free) as a negative reference diet. The authors concluded that the diets tested could effectively supplement Nutrend, thereby increasing the availability and affordability of weaning foods.

Another study involving bambara groundnut as a component in weaning foods was conducted by Ijarotimi and Keshinro (2013). They formulated three weaning foods and analysed them for their nutritional composition. One formulated food had 70% fermented popcorn and 30% African locust bean; the second comprised 70% fermented popcorn and 30% bambara groundnut; and the third consisted of 70% fermented popcorn, 20% bambara groundnut and 10% African locust bean. They found that all the formulations possessed protein of high quality, with a good balance of amino acids and sufficient carbohydrates. The weaning formulations were nutritionally superior to a traditional complementary food called *ogi* and comparable to Cerelac, a commercial weaning food product (Ijarotimi and Keshinro, 2013).

Apart from its use at the farm level, some scientists have started to explore the use of bambara groundnut at the industrial level. The main uses under consideration are for starch and protein extraction. Both modified starch and protein extract could be used as ingredients in food and pharmaceutical industries (Adebowale *et al.,* 2002; Lawal *et al.,* 2004; Afolabi, 2012; Muhammad, 2014; Oyeyinka *et al.,* 2017; Oyeyinka *et al.,* 2018; Oyeyinka and Oyeyinka, 2018). Bambara groundnut has also been investigated for blending its native starch with starch from other sources to improve its starch functionality. Further, the new trend is for consumers to avoid foods containing starch modified with synthetic substances in preference for foods with starch from natural sources. Because starch functionality is known to vary with the crop and the soil where the crop was grown, blending starches from different sources affects their functionality. Moreover, starch from under-utilized legumes like bambara groundnut is cheaper than that from conventional sources such as rice (Ashogbon, 2014). Ashogbon (2014) blended native starches from pigeon pea, rice, bambara groundnut and cassava into six different blends in the proportions of 70:30, 50:50 and 30:70 for pigeon pea and rice starches or bambara groundnut and cassava starches. The conclusion from the study was that blending native starches from different plant sources can result in blends with superior functional properties, and this is a way of getting cheaper starch devoid of any addition of expensive substances for modification of native starch.

The flour from bambara groundnut has also been preliminarily evaluated for use in fish feed formulation as a possible replacement for maize starch or wheat flour. A proximate analysis of the feed formulations showed that bambara groundnut flour was superior to both maize starch and wheat flour in protein and fat content, and bambara groundnut flour could therefore replace maize starch and wheat flour in fish feed (Katya *et al.,* 2017).

Bambara groundnut has also been suggested for use as a probiotic drink where probiotic is defined as “live organisms which when administered in adequate amounts, confer a health benefit on the host” (Murevanhema and Jideani, 2013).

Being a high protein crop, bambara groundnut could also play a role as a neutraceutical crop. Carbonaro *et al.* (2015) indicated that there are many proteins and peptides originating from seeds of legumes that qualify to be “neutraceuticals”, a term describing food or parts thereof that possess medicinal attributes or disease prevention properties.

Bambara groundnut has also been reported to possess antioxidant properties (Ngafa *et al.* 2012).

Chinnapun (2018) has defined antioxidants as “substances that have the ability to protect the body from damage caused by free radical-induced oxidative stress”. The antioxidant attribute is also present in other food grain legumes. The abundance of antioxidants in foods is affected by methods of preparation. Pal *et al.* (2016) investigated the effect of dehulling and germination on nutrients, antinutrients and oxidants in seeds of 12 elite advanced lines of horse gram [*Macrotyloma uniflorum* (Lam.) Verdc] seeds. Significant reductions in the levels of antioxidants in both treatments were seen, compared to the control samples.

3. Nutritional markers and content in bambara groundnut

An assessment of the nutritive constituents of bambara groundnut is a tool for popularizing the crop as a valuable source of nutrients for consumers (Amarteifio *et al.,* 2006). Bambara groundnut, in as much as it may be an underutilised crop, is famous for its high and balanced nutritional content such that it has been described as a “complete food” (Ahmad *et al.,* 2015). It is high in carbohydrates, and protein, and has appreciable amounts of minerals. However, nutritional content has been found to vary with the types of bambara groundnuts. Gibbons (1994) reported that landraces with dark-coloured seeds such as red or black, generally contained higher levels of nutrients and minerals than the cream-white or plain-white coloured landraces. This variation in nutritive content provides scope for genetic improvement of the bambara groundnut cultivars that possess low levels of nutrients so that they become more nutrient-dense.

3.1 Oil content

The oil content of bambara groundnut is low, ranging from 3 to 7.5% (Minka and Bruneteau, 2000; Emendu and Emendu, 2014), compared to leguminous oil crops such as soya bean (*Glycine max* (L.) Merr.) with a mean of 20% (Duke 1981; Clemente and Cahoon, 2009) and groundnuts with the mean of 50% (Wang *et al.,* 2015). However, Mohale *et al.* (2013) reported a higher range of 6 to 12% oil content in bambara groundnut. This means that bambara groundnut is not a crop that can be used for commercial oil extraction (Emendu and Emendu, 2014). Bambara groundnut oil contains both saturated and unsaturated fatty acids (Minka and Bruneteau, 2000).

3.2 Fatty acid profiles

Bambara groundnut oil is made up of palmitic acid (19.4%), stearic (11.8%), oleic (24.4%), linoleic (34.2%), arachdnic (5.3%) and behenic (4.9%) (Duke 1981). Minka and Bruneteau (2000) reported that the fatty acids were constituted of the unsaturated palmitic (30%) and stearic (5%) acids, and the polyunsaturated linoleic (44%) and linolenic (21%). Polyunsaturated fatty acids (PUFAs) such as omega-3 and omega-6 fatty acids are of extreme importance for human health (Darios and Davletov, 2006). Therefore, the abundance of linoleic acid makes bambara groundnuts a good choice for healthy eating (Sandoval-Oliveros and Paredes-López, 2012). Moreover, linoleic acid is an essential fatty acid as it cannot be synthesized by human beings and animals (Calder, 2012).

3.3 Starch

Starch is defined as a glucose polymer comprising amylose and amylopectin macromolecules (Awolu *et al.,* 2017). It is the major component of the carbohydrate constituents in plants (Imberty *et al.,* 1988; Singh *et al.,* 2004) and it serves as the main carbohydrate fraction in seeds of pulses which contain 22 to 45% carbohydrate (Hoover *et al.,* 2010; Oyeyinka *et al.,* 2015).

Starches are abundantly available, renewable, safe to use, biodegradable and low-cost material. Starches from different plant materials differ, and the differences have been attributed to the soil type where the plant grew, the ratio of amylose to amylopectin and the morphology of the starch itself (Ashogbon, 2014; Oyeyinka and Oyeyinka, 2018). Bambara groundnut has been considered for starch extraction for the food industry owing to its rich carbohydrate composition (Adebowale and Lawal, 2002; Sirivongpaisal, 2008). Afolabi (2012) reported a starch yield of 40.35%, with a protein concentrate as a by-product.

Starch functionality is governed by the amylose and amylopectin ratio (Zhu *et al.,* 2008; Oyeyinka *et al.,* 2018), with normal starch comprising 20 to 30% amylose and 70 to 80% amylopectin. Starches rich in amylose have less than 50% amylopectin (Maaran *et al.,* 2014). Oyeyinka *et al.* (2015) also found significant variation in amylose levels among bambara groundnut genotypes where the range was 20 to 35%. However, in addition to cultivar and environment of crop production, other factors such as methods of extraction and seed physiology can influence the level of amylose in starch (Oyeyinka and Oyeyinka, 2018).

Like other food legumes, bambara groundnut has high levels of resistant starch which confers digestive benefits, and it could be used as an ingredient in the food industry (Oyeyinka and Oyeyinka, 2018). Resistant starch is that portion of broken-down starch that passes through the small intestine unabsorbed (Kumar *et al.,* 2016). When it reaches the large intestine, it serves as a

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prebiotic for the bowel microbes (Ahuja *et al.,* 2013; Kumar *et al.,* 2016). Thus, resistant starch is hydrolysed in the large intestine by microbes into short-chain fatty acids that confer a range of health benefits to the individual (Oyeyinka and Oyeyinka, 2018). Another portion of starch that possesses prebiotic properties is the raffinose family of oligosaccharides (RFO), also known as α-galactosides (Murevanhema and Jideani 2013; Halimi *et al.,* 2019). While RFOs offer health benefits to consumers, their increase above optimum levels results in flatulation as they ferment (Murevanhema and Jideani, 2013; Kumar *et al.,* 2016).

3.4 Total protein

Storage proteins are the main proteins in seeds where they constitute 60 to 80% of total proteins (Sandoval-Oliveros and Paredes-López, 2012). In legumes, these proteins consist of two globulins, such as legumin and vicilin (Swanson, 1990). The nutritional importance of these two globulins is that they have low levels of cysteine and methionine (Shewry *et al.,* 1995). However, unlike cereals and some pulses, bambara groundnut is a rich source of lysine (Ahmad *et al.,* 2015). The nutritional drawback of bambara groundnut, like other pulses, is its deficiency in methionine, cysteine and tryptophan, all of which are sulphur-based amino acids (Sharma *et al.,* 2013a; Yao *et al.,* 2015). In addition to their nutritional roles, proteins also find their use as food ingredients, where they confer certain functional properties (Wright and Bumstead, 1984).

Protein content in crops is a function of the crop's genetic make-up and the environment in which it is grown (Kumar *et al.,* 2016). Amarteifio *et al.* (2010) found the protein content of nine bambara landraces they analysed from Namibia, Botswana and Swaziland to be in the range of 17.10 to 22.94%. A landrace, Ci12, grown in Côte d'Ivoire, was analysed by Yao *et al.* (2015) and found to contain a protein content of 19%. Working with four accessions of bambara groundnut, Onimawo *et al.* (1998) reported protein contents from 17.5 to 21.2%. The wide range of protein content in bambara groundnut presents not only an opportunity for identification and recommendation of accessions with superior levels of protein content for direct cultivation by farmers but for use in the development of protein-rich cultivars (biofortification), considering that they meet other agronomic requirements, as noted in the case of lentils by Kumar *et al.* (2016). Anhwange and Atoo (2015) assessed three accessions of bambara groundnut for protein content. The lowest level was 18.25%, followed by 19.79% and 20.44% as the highest. The authors concluded from these findings that bambara groundnut could be used to supplement meat protein. Klompong and Benjakul (2015) in Thailand determined the proximate composition of seed coats of one accession of bambara groundnut purchased from a supplier. They reported a mean protein content of 11.56% in the seed coat. This indicated that the testa of bambara groundnut could also be a good source of protein for livestock if bambara groundnut seed is dehulled during the preparation of certain kinds of human food.

3.5 Iron and zinc

Iron is the number one essential element required nutritionally by humans, followed by zinc (Hambidge and Krebs, 2007). Iron is an essential component of the blood haemoglobin. Its inadequacy results in low blood haemoglobin and hence anaemia, which has dire consequences in pregnant women, and lactating mothers, particularly those in the juvenile age group, and the infants (WHO, 2014). Iron is also essential in the functioning of the mitochondria (Gille *et al*. 2011).

Zinc is involved in the functioning of insulin and the metabolism of carbohydrates and protein in the human body (Baiyeri *et al.,* 2018). MacDonald (2000) has given a detailed account of the role of zinc in a mammalian body. Being a component of proteins, zinc is involved in the synthesis of DNA, RNA and proteins themselves. As such zinc has a function in cell division and hence growth.

A global estimate is that over 3 billion people are deficient in iron (Blair *et al.,* 2011). Human requirements for iron and zinc are 15 mg per day for both micronutrients (Welch, 2012). Bambara groundnut generally contains high levels of minerals, especially iron (Hillocks *et al.,* 2012; Yao *et al.,* 2015). However, the levels of iron have been found to vary with colour of the bambara groundnut seeds. Red-coloured seeds have been found to contain iron almost double that contained in the cream-white seeds, suggesting that the red genotypes could be beneficial if deployed and consumed in regions with iron deficiency problems (Hillocks *et al.,* 2012).

Iron bioavailability has been estimated to range between 14 to 18% in general diets and 5 to 12% for vegetarian diets. The assessment was done on individuals who lacked iron reserves in their bodies (Hurrell and Egli, 2010).

There are wide variations in the levels of iron and zinc contents in seeds of bambara groundnut accessions (Dansi *et al.,* 2012). Oyeleke *et al.* (2012) reported iron content of 18.51 mg/100 g in bambara groundnut flour in a sample of grain purchased from a market in Nigeria. The sample was dehulled prior to milling. Olaleye *et al.* (2013) analyzed one accession of bambara groundnut

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collected from Ekiti State University in Nigeria and reported 4.25 mg/100 g and 5.27 mg/100 g iron for hulled and dehulled seeds, respectively. In the same accession, zinc was 25.6 mg/100 g and 40.2 mg/100 g for hulled and dehulled seeds, respectively. In the analysis of one black accession and a cream-white accession, Adebowale *et al.* (2013), found 420 mg/100 g zinc in the flour of whole black seeds and 976 mg/100 g zinc in the flour of whole cream-white seeds.

4. Anti-nutritional factors

Although bambara groundnut may have appreciable quantities of protein, iron and zinc, the bioavailability of these nutrients, like in many other grain legumes, is hindered by the presence of substances referred to as antinutrients (Welch and Graham, 2005). Antinutrients are biochemical substances that hinder the bioavailability of particular food nutrients by the body (Mahlangeni *et al.,* 2016). Examples of these are oxalate, phytate (phytic acid), hydrogen cyanide, tannins and trypsin inhibitors (Ghavidel and Prakash, 2007; Remans *et al.,* 2011; Oyeleke *et al.,* 2012; Pinkaew *et al*., 2013; Yao *et al*., 2015; Pal *et al*., 2016).

The problem of impaired bioavailability of nutrients only occurs in monogastric such as humans and poultry because they do not possess phytase, the enzyme that breaks down phytic acid (Mullaney *et al.,* 2000; Pilu *et al.,* 2003; Akomo *et al.,* 2016) thereby releasing the minerals, such as iron and zinc (Pilu *et al.,* 2003).

Among the antinutrients impeding the bioavailability of minerals and protein, phytic acid appears to be the major one as it has been more frequently investigated or alluded to than other antinutritional factors (Mullaney *et al.,* 2000; Rehman and Salariya, 2005; National Research Council, 2006; Olaleye *et al.,* 2013; Sharma *et al.,* 2013b; Yao *et al*., 2015; Kumar *et al.,* 2016; Mayes *et al.,* 2019), to mention just a few studies. Empirical data reported by Rehman and Salariya, (2005) demonstrated that phytic acid content is higher than tannin content in the five grain legumes they studied. In blackgram, tannins were 890 mg/100 g while phytic acid was 1100 mg/100 g wet weight. In the other pulses tannins and phytic acid were, respectively, as follows: chickpea (770 and 970 mg/100 g), lentils (915 and 1250 mg/100 g), red kidney beans (1100 and 1440 mg/ 100 g), and white kidney beans (980 and 1230 mg/100 g).

Evaluation of phytic acid in food is a necessity for the improvement of deficiency estimates in conjunction with measurements in human subjects, national Food Balance Sheets, and other parameters (Reason *et al.,* 2015). Phytic acid is concentrated in the seed coat of seeds of legumes as well as cereals (Williams, 1970). In India, Ghavidel and Prakash (2007) studied the influence of germination and dehulling on the bioavailability of calcium and zinc in Greengram (*Phaseolus aureus*), cowpea (*Vigna catjang*), lentil (*Lens culinaris*), and chickpea (*Cicer arietinum*). Dehulling resulted in a reduction of 47 to 52% for phytic acid and 43 to 52% for tannin (Ghavidel and Prakash, 2007). Olaleye *et al.* (2013) determined the chemical composition of the seed components of a sample of bambara groundnuts in Nigeria. They created three treatments: testa, dehulled and whole seeds. They found that there was a high concentration of antinutrients in the testa. For this reason, they encouraged the removal of the testa when preparing food based on bambara groundnut for infants because their digestive system is still underdeveloped.

Pal *et al.* (2017) working with lentils in India reported a reduction of 52.63 to 56.00% in phytic acid following testa removal in contrast to lentil samples with intact testa. All these findings confirm that phytic acid is located mainly in the testa of seeds. Ndidi *et al.* (2014) did a comparative study of roasting and boiling to reduce the levels of antinutrients in bambara groundnut. They reported a higher effectiveness of boiling than roasting in the reduction of phytic acid levels and other antinutrients.

The degree of bioavailability of zinc in the presence of phytic acid is determined by the phytic acid to zinc molar ratio. A phytic acid:zinc molar ratio of less than 10 shows sufficient bioavailability of zinc, whereas a molar ratio greater than 15 such as 15:1, leads to a decline in the bioavailability of zinc in the food (Olaleye *et al.,* 2013). These authors reported phytic acid:zinc molar ratios of 25.8, 4.31 and 5.57 for testa, dehulled and whole seed, respectively, of bambara groundnut samples when they worked with one accession in Nigeria.

Phytic acid (1,2,3,4,5,6-hexakis-myo-inositol phosphate) (Yao *et al.,* 2015; Kumar *et al.,* 2016) is the compound in which phosphorus is mainly found in most crops (Kumar *et al.,* 2016). It is found in both whole legume seeds and cereal grains (Welch and Graham, 2012). The phytic acid content levels in crops have a very wide range. According to Bueckert *et al.* (2011) phytic acid content in most crop plants ranges from 500 to 5000 mg/100 g. Phytic acid binds iron and zinc by chelation, thus reducing their bioavailability. Although it acts as an antinutrient that reduces the bioavailability of micronutrients, phytic acid has some positive attributes for humans and plants.

In humans, it serves as an antioxidant, reduces the risk of cancer, and retards the development of kidney stones (Bueckert *et al.,* 2011). The antioxidant property of phytic acid deters or at least mitigates the oxidation of

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lipids, proteins as well as DNA. In this way, phytic acid prevents the diseases that are triggered by oxidation, such as those mentioned above.

While phytic is known to decline in concentration after cooking (Ghavidel and Prakash, 2007; Ndidi *et al.,* 2014; Pal *et al.,* 2016), other antioxidant compounds from plant sources, such as tocopherols and carotenoids have been shown to increase in concentrations and hence in antioxidant activity during cooking (Zhang *et al.,* 2014). Because bambara groundnut contains an appreciable concentration of α-tocopherol in quantities similar to other pulses (Yao *et al*., 2015), a reduction of phytic acid concentration arising from cooking does not necessarily eliminate the antioxidant property of this vital seed.

Effects of anti-nutrients on the availability of nutrients from plant foods can be reduced by food preparation methods, plant breeding or a combination of both methods (Bueckert *et al.,* 2011). Different methods of food preparation to mitigate phytic acid effects have been tested. Some of these are fermentation (Yao *et al.,* 2015), dehulling and cooking (Ghavidel and Prakash, 2007; Pal *et al.,* 2016). Ghavidel and Prakash (2007) observed a marked improvement in fat, protein and thiamine levels following the dehulling of legume seeds. Pal *et al.* (2016) recorded an 89.5 to 93% reduction in tannins and a 52.63 to 60% reduction in the phytic acid content of dehulled seed compared to hulled samples of horsegram [*Macrotyloma uniflorum* (Lam) Verdcourt]. Phytic acid content can be reduced in plants by crop breeding, but care has to be taken to avoid physiological problems of low phytate in the seed as described above (Bueckert *et al.,* 2011).

5. Genetic improvement of bambara groundnut through breeding

5.1 Pre-breeding

For years, bambara groundnut has been cultivated using local landraces from the previous harvest in most of the sub-Saharan countries. The production of bambara groundnut has remained low due to the unavailability of improved varieties. The lack of improved varieties could be attributed to the lack of research and crop improvement. Bambara groundnut landraces were produced from the wild progenitor and they are phenotypically and genotypically diverse, making them a potential source of genetic variation for breeding and crop improvement (Massawe *et al.,* 2005). The main germplasm collection of bambara groundnut landraces is held by IITA in Ibadan, Nigeria (Goli, 1997). The IITA has an international mandate for bambara groundnut germplasm conservation, with over 2000 accessions in stock, and there are over 1000 accessions at the Office of Scientific and Technical Research Overseas (ORSTOM) in France. A proportion of the germplasm collections has been evaluated for phenotypic diversity and other agronomic attributes (Tanimu and Aliyu, 1990). The Institute for Agricultural Research at Ahmadu Bello University, in Nigeria, and the Agricultural Research Council in collaboration with the University of the Free State, in South Africa, among many others, have a mandate for the genetic improvement of the bambara groundnut alongside other legumes including cowpea. In these research institutions, more than 100 accessions were collected and evaluated for morphological and yield traits (Tanimu and Aliyu, 1990).

5.2 Cross-breeding

In self-pollinating crops such as bambara groundnut, the available genetic variability is narrow, making it difficult to select for improved genotypes. The genetic variability can be improved through cross combination of desirable traits. Cross-breeding of specific parental genotypes provides controlled combination of traits, while cross-breeding of random genotypes creates large variability in populations. The variability created through cross-breeding is most likely to create new traits and allow effective selection. Previous research (Massawe *et al.,* 2004) has been successful in hybridizing bambara groundnut wild and cultivated parental genotypes which were selected based on grain yield and other important morphological traits. The research of Massawe *et al.* (2004) was the first to successfully produce crosses of bambara groundnut. The first successful intraspecific and interspecific artificial hybridization in bambara groundnut was reported by Basu *et al.* (2007). The within-species crosses were done among landraces and the wide crosses were done between some landraces and the wild progenitor of bambara groundnut. The success of cross-breeding for bambara groundnut crop created a potential for genetic improvement through breeding.

5.3 Mutation breeding

In self-pollinating crops such as bambara groundnut, genetic variability can only be created through cross-breeding. Although cross-breeding has proved to be a very important tool, it has its own limitations. Breeding involves two or more plants that are sexually compatible. This has the potential of limiting the introduction of new traits. Radiation, chemical mutagens and other appropriate biotechnology approaches have been used to induce variability in crop plants (Adu-Dapaah and Sangwan, 2004; Chaudhary *et al.,* 2019). Gamma irradiation has proved to induce higher genetic variation in bambara groundnut populations compared to conventional breeding (Adu-Dapaah and Sangwan, 2004). In addition, innovative biotechnology methods have also been used in shortening the generation cycles for faster breeding of legume crops such as pea and bambara groundnut. It has been reported that the use of in vitro and in vivo systems and embryo axis explants can produce more than four generations per year compared to one or two in the field (Adu-Dapaah and Sangwan, 2004).

5.4 Genetic diversity assessment

Genetic assessment of the available germplasm is of utmost importance for crop improvement. It is one of the essential components of pre-breeding in a crop species which serves as a link between germplasm resources and crop improvement (Sharma *et al.,* 2013a). Information about genetic diversity is used for making informed decisions regarding the choice of parent genotypes with traits of interest and high yield potential, thus, helping in the effective design of breeding programmes (Hornakova *et al.,* 2003; De Gioia *et al.,* 2005; Olukolu *et al.,* 2012; Simbarashe, 2013; Gepts, 2014; Aliyu *et al.,* 2016). This, in turn, increases the utilization of genetic resources. Knowledge of the phenotypic and genetic diversity of gene bank accessions is also essential for the effective management of accessions including the identification of duplicates (Upadhyaya, 2003; Kafkas, 2006; Olukolu *et al.,* 2012; Ríos, 2015; Aliyu *et al.,* 2016).

Genetic variability between and within a breeding population can be determined using different types of markers. These include morphological, molecular and biochemical markers (Mwenye, 2009; Mawgood, 2012; Mwenye *et al.,* 2016). Nutritional content variability is another measure of genetic diversity, but it was not widely used as one of the techniques for measuring genetic diversity in the past. This has, however, recently gained popularity in crop plants (Shegro *et al*., 2010; Upadhyaya *et al.,* 2011; Alake and Alake, 2016; Kahraman *et al.,* 2017; Wood, 2018).

Genetic diversity in bambara groundnuts has been studied by many scientists using different types of markers. Morphological assessment, which is a primary step in the study of the genetic diversity of a plant species (Mawgood, 2012; Shegro *et al.,* 2013; Mwenye *et al.,* 2016) has been used by a number of scientists to investigate genetic diversity in plants. This technique has been used as a stand-alone technique or in combination with molecular markers (Olukolu *et al.,* 2012; Molosiwa *et al.,* 2013; Mwenye *et al.,* 2016).

There have been mixed findings about the degree of diversity in bambara groundnuts. While many investigators have found wide diversity in the crop between accessions and to a lesser extent within accessions, some researchers have reported low genetic diversity in the crop (Pasquet *et al.,,* 1999). In the cases where genetic assessment studies have included wild relatives of bambara groundnut, scientists have found more polymorphism in the wild accessions than in the cultivated ones (Pasquet *et al.,* 1999). They studied 79 domesticated and 21 wild accessions of bambara groundnut for their genetic diversity using isozymes. They found that wild accessions had much higher genetic diversity than the more domesticated ones. The strongly self-pollinated nature of the cultivated bambara groundnut is thought to be the reason for low diversity, which is collaborated by the crop's high homozygosity (Stadler, 2009). Such findings have also been reported in other legume crop species, such as in lentils (*Lens culinaris* Medik.) (Lombardi *et al.* 2014), groundnuts (Moretzsohn *et al.,* 2013) and pigeon peas (*Cajanus cajan* L.) (Smýkal *et al.,* 2015).

According to Stadler (2009), there is low genetic diversity in bambara groundnut accessions south of the equator. A landrace known as Swazi Red was found to be an exception for it exhibited high genetic diversity. Although there is low diversity in other food legume species, that of bambara groundnut is even lower. It is only comparable to pigeon peas, its close relative (Stadler, 2009).

Several molecular markers such as Amplified Fragment Length Polymorphism (AFLP), Simple Sequence Repeats (SSRs), Random Amplified Polymorphic DNA (RAPD), DArT array markers, and Single Nucleotide Polymorphism (SNP) markers have been used in bambara groundnut improvement to determine the genetic diversity of the crop. Massawe *et al.* (2002) reported sufficient polymorphism when AFLP markers were used to determine the amount of genetic diversity and genetic relationships in bambara groundnut landraces. Minnaar-Ontong *et al.* (2021) reported high genetic diversity within and between bambara groundnut landraces in South Africa when SSR markers were used. Mukakalisa *et al.* (2017) reported significant polymorphism using RAPDs among bambara groundnut varieties. DArTseq markers were used to construct intraspecific maps from bambara groundnut F2 and F3 lines (Ho *et al.,* 2017), and they reported polymorphism in both populations. The findings from the above-mentioned studies can potentially be used in bambara groundnut breeding programmes for crop improvement.

6. Conclusion

Bambara groundnut is a highly nutritious, but underutilized crop. It has significant potential as a food security crop, especially in Africa, but far more efforts should be made toward marketing the crop for its value.

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Concerted efforts should be made by governments to market the crop, and to develop products and new uses for the seed and the plant as a whole. Plant breeders could develop improved cultivars with higher yield, and better cooking quality characteristics. Bambara can become part of a balanced and nutritious diet for millions of people in rural and urban Africa.

Conflict of interest

The authors declare no conflict of interest.

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