

# Exploring the Potential of Bambara Groundnut Crop for Agricultural Improvement and Global Food Security: A Review

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**Abstract:** *Bambara groundnut is an essential but underutilized African annual leguminous crop, originating in northeastern Nigeria and northern Cameroon. It is cultivated in Central and West African regions for its nutritional benefits and high tolerance to drought stress. Bambara groundnut is the third most important grain legume in Africa after groundnut and cowpea. Its leaves can be used to feed livestock and traditionally cure nausea in pregnant women. Bambara groundnut's high yield under drought conditions and resistance to pests and diseases make it a valuable crop for other crops. However, the global population is projected to reach 9.7 billion by 2050, and the harvested yield from major food crops may be insufficient to meet the projected demand. Climate degradation threatens food security, with fluctuating temperatures, prolonged droughts, soil degradation, salinity, flooding, and increased disease and pest conditions disrupting major crop species' growth and performance. Exploring plant genetic diversity resources is crucial to boosting food production and supply, reducing overreliance on major food crops, and promoting global food security. However, these species often lack essential, commercially valued crops, such as high-yielding varieties. The development of underutilized crops, with their vast genetic resources and beneficial traits, can help solve food security challenges by offering a multifaceted agricultural system. Understanding the variation among traits and determining the breeding potential for agricultural improvement programs is crucial in the current context of global climate change. This review highlights the potential of Bambara groundnut, its morphological variability, and breeding potential for agricultural improvement programs*

**Keywords** Bambara groundnut, underutilized, food security

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## INTRODUCTION

Bambara groundnut (*Vigna subterranean* L.Verdc) ( $2n = 2x = 22$ ) is one of the essential but forgotten and underutilized African annual leguminous crops belonging to the Fabaceae family, which is indigenous to the tropical African region (Gbaguidi *et al.*, 2018). The center of origin of Bambara groundnut is probably northeastern Nigeria and extends to northern Cameroon (Shim *et al.*, 2018). Bambara groundnut is confined to the dry regions, between the desert and the savanna (Southern fringe of the Sahara), and adapted to growing areas of relatively higher temperatures(Paliwal *et al.*, 2020). The plant looks similar

to peanuts, with compound trifoliolate, and the pods contain one to two seeds that are born underground just like peanuts.

This crop is commonly cultivated in Central and West African regions, mainly for its nutritional benefits and high tolerance to drought stress, unlike other essential legumes(Majola, Gerrano, and Shimelis, 2021). Global production of Bambara groundnut was 160,378 tons of which 111,562 tons have been produced in West Africa, Burkina Faso occupied the major portion in Africa with Nigeria leading its production at 100,000 metric tons per annum (Khan *et al.*, 2020). Bambara groundnut is essentially grown for human consumption and has been described as a completely balanced diet due to the high carbohydrate (65%) and protein (18%) content of its seed(Tan *et al.*, 2020). For its various importance, the crop ranked as the third most important grain legume after groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata*) in Africa (Mubaiwa *et al.*, 2017). The leaves can also be used to feed livestock; traditionally it is used to cure nausea, especially in pregnant women by chewing and swallowing the raw bean (DAFF, 2011). Beyond its cultural importance, one of the major reasons why Bambara groundnut is still cultivated by local farmers is due to its characteristic high yield under drought conditions (Muhammad *et al.*, 2020). Being a legume, it provides a benefit to other crops due to its ability to fix atmospheric nitrogen in the soil. It is also resistant to pests and diseases and can grow on poorly drained soils where many other crops cannot. It is a drought-tolerant crop that is readily adaptable to different environmental conditions and can be intercropped with different crops (Sarkar, VanLoon, and Sensarma, 2019).

There is increasing concern over the state of food and nutritional security in the world due to the over-reliance on major crop species as the main source of food and nutrition but, the global population is projected to reach about 9.7 billion by 2050 and the harvested yield from the major food crops may be insufficient to meet the food demand of the projected population(Onyutha, 2018). Similarly, the threat of global climate degradation on food security has become evident, for example, in fluctuating temperatures, prolonged droughts, soil degradation, salinity, and flooding, as well as an increase in disease and pest conditions that considerably disrupt the growth and performance of the major crop species. Therefore, it is imperative to explore the available plant genetic diversity resources to boost food production and supply as a means of reducing the overreliance on major food crops and promoting global food security. A more diversified system of agriculture that can provide a solution to the aforementioned problems could be achieved through the incorporation and utilization of underutilized crop species as the chief source of nutrition this will prove beneficial in achieving global food security (Muhammad *et al.*, 2020).

Furthermore, underutilized species are generally categorized as crops with little relevance on the global level, these species are either harvested in the wild for cultivation as future or domesticated crops; thus, the underutilized crops are mostly cultivated and valued at subsistence or regional levels. In all cases, there is a dearth of research on the production of these underutilized crop species. However limited scientific research has been conducted on underutilized crop species, a small number of these species have been adequately researched, mainly due to the commitment of institutions and researchers in the developing world, as well as technical and financial aid from the developed world (Muthamilarasan, Singh and Prasad, 2019). Considering their numerous dietary values and tolerance to harsh environmental conditions, some of these underutilized crop species, such as Bambara groundnut, are regarded as crops

for the future. However, these important species usually fall short of essential, commercially valued crops, such as high-yielding varieties that may attract growers with extensive resources and inputs required to achieve the improved yield performance of the crops (Kahane *et al.*, 2013). The development of underutilized crops, with their vast genetic resources and beneficial traits, is a useful step towards solving food security challenges by offering a multifaceted agricultural system that includes additional important food resources. Despite its various advantages, to date, the genetic potential of Bambara groundnut remains largely unexploited. The crop remains cultivated as landraces comprising selected inbred lines based on agroecology. As such the breeding technique of Bambara groundnut is undefined, and there are no high-yielding cultivars available only local landraces are still grown in most African countries. Henceforth, germplasm collection, diversity analysis, and selection techniques for the introduced accessions are the best approaches for the diversification and utilization of any crop (Khan *et al.*, 2020). Knowledge of morphological variability of germplasm collections is used to understand the relationship between the structural morphology of plants and their corresponding functional botany (Jared *et al.*, 2019). The use of morphological and agronomic traits is a standard way of assessing genetic variation for many species, especially under-researched crops such as Bambara groundnut (Azam-Ali *et al.*, 2001). Since Bambara groundnut is an underutilized crop, studies of its genetic diversity are scarce. Goli *et al.*, 1995, were characterized and evaluated approximately 1400 Bambara groundnut accessions at the International Institute of Tropical Agriculture (IITA) in Nigeria based on 38 characters, which included both quantitative and qualitative traits. Ntundu *et al.*, 2006 also reported on morphological diversity of Bambara groundnut from Tanzania of which quantitative traits contributed much of the diversity. Hence this review would emphasize the potential of the Bambara groundnut crop with a view of the variation that existed among the traits, and determine the extent of morphological variability and breeding potential for agricultural improvement programs in the current background of global climate change.

## LITERATURE REVIEW

### Origin of Bambara groundnut

Bambara groundnut, (*Vigna subterranean* L Verdc.) is an indigenous African leguminous crop and one of the most important pulses grown in the continent (Massawe *et al.*, 2005). The center of origin of Bambara groundnut is probably northeastern Nigeria and northern Cameroon since it is found in the wild from central Nigeria eastwards to southern Sudan, and is now cultivated throughout tropical Africa and to a lesser extent in tropical parts of America, Asia, and Australia. Bambara groundnut was domesticated in the semi-arid zone of West Africa, around the Niger River, from where it spread in ancient times to Central Africa, and more recently to the Malagasy Republic, Asia, and South America (Gao *et al.*, 2020). Bambara groundnut has been cultivated throughout tropical Africa for many centuries and it was taken at an early date to Madagascar, probably by Arabs, and reached Brazil early in the 17<sup>th</sup> century and was later taken to the Philippines and Indonesia (Omogbai and Aghahowa, 2017).

### Taxonomy of Bambara groundnut

Bambara groundnut (*Vigna subterranean* L. Verdc.) is an herbaceous, self-pollinating plant with an indeterminate growth habit. The domesticated Bambara groundnut landraces have quite a distinct tap root

and numerous short lateral stems on which the trifoliolate leaves are borne, while the wild forms have a limited number of elongated lateral stems with no clear tap root. The petiole is long, stiff, and grooved with a base of a wide range of colors such as green, purple, or brown (Shim *et al.*, 2018). The species subterranean is further divided into two groups: var. *spontanea*, comprising the wild forms, found in a small area around northern Cameroon and Nigeria, and var. *subterranean* comprising the cultivated forms in parts of the tropics, mostly in sub-Saharan Africa. The chromosome number in both wild and cultivated plants is  $2n = 2x = 22$  (Ahmad *et al.*, 2015). The wild Bambara groundnut landraces usually have a spreading growth habit, compared to the compact type of domesticated landraces (Siise and Massawe, 2013). The other major difference between the two types is that of pod size, with domesticated landraces having bigger seeds that do not wrinkle upon drying compared to the wild type. The germination of cultivated forms is rapid and uniform while in the wild forms, it is erratic and takes longer approximately 15 to 30 days. Generally, the domestication of crops involves several major steps, with the development of altered plant architecture and harvest ability of the traits. So that a wild-form plant can be domesticated and made more amenable to intensive agriculture (Basu *et al.*, 2007). Bambara groundnut is related to cowpea and has a pod habit similar to that of peanut (*Arachis hypogaea*) in that the pale yellow flower stalk bends downward after fertilization, it produces perfect flowers, it is self-pollinating and the fertilization of the ovule occurs on the day of anthesis (Lim, 2012).

### **Importance of Bambara groundnut**

Bambara groundnut is a rich source of protein and along with other local sources of protein could help to alleviate nutritional problems in areas where staple foods are predominantly carbohydrate sources (Azman Halimi *et al.*, 2019). This legume is a useful ingredient for different beverages, infants, and children's milk food (Eltayeb *et al.*, 2011). Bambara groundnut seed makes a 'complete food', as on average the seed contains sufficient protein (19%), carbohydrate (63%), and fat (6.5%) for a nutritionally balanced diet (Tan *et al.*, 2020). Furthermore, Lin *et al.*, 2020 noted that the mineral content estimated for 100g seed gives 59 mg for iron, potassium (1240 mg), phosphorus (296 mg), sodium (3.7mg), and calcium (78 mg). Also, it has high protein quality with a good balance of essential amino acids, compared to most of the other grain legumes, with relatively high lysine (6.8%) and methionine (1.3%) (Ellah *et al.*, 2010) which are often only available at low levels in legumes. Some anecdotal medicinal uses of Bambara groundnut seed and leaves mixed with other crops in North-Eastern Nigeria have also been noted (Directorate of Plant Production, 2011).

Bambara groundnut Symbiosis with Rhizobium bacteria to fix atmospheric nitrogen enhances the value of this crop for crop rotation and intercropping, as it contributes to the supply of soil nitrogen for other crops. Additionally, naturally occurring NO<sub>3</sub><sup>-</sup> ion tolerant symbioses in Bambara groundnut have been identified, these compare well to the tolerance of artificial nitrate in other legumes, where there is a strong inhibitory effect on symbiosis, so this potential allows Nitrogen fertilization in intercropping systems without inhibiting nitrogen fixation in the associated legumes (Gomoung *et al.*, 2017). Bambara groundnut is mainly cultivated for human consumption, apart from food applications, some cultures believe that Bambara groundnut has medicinal properties and can be used in traditional ceremonies such as funerals and gift exchanges (Yao *et al.*, 2015).

Bambara groundnut seeds are utilized mostly at the household level. The fresh or dry seeds are boiled or roasted and consumed on their own or are incorporated in other dishes the various food uses of the crop are listed in the table below.

**Table 1** Various food uses of Bambara groundnut

Form	Uses	Sources
Mature, fresh, or dry seeds	Eaten as pulse	(Brink <i>et al.</i> , 2006)
Dried seeds (ground)	Added to maize flour for porridge	
Soaked and ground seeds	Paste for fried or steamed dishes	(Lim. 2012)
Dried seeds (whole or split)	Boiled with maize or plantains	
Boiled salted seeds	Appetizer	
Dried seeds	Commercially canned in gravy	
Crushed, roasted seeds	Relish	(Murevanhema <i>et al.</i> , 2013)
Dried and boiled	Used in soups	
Flour and milk derived from BGN	beverages, bread	
Testa-free fresh seeds	Consumed as a complete meal by cooking with seasoning	(Jideani <i>et al.</i> , 2014)
Dry BGN seeds	Boiled and crushed seeds used to form cakes	

### Bambara groundnut Adaptability

Bambara groundnut is adapted to wide climatic zones, it can be cultivated from sea level up to 1600 m altitude and an average temperature of 20-28 °C is considered ideal for the crop. Bambara groundnut has wide adaptability since it can grow in ecological zones of varying climates, ranging from areas with annual rainfall as low as 300 mm annually in Botswana to high annual rainfall of 1250 mm in Swaziland (Massawe *et al.*, 2005). A growth period of 110 to 150 days is required for the crop to develop, although a reduced growth cycle of approximately 90 days is observed in Ghana and it is usually grown in mixed intercropping systems with no application of fertilizers (Jeuorobo *et al.*, 2019). Bambara groundnut can produce a reasonable yield when grown in poor soils low in nutrients but application of phosphorus results in better nitrogen fixation which increases stover and kernel yield (Ellah *et al.*, 2008). It grows well on well-drained soils, but sandy loams with a pH of 5.0 to 6.5 are most suitable (Tettey, 2014). In a controlled environment, the crop is more adaptive than groundnut since it forms pods even where groundnut fails which is a clear indication of the crop potential (Azam *et al.*, 2001).

### Morphological Characteristics of Bambara groundnut

Bambara groundnut is a herbaceous, intermediate, annual plant and is believed to be mainly self-pollinating (Heller *et al.*, 1997). The morphological structure of the crop largely matches that of the groundnut (*Arachis hypogaea*), in that the pale yellow flower stalk bends downwards after fertilization bearing its pods below the ground (Uguru and Ezeh, 1997).



Figure 1 Bambara groundnut morphology

It has two main contrasting growth habits; the branched form and the bunched habit, with a reproductive cycle of usually 90 to 150 days, depending on the environment and landraces (Berchie *et al.*, 2010). The taproot is well developed with many profuse geotropic lateral roots of around 20 cm long on the lower part (Akpalu. 2010). Nodules formed on the roots fix atmospheric nitrogen through symbiosis with *Rhizobium* bacteria, which makes them useful for crop rotation and intercropping (Karikari *et al.*, 1999). It is believed to be autogamous and floral reproduction starts 30 to 35 days after sowing and may continue until the end of the plant's life. Flowers are normally carried in pairs on short peduncles by a pedicle that arises from the axis formed by the petioles and the stem (Doku. 1968). Flowers produced on the same peduncle do not open synchronously, although they will open within a 24-hour interval. Delayed flower openings may be caused by low temperatures and cloudy skies (Massawe *et al.*, 2003). It has been reported that fertilization in Bambara groundnut takes place on the same day as anthesis (Craufurd. 1994). After fertilization, the flower stem elongates initiating the physiological processes leading to the formation of pods (Heller *et al.*, 1995). The sepal enlarges and the fruit develops above or just below the soil surface. Pod development lasts up to 30 days after fertilization and the seed develops over a further 10 days (Swanevelder. 1998). The pod is small, round, or slightly oval-shaped and wrinkled. Seeds mature when the parenchymatous layers surrounding the embryo have disappeared and the pods become light brown (Toungos *et al.*, 2009). The seeds are round, smooth, and very hard when dried, with highly variable testa colors, including cream, brown, red, and blotched (Stephens. 2003).

### **Yield potential of Bambara groundnut**

Most African countries rely on rain-fed agriculture, but such agriculture is particularly vulnerable to climate change, in addition, there are usually other concerns such as poverty, soil degradation, and recurring drought (Mendelsohn, 2000). In most countries in sub-Saharan Africa that are prone to drought, unreliable rainfall, poor soils, and poor crop productivity, the production of more drought-tolerant, indigenous crops, such as Bambara groundnut is encouraged. There is evidence that the crop is more resilient to adverse environmental conditions as it tolerates low soil fertility soils and low rainfall. Bambara groundnut landraces have been shown to tolerate drought as they can sustain leaf turgor pressure by employing a combination of osmotic adjustment, leaf area reduction, and effective stomata regulation

of water loss (Collinson *et al.*, 1997). The crop is endowed with the advantages of being relatively resistant to pests and diseases, and has substantial morphological diversity, with good adaptation to marginal areas and poor conditions (Azam *et al.*, 2001). It also contributes to soil fertility through biological nitrogen fixation making it beneficial in crop rotations and intercropping, hence farmers do not normally apply chemical fertilizers to Bambara groundnut (Mkandawire. 2007).

Bambara groundnut landraces produced as much as 4 tons per hectare (Feldman *et al.*, 2019). In the field in Swaziland, (Sesay *et al.*, 2008) seed yield of 2.6 tons per hectare was obtained while in Cote d'Ivoire (Zoro *et al.*, 2009) seed yield was as high as 4 tons per hectare was obtained. If these landraces are developed further to produce cultivars and varieties they could produce even greater yields. According to the Food and Agriculture Organization 2018, most Bambara groundnut production takes place in West African countries (Burkina Faso, Cameroon, Niger, Mali, and the Democratic Republic of Congo). According to (FAO.,2018) world production since 2018 was 164,589 tons among Burkina Faso 53,141, Cameroon, 42,041, Mali, 25,963, RDC, 10,819. Using Geographic Information Systems (GIS) technology identified some areas in America, Australia, Asia, as well as in Africa, where Bambara groundnut could produce significant pod yields, and some areas in the Mediterranean where it is predicted to have the potential of producing yields as high as 8.5t/ h (Azam *et al.*, 2001)

### **Breeding of Bambara groundnut**

Genetic diversity analysis using morphological traits of Bambara groundnut is primarily grown using landraces or farmers' varieties. Farmers grow local landraces from previous harvests or buy from local markets because there are no available improved varieties of the crop for small or large-scale production. This has been due to the lack of research on the crop towards its genetic enhancement. Landraces are more phenotypically and genotypically diverse than pure lines and are excellent sources of genetic variation for breeding (Zeven, 1998). Cultivated landraces were developed from the wild progenitor (*Vigna subterranea* var. *spontanea*) (Massawe *et al.*, 2005). Bambara groundnut is grown from landraces in all the major growing regions, particularly in sub-Saharan Africa. Initial collections and evaluations of Bambara groundnut landraces were carried out by the International Institute of Tropical Agriculture (IITA) (Anonymous, 1947). Most national programs in Africa reportedly have multiple accessions of Bambara groundnut landraces in their germplasm collections. Some of these collections have been evaluated for diversity, multiplication, or agronomic research such as seed yield and plant population. The IITA in Ibadan, Nigeria has an international mandate for Bambara groundnut germplasm conservation, with over 2,000 accessions in stock, and there are over 1,000 accessions at the Office of Scientific and Technical Research in France (Ouedraogo *et al.*, 2008).

The information provided by FAO Early Warning System on Plant Genetic Resources databases shows other countries in Africa and Asia also have numerous Bambara groundnut accessions, Benin 3, Botswana 26, Burkina Faso 143, France, ORSTOM 1000, Ghana, University of Ghana 80, Ghana, Savanna Agricultural Research Institute (SARI) 90, Ghana, Plant Genetic Resources Centre (PGRC) 166, Guinea 43, Kenya, National Gene bank 6, Kenya, Kenya Agricultural Research Institute (KARI) 2, Kenya, National Museums 2, Mali 70, Mozambique 12, Namibia 23, Nigeria, IITA 2035, Niger 79, South Africa, Grain Crops Institute 198, South Africa, Institute for Veld and Forage Utilization 117, South Africa,

Department of Agriculture 20, Tanzania, The National Plant Genetic Resources Centre of Tanzania (NPGRC) 22, Zambia, University of Zambia 463, Zambia, The National Plant Genetic Resources Centre 124, and Zimbabwe 129. (Goli, 1997).

As Goli, 1997, the Bambara groundnut germplasm held at IITA has not been adequately characterized for its use in breeding programs especially relative to other legumes such as cowpea and groundnut. Padulosi *et al.*, 2002 proposed that neglected and underutilized crops such as Bambara groundnut could play a prominent role in sustaining impoverished rural populations by increasing their available food and protein uptake. (Goli *et al.*, 1997) characterized 1384 Landraces of Bambara groundnut out of more than 2000 accessions kept at IITA, and found significant genetic variation in growth habits and leaf shapes. Similar reports were made by Ntundu *et al.*, 2006 on the morphological diversity among Bambara groundnut landraces in Tanzania and they observed variation among Bambara groundnut landraces. Ofori *et al.*, 2009 characterized Bambara groundnut landraces and observed variations in the number of days to flowering, pod length, and pod width presented low coefficients of variability when compared with the number of leaves per plant, canopy spread, and petiole length. Ofori *et al.*, 2009 reported five groups in a principal component analysis of nine characters, with a minimum similarity of 40%, which corresponded to 58 different morpho-types out of the 70 accessions. Maréchal *et al.*, 1978 found variations between Bambara groundnut and other species of the genus *Vigna* to which Bambara groundnut belongs, including cowpea (*Vigna unguiculata* L.). Bambara groundnut differs from cowpea in that the latter bears its long pods above the ground on long robust stems. Distinctive morphological features of Bambara groundnut have been described by several authors (Linnemann, 1994); (Goli, 1997); (Uguru and Ezeh, 1997); (Basu *et al.*, 2007).

### **Phenotypic Variability of Bambara groundnut**

The morphological method is the oldest and is considered the first step in the description and classification of germplasm (Hedrick. 2005). However, morphological estimations are more dependent on the environment and are more subjective than other measurements (Li *et al.*, 2009). Morphological variability depends on a limited number of genes, and may not access much of the potential variability for the agronomic traits present in a crop (Mayes *et al.*, 2009). The use of morphological and agronomic traits is a standard way of assessing genetic variation for many species, especially under-researched crops such as Bambara groundnut (Muhammad *et al.*, 2020). Substantial morphological diversity was revealed in the characterized and evaluated approximately 1400 Bambara groundnut accessions at the International Institute of Tropical Agriculture (IITA) in Nigeria based on 38 characters, which included both quantitative and qualitative traits which they recommended to be confirmed using molecular markers (Ntundu *et al.*, 2006) identified some vegetative traits that had prominent loadings in principal components analysis, and these are useful in distinguishing Bambara groundnut landraces. Similar traits, like seed weight, internode length, petiole length, leaflet length, and leaflet width, were identified as important traits in distinguishing between wild and domesticated Bambara groundnuts when analyzed with isozyme markers (Pasquet *et al.*, 1999).

Besides, morphological characters which can be highly correlated to grain yield give breeders the choice to make decisions as to which traits to select for in Bambara groundnut landraces (Karikari. 2000). Several

numerical taxonomic techniques have been successfully employed to classify and measure the patterns of genetic diversity in the germplasm collection by other researchers working on crops such as black gram (*Vigna mungo*) and Mungbean (*Vigna radiata*) (Ghafoor *et al.*, 2001) and wheat (*Triticum aestivum*) (Bechere *et al.*, 1996). The comparison of phenotypic and genotypic variation within and between several other crops has been examined to provide accurate taxonomic and genetic differentiation in cowpeas (*Vigna unguiculata*) (Omiogui *et al.*, 2006) and sorghum (Sorghum bicolor) (Yoshida *et al.*, 1999). Agronomic and morphological traits have been used to identify traits contributing to important traits such as yield in crops like Bambara groundnut (Makanda *et al.*, 2009).

### **Genetic Variation and Variability**

Variation is the occurrence of differences among accessions due to their genetic makeup and environmental effects in which they were raised (Allad, 1990). Phenotypic variability is the observable variation present in a character in a population due to both genotypic and environmental variation. Its magnitude differs under different environmental conditions. Genotypic variability is the component of variation, which is due to the genotypic differences among individual accessions within a population (Singh, 2001). Genetic similarity causes vulnerability of crop species to epidemics diseases and environmental disasters. Measuring genetic variation is very useful for selective breeding, rapid domestication, and conservation in populations (Tahir *et al.*, 2011). Burton, 1952 suggested that the genotypic coefficient of variation together with a high heritability estimate would give the best results expected for selection. For rapid and efficient crop improvement progress through plant breeding, there should be genetic variability because superior accessions can be selected from different populations.

Genetic variation is mostly interesting for plant breeders since proper management and utilization of such variation could result in a good impact on the performance of the crop. The existences of genetic variability among individuals due to genetic composition differences have immense importance in plant breeding programs because the permanent gain in the performance of plants can be assured through proper management of diversity (Sharma, 1998). The genotypic coefficient of variation and phenotypic coefficient of variation have an important role in measuring the amount of genetic variation that exists in the accessions. The study of genetic variability for agronomic traits is a key activity for the breeders in the breeding program for boarding the genetic base (Singh, 2001). Once they have a sufficient amount of genetic variability in the population crop improvement is easy through the use of appropriate selection methods on yield components (Dudly and Moll, 1969). Selection is effective in the breeding program only when there is a significant amount of genetic variability among the individuals. Generally, the achievement of crop improvement through a breeding program largely depends on the extent of genetic and phenotypic variability that exists among individuals.

The genetic variability can be also measured using genetic distances and  $D^2$  analysis provides a means of grouping the accessions based on their genetic divergence (Mahalanobis, 1936). Clustering using the  $D^2$  (genetic distance) matrix is useful for analyzing the divergence of the population to identify genotypic variability. The  $D^2$  statistics measure the forces of differentiation at intra and inter-cluster levels and determine the relative contribution of each component trait to the total divergence (Sharma, 1998). Clusters separated by the largest Mahalanobis  $D^2$  (genetic distance) show the maximum divergence, while

the accessions in the same clusters are less divergent (Singh *et al.*, 1977). According to Allard and Hansche 1964, progress in plant breeding depends on variability because superior accessions obviously cannot be selected from homogenous populations, but homogeneity is desirable in the final product. In initiating a breeding program with any crop, information on the nature and magnitude of genetic variation within the species for traits of agronomic importance greatly helps in formulating a sound crop breeding program and in efforts to breed better varieties.

### **Heritability and Genetic Advance**

Heritability is the degree to which the variability of a character is transmitted from the parent to the next generation of progeny. It is the measured degree of correspondence between breeding values and phenotypic values (Falconer and Mackay, 1996). The broad-sense heritability ( $H^2$ ) is defined as the ratio of the total genetic variance to the phenotypic variance. It is important for obtaining information on the magnitude of variability and for successful breeding programs in selecting accessions with desirable traits (Dudly and Moll, 1969). Heritability is essential to divide the observed variability into heritable and non-heritable components. Highly heritable traits might be used for the rapid selection of large volumes of early-generation materials for specific traits and to select indirectly for associated traits with low heritability. Heritability estimates in a broad sense were estimated and categorized as high (> 70 %), moderate (50-70 %), and low (< 50 %) (Robinson 1966).

Genetic advance is the estimate of the expected gain for a particular character through selection from generation to generation and it depends on genetic variability, heritability, and selection intensity (Allard, 1999). It measures the difference between the genotypic values of generations obtained from the selected population over the mean value of the population. If there is a wide range of variability in the population genetic progress through selection would increase. Therefore, the utility of estimates of heritability is increased when they are used in conjunction with the selection differential, the amount that the mean of the selected lines exceeds the mean of the entire group (Johnson *et al.*, 1955). Genetic advances as a percentage of the mean (GAM) are classified as high (>20%), moderate (10-20%), and low (<10%) (Johansen *et al.*, 1955)

### **Correlation Analysis**

The interrelationship of different characters with yield determines the efficiency of selection in the breeding program. Genetic correlation is the association of breeding values of the two characters, while phenotypic correlation reflects the observed relationship. Environmental correlations arise from the effect of overall environmental factors that vary in different environments. Studies on genotypic and phenotypic correlations among characters of crop plants are useful in planning, evaluating, and setting selection criteria for the desired characters in a breeding program (Johnson *et al.*, 1955). Correlations due to genetic causes are mainly the pleiotropic effects of genes and the linkage between genes affecting different characters. The association between two characters that can be directly observed is the correlation of phenotypic values or phenotypic correlations. Phenotypic correlations involve both genetic and environmental effects. Both measure the extent to which the same genes or closely linked genes cause co-variation in two different characters. The degree of relatedness between important plant traits is an index that can be used to predict yield responses concerning changes associated with a particular trait. Grain

yield is a complex trait; indirect selection through correlated, less complex, and easier measurable traits would be an important strategy to increase grain yield. Path coefficient analysis furnishes information on the influence of each contributing trait to yield directly as well as indirectly (Farshadfar, 2004). The breeders can rank the genetic attributes of each trait according to their contribution and thus be useful in the indirect selection of elite accessions from diverse genetic populations.

### **Cluster Analysis**

Cluster analysis refers to a multivariate statistical analysis technique used to partition a set of accessions into groups based on the uniformity of traits they possess. Each cluster within a group is more similar among individual accessions and different from the individual in other Cluster. The cluster analysis based on the UPGMA model using numerical traits constructed four distinct groups of Bambara groundnut accessions in South Africa reported by (Unigwe *et al.*,2016) and constructed a dendrogram using statistical analysis software (SAS version 9.3). (Mohd Y. Rafii *et al.*, 2020) used the homogenized data to calculate the Euclidean distances among the 150 Bambara groundnut accessions and the cluster analysis presented as a dendrogram using UPGMA (average linkage cluster analysis) revealed numerous clusters depicting associations among these collected accessions. To categorize against the relations in the accessions, accessions were clustered into five major clusters based on their twenty-seven measurable traits at the dissimilarity of 496.7 for picking cluster number and ease of interpretation using Mojena's stopping rules and D-square statistics ( $D^2$ ) developed by Mahalanobis (1936), is one of statistical technique used to classify the accessions into different clusters.

### **Principal Component Analysis**

Principal component analysis (PCA) is one of the multivariate statistical techniques that explain the contribution of the most important traits that account for the total genetic variation (Sharma, 1998). The first step in PCA is to see Eigenvalues which define the amount of total variation that is displayed on the PC axis and the Eigenvalues greater than 1 ( $> 1$ ) are considered the best representative of system attributes in principal components (Mahmudul *et al.*, 2020). Mahmudul *et al.*, 2020 reported that 78.99% of the total variation was explained by the first four principal components. The 1st PC gained and recorded for the topmost proportion of the variance in the set of all PCs and the rest for gradually smaller and smaller amounts of variation. However, the percent of variation for PC1 and PC2 was 34.29% and 11.63%, respectively, while the 9th PC accounted for 3.28% of the variation. Total no. of pods, number of mature pods, fresh pods weight, dry pod weight, number of seed/plant, seed length, dry seed weight, hundred seed weight, and yield) and traits (petiole and leaves number, biomass fresh and dry weight, and seed length and width) had a positive correlation with PC1 and PC2, respectively.

### **CONCLUSION**

Bambara groundnut is an important but often overlooked crop native to Africa, particularly in the dry regions between the desert and savanna. It is known for its nutritional benefits, drought tolerance, and ability to fix atmospheric nitrogen in the soil, making it a valuable crop for food security and sustainable agriculture. Despite its many advantages, Bambara groundnut remains largely underutilized, and more

research is needed to explore its full potential. By diversifying crop species and incorporating underutilized crops like Bambara groundnut, we can enhance global food security and adapt to the challenges of climate change.

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