Bambara Groundnut

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Currently, the global agricultural system is focused on a limited number of crop species, thereby presenting a threat to food security and supply, especially with predicted global climate change conditions. The importance of ‘underutilized’ crop species in meeting the world’s demand for food has been duly recognized by research communities, governments and policy makers worldwide. The development of underutilized crops, with their vast genetic resources and beneficial traits, may be a useful step towards solving food security challenges by offering a multifaceted agricultural system that includes additional important food resources. Bambara groundnut is among the beneficial underutilized crop species that may have a positive impact on global food security through organized and well-coordinated multidimensional breeding programs. The excessive degrees of allelic difference in Bambara groundnut germplasm could be exploited in breeding activities to develop new varieties. It is important to match recognized breeding objectives with documented diversity in order to significantly improve breeding.

Keywords: bambara groundnut ; climate change ; crop improvement ; food security ; underutilized species

1. Introduction

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 [1]. 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 [2][3]. 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 to promote global food security [4][5]. 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 [6].

The term ‘Underutilized’ can be used to describe the abandonment of a species by indigenous and international research communities. Underutilized species are generally categorized as crops with little relevance on the global level. These crops, however, play a significant role in terms of climate change and food security, while improving the living standards of low-income families and consumers in developing nations [7][8]. Underutilized crop species, with essential nutrients, can fit into several niches in food production systems and can better adapt to low-input systems in resource-poor regions of the world [9][10]. Presently, these species are either harvested in the wild for cultivation as future or domesticated crops; however, 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. Despite their neglect, underutilized crops have gained considerable attention from the media in recent times [11], due to their prospects in addressing several UN Sustainable Development [12], and in poor nations of Africa [13] and the Latin America [14]. Additionally, the increasing interest on healthy food alternatives by Western consumers have aided the recent popularity of underutilized crop species [15]. While 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 [16]. 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. Additionally, these crops are highly fortified, with essential nutrients that are excellent in promoting health, and have the ability to combat malnutrition and other related diseases. However, these important species usually fall short of essential, commercial 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 [17][18]. Incorporating these underutilized crop species, specifically Bambara groundnut, in diversifying the food chain can have a positive impact by serving as a general tool for improving human nutrition. Bambara groundnut is highly nutritious, making it relevant in the nutritional formulation of people that cannot afford expensive protein sources, especially animal-based protein [19]. The seed of Bambara groundnut contains 61–69% carbohydrate, protein 17–27%, fiber 3.3–6.4%, ash 3.1–4.4%, and fat 3.6–7.4%, thus making it a valuable dietary source [20][21]. It also contains 95.5–99.0 mg Ca, 5.1–9.0 mg K, and 2.9–10.6 mg Na per 100 g, with a substantial amount of Zinc (20.98 ± 1.07 mg/100g), which may have a significant impact on preventing prostate cancer in men [22]. The freshly harvested pods, as well as the dry seeds, are processed and consumed in different forms (Figure 1). Freshly harvested pods are boiled or grilled and consumed as snacks [23]. The seeds have a higher content (80%) of high-quality amino acids, such as arginine, leucine, valine, methionine, and lysine, as compared to cowpea, soybeans and groundnut (64%, 74% and 65%, respectively), and may potentially complement the deficient essential amino acid content of foods [22].

Figure 1. Some examples of processed food products made from Bambara groundnut.

Bambara groundnut (*Vigna subterranea* (L.) Verdc.) is one of the essential but forgotten and underutilized annual leguminous crops belonging to the Fabaceae family, which is indigenous to the tropical African region. 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 [24]. Generally, the plant looks similar to peanuts, with compound trifoliate. The pods contain one-to-two seeds that are born underground just like peanuts. Being a legume, it provides a benefit to other crops due to its ability to fix atmospheric nitrogen to the soil. It is also resistant to pests and diseases and can grow on poorly drained soils where many other crops cannot thrive [25]. It is widely accepted that Africa is the geographical origin of Bambara groundnut [26][27][28]. Despite the agreement on Africa as the geographical origin of Bambara, the precise area of its domestication has been widely speculated [29]. The most abundant genetic resources exist between the corridor of Nigeria and Cameroon, which is believed to be its origin of dispersal [30]. Goli [31] reported the distribution of wild Bambara types from Jos Plateau and Yola Adamawa in Nigeria to Garoua in Cameroon. It was thought that Bambara groundnut was first introduced to East Africa and Madagascar and then subsequently to South and South-East Asia during the slave trade era. In a study by Takahashi et al. [2], it was stated that landraces of the Thai's Bambara were from both West Africa (Nigeria) and East Africa, thus implying that this crop may have been introduced to Thailand on several occasions. 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 [32]. However, this crop remains cultivated as landraces comprising selected inbred lines based on agro-ecology. Hence, this review provides an overview of the impact and constraints to Bambara groundnut production, and the major achievements recorded to date in Bambara groundnut research with regards to its agronomy, breeding, and improvement. Through retrospective assessments, this review ultimately intended to present the highlights of the improvement prospects of this crop for future directions.

2. Genetic Diversity in Bambara Groundnut

The assessment of available genetic diversity is fundamental in the improvement of Bambara groundnut, which is mostly restricted to small scale traditional farming systems in which they have been commonly cultivated from the existing landraces [33]. Landraces are more phenotypically and genotypically diverse compared to pure lines and are excellent sources of genetic variation for breeding [34]. Cultivated landraces were developed from the wild progenitor (*Vigna subterranea* var. *spontanea*) [35]. Bambara groundnut is grown from landraces in all the major growing regions, particularly in sub-Saharan Africa, and its yield can be unstable and unpredictable across different geographical regions. While being adapted to their current environment, landraces may not contain the optimal combination of traits [36].

Globally, up to 6145 Bambara groundnut landraces/accessions are conserved ex-situ and these collections are kept in trust by international or regional gene banks, which are comprised of several countries (Table 1). Genetic variability, which could be beneficial for the improvement of the genetic performance of any crop species [37], is largely preserved in the form of landraces [37]. A significant quantity of genetic diversity has been maintained in the landraces of Bambara groundnut under low input systems of farming [35]. Traditional farmers of Bambara groundnut depend on the prevailing diversity among the cultivated landraces and this has enhanced the maintenance of on-farm genetic diversity in its conservation [38]. Ex-situ conservation of Bambara groundnut landraces is necessary for the crop's future genetic improvement programs. However, landraces are problematic when it comes to understanding the genetic background of traits of interest for crop improvement because they are a mixture of numerous genotypes (Figure 2), which may bring about confusion between genotypic and environmental effects [39]. These genetic resources are the basis for present and future food security [40]. Genetic diversity within lines and populations is central to breeding and germplasm conservation programs [41]. As such, it is pertinent to know the genetic diversity among breeding materials to avoid the risks related to increased uniformity in elite germplasm, and to ensure long-term selection gain as a cross between the limited number of elite lines that put them at risk of losing their genetic diversity [42].

Figure 2. Seed morphological genetic diversity among different landraces of Bambara groundnut (**Note: A** = Bidi, **B** = Maiki, **C** = Bidilalle, **D** = Karu, **F** = Maizane, **G** = Doii, **H** = Ex-Sokoto, **I** = Jatau, **J** = Bidiyashi, **K** = Hawayenzaki, **L** = Zabuwa, **M** = Yar-Gombe, **N** = Maibargo, **O** = Giwa, **P**-Dunabaki, **Q** = Cancaraki).

Table 1. Bambara groundnut landraces/accessions and wild-type genotypes held by international institutions across some selected countries.

S/N	Country	Inst. Code	Acronym	Accessions Type						
				Accessions No.	%	WT	LR	BL	AC	OT
1	Nigeria	039	IITA	2031	33	<1	100	-	-	-
2	France	202	ORSTMONTP	1416	23	-	100	-	-	-
3	Botswana	002	DAR	338	6	-	2	-	-	98
4	Ghana	091	PGRRI	296	5	-	-	-	-	100
5	Tanzania	016	NPGRC	283	5	<1	81	-	-	18
6	Zambia	030	NPGRC	232	4	-	100	-	-	-
7	Others	(26)	Others (26)	1549	25	1	59	9	1	29
		TOTAL		6145	100	<1	79	2	<1	18

Note: Negative (–) sign indicates an unspecified number of accessions. WT: wild types; LR: landraces; BL: breeding lines; AC: advanced cultivars; OT: others. Source: [43][44]. International Institute of Tropical Agriculture (IITA). Office De la Recherche Scientifique et Technique Outre-mer (ORSTOM). Departement of Agricultural Research (DAR). Plant Genetic Resources Research Institute (PGRRI). National Plant Genetic Resource Centre (NPGRC).

The landmass of a country is usually made up of predominantly different soil types [45] and the variation in soil types may contribute to the diversity of Bambara groundnut. In addition to autogamy and farmer preferences, geographic and ecological isolation fosters agro-morphological diversity among local populations of Bambara groundnut for their adjustment and adaptation to their respective growing areas [46]. The constant influence of these evolutionary factors results in the adaptive characteristics of the accessions of each population [37][47]. Knowledge of the genetic potentials of Bambara groundnut is managed by local farmers in the different agro-ecological zones, which are considered limited, and as a result, the crop has been poorly exploited [31]. Furthermore, in-depth information on the constraints and difficulties faced by an individual underutilized crop, like Bambara groundnut, may perhaps be translated to the general improvement of other underutilized species. Generally, the results demonstrated that different local populations of Bambara groundnut have several genotypes with the potential capacity to produce and adapted to changing environmental conditions [48]. These genotypes could avail options of plant breeders in regards to improving the adaptation and yield of Bambara groundnut in different agro-ecological zones, in consideration of climate change. To achieve a well-coordinated plant breeding and improvement program, it is necessary to embark on an excellent germplasm collection of superior qualities, where scientists and breeders can utilize the information to classify and select parental genotypes for crop improvement schemes [49][50]. Genotypes collected from a country or different locations in a country may be similar or may have common ancestry with diverse native terms [36]. For example, Bonny et al. [51] conducted a study on variability, based on agro-morphological characters among and within the population of four agro-ecological regions of the species in Côte d'Ivoire. Results from their study indicated a significant phenotypic variation among all the traits studied and in the overall population. Consequently, their findings proposed that at every agro-ecological region, Bambara groundnut farmers hold a significant genetic diversity on their farms. Taking into account the results of individual and overall population, mean, dispersion and the coefficient of variation obtained for every character were significantly greater than those obtained in a similar study by Ntundu et al. [52] who worked on 100 accessions in Tanzania and at IITA in Nigeria by Goli [28] who used 1384 accessions collected across Africa.

Bambara groundnut has become a model drought-tolerant crop due to its ability to grow in a wide range of agro-ecological zones with varying soil conditions and the ability to produce a significant amount of yield under moderate or extreme drought stress. This tolerance to a wide range of environmental stress conditions makes Bambara groundnut an important crop for cultivation in an arid environment and equally as a future crop in regions where projections of climate change indicate a likely occurrence of drought and/or intermittent rainfall patterns [53]. Furthermore, the crop has adapted to different environments, ranging from high daytime temperatures and extreme low night-time temperatures in arid areas of Botswana, to the more humid and far milder climate of Indonesia. Thus, their ability to grow under terminal soil and climate conditions cannot be underestimated. For instance, Mabhaudhi et al. [24] predicted that Bambara groundnut yield and water productivity can increase by 37.5% and 33%, respectively, under the predicted climate change scenario. Similarly, Mabhaudhi et al. [54] established that a suitable environment for the production of Bambara groundnut under climate change would increase, thereby ascertaining its resilience to change in the climate.

Identification of important traits through agro-morphological characterization remains the first step in the collection of available genetic germplasm resources [33]. This procedure is inexpensive, direct and easy to practice; therefore, it is among the standard procedures for assessing genetic variability in many species, particularly for under-researched crop species like Bambara groundnut [55][56], and this procedure is employed for legume characterization using qualitative and quantitative characters. Additionally, Hoque et al. [57] employed a similar process to achieve significant agro-morphological diversity in characterizing rice genotypes. Additionally, this procedure is used to select morphological traits that can be positively correlated with grain yield and can allow plant breeders to make a decision on traits of choice for selection among the evaluated species. According to Eckert et al. [58], agro-morphological divergence in a population is primarily due to environmental influences. Thus, this spatial structuration of agro-morphological diversity could be the result of the influence of variations in climatic factors, especially rainfall, temperature and probably day length. Several studies have shown that temperature [59], humidity [60] and day length [61] have variable effects on the vegetative, phonological and reproductive development of Bambara groundnut. This spatial structuration could also be accentuated by divergent selection and continuous inbreeding because of the species autogamy [62]. Wet climates usually entice farmers to grow accessions of the spreading type that are well suited to long cropping seasons, while in dry climates, farmers would prefer to grow the bunch type due to the short cropping season. Previous research has shown that a significant agro-morphological variation exists among many local genotypes of Bambara groundnut [45]. Bambara groundnut demonstrates a considerable amount of genotypic variability for various phenotypic, physiological, agronomic and seed traits [44].

Studies focused on variation in inter and intra-landrace morphological descriptors (both as sovereign research and as an extensive classification of germplasm) in Bambara groundnut has been comprehensively reported [63][64][65]. Bambara groundnut standard descriptors (Table 2) were used for the phenotypic classification exercise [65][66]. The International Institute of Tropical Agriculture (IITA) in Nigeria evaluated and characterized approximately 1400 accessions of Bambara groundnut using 28 characters (Table 2), and it was discovered that there was significant agronomic and morphological diversity among the accessions, both in terms of qualitative and quantitative characters, and recommended their confirmation through molecular markers [52].

Table 2. Select documented qualitative morphological variants in Bambara groundnut germplasm.

S/N	Trait Descriptor	Scale (Measure)	References
1	**Habit of growth**	**Spreading Branch Semi-branch**	[28] [67] [49] [52] [68]
2	**Fully expanded terminal leaflet color**	**Green Purple Red**	[51] [56]
3	**The shape of the terminal leaflet**	**Elliptic Lanceolate Round Oval**	[69] [69] [63] [70]
4	**Pigmentation on the petiole**	**Pinkish green Green**	[71] [72]
5	**Color of pod**	**Purple Black Brown Yellowish-brown**	[71] [55]
6	**Pod texture**	**Smooth Rough Many grooves Little groove Folded**	[31] [52] [69] [30]
7	**Pod shape**	**Book pointed end on the other side Round pointed end on the other side No point at all sides**	[52] [69]
8	**Shape of seed**	**Oval Round**	[54] [63]

Ntundu et al. [31] and Bonny et al. [51] discovered certain vegetative characters that had prominence in principal component analysis and can be used to distinguish between landraces of Bambara groundnut. Using isozyme markers, traits such as pod weight, seed weight, number of petioles, internode length, leaflet width, and leaflet length were recognized as significant traits to distinguish between domesticated and wild species of Bambara groundnuts [73]. Furthermore, other researchers who worked on crops such as Mungbean, Black gram, rice [74][75] and wheat have successfully used several numerical taxonomic procedures to classify and measure genetic diversity patterns among the collected germplasms, using morphological and agronomic traits to classify the traits responsible for qualities such as yield in a similar manner to Bambara groundnut [76] and soybean [77]. To date, there is no report on the relative characterization of larger Bambara groundnut landraces with regards to the photoperiodic response, pigmentation on banner and wings, and stem hairiness in quantitative traits analysis of this plant. The lack of reporting on the photoperiodic reaction in Bambara groundnut landraces is due to the nonexistence of the protocol for high throughput phenotyping. In many ecological settings, such a phenotyping protocol requires a highly controlled environment, particularly around tropical zones where day length variation is partial. Nonetheless, research on Bambara groundnut focusing on the mechanism of the photo-thermal reaction have been documented by many researchers [78][79][80][81][82]. Aliyu and Massawe [73] used petiole pigmentation in their investigation of the photo-thermal reaction; however, this was not among the listed standard descriptors for Bambara groundnut.

Molecular genetic diversity analyses have aided breeding conclusions and germplasm conservation in crop species [83][84]. Over the past twenty years, various molecular markers for analyzing genetic diversity, specifically designed for Bambara groundnut, were documented to either oppose or validate the reports on phenotypic descriptors (Table 3; [85]. Numerous studies have discussed ways that molecular markers can: offer information and knowledge on genetic diversity in Bambara groundnut [85], determine heterozygosity for the purification of seed [86], link germplasm to specific features such as the geographic region [33], function in quality regulation and can be useful in realizing breeding objectives [69]. Similarly, various studies have been conducted to explore the genetic mechanism of significant traits, such as leaf appearance, stress tolerance [87][88] and can provide a basis for the comparison of crops, with and without complete genome sequences, to pave the way for the translation of positional data into underutilized crops [89]. The use of isozymes among 79 domesticated accessions of 21 wild type populations, to study their genetic diversity, was reported by Pasquet et al. [90], the use Random Amplified Polymorphic DNA RAPD was documented by Rungnoi et al. [91], and Massawe et al. [92] and Ntundu et al. [65] used amplified Fragment Length Polymorphism AFLP on 16 landraces, with cluster analysis that categorized the landraces into three clusters, and principally based their location or geographical origin. The low cost of genotyping per sample has allowed for the development of high throughput genotyping for several species of legume [93]. For example, a 60 k cowpea iSelect Consortium Array to screen 51,128 Single Nucleotide Polymorphism SNPs [92] and a flexible throughput Competitive Allele-Specific Polymerase chain reaction PCR (KASPar) assay for 2005 SNPs in chickpea (*Cicer arietinum*) [94]. Lately, the University of Nottingham was credited with the development of molecular mapping populations that can aid in the marker-assisted selection of additional improved lines for daylength insensitivity [53].

Table 3. Some reported molecular marker analyses of genetic diversity in Bambara groundnut.

Crop Type	Types of Markers	Nature of Research	References
Bambara groundnut (*Vigna subterranea*)	**Sing Sequence Repeat (SSR)**	**SSR-based analysis of genetic diversity of Ghanaian Bambara groundnut landraces**	[71]
	Sing Sequence Repeat and Diversity Array Technology (SSR, DArT)	**SSR-based analysis of genetic diversity and population structure in Bambara groundnut landraces**	[68]
	Sing Sequence Repeat and Diversity Array Technology (SSR, DArT)	**Construction of linkage map and QTL analysis of phenotypic traits in Bambara groundnut**	[87]
	Directed Amplification of Minisatellite and Start codon targeted (DAMD, SCoT)	**Competency assessment of directed amplified minisatellite DNA and start codon targeted markers for genetic diversity study in Bambara groundnut**	[95]
	Random Amplification of Polymorphic DNA (RAPD)	**Assessment of genetic relationships based on the morphological characters and RAPD markers in Bambara groundnut**	[96]
	Sing Sequence Repeat (SSR)	**Microsatellite-based marker molecular analysis of Ghanaian Bambara groundnut landraces alongside morphological characterization**	[68]
	Diversity Array Technology (DArT)	**DArT-based marker genetic diversity analysis in Bambara groundnut, as revealed by phenotypic descriptors**	[33]
	Random Amplification of Polymorphic DNA (RAPD)	**Genetic diversity in Bambara groundnut landraces assessed by Random Amplified Polymorphic DNA RAPD markers**	[97]

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