

## Review

# Bambara Groundnut (*Vigna subterranea* L. Verdc): A Crop for the New Millennium, Its Genetic Diversity, and Improvements to Mitigate Future Food and Nutritional Challenges

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**Abstract:** The world's food and agricultural schemes have gradually fallen into an alarming state due to challenges such as high population birth rates, diverse agro-climatic zones, a lack of measures to counter global warming, severe practices of sole-culture cultivation, and asset reduction. A very high dependency on limited staple food crops is associated with repetitious diets, deprivation of food, and shortages of trace minerals, which often causes dietary sicknesses. To ensure nutritious diets worldwide, a real-world and justifiable scheme is provided to garner extra attention towards variation in both agriculture/farming approaches and food habits. The EAT-Lancet statement emphasized an increase in agri-based diets as a way of attaining global generational health. Enlarging neglected crops with plenty of genomic stocks and potentially profitable attributes is a solution that could address food and nutritional security concerns. Bambara groundnut is one such imperative and neglected legume crop that contributes positively to improving global food and nutrient safety. As a "complete food", this crop has recently been treated as a new millennium crop, and furthermore, it is more adjusted to poor soil and climatic conditions than other dominant crops. Bambara groundnut is a repository of vital nutrients that provides carbohydrates, crucial amino acids, proteins, and energy as well as minerals and vitamins to developed and low-income countries where animal proteins are not readily available. This review explores the potential of Bambara groundnut in ensuring food and nutrient security; its variables, production, processing, nutrient values, role in reducing the nutritional gap, and diverse uses; and attempts in improving its traits. To strengthen food production, an agricultural revolution is required for underutilized crop species to feed the ever-expanding population in the world. Henceforth, advanced plant-breeding procedures, such as next-generation breeding techniques, various molecular tools, TILLING, Eco-TILLING, proteomics, genomics, and transcriptomics (which has been used for major crops), also need to be practiced to intensify production. To boost productivity and to feed the most starved and malnourished populations of the world, it is assumed that the application of modern techniques will play a vital role in the advancement of the underutilized Bambara groundnut.

**Keywords:** Bambara groundnut; new millennium crop; genetic diversity; food and nutritional security; genetic improvement

## 1. Introduction

Eradicating poverty and malnutrition involves the copious consumption of a balanced diet, confirming that daily uptake of nutritional elements is essential. Despite a greater

diversification of agri-based food on the planet, people are used to a monoculture of limited crops for nourishment in their daily diets [1]. However, this may not ensure nutrient security and does not ensure nutrient affectability, accessibility, or availability. In the current era, measures such as poverty, infant weight, and adult obesity have gained increasing attention [2]. With a continuation of the present food production and diet patterns, unfortunately, we will be unable to reach the UN's Sustainable Development Goal (SDG) of eliminating poverty by 2030. Several issues, such as industrialization, urban expansion, rapid birth rate, insect/pest and disease epidemics, provincial battles, unpredictable weather, and asset reduction, hasten the need for extra food consumption and production [3]. To eliminate poverty and malnutrition and to achieve the UN Sustainable Development Goal by 2030, it is necessary to produce quality foods, especially for low-income countries. To retain food quality and nutritional safety while also attaining the UN's second Sustainable Development Goals [4], efforts must be directed towards agri-based diets such as minor cereal crops and legumes, neglected crops, underutilized crops, root vegetables, agro-ecology-specified crops, fruits, and whole grains.

About ten thousand years ago, humans invented agriculture for the domestication of wild plants for human use. Globally, population growth rate trends are increasing at an alarming pace, and modern techniques must be introduced to increase production; to upgrade nutrient availability; and to produce disease-, pest-, and insect-resistant crops. Since ancient times, humans have attempted to implement techniques and approaches to heighten production and to protect crops from various diseases by applying conventional methods. Unfortunately, conventional methods are no longer serviceable for current demands. It is advised that the global food stock must be increased by 70% by 2050 to satisfy the requirements of the increasing world population [5].

Global food and nutritional safety has become an important issue owing to over-dependence on, primarily, cereal crops as the principal basis of diets and nutrition [6]. Hence, current production from dominant crops might be inadequate to provide for the predicted population [7]. Furthermore, the dangers that environmental change poses to food safety have become an obvious effect of the temperature variations, prolonged droughts, soil degradation, salinity, flooding, and increases in insect pest and disease severity that significantly impede the development and production of principal food crops. Now, it is important to discover resources to address the genetic inconsistency of crops to accelerate crop production and to produce stock that consequently reduce extreme dependence on an inadequate quantity of food crops as well as to attain world food security [8,9]. Only diversified farming practices can offer a resolution to these obstacles in terms of the establishment, integration, and application of underutilized crops as a strong basis of nutrition to overcome food security challenges [10,11]. Research has shown that concentrated efforts and attention to a limited number of crops with a lack of genetic diversity can have injurious effects on the human diet, leading to malnutrition and/or a food crisis [12].

The Bambara groundnut (*Vigna subterranea* L. Verdc.; Syn: *Voandzeia subterranean* L. Thouars.) is an underutilized legume species widely produced in Africa [13]. This crop is a legume that is cultivated well in Africa and Asia. It is ordinarily regarded as a "poor man's" crop, and mostly known as a "women's crop" grown only to achieve family food security [13]. It was also recently declared one of the "crops for the new millennium" [14]. Oyugi et al. [15] reported that the main production activities analyzed in terms of gender involvement, including land preparation activities, planting, weeding, pest control, harvesting, drying activities, threshing, and winnowing, were performed by women. This is the main reason for indicating that this crop is a "women's crop". The Bambara groundnut is considered the third most common major legume after groundnuts (*Arachis hypogaea*) and cowpeas (*Vigna unguiculata*) on the African continent. This crop is efficient at promoting nourishment, boosting food assurance, fostering pastoral improvement, and supporting sustainable land uses.

Underutilized Bambara groundnut crops are not classified as commodities in the global trading scheme, and researchers have paid little attention to them because of their low production rank [16]. The cultivation of such crops has a significant effect on food and nutritional protection by providing income to marginal farmers; by reducing the over-reliance on limited crop plants as sources of diet, fuel, and food; and by requiring low input in comparison to conventional agriculture systems [17,18]. Due to its high yield under drought stress conditions, local and marginal farmers still grow Bambara groundnut [19].

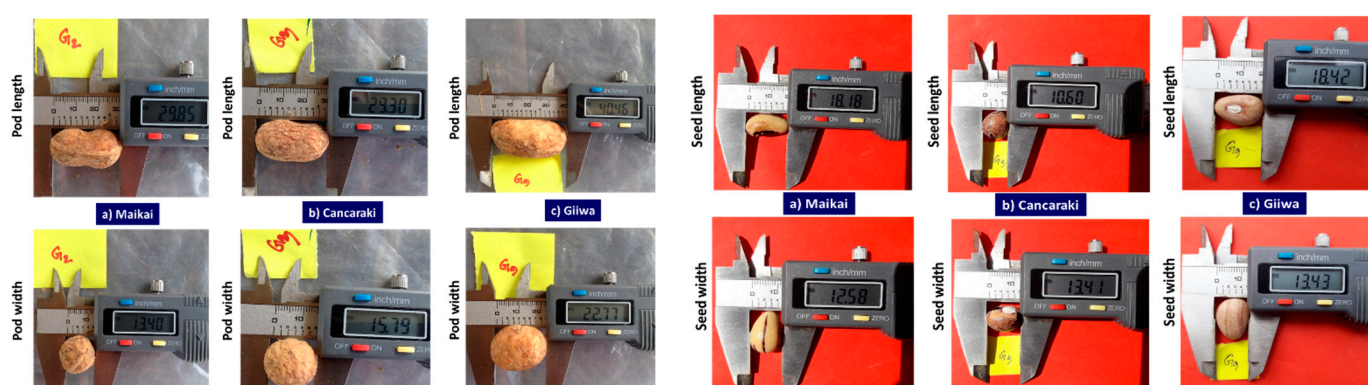
As a nutrient-rich legume, Bambara nut is often termed as a “complete balanced diet”. Dried Bambara seeds possess carbohydrates (64.4%), protein (23.6%), fat (6.5%), and fiber (5.5%) as well as are rich in micronutrients such as K (11.44–19.35 mg/100 g), Fe (4.9–48 mg/100 g), Na (2.9–12.0 mg/100 g), and Ca (95.8–99 mg/100 g), as reported by Paliwal et al. [20] and Lin Tan et al. [21]. It is underutilized in comparison to other major lucrative crops and is frequently grown on marginal land and in survival farming, and in the majority of cases, women are the primary contributors in the production and processing of these crops [21]. The Bambara groundnut on the other hand, is drought-tolerant, has a healthynutritional composition, and can trap nitrogen from the atmosphere. Bambara groundnut has the potential to help protect our future food and dietary needs in the face of climate change as part of more diverse and resilient agricultural farming due to its intrinsic resistance to stressful conditions and its capacity to generate yield in soils that are too poor for the cultivation of drought-prone species such as peanuts. In the field of agriculture, current technologies and biotechnology have afforded improved genotypes that can persist in a changing world. Knowledge about genetic relatedness among prospective parents is needed for the production of new cultivars. Prior to beginning breeding, morphological and molecular methods must be used to discover information about the genetic gap in parents [22]. Several methods are used in crop advancement to adopt better agronomic characteristics, including mutation, mutagenesis, genome editing, and proteomics profiling. For a plant breeder, the primary intention is to create new, enriched varieties in order to generate genetic differences in the traits of a breeding program. Following the development of such types of variety, it is necessary to identify and then to choose the preferred types among those that provide a greater description of the trait and/or combination of traits. If the targeted desirable traits are established, they must be stabilized and popularized for applications and understanding. However, the influence of the environment on traits, either alone or in combination with the genotype, provide better evidence of the genotype than phenotype inspection alone. Plant breeders must conduct a  $G \times E$  interaction analysis to validate the stable and superior plant before releasing a commercially improved variety [23].

This review provides an outline of the impact and major limitations of Bambara groundnut production as well as the main advancements and achievements that have been recorded to date in Bambara groundnut research on agronomy, breeding, and crop improvement in terms of food and nutrition. Moreover, this review summarizes the significant role of *V. subterranea* in mitigating the gaps in the food chain by ensuring long-term food and nutrient security. This study conclusively aims to present the improved prospects of this crop in terms of future patterns by proactive assessments. Here, we also focused on the origin, distribution, domestication, global production, nutrient values, processing, and research for improving Bambara groundnut through classical breeding, modern molecular breeding, and marker-assisted selection.

## 2. Botanical Description of Bambara Groundnut

Bambara groundnut is a legume that is cultivated in soil-cover situations. Bamshaiye et al. [24] explained that it is an intermediate form, the herbaceous, of the year-round plant, with crawling stems at the earth’s surface. The Bambara groundnut plant grows to a height of 30 to 35 cm with a well-developed taproot system and numerous small sidelong stems of one petiole with three leaflets. According to Linneman and Azam-Ali, [25], the roots appear rounded and as rarely lobed nodules due to the symbiotic relationship with

atmospheric nitrogen-trapping bacteria such as *Rhizobium*, *Cholestridium*, and *Azotobacter*. A special A unique feature of Bambara groundnut, according to Toungos et al. [26], is that pod formation begins with a fertilized flower above the soil surface, whereas pods and seeds develop and mature only beneath the earth's surface. Following pollination and fertilization, light yellow flower buds appear on the freely branching stems, which then spread downwardly into the soil, bearing a developing embryo that becomes a seed in the future. [27]. When dry, pods are round, wrinkled, and over half an inch long, bearing one or two oval or round seeds, smooth and multicolor testa, and hard seeds per pod. The typical pod length vs. width and the seed length vs. width of some accessions such as (a) Maikai, (b) Cancaraki, and (c) Giiwa are displayed in Figure 1a–c. When young, Bambara pods are greenish-yellow, turning brownish-yellow or purple when they mature. This plant's stems can be hairy or hairless, and its leaves can be round, lanceolate, or elliptical [27]. The color of the testa varies depending on the seed's ripeness, varying from pale yellow to black, purple, cream, and other shades [28], and the seed's color differs from black, red, or brown to mottled or black-eyed, with or without hilum coloration. Seed color and texture of some accessions such as (a) Duna, (b) Roko, (c) Katawa, (d) Ex-Sokoto, (e) Maikai, (f) Maibergo, (g) Karu, (h) Cancaraki, (i) Bidillali, (j) Jatau, and (k) Giiwa are shown in Figure 2. The hundred-seed weight of Bambara groundnut ranges between 280 g and 320 g [29]. In the roots of Bambara groundnut, the plants produce nodules that trap atmospheric nitrogen (28.4 kg N/ha) in phosphorous (P)-deficient soils but this increased to around 41 kg/ha when P fertilizer was applied, according to Yakubu et al. [30].



**Figure 1.** Pod length vs. width and seed length vs. width of some accessions. Legend: (a) Maikai, (b) Cancaraki, and (c) Giiwa (pictured taken from author research (unpublished)).



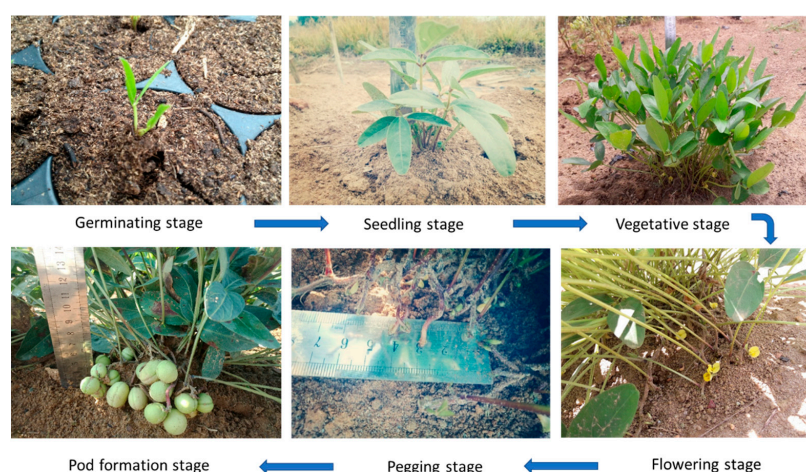
**Figure 2.** Seed color and texture of some accessions. Legend: (a) Duna, (b) Roko, (c) Katawa, (d) Ex-sokoto, (e) Maikai, (f) Maibergo, (g) Karu, (h) Cancaraki, (i) Bidillali, (j) Jatau, and (k) Giiwa (pictured taken from author research (unpublished)).



### *Agronomic Attributes of Bambara Groundnut*

Typically, Bambara groundnut is a year-round growing plant and its incorporation into an established cropping pattern can improve soil physical conditions [31]. The yield of Bambara groundnut is greatly influenced by sowing date; the optimal time is in early November, recording high yield, rather than late sowing in late December to January [31]. Due to numerous advantages such as high tolerance to drought, the capability to grow in poor fertile soil, and high nutritive features, Bambara groundnut is regarded as a hardy and robust plant [24,32]. Bambara groundnut is a fast-growing plant that does not tolerate freezing temperatures at any stage of its development. Warm temperatures are also ideal for optimal growth [32].

The optimal temperature for Bambara groundnut seed germination is 30–50 °C while the ideal daytime temperature for normal crop growth and development is 20 °C to 28 °C [33]. The regular growth of Bambara groundnut is influenced by the duration of daytime or the photoperiod, which mainly affects the pod set and filling. It is a short-day plant that needs at least 3–5 months of frost-free growth [33]. Due to high temperatures that cause the leaves to die, the biomass yield of this crop is decreased. Bamshaiye et al. [24] reported that this crop can be grown successfully, where the annual rainfall should be less than 500 mm, and that its best growth reaches between 900 and 1000 mm. The plant grows fine in well-drained rainforests and cool moist highlands and can tolerate heavy rainfall, except at the time of maturity. After sowing, seed emergence takes 5–21 days. The plant starts flowering from 30 to 55 days after planting and may continue until the plant dies [34]. Linnemann and Azam-Ali [25] reported that, after fertilization, pods take 30 days to reach their full size and seeds take the following ten days to grow large enough to reach maturity. However, in damp conditions, it may be susceptible to various fungal diseases [35]. Seeds that have been stored for more than a year have reduced viability [31]. Limited irrigation induces early flowering, though pod and grain formation start 30–40 days after fertilization. Fifty percent of flowering starts 86–88 days after planting in well-irrigated situations but while 64–66 days after planting in a rain-fed situation [36]. Loosening and earthing up the soil had a positive effect on pod formation and pod growth under and above the soil surface after successful fertilization and the peg goes into the soil. The pod is usually 17.96–53.54 mm long and contains one or two seeds, 7.54–22.48 mm long [37]. Plant population density should be held between 6 and 29 plants·m<sup>-2</sup> for optimal growth and development, and it requires mild temperatures, bright sunlight, and evenly distributed precipitation. The best soil for Bambara groundnut production is well-drained sandy-loam soil with a pH of 5.0–6.5, and the seed should be sown 2.5–7.5 cm soil deep [31]. The typical growth and development stages of Bambara groundnut are illustrated in Figure 3.



**Figure 3.** A typical growth and developing stage of Bambara groundnut (picture captured from the author's research field (unpublished)).

### 3. Production Scenario of Bambara Groundnut

#### 3.1. Major Production Areas

After peanut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*), Bambara groundnut is the third most common crop, likely due to its ease of processing, despite its origin in Brazil and subsequent transfer to Africa just 400 years ago, where it is now ranked first. On the other hand, inconvenient postharvest processing is the exact reason for Bambara groundnut's slow expansion [38]. Recently, several semiarid and sub-Saharan African nations such as Nigeria, Ghana, Cameroon, Togo, and Mali are well-known areas of Bambara groundnut cultivation. South Africa and Zimbabwe are the main growing regions for Bambara nuts, while Southeast Asia, especially Thailand, Indonesia, and Malaysia, is a secondary growing region [39]. They are mostly grown by women as part of an intercropping scheme with maize, millet, sorghum, and cassava. Bambara groundnut improves soil nutrient status, especially nitrogen status, as a result of its nodulation process, which traps nitrogen from the atmosphere [40] (Bambara groundnuts are traditionally grown by marginal farmers in harsh tropic climates, making irrigation and fertilizer applications a challenge). According to Azam-Ali et al. [41], Bambara groundnut can be grown in a variety of Mediterranean climates, including Italy, Greece, Spain, and Portugal. The best usages of land for Bambara groundnut were found in Zimbabwe (84%), Burundi (89%), Zambia (95%), Uganda (98%), Central African Republic (79%), and Swaziland (100%), and another finding reported that more than 3 ton/ha of yield were predicted for the semiarid region in eastern and southern Africa, reported by Azam-Ali et al. [41].

#### 3.2. General Production Scenario in Bambara Groundnut

The production of Bambara groundnut in Nigeria takes the leading position, with its production at about 100 thousand metric tons per annum, reported by Hillocks et al. [42] (Figure 4), whereas Burkina Faso attained the number one position for the yield of Bambara groundnut reported by FAOSTAT [43] (Figure 5). One of the most pressing issues faced by humanity is the availability of precisely sustainable food for the world's ever-increasing population, which is expected to reach 9 billion by 2050 [5]. To meet this projected population, global agricultural production schemes will need to expand significantly, especially in developing countries [44]. One researcher paid attention to the development of this crop, which was previously not extensively cultivated [45], in his quest for diverse sources of diet to feed the steadily progressing population. One of the significant features of this crop is its ability to thrive in a variety of agro-climatic regions, allowing it to gain greater visibility and suitability as a substitute food [46]. When viewed from a global perspective, the global yearly production is estimated to be about 330 thousand tons, with west African nations (Burkina Faso, Cameroon, Mali, Niger, Togo, and the Democratic Republic of the Congo) as the major growing regions, with annual production at about 0.3 million tons [42] and with Burkina Faso estimated to provide the most extensive yield at around 0.1 million tons annually [47]. However, according to the survey, the demand for Bambara groundnut far exceeds its output [24]. Despite the fact that Bambara groundnut production increased significantly in 2008, the amount of land allocated to it decreased between 2002 and 2011 [48]. Ibrahim et al. [45] noted that the trend in Bambara groundnut production increased by 10% from 2007 to 2014, with a 4% increase in the growing area. A report on the hereditary potential of Bambara nut found a yield of up to 4000 kg ha<sup>-1</sup> [49]. In African countries, seed yield (0.5–3 t ha<sup>-1</sup>) depends on the variation in cultivated areas and landraces, with a significant yield of 3–4 t ha<sup>-1</sup> [50,51]. On average, the yield of the Bambara groundnut was recorded as 0.85 t ha<sup>-1</sup> (Table 1) compared with that for other legumes [47]. Despite the mentioned profitable properties of the Bambara groundnut, rural farmers in sub-Saharan Africa recorded lower yields. This emphasizes the requirement for Bambara groundnut breeding to enrich varieties and to improve agronomic practices as well as yield enhancement. In future plant-breeding efforts, it is critical to ensure the use of traditional methods, the adjacent involvement of farmer groups, farmer empowerment, and the identification of appropriate accessions selected to meet immediate demand.

Once selected, the lines are hybridized with local established varieties with desirable features if required. From a socioeconomic view, this method is significantly, as highlighted by Hillocks et al. [42]. According to a survey, planting time has an effect on Bambara groundnut yield. Maximum yields were reported during the dry season, which had lower rainfall than the primary rainy season [52]. In comparison to forest climatic zones, the yield of Bambara groundnut is recorded as high in the alternation of agricultural climate with high temperature and low precipitation [36]. During germplasm screening in Ghana and Tanzania, it was reported that Bambara groundnut production varied from below 10 kg ha<sup>-1</sup> to above 800 kg ha<sup>-1</sup> [42]. In tropical regions such as Malaysia, the yield of Bambara groundnut was recorded as 380.48 to 1635.29 kg ha<sup>-1</sup> [37], with an average of 1180 kg ha<sup>-1</sup> [53]. To evaluate the yield potentiality of Bambara groundnut in African regions, Azam-Ali et al. [41] applied computer-based analytical tools (CBATs), especially crop simulation models (CSM) and geographic information systems (GIS). Since this crop tolerates or even prefers poor nutrient soils; has low inputs; and in some cases, produces yields better than any other cultivated pulses, it is highly efficient in meeting the needs of poor resource farmers for increased food production [39].

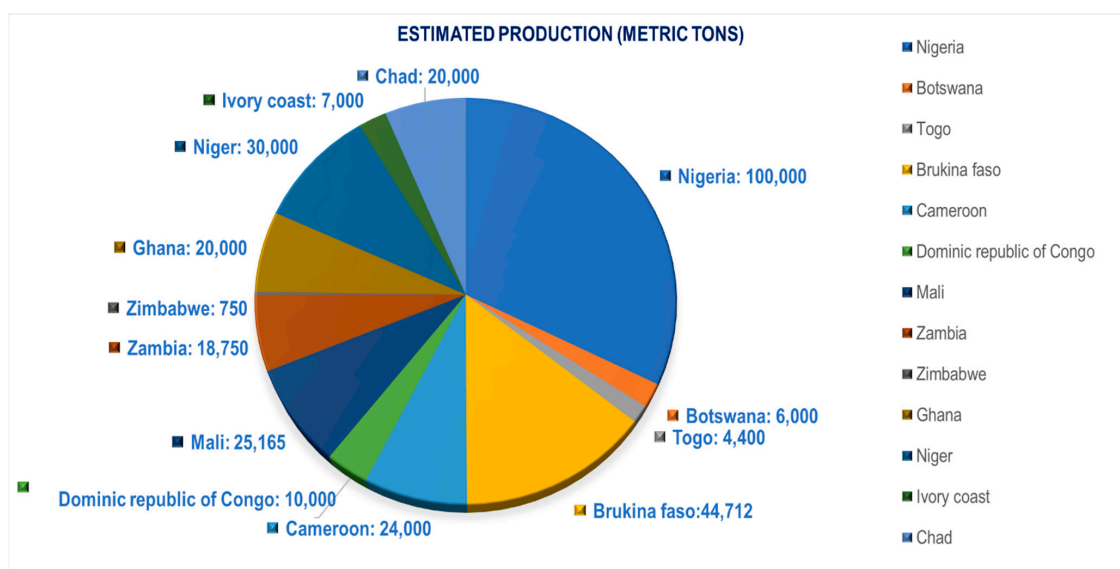


Figure 4. Major Bambara groundnut-producing countries and their contributions.

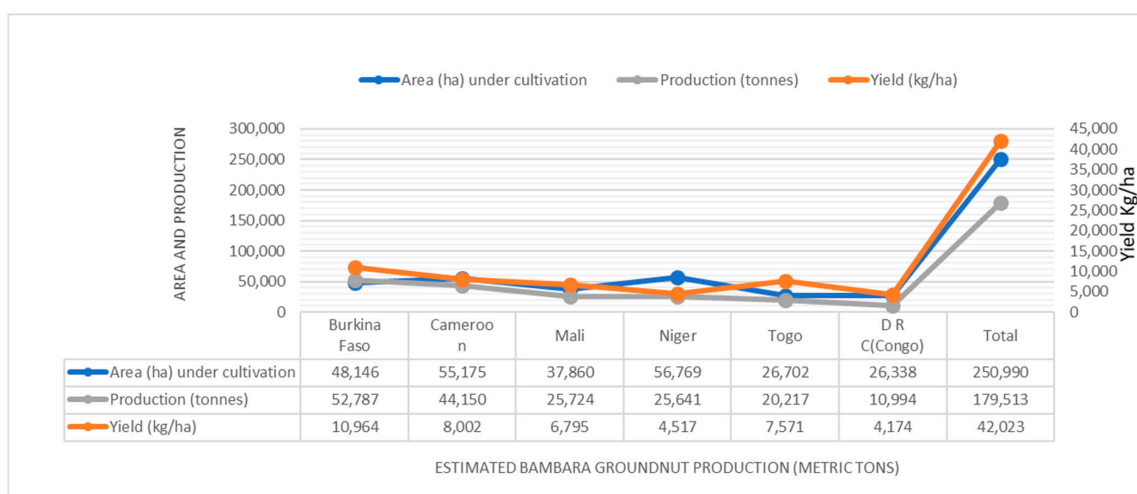


Figure 5. Cultivated area (ha), production (tons), and yield (kg/ha) of Bambara groundnut.

**Table 1.** The comparative yield of major cultivated legumes from the African region (adopted from Mayes et al. [47] and Hillocks et al. [42]).

Common Names (Major Legumes)	Scientific Name	Production/Year (Million tons)	Production (ton/ha)
Cowpea	<i>Vigna unguiculata</i> (L.) Walp	4.9	0.49
Dry bean	<i>Phaseolus vulgaris</i>	3.8	0.66
Faba Bean	<i>Vicia faba</i>	0.6	1.22
Chickpea	<i>Cicer arietinum</i>	0.3	0.94
Lentil	<i>Lens culinaris</i>	0.1	1.10
Groundnut	<i>Arachis hypogaea</i>	9.0	0.91
Soybean	<i>Glycine max</i>	1.4	1.22
Pigeon bean	<i>Cajanus cajan</i>	0.4	0.77
Dry bean	<i>Phaseolus vulgaris</i>	3.8	0.66

### 3.3. Center of Origin and Distribution of Bambara Groundnut

Bambara groundnut (*Vigna subterranea* L. Verdc.) belongs to the family Fabaceae and subfamily Faboidea under Plantae [24]. Many researchers have been notified individually about the origin of Bambara groundnut. According to Hillocks et al. [42], the Bambara groundnut was first found in West Africa, from which it seems to have spread across sub-Saharan Africa [54]. The Bambara groundnut is thought to have originated in a place called “BAM-BARA”, which is home to an agriculturist tribe who lived primarily in the state of Bambara near Timbukutu in the west African region of central Mali, and the suffix “GROUNDNUT” [55], which is derived from the action of its pods, is similar to groundnut (*Arachis hypogaea*). As a result, the agreeable English or common name of *Vigna subterranea* as “Bambara groundnut” is linked to an agriculturalist tribe (derive from the Mande group of languages). The crop is now widely distributed and grown throughout northern Australia, Asia (especially in India, Indonesia, Malaysia, Philippines, and Thailand), New Caledonia, South America, and unusually Brazil [56]. Bambara groundnut was reportedly introduced from the Nigeria–Cameroon corridor, where its genetic resources are plentiful but was eventually transferred due to human trafficking or transhumance of the Hausa–Fulani traders to the Bambara province, where it is considered an aspect of their trade stuff and feedstocks [57]. Rungnoi et al. [58] used molecular markers to show that Thai Bambara groundnut landraces were introduced from both West Africa (Nigeria) and east Africa, implying that they were introduced into Thailand several times. Bambara groundnut is widely grown in tropical Africa, India, Sri Lanka, and Indonesia [58] as well as in other parts of the world such as south and central America and northern Australia.

### 4. Potential Uses of Bambara Groundnut for Food Security

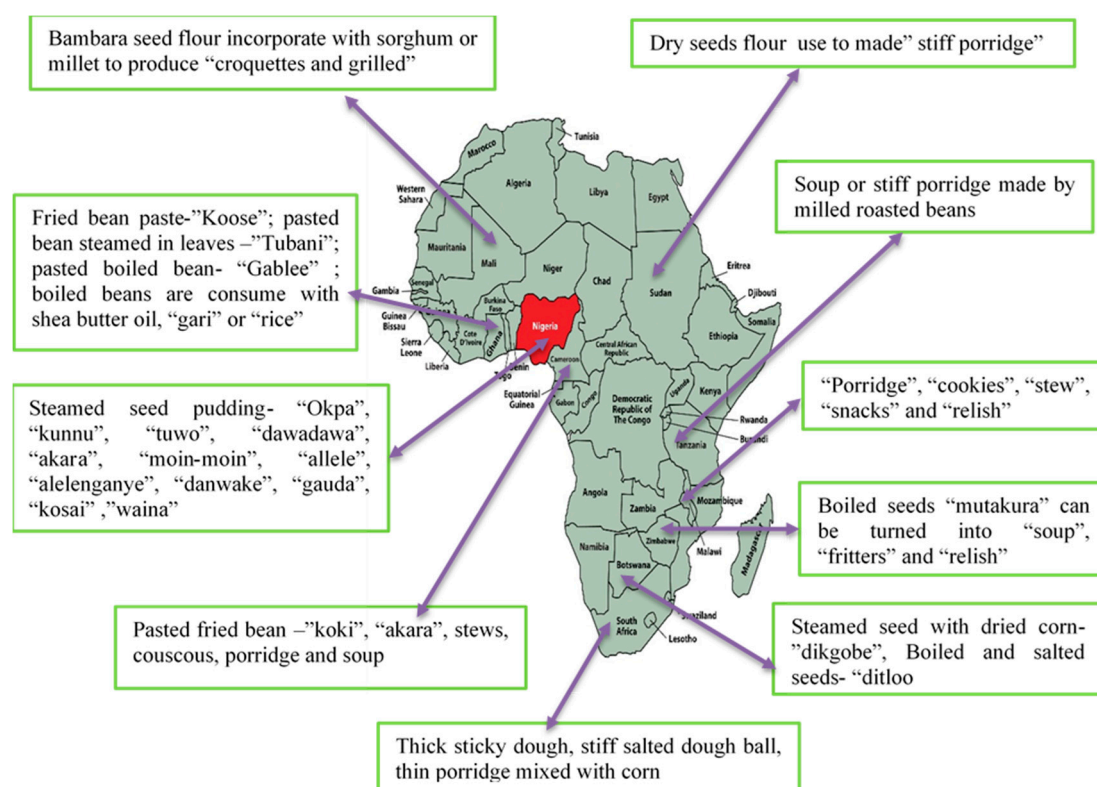
Bambara groundnut is used in a variety of ways by local consumers in different countries. A great deal of effort has gone into promoting the use of this crop in various manners. The biggest drawback to using it is that it takes a long time to boil or prepare. Dried Bambara beans take 3 to 4 hours to cook, while green fresh beans take 45–60 min to boil and green nuts can be boiled with salt and pepper and then eaten as a snack by West Africans. [42]. Mazahib et al. [59] reported that shortening the cooking time is the foremost challenge for researchers and farmers. A large number of reports on the use of Bambara groundnut show that grains are very nutritious, which makes them ideal for people who cannot afford to buy the valuable protein in animal products [60]. Green pods and dry nuts as well as grains are processed and refined into a variety of foods. Figure 6 shows some processed and confectionary food items manufactured by the center for the future crop (CFCF) and in different regions of the world such as Indonesia, India, Mexico, and Malaysia [11,61–63].





**Figure 6.** Bambara groundnuts using various processing methods and confectionary food products. Some of the product were made at the center for the crop for future crop, while others were produced from other parts of the world, such as Indonesia, India, Mexico, and Malaysia. All sources of the adopted images are duly acknowledged as follows. Adapted with permission from [11,61–63]. Copyright Springer 2019, Science and Education Publishing 2018, Springer 2018, Gregory et al. 2019.

Freshgreen nuts are steamed or grilled and served as titbits [16,32]. Its seeds are very caloric, and flour can be used to make a thick and tiny porridge [8]. Due to their toughness, dehydrated seeds are difficult to crush into powder, but when crushed into powder, delicious bread and flat cakes can be made [18]. The flour of Bambara seeds is used to prepare soup and can also serve as a coffee substitute, as noted by Hillocks et al. [42]. According to Mazahib et al. [59], the Bambara nut can be used as a cooking ingredient by mixing its flour with other components to prepare diverse food items. According to FAO [54], it is used to prepare dumplings. In a formulation stated by Akpalu et al. [64], the seeds are milled into flour and mixed with corn to enhance the conventional diet. Bamshaiye et al. [24] mentioned that different types of porridge and bean cakes (Akara) can be made using Bambara flour solely or by mixing with other cereal flour. The seeds are baked or roasted and consumed with palm kernels in southeastern Nigeria. A brewed gel made from the slurry of Bambara beans is known as Okpa or Ukpa (by the northern cross river) or Moi-Moi (by the Igbos) in Nigeria [65]. Various forms of traditional or indigenous foods were listed by Lin Tan et al. [21] using green young pods, harvested mature pods, and dried seeds of Bambara groundnut (Figure 7). Traditional/indigenous food product(s) in a given community are acquired and processed from bio-diverse plant sources available in their ecology. Most agri-based native foods are low in sugar and fat but are wholesome (whole grains, with dietary fibers) and have high potential for diet diversification. The documentation provided helps to create awareness for the preservation of traditional foods/dishes and beverage culture and as baseline information for further studies for those nutrients and bioactive compounds in which data are not available.



**Figure 7.** Some traditional or indigenous food or dishes using Bambara groundnut in the different region of Africa (adopted with permission from Lin Tan et al. [21]). Copyright Lin Tan et al. 2020.

According to a study by Bamshaiye et al. [24], milk made from Bambara nuts is identical to soybean milk and is frequently used as supplemental milk for babies in several African countries. Bambara nut milk has a higher acceptance rate than soybean and cowpea milk [66]. Adebanke et al. [67] stated that milk made from soybean, cowpea, and pigeon pea had less appealing flavors than milk made from Bambara groundnut. Supermarkets in Indonesia make a lot of money selling deep-fried snacks made from young Bambara seeds known as "Kacang Bogor" or "Bogor nut", which are in high demand and can also be found in high-end grocery stores in European markets. Mayes et al. [47] suggested that snacks prepared from the Bambara groundnut mixed with the roasted groundnut (*Arachis hypogaea*) are less sticky and are highly delicious. Cooked bananas can be serves as a weaning diet for children, and their nutritional value can be improved by adding Bambara flour [68]. Recent studies on various food processing enterprises have shown that Bambara groundnut can be incorporated into their commodities [67,69]. The Center for Feature Crop (CFC) disclosed strategies for substituting other ingredients into Bambara groundnut recipes [11]. The protein from leaves and Bambara nuts were used as an animal meal, such as to increase the growth of tilapia fish, as reported by Adeparusi and Agbede [70]. The weaning diet is made up of 70% cooking banana and 30% Bambara flour, according to Ijarotimi [71], and is nutritionally sufficient to help children grow and develop. According to a study released by the OECD-FAO-UN [72], protein and energy shortage is a major challenge for public health in developing countries; however, plant protein plays a potential role in global food safety, providing 65% of the world's supply of proteins, with up to 15% of that coming from legumes and with Bambara groundnut contributing 25% of the total protein. Doku and Karikari [73] stated that, in rural areas, Bambara nut has the potential to improve marginal people's food security; however, since Bambara seeds contain a relatively limited amount of oil, though, some people in Congo have been discovered to extract oil from Bambara seeds.

#### 4.1. Health and Medicinal Significance of Bambara Groundnut

Atoyebi et al. [61] stated that, besides the nutritional significance of Bambara groundnut, it also has different physical and medicinal benefits; for example, the water from steamed seeds of Bambara groundnut is used to remedy diarrhea by Lio Kenya's tribe. Lin Tan et al. [21] stated that the macro-nutrient, micro-nutrient, and anti-nutrient components possessed by Bambara groundnut are listed in Table 2. Nutraceuticals, a form of medication used to prevent high blood pressure and oxidative stress, may be derived from Bambara groundnut diets [74]. Bambara groundnut leaves can be used specifically to heal untreated wounds, inflammations, and abscesses, and the sap from leaves can be used to treat epilepsy when applied to the eyes. Raw seeds are chewed and swallowed to control nausea and vomiting in pregnant women [75] in South Africa. In Senegal roots of Bambara, plants are used as an aphrodisiac or herbal remedy and pulverized seeds are incorporated with water to cure cataracts. Hillocks et al. [42] noted that the Igbo tribe in Nigeria applied the Bambara plant in nursing venereal diseases.

**Table 2.** Major nutritional and anti-nutritional profile of Bambara groundnut seeds.

Macronutrient	
Depending on Genetic and Environmental Factors, Stage of Maturation, and Method of Analysis	
Carbohydrate	64.4% of total dry seed weight
Polysaccharides and oligosaccharides complex	22 to 49.5% of total dry seed weight
Amylose	19.6–35.1%
Amylopectin	1–2%
Protein	9.6–40% (average 23.6%) Vicilin (7s) and Legumin (11S) reported as major elements of protein
Bambara groundnut protein isolate (BGPI)	Varied from 81.4 to 92.8%
Invitro protein digestibility (IVPD)	70–81% raw BG 82–87.5% cooked BG
Lipids	1.4–9.7%
Fatty acids	Major: oleic and linoleic acid (omega 6); third most: palmitic acid and linolenic acid exist in small amounts
Micronutrients	
K, Ca, Mg, Fe, P, and Zn	Abundant: the handiness of micronutrients was poorly affected by anti-nutritional factors in seeds. The density amount and availability of K, Ca, Mg, Fe, P, and Zn in Bambara grains were affected by a storage system, duration, approach of processing, and the position of trace nutrients (seed coat, hilum, testa, seed leaf, or cotyledon). A red-coated seed contains more Fe than cream- and black-coated seeds.
Phytochemicals	Flavonoids and tannins (generally in seed coat; majorly in dark or red-colored seeds)
Flavonoids	Epicatechin major: in raw red seed Catechin major: in cooked red seed
Proanthocyanins	Polymers of epicatechin and catechin also have neuroprotective, antitumor, cardioprotective, and antioxidant properties (abundant in brown and red seeds)
Fiber	1.4 to 10.3%
Anti-nutrient factors	
Tannins condensed	0.0011–18.61 mg/g
Phytic acid	1.10–15.11 mg/g
Inhibitor trypsin	0.06–73.40 TI mg/g
Pectin	Bind the micronutrients (Ca, Zn, and Fe)
Raffinose and stachyose, flatus causing–alphaoligosaccharides, Saponins, Oxalate, Hydrogen cyanide	Trace amount present in Bambara groundnut

#### 4.2. Role of Bambara Groundnut to Overcome Malnutrition and Nutritional Gap

In previous decades, the Bambara groundnut played a minor role because little to no effort was put into its improvement, nourishment, and exploration of its nutritional

values. Since they had not discovered its nutritional profiles, people were blind to and uninterested in this crop development. [24]. Later on, some researchers explored its nutritional content: CHO—63%, protein—19%, oil—6.5%, fiber—4.8 g, ash—3.4 g, and water—10.35 g. Moreover, it contains 367–414 calories per 100 g, which is more than other legumes such as cowpea, lentil, and pigeon pea [31]. Despite the limited oil content, tribes of the DR of Congo extracted considerable amounts of oil from Bambara groundnut seeds locally [40]. Recent biochemical research by Dansi et al. [76] noted that it contains a significant amount of macro-elements (mg/100 g dry weight) such as calcium, 37–128 mg; potassium, 1545–2000 mg; magnesium, 159–335 mg; sodium, 16–25 mg; and phosphorus, 313–563 mg and micro-elements such as copper, 3.0–13.2 mg; iron, 23.0–150 mg; zinc, 13.9–77.0 mg; beta-carotin, 10 µg; thiamin, 0.47 mg; riboflavin, 0.14 mg; niacin, 1.8 mg; and ascorbic acid traces. The essential amino acids per 100 g are tryptophan, 192 mg; lysine, 114 mg; methionine, 312 mg; phenylamine, 991 mg; threonine, 617 mg; valine, 937 mg; leucine, 1385 mg; and isoleucine, 776 mg [76]. A pilot-feeding project was introduced to eliminate infant malnutrition by preparing agri-based milk, such as soybean milk, peanut milk, cowpea milk, and Bambara milk, while researchers and consumers ranked Bambara milk first for its odor, color, and nutrient profile [31]. Due to its high protein content, this crop has the potential to challenge global food shortages and malnutrition in the future. Recently, people have veered away from animal protein due to its high cholesterol content and high prices; thus, Bambara groundnut has the potentiality to contribute up to 25% protein and to be a substitute for animal sources. People must consume 60 to 100 g at least 3–4 times per week to obtain the necessary amount of protein from plant sources [31]. Bambara groundnut is unique in its potential to minimize the nutrition gap, to reduce food insecurity, to alleviate hunger, and to ensure agricultural productivity and food production as well as to ensure agricultural sustainability in developing countries.

#### 4.3. Anti-Nutritional Ingredients in Bambara Groundnut

Generally, legumes possess a considerable number of anti-nutritional components such as phytate, tannic acid, phenolics, and additional complexes that can reduce the nutritional value by rendering some elements unable to be metabolized entirely or partially. During famine [77], anti-nutrient factors such as the amino-acid  $\beta$ -N-oxalyl- $\alpha$ , ODAP ( $\beta$  di-amino propionic acid), in pulse crops (grass pea; *Lathyrus sativus*) may cause paralysis when eaten as the only staple food source. Easy and simple strategies such as fermentation, germination, soaking, drenched, cooking, and dehulling can effectively decrease anti-nutrient factors and can improve food safety [61,78]. Ijarotimi and Esho [79] stated that fermentation improved the mineral structure but had a small effect on amino acid content and reduced non-nutrient components such as tannin, trypsin, oxalate acid, and phytic acid. According to Ndidi et al. [60], anti-nutrient factors such as phytate, oxalate, hydrogen cyanide, and trypsin inhibitors exist in more than the allowable limit in raw Bambara groundnut, which can be greatly reduced to a tolerable limit through steaming and roasting. The processing of Bambara nut flour with 60% alcohol may reduce the anti-nutrient components while also lowering flatulence-inducing sugars, as stated by Alain et al. [80].

#### 4.4. Processing of Bambara Groundnut

After harvesting, sun-drying is an effective way for long-term preservation of seed. Before cooking or eating, the dried seed may be rehydrated by water or pulverized into flour. Most of the traditional pretreatment methods increase or decrease the nutritional quality of Bambara groundnut seeds. According to the discussion by Lin Tan et al. [21], here, some of the approaches for Bambara groundnut processing are stated. Dehusking is a tedious operation among the post-harvest activities due to its very hard nature; for convenience, mechanical defusing is effective. Dehulling is a separation of the testa, seed coat, or hilum from the seed cotyledon. A significant number of antinutrients exist in testa; removing them can increase nutrient content and digestibility. Milling is the



process of grinding the Bambara seeds into a powder, but in the household condition, it is extremely tedious due to its “hard to mill” phenomenon. Milling can incorporate micronutrients and anti-nutrients, resulting in a reduction in mineral obtainability. Soaking is the typically dried seed of Bambara being saturated in water for 12–24 h as a pre-cooking treatment. Soaking at 60 °C enhances the water absorption rate and increases the dehulling potentiality without physical losses in the soaked seeds. Sprouting is a pretreatment keeping the seed at low temperatures or saturating it in water for up to 3 days. During sprouting, the CHO and lipid content are degraded while the amino acid and protein profiles are upgraded. Sprouting ensures the reduction in anti-nutrients such as saponin, oxalate, oligosaccharides, tannins, and trypsin and, at the same time, helps dehulling by splitting the seed coat during germination or malting. Boiling is the process of cooking Bambara nuts in excessive water for various durations of time. Usually, the cooking period depends on the measures followed during harvesting to storage. Cooking with boiled water ultimately breaks down the cell skeleton; denatures the proteins, carbohydrates, and water-soluble minerals; and drains the anti-nutritional factors with increasing nutrient solubility, availability, and digestibility. Fermentation is a low-cost approach in Bambara groundnut processing consisting of 96 h of soaking in water, followed by dehulling, cooking, and covering with banana leaves before the fermentation process. It helps in the conversion of flatus, causing oligosaccharides and polysaccharides to become digestible monosaccharides with the depletion of phenols and anti-nutritional factors. Yogurt from Bambara milk was also prepared by the fermentation process, which improves the protein quality and digestibility with a lower phytate profile. However, the application of several approaches of Bambara nut processing harmful and beneficial impacts on diet and nutrient safety. Additionally, besides old-style processing of Bambara groundnut, there are some advanced approaches such as irradiation, autoclaving, pressure cooking, and infrared heating that can be implemented to process the Bambara nuts but need skilled personnel and sophisticated tools, usually convenient only in a large-scale commercial manner.

### 5. Bambara Groundnut Considered Underutilized Crops: Why?

Underutilized crops can commonly be defined as crops or species that have vast prospects for food production and improvement but for which the efficiency is not amply appreciated and fully exploited [81]. A key feature to strengthen underutilized crops is that they differ from one location to another. The following principle criteria must be met for the plant to be an underutilized crop [82].

- I. Certified food and nutrient values.
- II. The plant has been broadly grown in the past, or the plant is presently grown in a short geological region.
- III. Directly grown less than other comparable plant species.
- IV. The traditional or cultural heritage of their area of origin.
- V. Their cultivation and usage are poorly documented.
- VI. Adaptation to a certain agro-ecological zone.
- VII. Adaptation to marginal and poor soil conditions.
- VIII. Limited or no established seed supply scheme.

Although Bambara groundnut has a long history, still only local landraces are used for cultivation due to a lack of stable varieties for certain agro-ecological regions [83]. The Bambara groundnut has been practically neglected by global research bodies and sponsors. Due to a lack of economic importance compared to lucrative crops such as rice, maize, potato, wheat, etc.; a lack of commercial uses; less interest from global researchers and scientific communities; and lower yield and seed quality due to the lack of proper genetic improvements, the Bambara groundnut crop is regarded as an under-researched, ignored, or underutilized species [84]. It is believed that Bambara groundnut remains ignored and underutilized due to its low commercial potentials outside its growing zone [85]. The hard-to-cook phenomenon, which is linked to poor processing methods, is the most significant explanation for Bambara groundnut’s continued underutilization [86]. Bambara

groundnut being hard to cook was noted by Khan et al. [87], requiring an extended cooking time (3–4 h) to obtain proper melting during preparation food. The stiffness of the Bambara nut coat makes it relatively tough to achieve good dehusking. The shortage in functional marketing chains that ensure the shipping of this crop from farmers to the ultimate consumer as well as a lack of processed commodities are contribute to Bambara groundnut being underutilized. [42]. Bambara groundnut is an underutilized crop due to the lack of mechanization related to seed sowing, harvesting, and different post-harvest operations, such as its drying, de-husking, hard-to-cook (HTC), and hard-to-mill (HTM) properties [87]. Relatively low yields of this crop cause it to be underutilized, e.g., in West Africa, the recorded yield is 1716 kg ha<sup>-1</sup>, which is higher than the estimated yield of 703.3 kg/ha from an area of 158,635 hectares [43], while the groundnut (*Arachis hypogaea* L.) migrated from South America has an estimated yield of 1.058 ton/ha from an average cultivated area of 62.07 lakh hectare. As a result, this crop is considered an underutilized and ignored crop in west Africa, according to Dansi et al. [76]

## 6. Genetic Assets of Bambara Groundnut and Its Improvement

### 6.1. Characterization and Conservation of Genetic Resources

The International Institute of Tropical Agriculture (IITA) in Nigeria was the first to collect Bambara germplasm (around 2000), and the majority of the collections (1400) have been characterized. The Institut de Recherche pour le Developpement (IRD) collected sixty wild and twelve thousand cultivated races in Cameroon, fifty of which were characterized; the university of Zambia collected about 460 accessions; the Grain Crops Institute, Potchefstroom, South Africa collected about 200 accessions; and the Plant Genetic Resources Center (PGRC), Accra, Ghana, collected about 170 accessions. In recent years, attempts have been made around the world to promote the richness of Bambara groundnut. According to FAO [54], nearly 6145 Bambara germplasms are held in ex situ conservation around the world, with collections from the national and international gene banks (Table 3). Waziri et al. [88] reported that the Genetic Resource Center (GRC) under IITA, Nigeria, has 2031 accessions accumulated from several sub-Saharan African countries. Traditional or rural growers of Bambara groundnut farmers depend on the existing diversity among the germplasm, which they cultivate, and ecological selection on Bambara groundnut germplasms has helped to maintain genetic diversity [78]. For future genetic improvements, ex situ and in situ conservation, on-farm conservation, as well as farmer's conservation of Bambara groundnut germplasms have significant potentials. However, germplasms from a variety of origins can be troublesome [47], causing problems with genetic arrangement and environmental consequences. In order to achieve strong, coordinated plant breeding and enhancement programs, it is important to accumulate particular germplasms based on preferred attributes, so researchers and breeders can use the parental lines to select crop advancement programs [39,89]. Massawe et al. [90] reported that accessions taken from a country or several regions within a country have a common pedigree with different regional titles. To solve this duplication among the collected accessions, IITA, Nigeria, implemented genome-wide genotyping and sequencing to characterize Bambara groundnut.

### 6.2. Genetic Improvement of Existing Bambara Groundnut Germplasms

For improving current crop varieties and cultivation techniques, integrative research strategies are required. Despite this, underutilized species researchers had no exposure to advanced scientific expertise and techniques due to a lack of awareness and capital. The methods of crop improvement are widely classified into (1) mutation breeding, interbreeding (hybridization), traditional methods involvement of different selection procedures and (2) MAB (marker-assisted breeding), involving genetically engineered (GE), transgenic and non-GE, or non-transgenic approached via molecular and biotechnological methods and Targeting Induced Local Lesions in Genomes (TILLING) [91]. Azam-Ali et al. [32] proposed a technical framework for expanding underutilized crop research by minimizing

duplication of efforts, by maximizing awareness, by identifying fields of preference for further research, and by developing common policies to represent all underutilized crop species. The development of sophisticated molecular processes that were first discovered for other major crop species is directly accelerated the breeding and genetic enhancement of this crop. Existing forms of this crop were derivatives of its wild relatives through a natural and unnatural mixture of selection effects [92]. It was exposed to prospective growers at drastic levels based on the preliminary performance of newly developed lines. By establishing inclusive teams on a common platform, for instance “BamNetwork [27]” ([bambaragroundnut.org](http://bambaragroundnut.org)) or within a sole institution such as “Crop for the Future (CFF)” ([cffresearch.org](http://cffresearch.org)) [11], the existing problems within the research value chain, comprising molecular genetics, throughout policy, interdisciplinary or multidisciplinary institutional diverseness can be overcome. However, the first initiative could be the most challenging: ensuring that all types of specialists are associated with existing research goals. The combined activities of a genetics board take this selection to the next level, with identical genetic materials being evaluated in various climate conditions and promising lines being provided to global farmers and research organizations.

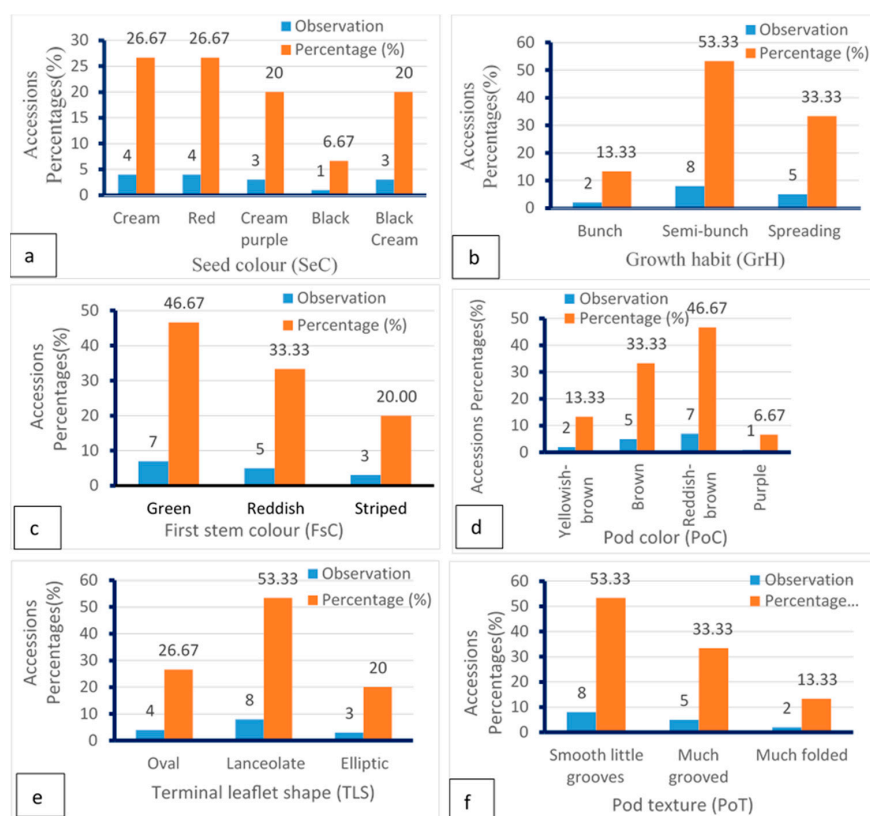
**Table 3.** Germplasm and wild races of Bambara groundnut collected by some international organization over several countries.

Institutions	Accession Number	Percentage (%)	Genotype Type				
			Wild Species	Landraces	Breeding Lines	Advanced Cultivars	Others
International Institute of Tropical Agriculture, Nigeria	2031	33	less than 1	100	x	x	x
ORSTMONTP, France	1416	23	x	100	x	x	x
Department of Agricultural Research, Botswana	338	6	x	2	x	x	98
Plant Genetic Resources Research Institute, Ghana	296	5	x	-	x	x	100
National Plant Genetic resources Center, Tanzania	283	5	less than 1	81	x	x	18
SADC Plant Genetic Resources Centre, Zambia	232	4	x	100	x	x	x
Others (26)	1549	25	1	59	9	1	29
	6145	100					

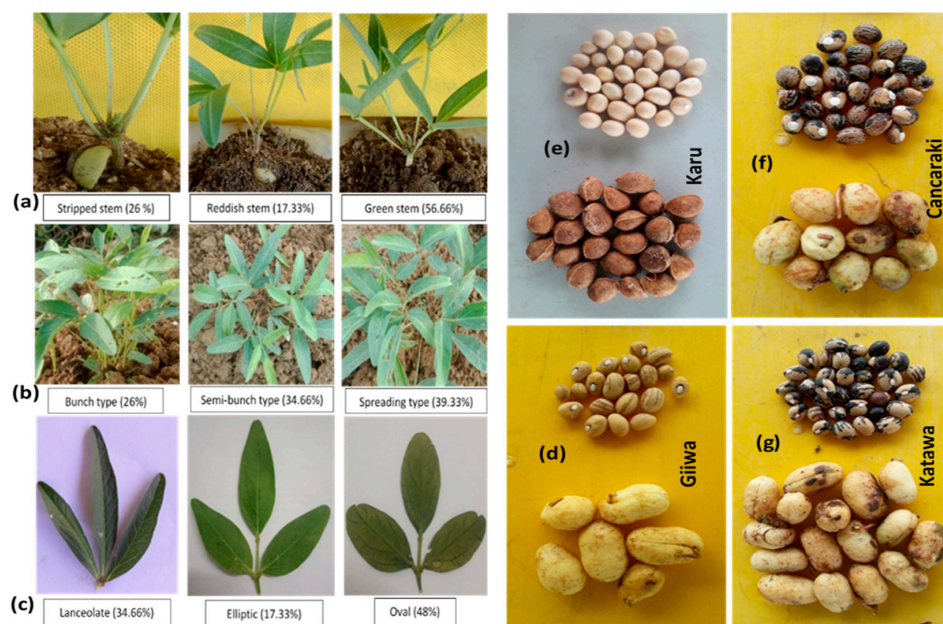
Cross sign (x) notes the unnamed quantity of genotype; adopted from FAO [54] and Muhammad et al. [93].

## 7. Qualitative and Quantitative Morphological Diversity Studied

The resulting qualitative (Figures 8 and 9) criteria were taken as guidelines: growth habits; the shape of the terminal leaflet; hairiness of stem; entirely prolonged terminal leaflet color; petiole pigmentation; pod size, shape, texture, and color; and seed color, shape, and pattern. Aliyu et al. [39] and Khan et al. [37] summarized the findings of several researchers on Bambara groundnut landrace accumulation and investigation as well as highlighted the prominent distinct phenotypic characteristics in Table 4. To date, there have been little or no studies on qualitative traits such as photoperiodic reaction, banner and wing coloration, or stem hairiness, owing to the lack of an accepted procedure for photoperiodic response and large-scale phenotyping. Moreover, in a variety of agro-ecological environments, this type of phenotyping procedure necessitates a well-tested environment, especially in the tropical-humid zone, where the photoperiod differences are affected. Aliyu and Massawe [94] used petiole pigmentation for an easy and secure approach to scoring phenotypic markers in their analysis. Bambara groundnut official descriptors have identified a number of phenotypic characteristics that have been widely documented by Aliyu and Massawe [94] and by Molosiwa et al. [89].



**Figure 8.** Qualitative traits' variation. (a) Seed colour (SeC), (b) growth habit (GrH), (c) first stems colour (FsC), (d) pod colour, (e) terminal leaf shape (TIS), and (f) pod texture (unpublished).



**Figure 9.** Qualitative variation of Bambara groundnut (a) stem color, (b) growth habit, and (c) leaf shape (adopted with permission from Khan et al. [37]); (d–g) represents the fresh and dry pods and seeds of some accessions (unpublished). Copyright Khan et al. 2020.



**Table 4.** Reported major qualitative trait variation in Bambara groundnut races (adopted from Aliyu et al. [39] and Khan et al. [37]).

Sl. N0.	Qualitative Traits (Descriptors)	Scale	References
1	Growth habit (GrH)	1. Bunch type * 2. Semi-bunch type 3. Spreading type	Abu and Buah [83]; Aliyu and Massawe [94]; Molosiwa et al. [89]; Ntundu et al. [13]; Olukolu et al. [95]; Aliyu et al. [39], Khan et al. [37]
2	Stem Hairiness (StH)	0. Absent; 1. Sparse; 2. Dense	Gbaguidi et al. [62]
3	First stem Color (FSC)	1. Green; 2. Reddish; 3. Striped	Gbaguidi et al. [62]
4	Terminal Leaflet shape (TLS)	1. Oval *; 2. Round; 3. Lanceolate; 4. Elliptic	Molosiwa et al. [89]; Ntundu et al. [13]; Aliyu et al. [96]; Gbaguidi et al. [62]; Mayes et al. [97]
5	Terminal Leaflet Colour (TLC)	1. Red; 2. Green *; 3. Purple	Molosiwa, [98]
6	Pigment of petiole (PetP)	1. Reddish green; 2. Green *	Aliyu and Massawe [94]; Aliyu et al. [96]
7	Pod shape (PoS)	1. End in a point with hook another side 2. End in a point with round another side * 3. Without a point	Molosiwa et al. [89]; Ntundu et al. [13]
8	Pod color (PoC)	1. Reddish-brown *; 2. Yellowish-brown *; 3. Brown*; 4. purple *; 5. Black	Ntundu et al. [13]; Molosiwa [98]; Aliyu et al. [96]
9	Pod texture (PoT)	1. Much grooved; 2. Smooth few grooved. 3. Abundant folded	Molosiwa et al. [89]; Ntundu et al. [13]
10	Seed shape (SeS)	1. Oval *; 2. Round	Ntundu et al. [13]; Gbaguidi et al. [62]
11	Color of seed (SeC)	1. Cream *; 2. Red *; 3. Cream purple 4. Black; 5. Black bream	Gbaguidi et al. [62]
12	Eye Colour (EyC)	0. Absent 1. Black	Aliyu et al. [39]
13	Testa pattern (TeP)	1. Dotted 2. Marbled striped with the entire line 3. Slight rhomboid spot in one side of hilum only 4. Slight rhomboid spot on both side of the hilum 5. Abundant rhomboid spot in both side of the hilum 6. Holstein pattern 7. No pattern *	Aliyu et al. [39]
14	Fully expanded terminal leaflet color	1. Purple 2. Green * 3. Red	Aliyu et al. [39]; Molosiwa [98]

\* Prominent morphological traits at the time of characterization.

A considerable amount of variability was observed for various phenological, physiological, and agronomic characteristics [39,51,99]. Research emphasis on the variation between and within genotypes based on morpho-physiological descriptors in the Bambara groundnut has been broadly summarized by [62,89,100]. The majority of the study findings were highly country-specific, involving germplasm from Southeast Asia and Africa's major agro-climatic zones [39,95]. A few research works has been conducted using global germplasm diversity. Bambara groundnut descriptors identified by the international Bambara groundnut network, international institutes of tropical agriculture, and international plant genetic resources institutes were used for the phenotypic distribution study [101]. Additionally, Olukolu et al. [95] registered some floral investigation details (such as flag/banner petal length, the gap between wing tips and banners, wing length banner to wing length ratio, and pedicel and peduncle length) that was not considered in the IPGRI/IITA/BAMNET [101] descriptors. Typically, floral descriptors are rarely used in most reports when describing Bambara groundnut landraces. Globally, some research progress has been noted on underutilized crop species by several institutions and research platforms, which include African Orphan Crops Consortium (AOCC) [102], the Modern

Plant Breeding Platform (MPBP) [103], and the Center for Crops for the Future (CCFF) [63]. The African Orphan Crops Consortium, in particular, has focused its work on sequencing the genomes of 101 underutilized/neglected/orphan crops in Africa. Aside from that, several forums and organizations are continuing their awareness campaigns and marketing initiatives aimed at local consumers about the importance of underutilized crop species, and the Conference of International Food for Future was held in Cologne, Germany.

## 8. Research on Hybridization for Bambara Groundnut Improvement

The conventional (artificial) hybridization to develop a new variety of Bambara groundnut may be a brilliant strategy that incorporates a variety of lucrative characters; this technique has been improved in Thailand and the UK [56,104]. Due to a cleistogamous nature (i.e., pollen is dropped before the flower unfolds) and self-pollinated nature, artificial crossing among Bambara groundnut is difficult, as documented by Suwanprasert et al. [56]. Madamba [105] demonstrated a hybridization technique in Zimbabwe using a pair of forceps to open flower buds and to separate the anthers containing latent pollen grains. Pollen grains are then carefully targeted and pressed onto emasculated female flower buds. Massawe et al. [90] stated that Nottingham University, UK, has conducted some crossing programs on Bambara groundnut, but it is a challenging scheme with the possibility of success at only 2% recovery of hybrid plants. In these circumstances, it is possible to accelerate the success rate of hybridized Bambara groundnut by implementing several cross-breeding programs throughout Africa. It has been reported that yield improvement through the hybrid development of Bambara groundnut is difficult because emasculation and crossing are not easy to see with the naked eye due to the minute flower morphology [56]. It has also been reported that the most critical factor in artificial hybridization of Bambara groundnut is emasculation and pollination timing (anthesis period). Before the advent of cross-breeding methods, no one has had any experience with Bambara groundnut hybridization; as a result, Bambara groundnut landraces have been used for cultivation for several decades. Only successful crosses in this crop can be considered a meaningful achievement because they open the door to breeding the first modern varieties of Bambara groundnut.

## 9. Specific Molecular “Toolbox” Used for Bambara Groundnut Improvement

A molecular marker has emerged as a powerful instrument to assist and promote plant breeding programs [106]. Three types of markers such as genomic markers (DNA based), biochemical (storage protein and isozymes), and morpho-physiological (character) markers are probably serviceable in the genetic enhancement of Bambara groundnut. The current group of markers that are applied in genetic mapping is DNA-based (molecular) markers. The development and application of molecular markers direct rapid plant material selections based on distinct characteristics, while morphological selection takes more time and space. Several studies have been published on Bambara groundnut, including how genomic markers provide knowledge of genetic inconsistency [89,107], how germplasm was collected to look for certain traits from various agro-ecological origins [95], how quality control was conducted, how knowledge of the breeding scheme was provided [97], the awareness of the breeding scheme, the examination of the genomic directions of such characteristics such as leaf physiology and drought tolerance [108,109], and the relationship between the absence and presence of whole-genome sequences in the crop [10]. The steady reduction in cost, along with increased access to new technology, such as next-generation sequencing, genome-wide analyses, and allelic diversity analysis of germplasm, have ushered in a new age of crop improvement. Genomic marker-based diversity-assisted plant-breeding annotations and landraces maintenance strategies have been proposed for this crop species [51,99]. Several molecular markers have been designed specifically for Bambara groundnut over the last 20 years to explore genetic variation based on phenotypic descriptors [89]. Several researchers have documented genotype-specific genomic tools, such as 10 SSR primers by Basu et al. [110], 143 SSR primers by Beena et al. [111], and 75

SSR markers in Bambara groundnut by Molosiwa et al. [89]. Molecular and biochemical analyses of genetic variation intra- and inter-genotype of Bambara have been documented, including the use of AFLP on 16 landraces to cluster them into three groups based on their location and geographical origin [112], microsatellite (SSR) markers [89], and use of Random Amplified Polymorphic (RAPD) markers [50,58]. Olukolu et al. [95] tested 554 DArT array markers on 44 different landraces of Bambara groundnut germplasm. At the Tropical Research Unit, University of Nottingham, UK, RAPDs revealed significant polymorphism among Bambara groundnut landraces, ranging from 63.2 to 88.2% with a mean of 73.1% [113]. Mukakalisa et al. [114] found substantial polymorphism in RAPDs among Bambara groundnut varieties grown. Somta et al. [107] used SSR markers for diversity analysis of Bambara groundnut grown in Namibia. A larger degree of allelic (both inter and intra) variability has been illustrated as a result of all of these inquiries. Six hundred and thirty-five DArT markers on 342 Bambara genotypes [115], both 68 SSR and 201 DArT array primers on 123 Bambara groundnut genotypes [89] discovered two primary subsectors focused on marker fingerprinting patterns: one is the west and central African group, and the other is the south and east African group. These two claims together establish strong proof of two distinct gene pools of Bambara groundnut. Genetic tools for agronomic characteristics can be enhanced and fully overcome by an improvement in genetic resources by using molecular markers, which leads to marker-assisted selection, quality inspection, and genome-enabled crop enhancement for global climate change [87,116]. Genomic association maps including Microsatellite markers, SNP markers, and DArT markers are used in genomic interaction maps to divide Bambara groundnut into domesticated and wild types [10,97,108,109]. The goal is to produce segregating populations for different characteristics such as growth habits, photoperiodic responsiveness, drought tolerance, and disease resistance for advancing improved varieties. To assist and improve the breeding program, the first genome sequencing for the Bambara groundnut was recently published [102,117]. Bambara groundnuts are unique crops and notably inbred [89,107]. Chang et al. [117] and Ho et al. [10] found a quiet mixture in inbred lines, and after molecular assessment, it has been observed that this type of mixture exists in released varieties. According to Somta et al. [107], there is a significant amount of heterogeneity in Bambara groundnut (average of 1.3%), with the highest heterogeneity in three accessions from Guinea (4.99%) and ten accessions from Burkina Faso (2.99%), indicating that outbreeding may occur. Likewise, mean heterozygosity (0.01) with a coefficient of inbreeding depression varying from 0.9 to 1.00 was recorded by Molosiwa [98] using twelve microsatellite markers on 123 accessions of Bambara groundnut. However, pure line selection or a single seed descent method may be the initial step for advancing homogenous lines before implementing a Bambara groundnut-breeding program. According to Barilli et al. [118], both co-dominant (SNP) and dominant silico (DArT) markers were created based on a diversity array technology platform and on Illumina next-generation sequencing. On average, 0.8% to 5.0% heterozygosity was recorded using 7894 primers on Bambara groundnut germplasm from the gene bank ( $n = 229$ ), establishing improved illustration “pure line” formation on Bambara groundnut [47]. Bambara groundnut heterozygosity was tested using a microsatellite marker before selecting specific plants for whole-genome sequencing [10]. The SSR markers aid in the evaluation of heterozygosity in large-scale genotype by environment ( $G \times E$ ) trials conducted during the same growing season. For example, Molosiwa et al. [89] used a multi-locational trial through the international organization IT-PGRFA 2016–20 (international treaty on plant genetic resources for food and agriculture) benefit joint project funded by Nigeria, Indonesia, Malaysia, and Ghana to validate F1 hybrid as well as to release as variety.

## 10. Bambara Groundnut Improvement Research on Future Aspect

For underutilized Bambara groundnut improvement, recently developed procedures have yet to be broadly implemented. Only traditional methods such as selection and hybridization are applied to this crop improvement by most breeders. Only a few breeders

use sophisticated techniques, including marker-assisted breeding, genomics, proteomics, next-generation sequencing, and transgenic breeding. Crop genomics, transcriptomics, bioinformatics, genome editing, and genetic engineering accelerate the investigation and learning of plant biology features in a large-scale, integrated mode and make it easier to transfer biological information from major to minor species [119]. The traditional approach in plant breeding is essential for effective genomic investigation of underutilized species [38,120]. According to Aliyu et al. [96], turning dynamic research from large crop species to underutilized species can be performed using two key methods: one is the transformation of technologies such as marker-dependent next-generation sequencing, and the other is the translation of true genetic characters from similar species based on location or environment.

### 10.1. Advanced Genomics

The use of comparative genomics is being broadly accepted and provides valuable knowledge on species, especially in crops for which the genomes have yet to be sequenced compared with an identified species [120]. In the case of major crop species, in-depth research into the functional and structural gene evaluation has been developed in crop genomics. Using suitable bioinformatics methods, it is possible to improve the incorporation of Bambara groundnut with significant traits as staple food crops. In legumes, some researches have proven that comparative genomics application can be applied in Bambara groundnut for improvements: (1) Armstead et al. [121] estimated the underlying genes in Mendel's locus corresponding to a seeds green or yellow color in meadow fescue grass (*Festuca pratensis*); (2) Chang et al. [117] reported that the application of the RCT gene provides resistance to numerous anthracnose races (*Colletotrichum trifolii*) in alfalfa; and (3) Cannon et al. [122] stated that regulatory genes of flora identified in *Arabidopsis thaliana* were applied in seeking genes in common bean. Therefore, organisms, tools, genomes, and traits were merged to transfer traits and the primary gene across models and species [121]. Additionally, underutilized crops can provide more valuable models for traits that are absent in major crops [123]. For example, dryness-tolerance genes traced in Bambara groundnut can be applied to major crop species that are susceptible to dryness through marker-assisted selection.

### 10.2. Advanced Transcriptomics

Effective research on comparative proteomics in the Bambara groundnut has been proven. Chai et al. [109] reported that the investigation of related genes among the Bambara groundnut leaf transcriptome and other crop species has been estimated to identify proper breeding populations and crop models. Chai et al. [109] documented that comparative transcriptome analysis revealed that soybean have the superior transcription arrangement similar to that of Bambara groundnut among other species (such as *Vigna radiate*, *Ricinis communis*, *Populus trichocarpa*, *Arabidopsis lyrata*, *Vitis vinifera*, and *Medicago truncatula*) and may be used as a genomic idol in the profiling of Bambara groundnut genome expression. The DNA of Bambara groundnut has been hybridized between *Medicago truncatula* and *Arabidopsis* ATH1 Affymetrix GeneChip Marks for a number of the high and low stems because of the lack of availability of Affymetrix GeneChip markers of Bambara groundnut [96,109,124]. Using gene marker arrays of soybean, the strategy of breeding population microarries associated with genomics and genetics in Bambara groundnut was used, and Chai et al. [125] researched drought in Bambara groundnut using the leaf RNA of F5 segregating populations generated from control breeding of DlipC and TigaNecaru cross-hybridized to *Glycin max* (soybean) gene marks. In Bambara groundnut, two intraspecific individuals derived from two lines (F2 lines: IITA 686 × Ankapa 4 and F3 lines: Tiga Nicuru × Dip C) were effectively mapped into well-known genetic linkage maps [10]. One thousand five hundred and thirty-one high-quality markers of gene expression were identified based on variation in hybridization signal strength and to construct a genetic map 165 gene expression primers. Significant QTLs were defined using gene expression



markers to outline diverse morphological traits, such as the number of pods per plant, the number of seeds per plant, peduncle length, internode length, biomass dry weight, pod weight per plant, 100-seed weight, and seed weight per plant [126]. To identify the precise genes and genomic segments linked to low-temperature responses in Bambara groundnut, Xspecies microarrays were used, resulting in 375 genes at 23 °C and 659 genes at 18 °C identified ( $p \leq 0.01$ ) [126], and the genomic segments used to discover varieties tolerance to temperature stress for Bambara groundnut were found. Basu et al. [124] reported that polymorphisms among individuals can be identified through gene expression marker approaches and a mutation that can promote populations for particular traits in the neglected Bambara groundnut crops.

### 10.3. TILLING and Eco-TILLING: Efficient and Rapid Approaches to Crop Improvement

TILLING is an effective and speedy process of mutation detection, non-transgenic and comparatively cheap reverse genomic approaches that use conventional mutagenesis reflected by high throughput mutation exposure. McCallum et al. [127], and Comai and Henikoff [128] reported that TILLING recognizes unique mutations on base pairs or minute omissions of base pairs, and specifically targeted genetic factors. McCallum et al. [127] reported that the first TILLING was discovered in the model plant *Arabidopsis thaliana* in 2000. Recently, this procedure was strongly adjusted to various plant and animal populations, though this approach may be implemented in every independent organism of the ploidy level; to regeneration time; to regeneration system; to and genomic size [128]. Thus far, TILLING has been successful in legume crops: soybean [129]; pea [130]; and neglected species such as *Musa spp.* [131] and *Eragrostis tef* [132]. The whole-genome sequence of Bambara groundnut is not yet available. To feed the world's ever-increasing population, the agricultural revolution must use advanced mechanisms to boost the potency of underrated Bambara groundnut crops. The underutilized Bambara groundnut will be taken into consideration to boost production and to expand the food program.

### 10.4. Genetic Mapping and Recombinant Inbred Lines (RILs)

Massawe et al. [90] noted that two F2 populations of Bambara groundnut are used to create genomic associations or linkage maps based on morphological and molecular markers as well as to generate RILs. Due to this situation, the creation of RILs is a key output for the Bambara groundnut development program, provides a resource for prospective research, as well as is made readily available to other scientific communities. The recombinant inbred lines (RILs) provides the fundamental starting line for investigating the heredity of growth and development pattern, drought sensitivity, and field maturity through quantitative trait loci (QTL) investigation once RILs have been developed [11]. The genomic markers linked to quantitative trait loci regulate root growth, water quality, production, and growth pattern as a function of physiological maturity. The University of Nottingham recently created genomic mapped populations using a marker-assisted collection of Bambara groundnut to find photoperiod-insensitive lines [11,33].

## 11. The Resulting Features Need to Be Acknowledged to Promote Research on This Underutilized Crop

- Heterosis vigor in a breeding scheme causes variety improvement. High levels of allelic diversity in the genotypes (between and within genotype) and across geographical origin are observed in the Bambara groundnut that causes high heterosis.
- From local landraces, pure lines should be developed after examining their stability in diverse climates (first in regulated climates such as greenhouses and then in open field environments).
- Multi-lines (a mixture of landraces) should be raised for a group of characteristics to adjust certain planting environments and other growers/consumers' choices.
- Mega-environmental trials (METs) should be evaluated considering the genetic and agronomic attributes over a range of environments.
- To introduce additional beneficial traits, pure lines should be used in crossing programs.

- To discover important Quantitative Trait Loci (QTLs), genomic maps from F2, genetically engineered (GE), or transgenic and recombinant inbred lines should be generated.
- In underutilized Bambara groundnut research, the application of advanced techniques including MAS, TILLING, tissue culture, and transgenic techniques should be encouraged.
- Future research on Bambara groundnut should be focused on four aspects: i) increasing yield per unit area, ii) breeding for tolerance to biotic and abiotic stresses, iii) enhancing seed size and nutritional quality through bio-fortification, and iv) manufacturing for markets and value-added products.
- The involvement of financial and technical support to researchers and institutions is encouraged in Bambara groundnut research.
- A network or unique research platform should be created at different levels: national, regional, and international.
- Effective conferences, workshops, and training related to Bambara groundnut research and development should be organized.

## 12. Conclusions

Underutilized Bambara groundnut crops are potentially excellent solutions in attaining food and nutritional security and that grow under severe climate conditions, while major crops are poorly suited to the environment. Although these crops are mainly unimproved, the application of advanced development mechanisms for this crop has multiple benefits. Traditional breeding is an age-old strategy for plant improvement, whereas advanced plant breeding is a systematic and well-organized strategy for plant improvement. Currently, genetically modified (GM) technology remains questionable and, in some cases, traditional plant breeding can provide better results compared to the use of molecular techniques to promote plants without incorporating foreign genes into the final product. Besides genetic enhancement of crops based on a farmer's interest, the mechanization and modernization of basic agriculture and its technologies should be emphasized in increasing the unique modes in which food distribution can be improved and food can become stable to ensure nutritional safety. A collective initiative has been started by an international organization crop for the future (CCF) in Malaysia, by Nottingham University in the UK, and by the international institute of tropical agriculture (IITA) in Nigeria to construct a common unique platform from their diverse network to improve underutilized crops. The modern model of using underutilized crop species regarding productivity, processing, consumption, and research is intended to broaden uniformity in the prevailing global diet that is vital for the current world situation. In this critical review, we explored the research by various scientists and researchers on Bambara groundnut and extracted outcomes from original research to collect evidence for future researchers. For Bambara groundnut to make a significant contribution to food security, a wide range of resources regarding its potential and awareness is needed.

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