

Chapter

Sustainable Cultivation Practices, Nutritional Optimization, and Food Processing Innovations for Bambara Groundnut in the Sub-Saharan and Namibian Context

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Abstract

Bambara groundnut (*Vigna subterranea* (L.) Verdc), an indigenous legume crop in sub-Saharan Africa, is a crucial source of protein. It is known for its ability to form symbiotic relationships with Rhizobia strains that fix atmospheric nitrogen through the Biological Nitrogen Fixation (BNF) process. In Namibia, it ranks as the second most important legume after cowpea and is grown in the northern communal regions of the country where it is also consumed. The crop's nutritional value beats that of many staple foods, providing comprehensive protein in addition to a significant amount of crucial nutrients, such as magnesium and iron, which help fight the major crisis of malnutrition in Africa. Despite its nutritional value, it has been neglected in scientific research and agricultural development programs. The crop faces challenges such as biotic and abiotic stresses, socio-economic constraints, and low yields. Its integration into sustainable food systems is urgently needed, given the challenges of climate change, food insecurity, and nutritional deficiencies. Improving Bambara groundnut requires identifying and selecting genotypes with desirable traits such as early maturity, drought tolerance, larger seed size, and higher yield. Significant genotypic and phenotypic variability exists within landrace populations. This chapter aims to examine sustainable cultivation practices, nutritional optimization, and food processing innovations in Namibia and elsewhere in the world. It emphasizes the need for improved agronomic practices, conservation agriculture, and breeding activities. The review also examines methods to broaden genetic diversity, utilize genomic resources, and employ high-throughput phenotyping to enhance the utilization of genetic resources in pre-breeding programs.

Keywords: Bambara groundnut, Sub-Saharan Africa, namibia, food security, crop improvement

1. Introduction

Bambara groundnut (*Vigna subterranea* [L.] Verdc.) is a nitrogen-fixing legume known for its ability to form symbiotic relationships with Rhizobia strains [1]. Although it is underutilized and largely overlooked both in Africa and globally, it remains an essential crop for many local farmers. Native to Sub-Saharan Africa, it is widely consumed across the region. While subsistence farmers cultivate Bambara groundnut in considerable quantities, information such as their varietal preferences, seed sources, production practices, and challenges remains unknown to crop breeders [2].

In Namibia, Bambara groundnut ranks as the second most important legume after cowpea and is grown in the northern communal regions of the country [3]. Unlike cowpea, this crop is, in most cases, grown as a monocrop in small plots in selected, suitable areas and grows well at an optimum pH of 5.0–6.5 [4]. It is also one of the few leguminous crops cultivated for human consumption that is well adapted to the country's increasingly dry climatic conditions [5, 6].

In the face of increasing climate challenges and acute malnutrition across Sub-Saharan Africa, Bambara groundnut emerges as an invaluable yet neglected crop [7, 8]. The Bambara groundnut, a resilient African indigenous legume crop, possesses both valuable agronomic and nutritional qualities that qualify it as an outstanding solution for addressing food insecurity and promoting sustainable agriculture [9]. Despite this, Bambara groundnut remains underutilized in formal agricultural systems across Sub-Saharan Africa, including Namibia. Its integration into sustainable food systems is urgently needed, given the challenges of climate change, food insecurity, and nutritional deficiencies.

2. Importance of Bambara groundnut that is still not exploited in Namibia and Africa in general

The Bambara groundnut is a vital crop in African agriculture. Although the crop can perform under challenging conditions while offering remarkable nutritional benefits, it remains overlooked in research and political discussions [7, 10]. In terms of climatic resilience, the crop thrives under devastating drought conditions, yielding 0.85–3 t/ha and outperforming other crops such as maize and beans [9]. Similarly, the Bambara groundnut's nutritional value surpasses that of many staple foods, providing complete protein in addition to a considerable amount of essential nutrients, such as magnesium and iron [9], which help combat the predominant crisis of malnutrition in Africa. Moreover, this presents an economic opportunity for food processing industries through value addition and product development, improving the livelihoods of smallholder farmers. Despite these benefits, there is minimal attention directed toward funding scientific research on Bambara groundnut in Sub-Saharan Africa, underscoring the neglect of such a valuable local crop [10].

3. Cultivation and agronomic traits of importance

3.1 Crop morphology and phenology

Bambara groundnut is a self-pollinating legume that is morphologically similar to the peanut (*Arachis hypogaea* L.) in terms of underground pod development. It is a low-growing annual plant with creeping stems, often forming a crown at the soil surface. The plant displays considerable morphological variation, reflecting its diverse genetic pool across geographic regions [11].

The leaves are trifoliate, alternate, and glabrous, with elliptical to oblanceolate leaflets ranging from 3 cm to 10 cm in length and 1 to 5 cm in width. The petiole can extend up to 30 cm and is thickened at the base. Flowers are typically papilionaceous, bisexual, and yellow or whitish. They are borne on long, hairy peduncles that emerge from the stem nodes. Following fertilization, the flower stalk (peduncle) elongates and directs the developing fruit toward the soil, a process known as geocarpy, similar to that of the groundnut. Pods develop underground and are usually indehiscent, containing one or two seeds [4, 12].

The seeds themselves are round to oval in shape, with various coat colors, including cream, red, black, and speckled patterns. Farmers often use seed color to differentiate local landraces, which may be associated with consumer preferences and marketability [11].

Phenologically, Bambara groundnut exhibits both determinate and indeterminate growth habits, depending on the genotype. This means flowering and pod development may occur continuously over an extended period, especially in indeterminate types. Flowering typically begins 30–55 days after planting, while pod development and maturity occur over the next 60–90 days [4, 12].

3.2 Environmental adaptability and resilience

Climate change poses a serious threat to crop production, especially in Africa, with its extensive arid and semi-arid regions. The cultivation of Bambara groundnut serves as a strategy to mitigate the effects of climate change [9]. Unlike other heavy-feeding crops, this crop has evolved to thrive in a broad range of agro-ecological zones, including semi-arid regions with low and erratic rainfall, poor soil fertility, and high temperature variability [12]. Its resilience is attributed to both genetic and physiological adaptations, making it a suitable crop for sustainable agriculture in marginal environments.

One of its most important agronomic advantages is drought tolerance. Bambara groundnut requires only 300–700 mm of rainfall during the growing season, significantly less than other legumes like soybeans or common beans [11]. Optimal growth occurs at 19–30°C, but the crop can withstand high daytime temperatures and cold nighttime temperatures, especially in arid zones such as Botswana and Namibia. However, growth is severely inhibited at temperatures above 35°C or below 15°C. Freezing temperatures at any stage of growth are fatal, which limits its cultivation to frost-free environments [13].

Bambara groundnut is also highly soil-adaptable, thriving in well-drained sandy loam soils with a pH between 5.0 and 6.5. It tolerates acidic and nutrient-deficient soils due to its ability to fix nitrogen symbiotically. Studies show that it can fix between 32 and 81 kg of atmospheric nitrogen per hectare, thereby enhancing soil fertility and reducing the need for synthetic fertilizers in intercropping or rotation systems [4].

Genotype-by-environment interactions are pronounced in Bambara groundnut, with different accessions showing localized adaptation. For instance, genotypes from arid sub-Saharan zones exhibit deep taproots and conservative water-use strategies, while those from wetter regions display shallower, highly branched root systems. Such root system architecture is critical for water capture and drought avoidance.

3.3 Key agronomic traits for improvement

One of the most outstanding agronomic traits of Bambara groundnut is its ability to thrive in nutrient-poor soils with a pH of 5.0–6.5 and survive droughts, even in areas that receive an average of 500–600 mm of rainfall per year [7, 10]. Furthermore, the crop can tolerate drought and survive in areas where other leguminous crops, such as groundnut and cowpea, fail. It has been reported [4] that the drought tolerance of Bambara groundnut is due to the plant's ability to maintain leaf turgor pressure through a combination of osmotic adjustment, reduction in leaf area, and effective stomatal control.

In addition, as a legume, Bambara groundnut plays a crucial role in crop production and sustainable agriculture in general, as it forms hosts for soil bacteria that facilitate the nitrogen fixation process and thus improve soil fertility [2, 10]. This helps to reduce dependence on the use of inorganic fertilizers, a cost-saving strategy that is particularly important for smallholder farmers with limited access to expensive inputs. Furthermore, Bambara groundnut plays a critical role in crop diversification, for example, intercropping with cereals, which leads to a yield increase of 20–40% compared to mono-cropping [10, 14].

As yield variability remains a challenge for most farmers due to their reliance on uncertified planting materials with inconsistent performance [2], there is a need to use improved seeds and adopt more context-specific, best management practices.

Improving Bambara groundnut requires identifying and selecting genotypes with desirable traits such as early maturity, drought tolerance, larger seed size, and higher yield. Significant genotypic and phenotypic variability exists within landrace populations, and these variations have been confirmed through morphological, agronomic, and genomic assessments [15]. According to [16], high heritability has been recorded for traits such as pod number, seed weight, and flowering time, indicating potential for selection-based improvement.

Furthermore, genomic tools, such as genome-wide association studies (GWAS), have identified several marker-trait associations related to seed coat color, days to flowering, pod width, and terminal leaf traits [17]. Trait preferences identified through participatory rural appraisals, such as early maturity, high yield, and drought tolerance, should inform breeding objectives [2]. Therefore, integrating farmer knowledge, modern molecular tools, and agro-ecological considerations will be key to developing improved Bambara groundnut varieties tailored to different regions and growing conditions.

4. Soil management practices for Bambara groundnut

4.1 Soil fertility requirement

Bambara groundnut can grow in a wide range of agro-ecological zones that differ in soil conditions. The crop can grow well even in soils characterized as poor

or infertile [18]. However, its productivity can be greatly improved if cultivated on healthy and fertile soils and supplemented with fertilizer. Several studies have examined the application of synthetic fertilizers and a combination of synthetic and organic (organomineral) fertilizers for Bambara groundnut production. For example, Temegne et al. [19] reported that applying phosphate (KH_2PO_4) at a concentration of 1,000 μM Pi increased Bambara groundnut growth and leaf P content, which was attributed to the N and P interaction in the root zone. Similarly, a study by Ramolemana et al. [20] on “The phosphorus and nitrogen nutrition of Bambara groundnut in Botswana soils”, results showed that under soils with low P, the application of P significantly improved Bambara groundnut yield and yield parameter such as number of pods, pod dry weight and dry matter production. However, these positive results were only observed when the P fertilizer was applied within two weeks after sowing. Legumes are known as phosphorus-loving crops [21]. P is needed in significant quantities and is involved in the key functions of several plants, including energy transfer, photosynthesis, sugar and starch transformation, nutrient movement in the plant, and transfer of genetic characteristics [22].

Like many other legumes, Bambara groundnut fixes atmospheric nitrogen through the biological nitrogen fixation (BNF) process. Legumes, including Bambara groundnut, can fix up to 11–20 kg of N/ha, but this is not achievable in the tropics because of low soil fertility and poor farming practices [23–25]. On the other hand, it has been reported that a high nitrogen level in the soil can lead to excessive vegetative growth instead of pod formation, resulting in a subsequent low yield. When nitrogen is added late during the growing season, it will also result in poor nodulation [4]. In fact, [26] found that applying 2 t/ha of ground cow manure produced significantly heavier dry nodules than 3, 4, and 5 t/ha. Therefore, nitrogen application for Bambara groundnut should be done with extra care.

The BNF process is also very important for improving soil fertility and supplying other non-leguminous crops with the nitrogen left in the soil after the legume is harvested. This BNF process in legumes is carried out by forming a symbiotic association with a group of soil bacteria, commonly known as rhizobia, which naturally fix atmospheric nitrogen by forming specialized structures on the roots, known as nodules.

4.2 Soil structure and drainage

The choice of land and soil type for Bambara groundnut cultivation is crucial, as this can profoundly affect the crop's growth and yield. The ideal site for Bambara groundnut should be fairly level to avoid water run-off. In addition, a well-drained site should be selected to prevent pod rotting caused by waterlogging. Moreover, stony areas should be avoided to ensure good pod development. Therefore, sandy loam soils are ideal for cultivating Bambara groundnut, as they ensure healthy pod development and easy harvesting [4].

4.3 Water management

Bambara groundnut can produce a significant yield under moderate or extreme drought stress. However, research has shown that drought stress on the crop leads to reductions in pod dry matter and, ultimately, reduced grain yields, particularly if it

occurs during the flowering stage. The total minimum rainfall requirement for Bambara groundnut is estimated to be 300 mm [26], but it performs better under annual rainfall levels between 750 mm and 1,400 mm [27]. Excessive rainfall conditions, especially during harvest, result in drastic yield losses [10]. During drought seasons, several management practices, such as the integration of landscape and field-scale conservation technologies, have been reported to positively affect dryland farming, including Bambara groundnut production in Sub-Saharan Africa, particularly in arid and semi-arid regions with limited water resources [28].

5. Available varieties and their sustainability

The Bambara groundnut crop is genetically diverse and offers opportunities for sustainable agricultural practices. In Sub-Saharan Africa, farmers typically rely on different landraces, which usually differ in seed color, size, and maturity [2]. This variability is particularly pronounced in Namibia. Although locally adapted varieties produce moderate yields of 0.85 t/ha, with a yield potential of 3 t/ha [9, 10], there is a need for breeding initiatives to develop improved varieties, such as early-maturing and high-yielding cultivars [2]. The cultivation of Bambara groundnut is ecologically, economically, and socially sustainable. It has higher water use efficiency and lower input costs compared to other crops and is mostly cultivated by women [10]. However, the loss of various genetic traits poses a major threat to valuable Bambara landraces, hence the need to conserve them while bridging the gap between seed banks and breeding programs [2].

6. Bambara groundnut: Production opportunities and challenges for local communities

6.1 Production challenges

Although most rural communities in both Namibia and Sub-Saharan Africa as a whole benefit significantly from the Bambara groundnut, challenges are inevitable. Several biotic and abiotic constraints hindering Bambara groundnut production have been documented. Biotic stressors include fungal, bacterial, and viral diseases, insect pests such as bruchids (*Callosobruchus maculatus*), and nematode infestations [2, 11]. These reduce both yield and quality. Although some diseases can be managed through crop protection chemicals and practices such as crop rotation, burning of infected residues, or the use of organic remedies, smallholder farmers often lack access to such interventions [28].

Abiotic stresses, such as erratic rainfall, extreme temperatures, and low soil fertility, are prevalent in Bambara-growing regions, including the sub-Saharan region [3]. Climate change exacerbates these stresses by altering rainfall patterns, reducing planting windows, and increasing the frequency of drought episodes [11]. Additionally, most Bambara landraces are photoperiod-sensitive, requiring short day lengths for optimal pod filling. Under long photoperiods, pod development is significantly impaired [28]. The simultaneous occurrence of heat and drought stress further complicates crop performance and may be governed by overlapping genetic mechanisms [17].

Equally important, socio-economic challenges have also been reported. Despite its resilience and nutritional potential, Bambara groundnut remains underutilized due to socio-economic barriers. It is often perceived as a “poor man’s crop” and is cultivated mainly for household consumption rather than commercial purposes [11, 12]. This perception has led to minimal investment in research, extension services, and input systems. Furthermore, there is a lack of well-structured value chains, formal seed systems, and marketing infrastructure. Farmers rely heavily on saved seeds and informal markets, contributing to inconsistent quality and low productivity [3].

Additionally, traditional beliefs have stigmatized the crop as a woman’s crop or even as one that brings bad luck, thereby limiting male participation and broader community support [13]. While these views are gradually shifting, the absence of national breeding programs, seed certification systems, and policy inclusion continues to hinder its expansion and development.

In Namibia, Bambara groundnut is cultivated by smallholder farmers primarily for household consumption. The crop is well-adapted to the country’s semi-arid environment, but the lack of improved varieties, access to inputs, and consistent extension services has constrained its productivity [10]. Studies have shown that yields in most farming systems are less than 1 ton per hectare, and the crop is typically grown on plots smaller than one hectare using traditional practices [2, 5]. Strategies to overcome such challenges include the formation of farmers’ associations to promote market accessibility, the introduction of economically viable processing machinery such as dehullers, and the formulation and implementation of relevant policies.

6.2 Production opportunities

Notwithstanding these constraints, Bambara groundnut offers considerable opportunities for sustainable agriculture, especially in marginal and drought-prone areas. Its ability to grow under low-input conditions, fix atmospheric nitrogen, and produce stable yields under adverse conditions makes it an ideal crop for climate-smart agriculture [11, 28]. It is highly nutritious, containing balanced levels of protein, carbohydrates, and micronutrients, and is sometimes described as a “complete food” [13].

Bambara groundnut’s adaptation to semi-arid climates, combined with its potential role in crop diversification, positions it as a strategic crop for enhancing food and nutritional security in Sub-Saharan Africa. With rising global interest in plant-based proteins and sustainable crops, Bambara groundnuts could be promoted as a health food in niche global markets [11]. Genetic diversity within landraces provides ample breeding material to improve drought tolerance, early maturity, and yield potential [12, 17].

Studies have shown that the inclusion of Bambara flour in school feeding programs has improved the nutrition of children in Malawi. Meanwhile, Namibian farmers, particularly those from the Omusati region, have achieved ideal yields with Bambara, even when the overall harvest for other crops was poor [2]. This also applies to the economic benefits and opportunities, as processed Bambara products yield an excellent profit compared to raw, unprocessed beans [10].

7. Nutritional value and opportunity for product formulation

The high nutritional composition of Bambara groundnut makes it the best choice for product development and value-added processing industries. Bambara is high in protein (23.6%), carbohydrates (64.4%), fat (6.5%), fiber (5.5%), and important minerals such as calcium, iron, and magnesium [9, 29]. According to [30], Bambara groundnut has a higher protein quality, recorded at 80%, which is more than that of groundnut (65%) and cowpea (64%). Bambara groundnut can be mixed into cereal products as an additive. It also has a low glycemic content, which makes it more suitable for products intended for diabetics [2]. Studies have shown that adding 15% of Bambara flour to bread can increase the protein content by 40% without compromising the bread's quality [29]. However, the processing of Bambara groundnut is quite laborious, for example, soaking and grinding/milling of the seeds, which highlights the need for advanced technologies to streamline the process and ultimately lead to lower production costs [10].

7.1 Nutritional profile and significance

Bambara groundnut is considered a complete food. The legume's excellent nutritional profile is characterized by the presence of various macro and micronutrients, which vary based on varieties and geographical conditions. The carbohydrate content makes Bambara groundnut an energy-dense food compared to other legumes, such as cowpea [31]. The rich carbohydrate content ranges between 49% and 63% of its dry weight [9, 32]. Due to its high content of complex starches and dietary fiber, Bambara groundnuts have a low glycemic index and provide long-lasting energy. This can help control blood sugar levels and reduce the risk of diabetes and obesity, which are major health issues in Namibia.

The protein content ranges between 9% and 40%, depending on the variety and other geographical conditions [9, 33]. The amino acid profile of Bambara groundnut shows high levels of glutamic acid, leucine, and lysine, while methionine is the limiting amino acid. This makes Bambara groundnut a good complementary protein source to cereals, which are often deficient in lysine but rich in methionine [9]. The protein profile in Bambara groundnut can serve as an affordable protein substitute that complements instant porridges for school-going children and snacks for pregnant women.

Although Bambara groundnut is praised for its excellent nutritional profile, the same does not hold true for its fat content. The fat content in Bambara groundnut can range from as low as 1.4% to as high as 12% [9, 34]. The fat content in Bambara groundnut has been reported to be lower compared to other legumes, such as soybeans and peanuts, which have fat contents ranging between 20% and 50%, respectively [6].

The fatty acid composition in Bambara groundnut is mainly made up of oleic acid and linoleic acid (omega-6) [9]. Oleic acid and linoleic acid in Bambara groundnut have the potential to reduce heart disease, support brain development in children, combat chronic illnesses caused by malnutrition, and limit diabetes-related complications [35], which are raising concerns in Namibia.

Bambara groundnut is rich in various micro-nutrients, which can address the issue of food insecurity that has proven to be a challenge for communities affected by malnutrition in Namibia. The legume is particularly rich in calcium (95.8–360 mg per

100 g), iron (4.9 mg–48 mg per 100 g), potassium (11.44–19.35 mg per 100 g), and sodium (2.9–12.0 mg per 100 g) [34]. Other studies have reported traces of zinc, magnesium, and phosphorus in Bambara groundnut. The combined presence of these minerals contributes to a range of functions in body development, including bone health, cardiovascular health, and boosting immune function.

7.2 Challenges to nutritional utilization

Despite the bountiful nutritional profile of the Bambara groundnut, several factors limit the bioavailability of the legume's nutrients.

7.2.1 Antinutritional factors (ANFs)

Despite its nutritional benefits, the accessibility of the dietary value of Bambara groundnut is limited by the presence of ANFs, which interfere with the digestion and bioavailability of essential nutrients [36]. ANFs are biological compounds naturally present in legumes that bind to essential nutrients, thus limiting the body's uptake and digestibility. Common ANFs found in Bambara groundnuts include tannins, trypsin inhibitors, and phytic acid [31].

Tannins are polyphenolic compounds that form complexes with Bambara groundnut, thus limiting protein availability [37]. There is a common notion [38] that the relationship between tannins and seed coat color plays a role in the taste of Bambara groundnuts. Tannins, which are more prevalent in darker-colored Bambara groundnuts, contribute to the bitter and astringent taste of the legume [9].

Trypsin inhibitors are also a group of ANFs that have been reported to significantly limit protein digestibility in raw or unprocessed Bambara groundnuts. These inhibitors limit the activity of trypsin enzymes, thus negatively impacting the digestion and absorption of proteins in the human body [39].

Phytic acid is another common ANF present in high volumes in Bambara groundnuts. Its presence is linked to the reduction in calcium accessibility [38], the inhibition of pepsin, lipase, and amylase activity [39], reduced iron bioavailability, and the formation of crosslinks with dietary proteins and starch [9].

7.2.2 Hard-to-cook (HTC) phenomenon

The HTC phenomenon is a characteristic that causes the hardening of the seed coat in Bambara groundnut when the legume is stored at excessively high temperatures (>25°C) and/or high levels of humidity (>65%) [9]. The hard seed coat of Bambara groundnut contributes to an increase in cooking time (up to four hours), which subsequently increases energy consumption and reduces milling efficiency [40]. This HTC phenomenon discourages consumption of the legumes, and cooking proves to be a challenge for rural households in Namibia that heavily depend on traditional cooking methods.

Nonetheless, the HTC can be reduced through processing methods, mainly fermentation and soaking. Significant research indicates that the HTC component in Bambara groundnut can be reduced by boiling the legumes in alkaline salts. Boiling Bambara groundnuts in a 0.5 g/100 mL solution of sodium bicarbonate, sodium chloride, and magnesium sulfate for 30 minutes had various nutritional effects [31].

Bambara groundnuts boiled in sodium bicarbonate had higher carbohydrate and crude fiber content, which suggests the effectiveness of the alkaline salt in softening the hardened seed coat. Bambara groundnuts boiled in magnesium sulfate had higher protein, potassium, and iron content, which suggests the effective destruction of ANFs. Bambara groundnuts boiled in sodium chloride had the highest fat and phosphorus content.

7.2.3 Processing techniques

In Namibia, Bambara groundnut is traditionally processed and consumed through various methods such as boiling, sun drying after harvesting, freshly cooking, or combining with other grains and cooking as food [41]. Sun drying of the pods is mainly practiced, and because the drying process lacks control, sometimes over-drying of pods occurs, leading to poor shelling output [42]. According to Gerrano et al. [4], processing methods not only affect the nutritional value of Bambara groundnuts but also have the potential to enhance their optimal utilization as a legume. There is a variety of processing methods for this legume, such as fermentation, germination, and soaking; however, there are no studies in Namibia that focus on the effects these methods have on Bambara groundnuts. In other studies, however, it has been proven that these methods can effectively break down non-digestible oligosaccharides, which are associated with the production of flatus, into simpler carbohydrates and enhance protein digestibility [36]. Soaking of Bambara groundnuts is done either in hot or cold water at varying time intervals. Studies have recognized a greater loss of trypsin inhibitors and tannins during immersion in hot water, whereas a contradictory observation was made for phytate [36]. A study by Adeleke et al. [37] assessed that soaking is more effective in reducing the ANFs of the samples, with the control seeds exhibiting lower values than the newly developed seeds. On the other hand, boiling time may be required to make the seeds soft enough to eat, which may require high energy during cooking, unlike other legume crops such as cowpea [4].

There is little information available on how long it takes for Bambara grains to cook fully; therefore, there is a need for research to focus on cooking time and the reduction of overall functional utility of Bambara. This is because the hardening of seeds causes a decrease in nutritional quality, and extended boiling leads to reduced nutritional quality and digestibility. The hardening of legume seeds is observed to cause a decrease in nutritional quality, while extended boiling leads to reduced protein digestibility [4].

7.3 Strategies for nutritional optimization

In view of standard processing methods, recent studies have discovered that inoculating Bambara groundnut with bacterial strains is likely to improve nutritional content. Research [31] found that Namibian-grown Bambara groundnut varieties inoculated with *Bradyrhizobium* bacteria displayed unique nutritional traits. In the study, red-colored Bambara groundnuts inoculated with *Bradyrhizobium* had higher fat, magnesium, copper, and iron content than red Bambara groundnuts not inoculated with *Bradyrhizobium* bacteria. A specific bacterial strain, such as *Bradyrhizobium*, can increase the

bioavailability of minerals in legumes by decreasing the amount of ANFs, such as phytic acid, which bind to minerals and reduce their absorption [43, 44]. Brown-colored Bambara groundnuts inoculated with *Bradyrhizobium* had protein content twice as high as brown Bambara groundnuts not inoculated. *Bradyrhizobia* form a symbiotic relationship with the root nodules of legumes, which increases the nitrogen content and has a significant impact on the protein content.

7.4 Integration into local diets: An example for Namibia

There have been various value-added products developed from Bambara groundnuts around the globe. In Zambia, Bambara groundnut flour is used in canned food; in Benin, dumplings are made; and in East Africa, coffee, milk, noodles, and baby porridge [31] are manufactured. Despite its versatile use, Namibia has only reported the traditional uses of Bambara groundnut to date. Researchers found, through surveys from Kavango East, that Bambara groundnut is used to prepare the following traditional dishes: a boiled snack; “mugombakapindi,” which is a stiff porridge made from mahangu flour and Bambara groundnut; “shikuvira,” made from roasted Bambara groundnut and peanut flour; and “rutura,” which is an instant porridge prepared by mixing warm water with roasted Bambara groundnut flour [41].

Given its high protein content, Bambara groundnuts can be processed into flour and blended with staple foods, such as porridge, to improve the nutritional quality of meals, particularly in school feeding programs, kitchen soups, and orphanage homes in Namibia. The excellent protein content of Bambara groundnuts allows for their versatile use in the manufacturing industry. Proteins in Bambara groundnuts can be isolated, which, in turn, can be used as vegan emulsifiers in sausages and cakes [45]. Furthermore, the starch in Bambara groundnuts can be extracted and utilized as a natural, gluten-, lactose-, and cholesterol-free thickener and stabilizer in various food products, such as sauces, soups, and desserts.

Improving not only the quantity but also the quality of food is essential for sustaining nutritional value [18]. Beyond its role as a food and income source, Bambara groundnut also holds potential for medicinal use and as livestock feed [46].

8. Breeding and genetic selection

In Namibia, efforts have been made to collect and evaluate Bambara groundnut germplasm since independence in the early 2000s, when a project known as BAMFOOD was initiated [47]. However, a formal breeding program for this resilient crop is still lacking [3]. The BAMFOOD (ICA4-CT-2000-30002) project, which took place between 2000 and 2003 through the collaboration of a UK-based organization with SADC member states, collected and assembled several pure lines isolated from the landraces collected from farmers in member states [48]. Recently, preliminary breeding research has been initiated, targeting traits such as drought tolerance, high yield, early maturity, and resistance to pests and diseases [1, 5, 49]. According to Valombola et al. [3], one way of increasing the speed of adoption of new varieties is to give farmers a wide range of novel cultivars to test for

themselves in their fields through participatory varietal selection (PVS). PVS is a breeding approach that is used to bring breeders, social scientists, farmers, and extension personnel together in a field to select cultivars based on traits of importance [50]. PVS methods have been well utilized in Namibia [51] and also in other African countries like Ethiopia [50] to test the adoption of several crops such as cowpea and potatoes.

Breeding and genetic selection involve the evaluation of phenotypes and genotypes, as well as the collection of landraces for use in variety improvement [12]. Farmers usually prefer quality traits such as high yield, large leaves, thick and yellow pods, specific seed shapes, bushy growth habits, medium-sized leaves, and nitrogen fixation ability in Bambara groundnut [5, 51]. Many farmers in Namibia indicated that Bambara groundnut plants with larger leaves, bigger pods, and higher yields were mostly preferred [12]. At the same time, in Malawi, small-seeded Bambara groundnut was also preferred and used for relish, while big-seeded Bambara groundnut was used for snacks [8]. Farmers need to have access to high-yielding crops in order to produce enough food for household consumption and also for income generation. Larger pod size is an essential factor for the marketing of Bambara groundnut; this will be required as genetic material in the development of improved varieties, besides an increase in production [12, 16]. It was also found that there is a need to carry out various research studies to determine factors such as the morphological and germination characteristics of Bambara groundnut in order to evaluate the benefits and drawbacks of various genotypes [49]. Several studies on the genetic and agronomic characteristics of the crop displayed the number of flowers, number of leaves, days to maturity, pod development, and yield as traits that vary among the landraces [12, 16]. The environmental conditions were also found to be critical for some growth parameters, but this varies across different locations.

There are no registered or improved Bambara groundnut cultivars known in Namibia, but research dedicated to crop improvement is ongoing, and farmers plant local germplasm, which is mixed and not uniform but exhibits genetic variability [2, 3, 51]. There is, therefore, a need to make Bambara groundnut breeding a priority in order to improve productivity. Selection for increased pod number per plant, pod weight, and seeds per pod can be a strategy for yield improvement and should be considered [2, 5].

9. Improved agronomic practices

The absence of improved agronomic management practices and high-yielding cultivars with pest and disease resistance reduces the production and productivity of Bambara groundnuts for small-scale and commercial farmers in developing countries [42]. In contrast, efforts in Namibia are increasingly focused on promoting improved agronomic practices aimed at enhancing yield, building resilience to climate stress, and improving soil fertility, all within the framework of sustainable agriculture.

Despite these efforts, farmers still rely on indigenous knowledge for crop management and seed preservation [2]. For instance, the use of traditional hoes as a tool for soil preparation has been shown to be effective in increasing growth and yield attributes of Bambara groundnut [52]. Land preparation is especially important for Bambara cultivation because pod formation occurs underground. Well-pulverized soil is believed to aid in the deep penetration of developing pods,

thereby supporting optimal growth [4]. Weeding is typically done manually using hand tools such as hoes or, alternatively, by hand-pulling, particularly during the seedling stage [3, 51]. To maximize the benefits of symbiotic nitrogen fixation with rhizobacteria, Bambara groundnut is often intercropped with cereals, either simultaneously or introduced in the middle of the cropping season with these cereals [4]. As in many other African countries, Namibian farmers commonly intercrop Bambara groundnut with staple crops such as maize, pearl millet, and sorghum [2, 5].

10. Conclusion(s)

Bambara groundnut is a drought-tolerant, nutrient-rich legume with great potential to contribute to food security, climate-smart agriculture, and rural livelihoods in Sub-Saharan Africa, especially in Namibia. Despite its adaptability and nutritional benefits, it remains underutilized due to limited research, the unavailability of improved seeds, and socio-economic challenges, among other factors. To tap into Bambara groundnut's full potential, there is a need for targeted breeding programs, improved agronomic practices, value addition, and supportive policies. In addition, integrating traditional knowledge with modern innovations will be crucial to unlocking the role of Bambara groundnut in sustainable agriculture and nutrition.

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Conflict of interest

The authors declare no conflicts of interest.

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