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Bambara groundnut (*Vigna subterranea* L.): A climate-resilient crop to address food and nutritional security

Authors:
Md Mahmudul H. Khan[1,2]
Mohd Y. Rafii[3]
Shairul I. Ramlee[4]
Mashitah Jusoh[4]
Md Al-Mamun[1]

Affiliations:
[1]Department of Genetics and Breeding, Laboratory of Climate-Smart Food Crop Production, Institute of Tropical Agriculture and Food Security (ITAFoS), Universiti Putra Malaysia (UPM), Selangor, Malaysia

[2]Department of Oil-crops Breeding, Faculty of Plant Breeding, Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh

[3]Department of Crop Science, Laboratory of Climate-Smart Food Crop Production, Institute of Tropical Agriculture and Food Security (ITAFoS), Universiti Putra Malaysia (UPM), Selangor, Malaysia

[4]Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia (UPM), Selangor, Malaysia

Corresponding author:
Md Mahmudul Khan,
mhasan.bari12@gmail.com

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Background: The climate change challenges coupled with global agricultural policies currently emphasise only a few crop species, which directs the threat to food security and supply.

Aim: This review comprehensively delves into the potential of Bambara groundnut as a catalyst for enhancing the nutritional composition of diets.

Setting: Regrettably, this emphasis has led to a dearth of knowledge and attention about alternative crops, particularly those that may be advantageous for sustainable agriculture. Bambara groundnut is one such crop that requires particularly low agricultural inputs.

Methods: Our exploration encompasses various dimensions, including the crop's genetic diversity, production dynamics, its socio-economic importance, and ongoing efforts in genetic improvement.

Results: Bambara groundnut stands out as a nutrient-rich source, providing essential nutrients, including carbohydrates, amino acids, proteins, and fatty acids. Its nutritional profile holds great potential for combating malnutrition and fostering growth, especially in economically disadvantaged regions with limited access to animal proteins. Furthermore, the crop displays resilience, showing relatively low susceptibility to diseases and insect infestations.

Conclusion: Bambara groundnut holds importance in addressing food and nutritional security amid the prevailing challenges of climate change. In common with other neglected crops, there exists insufficient information on contemporary cultivation methods and unfavourable traits such as prolonged cooking times. To ensure the prosperity of the crop for future generations, it is imperative to enhance these attributes through breeding techniques and refining processing procedures.

Contribution: This review contributes by highlighting the distinctive features of Bambara groundnut and elucidating effective strategies to unlock its full potential.

Keywords: *Vigna subterranea* L.; underutilised legume; climate smart crop; resilient crop; nutritional security.

Introduction

The Bambara groundnut (*Vigna subterranea* [L.] Verdc.; $2x = 2n = 22$) is a legume that belongs to the kingdom of Plantae, from the Fabaceae family and Faboidea sub-family. It is a geocarpic crop, a closer relative to *Vigna unguiculata* (cowpea), physiologically adaptable to the position of *Arachis hypogaea* (groundnut), even though physically its grains are like *Cicer arietinum* (chickpea) (Halimi et al. 2019; Mayes et al. 2019). Bambara groundnut is easy to cultivate in poor soil because it requires minimal fertiliser and fewer cultural practices (Oyeyinka et al. 2015). This pulse legume is commonly cultivated in many parts of Africa (Okonkwo & Opera 2010). It is also widely grown in tropical and humid regions, recently available in many regions of South America, Southeast Asia (Indonesia, Thailand, and Malaysia), and Oceania (Baudoin & Mergeai 2001). Despite its widespread presence, it remains underutilised: a term implying the species is disregarded or neglected by both domestic and international research and scientific communities. Underutilised species are typically characterised as crops with limited perceived significance. Indeed, unlike other significant legumes such as soybeans and groundnuts, Bambara groundnut has not received adequate financial support from governmental and non-governmental organisations for

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improvement, and has garnered less attention from the international research community as a whole (Oyeyinka et al. 2015). As such, extensive scientific research and financial assistance are still needed to enhance this crop's improvement.

There is also a need to enhance social awareness regarding the dietary and nutritional benefits of the Bambara groundnut. In particular, in the case of low-income countries, animal proteins are not readily available; hence, there is an extreme need to acquire protein from agri-based plant food sources. Bambara groundnut is viewed as completely balanced food (Mazahib et al. 2013) and owing to its rich nutrient content and adaptable nature in challenging environmental conditions, the Bambara groundnut serves as both a source of income for marginalised farmers and a staple diet for many low-income consumers. This dual role positions it as a valuable solution to address issues related to malnutrition.

Globally, the trend of population growth has increased, with a recent estimation of 8 billion and is projected to reach 9.7 billion by 2050 (Kakol 2011). Therefore, to narrow the nutritional gap and address recurring nutritional challenges while ensuring food security for a growing population, incorporating Bambara groundnut can be instrumental by helping to mitigate current challenges and lessen reliance on the consumption of staple food crops like wheat, corn, and rice in low-income countries (Feldman et al. 2019). However, optimal production technologies and seed processing techniques for Bambara groundnut have not received widespread recognition and global publication (Feldman et al. 2019).

Climate change and irregular precipitation patterns in several regions of the world have created a demand for agriculture and crop rearrangements based on their climate resilience properties (Mayes et al. 2012). According to Adzawla et al. (2016) and Olayide et al. (2018), local farmers continue to cultivate landraces of the Bambara groundnut owing to their resilience to drought and its consistently acceptable yields even in marginal conditions. Landraces of underutilised crops are cultivated using conventional methods of farming and fundamentally grown by indigenous people, but across centuries these have undergone biological and cultural evolution (Khan et al. 2022c). The incorporation of neglected crops, for example Bambara groundnut, into regular dietary habits not only contributes to a diverse food chain but also has a positive impact, serving as a customary means of promoting human well-being (Baldermann et al. 2016). Several studies have shown that neglected or underutilised crops can strengthen and advance the world's food security status. Various research efforts related to underutilised crops instil confidence in addressing food security challenges, particularly in regions where such concerns are unpredictable (Khan et al. 2022b; Massawe et al. 2005).

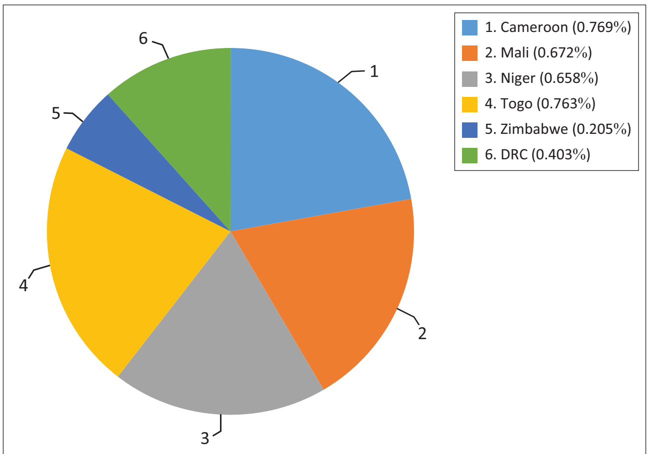
Globally, some research progress has been observed on underutilised crop species by several institutions and research platforms, which include the African Orphan Crops Consortium (AOCC), the Modern Plant Breeding Platform (MPBP), and the Centre for Crops for the Future (CCFF) (Muhammad et al. 2020). Specifically, the AOCC devoted its efforts to the sequencing of the genome of 101 underutilised and/or neglected and/or orphan crops in Africa. Besides this, several forums and organisations are continuing their awareness campaigns and promotion programmes related to the significance of underutilised crop species among local consumers, and recently the Conference of International Food for Future was held in Cologne, Germany. This study outlines the standards and notable applications of the Bambara groundnut, delving into its advancements in contemporary scientific research. It provides an evaluation of both beneficial and less favourable attributes, encapsulating the essential areas for improvement in breeding requisites and potential avenues for future development.

Origins of Bambara groundnut

According to Vavilov (1926), the fundamental principles of crop domestication revolve around the centre of domestication, closely linked to the geographic location where multiple families, including ancestral siblings, are concentrated. In the breeding context, the centre of diversity holds greater economic significance than the centre of domestication. Africa is the geographic origin of Bambara groundnut and has been broadly described by Basu et al. (2007). While Aliyu, Massawe and Mayes (2016) suggested Sudan as the likely origin, an alternative viewpoint presented in another report identifies West Africa as the central hub for the domestication of Bambara groundnut (Rungnoi et al. 2012). The wild landraces of Bambara groundnut are confined to the states of Nigeria (Yola and Plateau) and Cameroon (Garoua state), which have been described as the centre of domestication of the species (Basu et al. 2007). Research findings revealed that, compared to Cameroon and/or Nigeria accessions, Burkina Faso accessions exhibit the highest level of genetic diversity (Somta et al. 2011). Moreover, Burkina Faso, located in close proximity to Nigeria, is identified as the most reliable hub for the domestication of Bambara groundnut (Khan et al. 2020). Indeed, Somta et al. (2011) and Molosiwa (2012) reported that West African genotypes have more extreme genetic diversity than other regions. As indicated by Olukolu et al. (2012) and Somta et al. (2011), the landraces in East Africa are generally considered an extension of West African landraces. Olukolu et al. (2012) stated that the Bambara groundnut's secondary centre of cultivation is identified in Southeast Asia, particularly in South Thailand, West Java, and various parts of Malaysia. In this region, the crop is referred to as 'Kacang Poi' and is extensively cultivated, particularly in the Kedah state in the northern part of Peninsular Malaysia.

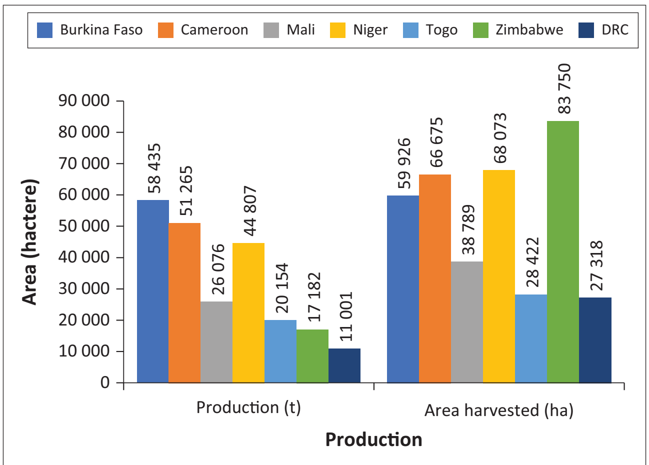
Socio-economic significance of Bambara groundnut

Bambara groundnut is regarded as the third most important grain legume after groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) (Howell et al. 1994). Bambara groundnut plays a crucial role in ensuring nutrient and food security while serving as a source of income for resource-poor farmers and consumers in developing nations. It can assure food and nutrient security locally as well as globally (Halimi et al. 2019). Small-scale cultivation of Bambara groundnut is prevalent among marginal rural farmers and individuals with low incomes (Feldman et al. 2019). Traditionally, the cultivation of this crop has been an assurance for farmers and consumers, contributing significantly to households' nutrition and food security (Mayes et al. 2019; Olayide et al. 2018). In the context of a rapidly increasing global food crisis, Tilman et al. (2011) project a simultaneous increase in crop demand of 100% – 110% from 2005 to 2050. As a neglected crop, Bambara groundnut exhibits resilience under severe soil and environmental constraints, particularly in the developing world, and specifically in Africa and Asia (Khan et al. 2021a). Almost all the African underutilised crops, especially Bambara groundnut, are drought tolerant, and some of them exhibit resistance to water stagnation for extended periods compared to major crops. The total global yield (Figure 1) and production (Figure 2) of the Bambara groundnut is unremarkable because of the use of ordinary plant materials and poor agronomic practices. Underutilised Bambara groundnut is also fit to the



Source: FAOSTAT, 2018, *Food and Agriculture Organization of the United Nations*, FAOSTAT, viewed 17 August 2021, from http://data.un.org/Data.aspx?d=FAO&f=itemCode %3A203

FIGURE 1: Yield (t/ha) of Bambara groundnut cultivation based on FAOSTAT 2018.



Source: FAOSTAT, 2018, *Food and Agriculture Organization of the United Nations*, FAOSTAT, viewed 17 August 2021, from http://data.un.org/Data.aspx?d=FAO&f=itemCode %3A203

FIGURE 2: Production and area of Bambara groundnut cultivation based on FAOSTAT 2018.

agroecology and socio-economic circumstances in the African and Asian continents (Khan et al. 2021c).

Bambara groundnut features associated with food and nutrient security

Achieving food security for a healthy life requires ensuring that the entire human population has social, physical, and economic access to sufficient, healthy, and nutritious food, meeting their dietary needs and nutritional preferences (Howell et al. 1994; Massawe et al. 2005; Mustafa, Mayes & Massawe 2019). Food security conditions are typically characterised by two key features: availability and stability. Availability pertains to the consistent presence of an adequate quantity of food, complete with the necessary essential components, either through local production or introduction. On the other hand, food stability is a policy ensuring a continuous and sufficient food supply throughout the entire year, catering to both households and unique populations. The concept of food availability is closely linked to individuals or groups having access to ample resources to meet their daily needs (Mustafa et al. 2019).

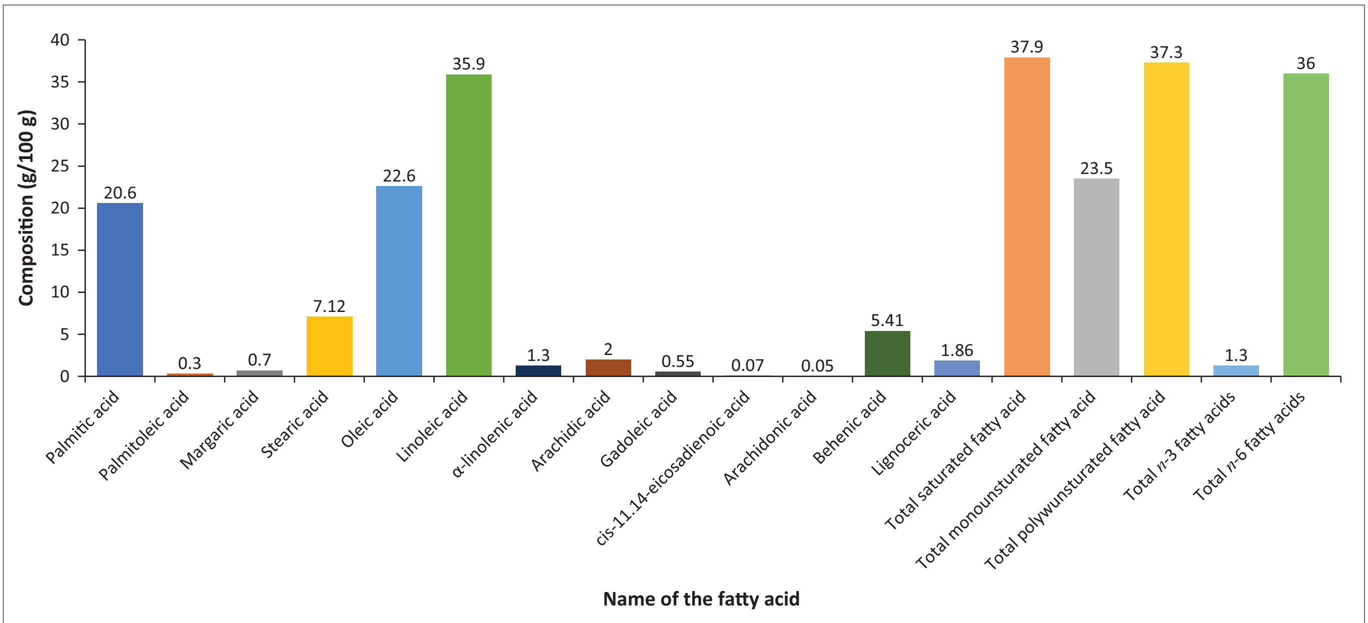
Although Bambara groundnut is considered a neglected and underutilised crop, it can address the challenges of climate change and food security (Olayide et al. 2018). This crop contributes an important function in the field of food security and the welfare of low-earnings producers and customers in developing countries (Mabhaudhi et al. 2019). Most underutilised crops are resilient to severe climatic conditions, can reduce greenhouse gases, and have better adaptability to poor soils (Mabhaudhi et al. 2018). For marginal farmers, the Bambara groundnut is an ideal crop because of its high-yielding potential using low input of management practices coupled with poor soil conditions (Begemann, Mukema & Obel-Lawson 2002). According to Yakubu, Kwari and Sandabe (2010), the Bambara groundnut crop has the capacity to fix atmospheric nitrogen, estimated at 28.42 kg N ha^{-1}. While the nitrogen synthesis serves a purpose beyond its immediate use, the leaves of the crop can deposit nitrogen into the soil for the subsequent crop when incorporated after harvest. Underutilised crops play a crucial role in providing nutrients and improving diets, especially for low-income individuals (Hunter et al. 2019). Among these underutilised crops, Bambara groundnut stands out because of its diverse food values and resilience to severe climatic stresses, positioning it as a prospective crop for the future or a new-millennium crop. This crop has the potential to enhance nourishment, contribute to food and nutrient security, facilitate rural development, and promote sustainable land use practices.

Nutritional values and uses of Bambara groundnut

The nutritional composition of Bambara groundnut reveals elevated values. According to Ouedraogo et al. (2008), the higher content of carbohydrates and protein makes this legume a primary choice for human food cultivation. Mazahib et al.'s (2013) findings emphasise the comprehensive nature of Bambara seeds as a complete diet, consisting of carbohydrates (63% – 65%), protein (18% – 19%), and fat (6.5%). Additionally, Oyeyinka et al. (2018) reported varying nutritional values, including carbohydrate (61% – 69%), protein (17% – 27%), fibre (3.3% – 6.4%), ash (3.1% – 4.4%), and fat (3.6% – 7.4%). Halimi et al.'s (2019) research further supports the nutritional richness of Bambara seeds, indicating protein content (18% – 24%), with high lysine and methionine, carbohydrates (51% – 70%), crude oil (4% – 12%), ash (3% – 5%), and fibre (9% – 12%). KariKari et al. (1997) found that per 100 g of Bambara seeds contain calcium (95.5 mg – 99.0 mg), iron (5.1 mg – 9.0 mg), potassium (11.45 mg – 14.36 mg), and sodium (2.9 mg – 10.6 mg). In line with this, Khan et al. (2020) reported that per 100 g of dry weight seeds, Bambara groundnut is rich in iron (4.9 mg – 48 mg), potassium (11.44 mg – 19.35 mg), sodium (2.9 mg – 12.0 mg), and calcium (95.8 mg – 99 mg), surpassing values observed in other legumes. Ojimelukwe and Ayernor (1992) noticed that Bambara groundnut with red seeds exhibited higher iron content compared to those with cream-coloured seeds. From the studies of Ndidi et al. (2014) and Mazahib et al. (2013), it was observed that the micro-nutrient combination was found to be calcium (95.5 mg – 99.0 mg), potassium (5.1 mg – 9.0 mg), and sodium (2.9 mg – 10.6 mg) as well as ample quantity of zinc (20.98 mg ± 1.07 mg) per 100 g dry seeds. According to United States Department of Agriculture (USDA), the daily recommended amount of minerals for an adult is above 15 mg/100 g/person. Bambara groundnut contains about 7% fat, which can be used in the formulation of a low-fat diet that can be revealed as a better plant source of fats. Furthermore, the gross energy contained in Bambara groundnut is more than other legumes (Feldman et al. 2019), with the estimated energy value being approximately 367 Kcal/100 mg – 414 Kcal/100 mg (Boateng et al. 2013).

Research from Bamshaiye, Adegbola and Bamishaiye (2011) and Mazahib et al. (2013) reported that Bambara groundnut seeds are rich in essential amino acids (80%) which is more than cowpea (64%), soybeans (74%), and groundnut (65%), particularly in terms of arginine, leucine, valine, methionine, and lysine. Moreover, the seeds contain significant amounts of minerals and vitamins, including zinc, iron, thiamine, riboflavin, niacin, vitamin A and B, and carotene. However, they are notably deficient in ascorbic acid (Mubaiwa et al. 2018). Bambra groundnut seeds also have a greater number of fatty acids such as linoleic acid, oleic acid, and palmitic acid (Mubaiwa et al. 2017). Fatty acid composition in lipid extract from Bambara groundnut seeds are displayed in Figure 3.

Because of the high protein content, Bambara groundnut supports in mitigating nutritional deficiencies both in humans and animals (Khan et al. 2021d). Also, because they grow well in areas where other legume production is risky owing to low precipitation, Bambara groundnuts have the potential to become a staple diet for people in places where animal protein is scarce or expensive (Khan et al. 2021d). Masindeni (2006) reported that Bambara groundnut can be used in regular foods and hydrated seeds can be milled and incorporated with traditional samp (a food made from dried corn kernels) or used to prepare soup in South Africa and Swaziland. Fresh beans and green leaves can be used as fodder by mixing with other grass or direct feeding to livestock. Composite flour is prepared using Bambara nut and mixed into noodles preparation thus protein rich diets can simply be made by Bambara nut flour fortification (Effa et al. 2016). Fresh, young Bambara seeds may also be cooked



Source: Khan, M.M.H., Rafii, M.Y., Ramlee, S.I., Jusoh, M. & Al-Mamun, M., 2021a, 'Bambara Groundnut (*Vigna subterranea L. Verdc*): A crop for the New Millennium, its genetic diversity, and improvements to mitigate future food and nutritional challenges', *Sustainability* 13(10), 5530. https://doi.org/10.3390/su13105530; Maphosa, Y., Jideani, V.A., & Maphosa, L., 2022, 'Bambara groundnut production, grain composition and nutritional value: Opportunities for improvements', *The Journal of Agricultural Science* 160(6), 448–458

Note: Faty acids composition g/100 g.

FIGURE 3: Composition of fatty acids in lipid extract from Bambara groundnut seeds.

and consumed, much like peanuts. In some regions of Nigeria, the steamed paste is also used to make a pudding known as Moi-Moi or Okpa (Okpuzor et al. 2010). In addition, in Nigeria, the protein percentage of Ojojo (fried yam cake) prepared from water Yam (*Dioscorea alata*) can be increased through the addition of Bambara flour (Khan et al. 2022a). In Indonesia and Malaysia, young Bambara groundnut seeds are roasted to produce snacks and are available in supermarkets, where they are known as 'Kacang Bogor' or 'Bogor nut', often sold at premium prices. Moreover, as highlighted by Adu-Dapaah et al. (2016), milk produced from Bambara groundnut boasts a higher protein content (15% – 16%) compared to soybean milk (4%). Furthermore, the colour and flavour of Bambara groundnut milk are favoured over those of other legumes. Recently, the Center for Future Crops (https://cropsforthefutureuk.org) and Feldman et al. 2019) devised versatile recipes using the Bambara groundnut.

Production trends of Bambara groundnut

According to Berchie et al. (2013), Bambara groundnut cultivation can be carried out in two seasons annually, particularly in areas characterised by bimodal rainfall patterns. Bambara groundnut has a maturity time of three to six months (Feldman et al. 2019), which provides chances to harvest all year-round while reducing yield losses. This crop's long storage life provides food supplements throughout the year, bridging the nutritional gap between harvest seasons (Islam et al. 2016). The yield of this crop is significantly influenced by the timing of sowing. Berchie et al. (2013) demonstrated that the yield of Bambara groundnut was higher (up to 4 t ha^{-1}) in the low rainy and temperate season compared to the heavy rainy season. Additionally, the pod yield was affected by the time of sowing. Collinson et al. (2000) noticed that the total yield of Bambara groundnut diminished from 3 t ha^{-1} to zero in Tanzania because of the delay of sowing by 60 days. Shiyam et al. (2016) reported the highest yield of Bambara groundnut, estimated at 1.95 t ha^{-1}, achieved through the incorporation of organic fertilisers at a rate of 2.5 t ha^{-1} in Calabar, Nigeria. Toungos, Sajo and Gungula (2009) documented a Bambara groundnut yield of 0.43 t ha^{-1} with the application of 60 kg ha-1 P_2O_5 in Yola, Nigeria. Conversely, in Igbariam, located in the southeast part of Nigeria, the highest yield (1.65 t ha^{-1}) was recorded using 110 kg ha^{-1} of P_2O_5 (Nweke & Emeh 2013). Khan et al. (2020) recorded a maximum average yield of 1.6 t ha^{-1} and a minimum yield of 0.38 t ha^{-1} from the evaluation of 150 genotypes of Bambara groundnut in tropical Malaysia. The plant density and growth habits of the crop influence the total yield and this was supported by Khan et al. (2021a), who recorded the highest yield with maximum plant density (250 thousand/ha) in plain land using semi-bunch types in Côte d'Ivoire. Abejide et al. (2018) reported that high nitrogen in soils cause more vegetative growth, especially in leaves by producing poor pod and seed set, thus it means the crop gives a better yield in poor resource soil, which is supportive to marginal farmers. Although peanuts may not produce as many pods under optimal management, Bambara groundnuts demonstrate a higher yield when cultivated in controlled settings (Gerrano et al. 2021), which indicates the potential of Bambara groundnuts.

Typical Bambara groundnut growers cultivate it for food, income, or both. In a survey carried out by Berchie et al. (2013) in Ghana, involving 200 Bambara groundnut farmers, 33 sellers, and 68 users, it was revealed that approximately 63% of individuals engaged in the cultivation of Bambara groundnut were women, with men constituting the remaining 37%. The majority of farmers (78%) cultivate the crop for food, emphasising its crucial role in local sustenance. Also, 73% cultivate it for cash, underlining its economic significance. The survey indicated that a considerable proportion (63% – 83%) of growers, utilise family-owned lands for Bambara groundnut cultivation. The mean production per grower varied from 0.6 to 1.0 t ha^{-1} under the cultivated land of an average of 0.45 ha (Berchie et al. 2013). However, the production trends of Bambara groundnut have not seen a significant increase, primarily attributed to factors such as unpredictable rainfall patterns, labour shortages, financial constraints, unavailability of viable seeds, and a lack of improved cultivation practices (Berchie et al. 2013). Aliyu et al. (2016) proposed that enhancing the production and yield of Bambara groundnut could be achieved through the inoculation of *Bradyrhizobium*, establishing an effective symbiotic relationship. As an underutilised crop, Bambara groundnut holds significant commercial value, particularly in terms of its high yield, making it an attractive option for farmers willing to invest in the necessary inputs to improve production and achieve abundant yields (Barbieri et al. 2014).

According to Olayide et al. (2018), the Bambara groundnut is one of the stable legumes and has been treated as a typical crop having resilience and verified traits suitable for adverse environmental challenges. Naturally, Bambara groundnut is a drought tolerant legume, easily adaptable to diverse ecological circumstances, and can be intercropped with non-legumes, making it an important lucrative crop in several emerging economies (Rungnoi et al. 2012). Research conducted by Berchie et al. (2013) that assessed different germplasm of Bambara groundnut for drought tolerance and heat resistance revealed that the plant can survive when water supply was stopped 30 days after planting, while some accessions showed resistance to drought for up to 120 days. Drought increases several responses of plants in both above and below-ground soil such as tolerance, avoidance, and escape (Mabhaudhi et al. 2013). Chai, Massawe and Mayes (2016) reported that all three mechanisms of drought, that is, tolerance, escape, and avoidance, exist in Bambara groundnut. Bambara groundnut has emerged as an optimal crop, demonstrating resilience to water deficits and exhibiting all three drought tolerance mechanisms that contribute to its ability to yield significantly under drought stress. According to Feldman et al. (2019), this stress-tolerant characteristic positions Bambara groundnut as a comprehensive model legume for cultivation in arid climates and suggests its potential as a future crop in regions experiencing increased incidents and severity of drought, coupled with irregular rainfall patterns because of climate change.

Pests and diseases as obstacles to Bambara groundnut improvement

Bambara groundnuts are believed to be resistant to disease infections and significant insect infestations in xerophytic settings. Khan et al. (2022b) highlighted the resilience of this crop in tolerating insect pests and diseases that typically impact growth and yield. Although it is noteworthy that in a two-year field trial on Bambara groundnut conducted during 2013–14, the first year recorded the highest seed yield at 1.68 t ha^{-1} from 111 111 plants per hectare (Effa et al. 2016). However, in the second year, a significant reduction in yield was observed because of the prevalence of viral leaf curl disease (Effa et al. 2016). Despite the resilient shell of Bambara groundnut, which typically acts as a deterrent to many insects, research by KariKari et al. (1997) reveals that bruchids (*Callosobruchus subinnotatus*) in the grain and weevils (Curculionoidea) specifically target the stored pods of Bambara groundnut. Numerous research has focussed on how to safeguard the Bambara groundnut while they are being stored, including looking for resistant types.

In various African nations, the successful identification of strains resistant to insect pests has been achieved through the screening of numerous seed variants (Ahmed & Yusuf 2007). Out of the 12 000 evaluated cowpea cultivars for grain legumes, three were discovered to exhibit sufficient resistance to two cowpea bruchids, *Callosobruchus maculatus* F. and *C. subinnotatus* Pic. (Ahmed & Yusuf 2007). Similarly, following screening, it was revealed that 6 out of 31 Bambara groundnut cultivars exhibited resistance to these bruchids (Ahmed & Yusuf 2007). When stored in unshelled conditions, Bambara groundnut seeds demonstrated high tolerance to both bruchids and weevils (KariKari et al. 1997).

In terms of diseases, the Bambara groundnut plant is commonly targeted by both viruses and fungi, as indicated by research findings from Tanimu and Aliyu (1995). Furthermore, certain genotypes, such as TVSU 218, have been observed to lead to a complete failure in plant development. The predominant sources of the prevalent viral infections in Bambara groundnut might be areas where other legumes, such as cowpea, are cultivated. Indeed, Ng et al. (1985) identified the two most common viral infections in Bambara groundnut as Cowpea Aphid-Borne Mosaic Virus (CABMV) and Cowpea Mottle Virus (CMV). According to Begemann et al. (2002), Bambara groundnut is also susceptible to diseases caused by fungi resembling *Cercospora* sp. leading to leaf spots, *Fusarium* sp. resulting in wilt, and *Sclerotium rolfsii* causing stem rot, particularly in humid environments. As reported by Tanimu and Aliyu (1995), the leaves of Bambara groundnut are prone to attacks by *Puccinia* spp. causing rust, *Colletotrichum* sp. resulting in leaf blight, and viral infections such as Rosette because of the dry and humid conditions prevalent in Nigeria. In a study conducted by Tanimu and Aliyu in 1995, it was found that aphids and the root-knot nematode (*Meloidogyne javanica*), comprising 65% of Zimbabwe's insect pests, can both inflict significant damage to Bambara groundnuts. Collinson et al. (2000) emphasised that, under certain conditions, experiments with Bambara groundnuts susceptible to pests and diseases might face substantial harm, affecting the entire study.

Research trends on Bambara groundnut improvement

Bambara groundnut research was started in 1971 when a group of agronomic experiments was carried out in the western and southern states of Africa. An extremely high coefficient of variation in terms of yield within the varieties was observed. Between 1972 and 1975, the predominant focus of research efforts was directed towards investigating the utilisation of fertilisers, as well as exploring ridging and spacing techniques to enhance the yield of Bambara groundnut. In pursuit of achieving a high yield potential coupled with resistance to diseases and insect pests, a collection of germplasm was gathered and systematically evaluated to identify the most promising selections. The initiated research projects encompassed activities such as landrace preservation, seed multiplication, characterisation, and evaluation. The 1989–1990 breeding plan marked a significant milestone as it introduced the first single-plant selection, followed by duplication and multi-location adaptive trials. Bambara groundnut improvement programmes were conducted using pure line selection methods through the isolation of the plants with maximum pod and seed numbers in Botswana in 1993 and 1995 (Massawe et al. 2005). A large variation among the accessions in Botswana was recorded for traits such as seed size, pod number, 100-seed weight, and total seed yield (Massawe et al. 2005). Through the optimum use of water and maintaining the day length at 12 h, the yield of Bambara groundnut was recorded as equivalent to 3.0 t ha^{-1} (Massawe et al. 2005).

From 1997 to 2000, the Tropical Crops Research Unit (TCRU) at Nottingham University (United Kingdom [UK]) undertook research on Bambara groundnut to assess the extent of diversity in both vegetative and reproductive traits among different genotypes. The findings by Massawe et al. (2005) revealed a weak association between the reproductive and vegetative traits within the studied Bambara groundnut genotypes. In a collaborative effort, the University of Nottingham in the UK and the Technical University of Munich in Germany conducted additional experiments from 1997 to 2003. This joint project focussed on applying molecular methods to enhance understanding of diversity within and between genotypes, aiming to facilitate the judicious utilisation of these resources in development programmes (Massawe et al. 2005).

Massawe et al. (2005) observed research findings conducted using Randomly Amplified Polymorphic DNA (RAPD) and Amplified Fragment Length Polymorphism (AFLP) primers explored the higher degree of polymorphism among Bambara groundnut genotypes. Building upon the preceding eight years of research focussed on increasing productivity in Bambara groundnut, a project was extended from 2000 to 2003. This project involved collaboration with African associate nations, including Botswana, Namibia, and Swaziland. The objective was to enhance several 'pure lines' and amalgamate them into composite 'multilines' to maintain genetic heterogeneity, thereby ensuring stable yields across different genotypes (Massawe et al. 2005). Recently, European Union (EU)-funded projects operated from 2006 to 2009 to develop ideal enriched varieties, use molecular schemes (AFLP, SSR, and DArT markers), and employ marker-assisted selection in Bambara groundnut advancement. Some research outputs of Bambara groundnut genetic analysis using molecular tools are summarised in Table 1 and Table 2.

Landraces conservation for future food security and breeding programmes

A healthy ecosystem relies on the preservation and stability of the gene pool offered by landraces, which concurrently enhance biodiversity. Worldwide, traditional crop cultivation plays a pivotal role in furnishing humans with vital regulatory services, such as soil erosion control, carbon sequestration, nutrient cycling, reduction of greenhouse gas emissions, and control of hydrological processes (Azeez, Adubi & Durodola 2018). This practice not only preserves agricultural biodiversity but also safeguards against the adverse impacts of climate change, ensuring both current and future food security (Azeez et al. 2018). To fulfil these conservation goals, it is imperative not only to preserve landraces but also to safeguard local varieties that have been replaced by newer, more productive ones. Despite the prevalent emphasis on landraces and exotic materials, older varieties contribute significantly to genetic diversity and should be conserved alongside other breeding materials. Ultimately, the conservation of germplasm and characterisation of important traits will provide breeders specific information that will encourage the scientific community to use genetic resources, despite the enormous efforts made by national and international programmes to conserve landrace diversities.

The genetic diversity of Bambara groundnut germplasm has been substantially influenced by low input agriculture practices (Massawe et al. 2005). According to Olukolu et al. (2012), participatory plant breeding proves advantageous in preserving germplasm when producers and consumers select their preferred ideotypes from a broad range of germplasms cultivated in research locations and/or farmer fields. Strengthening the grower's commitment to preserving pure germplasm while identifying promising new lines is a crucial aspect. Employing diverse methods such as wild landraces, germplasm, pure lines, mixtures, and cross-breeding programmes in the improvement of Bambara groundnut represents an impartial and comprehensive approach. This approach is appealing to producers because of its excellent performance in terms of productivity and

TABLE 1: Genetic analysis of Bambara groundnut using several molecular tools.

Crop	Name of primers	Research types	Sources
Bambara groundnut	SSR	Genetic study of Ghanaian Bambara groundnut accessions by SSR	Siise and Massawe (2013)
	SSR	Genetic diversity and population structure of Bambara groundnut accessions revealed by microsatellite (SSR)	Molosiwa et al. (2015)
	SSR, DArT	QTL analysis of morphological traits and linkage map construction of Bambara groundnut	Ahmad et al. (2016)
	DAMD, SCoT	Genetic diversity study by Directed Amplified Minisatellite DNA and Start Codon targeted marker and their competency valuation Bambara groundnut	Igwe and Afiukwa (2017)
	RAPD	Valuation of the genetic relationship of Bambara groundnut based on morphological traits and RAPD markers	Fatimah et al. (2018)
	SSR	Morphological characterisation of Ghanaian Bambara groundnut accessions based on SSR markers	Aliyu and Massawe (2013)
	DArT	Genetic diversity and phenotypic descriptors revealed by DArT markers in Bambara groundnut	Olukolu et al. (2012)
	RAPD AFLP	AFLP and RAPD markers based genetic diversity study of Bambara groundnut	Massawe et al. (2005)

Source: Khan, M.M.H., Rafii, M.Y., Ramlee, S.I., Jusoh, M. & Al-Mamun, M., 2021a, 'Bambara Groundnut (*Vigna subterranea L. Verdc*): A crop for the New Millennium, its genetic diversity, and improvements to mitigate future food and nutritional challenges', *Sustainability* 13(10), 5530. https://doi.org/10.3390/su13105530

SSR, simple sequence repeats; DArT, Diversity Arrays Technology; DAMD, directed amplified minisatellite DNA; SCoT, start codon targeted; RAPD, randomly amplified polymorphic DNA; AFLP, amplified fragment length polymorphism; QTL, Quantitative trait loci.

TABLE 2: Summarised research findings on Bambara groundnut diversity involving molecular markers.

No. of genotypes	Types and no. of markers	Markers linked to BG	Polymorphic (%)	References
223	AFLP = 10 SSR = 10	AFLP (N/A) SSR (No)	Range from 8.5% to 37.7% with a mean of 22% for AFLP For SSR- five among fourteen showed polymorphism	Sinigrin and Schenkel (2003)
240	SSR = 22	Five markers were linked	Average PIC 0.58 with a range between 0.10 and 0.91	Soma et al. (2011)
363	RAPD = 14 ISSR = 3	ISSR (No) RAPD (N/A)	Average 70% with a range between 50% and 100% for RAPD Average 72.4% with a range between 60% and 85.7% for RAPD	Ronni et al. (2012)
40	Darst = 554	Yes	-	Olusola et al. (2012)
24	Darth = 201 SSR = 68	Yes	Average 0.42 with a range between 0.08 and 0.89 for SSR.	Malesia et al. (2015)
44	ISSR = 32	Yes	Detected an average of 97.64% polymorphism while 35.15% and 51.08% polymorphism per population and geographical zone, respectively	Khan et al. (2021b) Khan et al. (2023)

Source: Khan, M.M.H., Rafii, M.Y., Ramlee, S.I., Jusoh, M. & Al-Mamun, M., 2021a, 'Bambara Groundnut (*Vigna subterranea L. Verdc*): A crop for the New Millennium, its genetic diversity, and improvements to mitigate future food and nutritional challenges', *Sustainability* 13(10), 5530. https://doi.org/10.3390/su13105530

SSR, simple sequence repeats; ISSR, Inter simple Sequence Repeat; DArT, Diversity Arrays Technology; RAPD, randomly amplified polymorphic DNA; AFLP, amplified fragment length polymorphism.

adaptability. Olukolu et al. (2012) highlight the challenge faced by researchers and scientists in preserving the genetic makeup of germplasms through breeding techniques and local conservation initiatives. For instance, the 'Sambou-touroukpa' line, known for its early maturity (achieving maturity within 103 days of sowing), was successfully released as a commercial cultivar to address the challenges posed by ongoing climate change in Benin (Olukolu et al. 2012). However, recognising the significance of molecular characterisation in safeguarding Bambara groundnut germplasm, Siise and Massawe (2013) in Ghana, and Somta et al. (2011) in African germplasm, employ this approach to prevent the crossing of identical genotypes and eliminate duplication issues.

Bambara groundnut genetic resources management

Nigeria's International Institute of Tropical Agriculture (IITA) held the leading position in the collection of Bambara groundnut germplasm (2000 accessions), with approximately 1400 accessions characterised among them. The Institut de Recherche pour le Développement (IRD) in France gathered approximately 1200 cultivated and 60 wild landrace accessions from Cameroon, with 50 of them characterised. The University of Zambia, Zambia, contributed around 460 accessions, while the Grain Crops Institute in Potchefstroom, South Africa, amassed about 200 accessions. In addition, the Plant Genetic Resources Centre (PGRC) in Accra, Ghana, collected around 170 accessions (Muhammad et al. 2020). Khan et al. (2021a) stated that the major drawbacks of this crop enhancement include the absence of genetic improvement, ineffectual information on the taxonomy, reproductive biology, the genetic background of agronomic as well as qualitative characters, and lack of insect- pest and disease management. Globally, in recent times, efforts have been ongoing to promote the richness of Bambara groundnut. The broadest database (Table 3) of Bambara groundnut germplasms is hosted by the IITA (Muhammad et al. 2020) from where specific studies of Bambara groundnut potentialities and other related studies are being planned.

Nigeria has the highest collection of Bambara germplasm followed by Zambia and Zimbabwe (Table 4). Because of the highest number of germplasms belonging to Nigeria, it will be meaningful if further strengthening of this crop improvement programme is taken effectively. According to FAO (2018) all over the world, nearly 6145 Bambara germplasms are kept in *ex situ* conservation and the collections are made from the national and international gene banks (Table 4). Muhammad et al. (2020) reported the Genetic Resource Centre (GRC) under IITA, Nigeria, has 2031 accessions accumulated from several sub-Saharan African countries. Genetic variation of any crop species may be potentially beneficial for the improvement of genetic performance as reported by Massawe et al. (2005). A notable amount of heterogeneity has been reported in the Bambara groundnut landraces following poor input cultivation practices (Massawe et al. 2005). Traditional or rural growers of Bambara groundnut depend on the existing diversity among the germplasm that they cultivate and continue to sustain genetic diversity with ecological selection on Bambara groundnut germplasms (Mubaiwa et al. 2018). For future genetic improvement *ex situ* and *in situ* conservation, on-farm conservation, as well as farmer's conservation of Bambara groundnut germplasms has significant potential (Aliyu et al. 2016) (Figure 4). Nonetheless, germplasm can pose challenges when it comprises a mixture of various sources, potentially causing complications in discerning genetic arrangement effects from environmental effects (Mayes et al. 2019).

To establish effective and well-coordinated plant breeding and enhancement programmes, it is essential to initiate a targeted germplasm collection focussing on desired traits. This approach enables researchers and breeders to leverage the acquired knowledge in the selection of parental lines for crop improvement programmes (Khan et al. 2021a, 2021b). Aliyu et al. (2016) reported an integrated crop improvement framework's conceptual for genetic diversity and population structure study of Bambara groundnut worldwide germplasm and its application to variety creation and genetic analysis (Figure 5). Massawe et al.

TABLE 3: Bambara groundnut accessions belong to International Institute of Tropical Agriculture collected from different countries of origin.

Country	No. of accessions
Benin	27
Botswana	5
Burkina Faso	27
Cameroon	207
CAR	103
Chad	70
Congo	42
Côte d'Ivoire	4
Ethiopia	1
Gambia	11
Ghana	120
Kenya	2
Madagascar	49
Mali	28
Niger	33
Nigeria	310
Senegal	36
South Africa	1101
Swaziland	11
Sudan	7
Tanzania	28
Togo	139
Zimbabwe	245
Zambia	284
Malawi	59
Unidentified accessions	160
Total	**2008**

Source: Goli, A.E., Begemann, F. & Ng, N.Q., 1997, *Characterization and evaluation of IITA's bambara groundnut collection*, Harare, Zimbabwe, 14–16 November, 1995, pp. 101–118; Mkandawire, C.H., 2007, 'Review of Bambara groundnut (Vigna subterranea (L.) Verdc.) production in sub-Sahara Africa', *Agricultural Journal* 2, 464–470 and Muhammad, I., Rafii, M.Y., Ramlee, S.I., Nazli, M.H., Harun, A.R., Oladosu, Y. et al., 2020, 'Exploration of Bambara groundnut (*Vigna subterranea* (L.) Verdc.), an underutilised crop, to aid global food security: Varietal improvement, genetic diversity and processing', *Agronomy* 10(6), 766. https://doi.org/10.3390/agronomy10060766

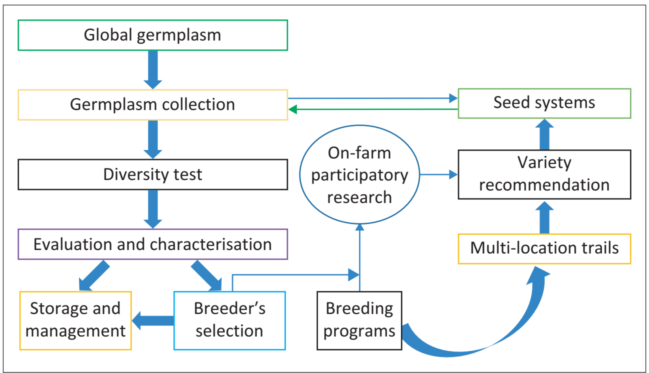
TABLE 4: Bambara groundnut landraces and wild type genotypes held by international institutions across some selected countries.

Region	Short name	Landraces categories						
		Landraces number	%	Wild species	Landraces	Breeding lines	Advanced cultivars	Others
Nigeria	IITA	2031	33	< 1	100	-	-	-
France	ORSTMONTP	1416	23	-	100	-	-	-
Botswana	DAR	338	6	-	2	-	-	98
Ghana	PGRRI	296	5	-	-	-	-	100
Tanzania	NPGRC	283	5	< 1	81	-	-	18
Zambia	SPGRC	232	4	-	100	-	-	-
Others	Others (26)	1549	25	1	59	9	1	29
Total		**6145**	**100**	**< 1**	**79**	**2**	**< 1**	**18**

Source: FAO, 2018, The future of food and agriculture–Alternative pathways to Rome, viewed 01 October 2018, from http://www.fao.org/3/I8429EN/i8429en.pdf; Muhammad, I., Rafii, M.Y., Ramlee, S.I., Nazli, M.H., Harun, A.R., Oladosu, Y. et al., 2020, 'Exploration of Bambara groundnut (*Vigna subterranea* (L.) Verdc.), an underutilized crop, to aid global food security: Varietal improvement, genetic diversity and processing', *Agronomy* 10(6), 766. https://doi.org/10.3390/agronomy10060766

IITA, International Institute of Tropical Agriculture; ORSTOM, Office De la Recherche Scientifique et Technique Outre-mer; DAR, Departement of Agricultural Research; PGRRI, Plant Genetic Resources Research Institute; NPGRC, National Plant Genetic Resource Centre; SPGRC, SADC Plant Genetic Resources Centre.

Negative (-) sign indicates an unspecified number of accessions.



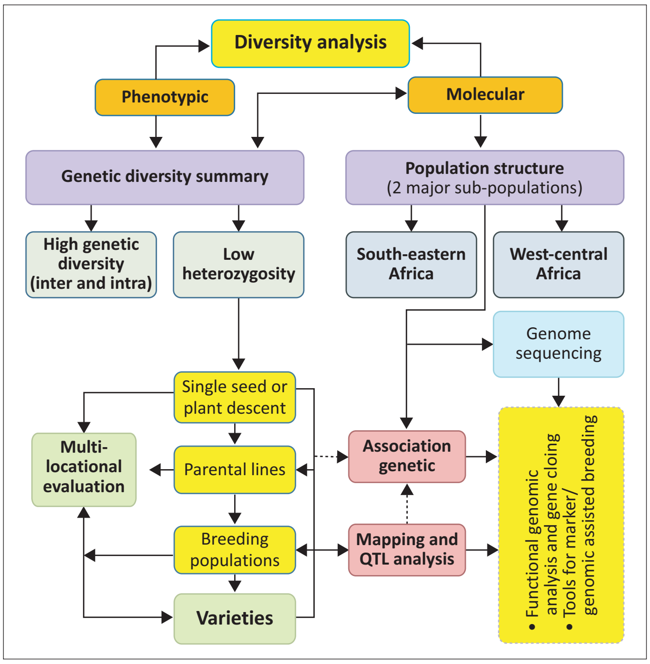
Source: Aliyu, S., Massawe, F. & Mayes, S., 2016, 'Genetic diversity and population structure of Bambara groundnut [*Vigna subterranea* (L.) Verdc.]: Synopsis of the past two decades of analysis and implications for crop improvement programmes', *Genetic Resources and Crop Evolution* 63, 925–943. https://doi.org/10.1007/s10722-016-0406-z

FIGURE 4: Bambara groundnut germplasm and framework for its improvement.

(2005) reported that the accessions taken from a country or several regions in a country have unique features and also have a common pedigree with various regional names. To solve this duplication among the collected accessions IITA, Nigeria, implemented genome-wide genotyping and sequencing to the characterisation of Bambara groundnut.

Conclusion

The underutilised Bambara groundnut is an excellent crop for contributing towards nutrition and food security. Its ability to thrive under severe climate conditions sets it apart, particularly in environments where major crops struggle. The expansion of underutilised crop plants, characterised by abundant genetic diversity and promising attributes, is seen as a viable solution to address concerns related to food and nutritional security. With the ongoing global climate change, the importance of genetic analysis and molecular research in underutilised crops, particularly Bambara groundnut, is imperative. This is attributed to their genetic tolerance, adaptability to environmental conditions, and resilience to both biotic and abiotic stresses. Expanding both the morphological and molecular genetic improvement of crucial traits in Bambara groundnut holds the potential to not only advance the genetics and breeding of this specific crop but also to contribute to overall underutilised crop breeding efforts. This approach can aid in adapting to climate change, boosting income generation, and ultimately improving nutrient and food security. The contemporary approach to utilising underutilised crop species, encompassing aspects of productivity, processing, consumption, and research, aims to diversify the uniformity in the prevailing global diet, a crucial consideration in the current world context. The significance of underutilised crop species for global nutrient and food security is gaining recognition within the global scientific community and among food security policymaking institutions. Modern enhancement policies, coupled with diverse genetic and genomic resources, are being implemented to accelerate the yield potential of these crops. This critical review delves into the contributions and insights of various researchers in the context of Bambara



Source: Aliyu, S., Massawe, F. & Mayes, S., 2016, 'Genetic diversity and population structure of Bambara groundnut [*Vigna subterranea* (L.) Verdc.]: Synopsis of the past two decades of analysis and implications for crop improvement programmes', *Genetic Resources and Crop Evolution* 63, 925–943. https://doi.org/10.1007/s10722-016-0406-z

QTL, Quantitative trait loci.

FIGURE 5: An integrated crop improvement framework for genetic diversity as well as genetic resources management and its application to variety creation and genetic analysis.

groundnut, drawing upon outcomes from original research to provide a foundation for future investigations aimed at enhancing Bambara groundnut productivity.

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Competing interests

The authors declare that they have no financial or personal relationship(s) that may have inappropriately influenced them in writing this article.

Authors' contributions

M.M.H.K. wrote the first draft and incorporated the reviewed inputs into this manuscript. Later, M.R.Y., S.I.R., M.J., and M.A.M. reviewed the draft and made inputs to improve the manuscript. M.M.H.K., M.Y.R., S.I.R., M.J. and M.A.M. have read and agreed to the published version of the manuscript.

Ethical considerations

This article followed all ethical standards for research without direct contact with human or animal subjects.

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Data availability

The data supporting the findings of this study are available within the article.

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