The Journal of Agricultural Science

cambridge.org/ags

Bambara groundnut production, grain composition and nutritional value: opportunities for improvements

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Crops and Soils Review

Cite this article: Maphosa Y, Jideani VA, Maphosa L (2022). Bambara groundnut production, grain composition and nutritional value: opportunities for improvements. *The Journal of Agricultural Science* **160**, 448–458. https://doi.org/10.1017/S0021859622000521

Received: 6 March 2022
Revised: 29 July 2022
Accepted: 3 August 2022
First published online: 6 October 2022

Key words:
Food security; legumes; nutrition; sustainability; underutilized crop

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Abstract

Bambara groundnut (*Vigna subterranea* L. Verdc; BGN) is an important legume grown mainly by small-scale subsistence farmers in sub-Saharan Africa, in parts of Thailand and Indonesia. It has a high concentration of seed carbohydrate (55–70%), protein (17–25%), fat (1.4–12%) and dietary fibre (5.2–6.4%). A range of biotic and abiotic stresses together with socio-economic constraints affect its productivity, yield and quality. The changing climate and a growing world population are putting pressure on food production, as world food supply is heavily reliant on few crops. As such, there is a need to broaden crop usage and increase yield of minor crops such as BGN. Improvements in production can potentially be achieved by a combination of advanced phenotyping, genotyping, environmental characterization and overall management approaches. Breeding for advanced lines is complicated by overreliance on landraces. This review aims to provide the current status of BGN production, production constraints and approaches to overcome these, as well as its grain composition and nutritional value. It further discusses and elaborates on potentially available opportunities for overall improvement, so that BGN, like all neglected crops, can play a valuable role in world food security. Efforts should be intensified to improve the overall utilization of BGN and its constituents to make it an economically viable crop.

Introduction

Bambara groundnut (BGN) (*Vigna subterranea* L. Verdc.; Syn: *Voandzeia subterranean* L. Thouars.) ($2n = 22$) is a highly inbred, self-pollinating annual crop belonging to the Fabaceae family and subfamily Faboidea under Plantae (Bamshaiye *et al*., 2011). In-breeding and self-pollination result in increased homozygosity and restricted gene flow which decreases genetic diversity in crops (Sharma, 2017). The crop is indigenous to Africa where it is known by different names such as earth pea, jugo bean, nyimo beans or ditloo (Majola *et al*., 2021). Other common universal names are Bambara nut, Bambara bean, Congo goober, earth pea, ground-bean and hog-peanut. The plant resembles peanuts in having compound leaves with three leaflets (Bamshaiye *et al*., 2011) and bearing the fruits underground.

It is an underutilized (syn minor, neglected or orphan) protein-rich (18–26%), legume mainly grown by smallholder and low-income female subsistence farmers in poor communities in sub-Saharan Africa, under arid or semi-arid conditions (Jideani and Mpotokwane, 2009; Bamshaiye *et al*., 2011; Yao *et al*., 2015). BGN is largely drought, disease and pest resistant, with the capability of thriving under nutrient-deficient soils (Olayide *et al*., 2018; Mayes *et al*., 2019; Pasipanodya *et al*., 2022). In terms of production, socioeconomic status and consumption, it ranks third amongst legumes in Africa after groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculate*) (Murevanhema and Jideani, 2013). It is used for human consumption as an important source of protein, especially for vegetarians and poor households who cannot afford meat-based protein sources, but it is also useful as fodder for livestock. Varieties such as South African genotypes SB11-1A, SB19-1A, SB12-3B and Bambara-12 with good vegetative biomass have been identified and these are more useful for livestock feed (Unigwe *et al*., 2016).

Its centre of origin can be traced to north-eastern Nigeria and northern Cameroon where undomesticated wild relatives still exist (Mayes *et al*., 2019). However, an alternative or a potential secondary centre of domestication, evolution or diversification for the crop has been proposed to be the Southern/Eastern African region (Aliyu *et al*., 2016). Due to different centres of origin, two subpopulations have been proposed (Pasipanodya *et al*., 2022), with subpopulation I consisting of West and Central African accessions, whilst subpopulation II consists of the Southern and Eastern African accessions (Molosiwa *et al*., 2015). There are opportunities for broadening the genetic diversity by looking for favourable genes from these centres of origin. The current cultivated species was probably domesticated from these wild species. The value of wild species, despite challenges with cross-ability and/or hybridization, is immense even in legumes (Maphosa *et al*., 2020).

The main limitations of their use in breeding are incompatibility and linkage drag of detrimental genes which compromise agronomic performance and grain yield (Bohra *et al*., 2021).

There is a high level of phenotypic and allelic diversity in the BGN germplasm across genotypes from similar and/or different geographic areas of origin (Aliyu *et al*., 2016; Unigwe *et al*., 2016; Ontong *et al*., 2021). Agromorphological variability is noticeable in BGN, with the wild types displaying more spreading growth habit, which is a dominant trait compared with the domesticated bunchy types (Basu *et al*., 2007). Its growth habit ranges from erect to spreading, and leaf shape varies between genotypes. It also shows indeterminacy as flowering can continue until maturity, enabling both vegetative and reproductive phases to co-occur and/or overlap. This means that vegetative and reproductive phases can be exposed to unfavourable and stressful growth conditions simultaneously.

The changing climate and a growing world population are putting pressure on food production, as world food supply is heavily reliant on few crops. Production of all crops will have to increase by at least 70% to ensure food security for the estimated nine billion people by 2050 (Godfray *et al*., 2010). As such, in addition to major cereal crops such as wheat (*Triticum aestivum*), rice (*Oryza sativa*) and maize (*Zea mays*), there is a need to broaden crop usage and increase yield of minor crops. Importantly, there is now increasing emphasis not only on food availability but also on its quality and nutritional value. The increased utilization of BGN is predicted to play a significant role in increasing food security, alleviating malnutrition, lessening over utilization of commercial legumes such as beans, lentils, chickpeas and soybeans, as well as in being a valuable ingredient in the production of affordable nutritious products (Shanmugasundaram, 2003).

This review aims to provide the current status of BGN production, its grain composition and its nutritional value. It identifies production constraints and discusses approaches as well as modern technologies to overcome these barriers. It further discusses opportunities for overall improvement, so that BGN, like all neglected crops, can play a valuable role in world food security.

Bambara groundnut production

Despite being an agronomically and nutritionally important crop, that is cheap to cultivate, with minimal inputs even under poor sandy soils and drought-prone environments, BGN remains relatively underutilized. This may be attributed to the perception that it is of low economic value, thus often termed a 'poor man's crop' (Azam-Ali *et al*., 2001). As such, farmers designate a very low amount of the total area for its cultivation and give priority to higher market value crops such as maize, peanuts and sorghum (Shanmugasundaram, 2003). Most production, especially in sub-Saharan Africa, is by small-scale farmers who have minimal to no record-keeping skills. This, together with lack of accessibility to the farmers by data collectors, compromises or underestimates the total yield and production area. Long-term data in Africa show that yields range from 0.5 to 3 t/ha (Azam-Ali *et al*., 2001) and are on average 0.85 t/ha and with a total of 0.3 million tonnes produced per annum (Mayes *et al*., 2019). However, yields of less than 0.1 t/ha in some fields have also been reported (Baudoin and Mergeai, 2001). There is a significant yield gap between the average yields of 0.85 t/ha and potential yields of over 3 t/ha that can be achieved when production is optimized (Mayes *et al*., 2019). The low yields are attributed to limited research investment on genetic, agronomic and management improvements (Majola *et al*., 2021). Amongst the common legumes, the average yield of 0.85 t/ha is only higher than that of cowpea, dry beans and Pigeon pea, and the 0.3 million tonnes annum production is similar to chickpea but only higher than lentils (Mayes *et al*., 2019). The drivers of crop productivity are genotypes (varieties), environment (production conditions) and management practices, and their interactions. Therefore, to close the yield gap there is a need to focus the research on understanding the contribution of each component and optimizing them.

The major producers of BGN (Table 1) are the West African countries (FAOSTAT, 2018), with Burkina Faso having the largest yield but not necessarily the biggest area harvested. The Democratic Republic of the Congo has the lowest yield while Niger has the largest harvested area. BGN is also grown in other sub-Saharan African countries such as South Africa, Swaziland, Zimbabwe, Zambia and Botswana (Masindeni, 2006; Majola *et al*., 2021), but probably the scale is too small for FAO to capture it. Furthermore, it is grown, albeit at smaller scale, beyond African borders in Southeast Asia mainly in Indonesia and Thailand. Therefore, it is able to grow in a range of different and/or contrasting environments, such as the arid environment in Botswana which experiences low night temperatures and high day temperatures as well as in milder and more humid environments such as in Indonesia (Mayes *et al*., 2019).

Globally, and represented by the six major producers (Table 1), production and cultivated areas have increased while yields have remained largely stagnant (Fig. 1). Production has been steadily increasing from a low of 66 485 tonnes in 1995 to a high of 236 276 tonnes in 2018 but this was largely underpinned by an increase in total harvest area, which also steadily increased from 91 653 hectares in 1998 to 376 595 hectares in 2017. However, in the past 25 years, yield gains (averaged across the six major producers, and seven from 2012 with the addition of Zimbabwean data) have been stable ranging between 0.57 and 0.85 t/ha. In 2008, average yield was 1.14 t/ha and this was driven by a very high yield of 3.4 t/ha in Togo. The 25-year average yield in Togo is 0.851 t/ha and when 2008 is excluded the average is 0.771 t/ha. Assuming the yield data for 2008 is accurate, then there is potential to improve it and close the yield gap by

Table 1. Total area harvested, production and average yields for Bambara groundnut in 2019

Country	Area harvested (ha)	Production (t)	Yield (t/ha)
Burkina Faso	59 926	58 435	0.975
Cameroon	66 675	51 265	0.769
Mali	38 789	26 076	0.672
Niger	68 073	44 807	0.658
Togo	26 422	20 154	0.763
Zimbabwe	83 750	17 182	0.205
Democratic Republic of Congo	27 318	11 001	0.403

Source: FAOSTAT (2018).

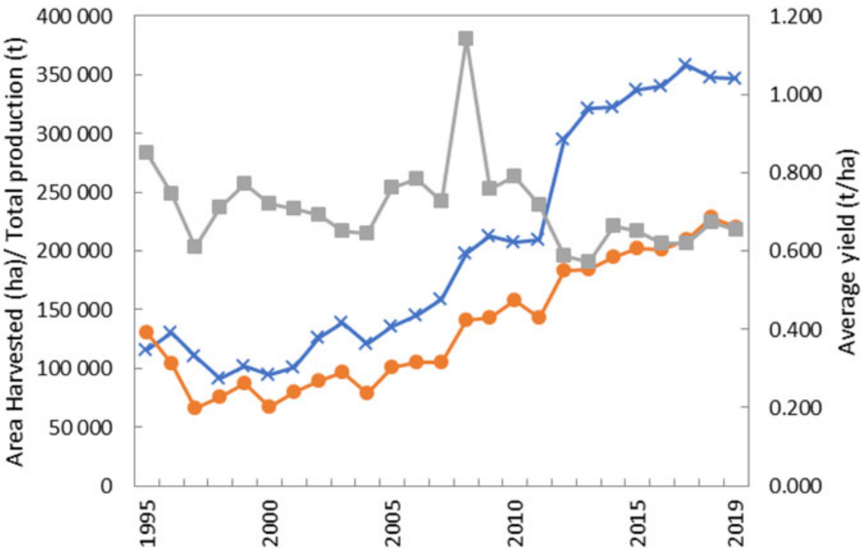

Fig. 1. Colour online. Global [represented by six* (and seven** from 2012) major producers] total production, cultivated and average yield of Bambara groundnut over a period of 25 years.

harnessing the approaches adopted in Togo in 2008. The stagnation of yield indicates that in the past two decades there has been less attention and/or attempt to close the yield gap through concerted and coordinated research, management practices and use of improved varieties.

Within agricultural systems, BGN is grown either in mixed/inter cropping with cereals, other legumes or as a standalone crop in rotation. As a legume, it has the capacity to fix atmospheric nitrogen thereby contributing to soil fertility and minimizing the need for artificial fertilizers (Mayes *et al.*, 2019). It can fix between 32 and 81 kg of nitrogen per ha (Majola *et al.*, 2021). The varieties mostly grown are landraces, where farmers use their own saved or locally procured seeds, an indication of lagging behind in terms of breeding progress and uptake of available commercial varieties.

BGN has a well-developed taproot with several lateral stems up to 20 cm long, from which leaves grow (Bamshaiye *et al.*, 2011). The leaves are trifoliate and can be up to 5 cm long. Their petiole is grooved, up to 15 cm long and their base is either green or purple in colour (Gulu, 2018). BGN flowers are typically *papilionaceos* and grow in a raceme on long, hairy peduncles, which arise from the nodes on the stem (Massawe *et al.*, 2005). Cross-pollination of the spreading type is commonly done by ants while the branching type usually self-pollinates. After fertilization, the flower stem elongates, the sepal enlarges and the fruit develops just above or just below the soil surface (Gulu, 2018). This makes mechanical harvesting very difficult, and as a result BGN is commonly handpicked, a major drawback when it comes to large-scale harvesting (Gulu, 2018). The pods are very small, about 1.5 cm in size depending on variety. They are wrinkled, round or semi-oval in shape and house one or two seeds (Bamshaiye *et al.*, 2011). The unripe pods are yellow-green while the mature pods are yellowish, reddish, dark brown or purple (DAFF, 2011).

Bambara groundnut varieties

There is a large variation in BGN seeds as demonstrated by different seed colours and patterns (Fig. 2). Seven seed types have been reported, namely cream with brown-eye, cream with black-eye, red, cream with no eye, black, purple and speckled/flecked/spotted (Diedericks, 2014). However, the most common type of BGN seeds is the cream varieties in sub-Saharan Africa. The black and purple varieties are common in Indonesia while the red seed is common in Thailand. The colour of the testa varies according to ripeness and variety, with colours such as cream, black, red and purple.

The cream with black-eye as well as the cream with brown-eye are generally high yielding and have large (>10.50 mm) and medium (9.50–10.49 mm) sized kernels, respectively, while the cream with no-eye are poor yielding, and have very small (<9.50 mm) kernels (Mpotokwane *et al.*, 2008; DAFF, 2011). The brown variety has medium (9.50–10.49 mm) to large (>10.50 mm) sized kernels varying between light and dark brown in colour (Mpotokwane *et al.*, 2008; Maphosa, 2016). The black variety is early maturing and has small to medium-sized (9.50–10.49 mm) kernels. The purple and speckled varieties have one-seeded pods and small (<9.50 mm) kernels (Anon., 2011; DAFF, 2011). The red variety is late maturing, has large (>10.50 mm) kernels and is prone to rotting onsite (DAFF, 2011). The red variety has been reported to have almost double the amount of iron as the cream varieties and, hence, it can be useful in curbing iron deficiency (Hillocks *et al.*, 2012).

Nutritional composition of Bambara groundnut

BGN has immense nutritional potential and, hence, is included as a valuable crop by the African Orphan Crop Consortium. It has nutrients in adequate quantities to provide a balanced diet (Maphosa, 2016). BGN has a high nutritional value with carbohydrates, proteins, dietary fibre and fat in the range 55–70%, 17–25%, 5.2–6.4% and 1.4–12%, respectively. The nutritional composition of BGN is given in Table 2.

BGN has a comparable protein (20.8%) and carbohydrate (61.9%) content to more commercialized legumes such as cowpea, kidney beans, broad bean and chickpea, but it has a lower protein and fat content than soybeans as shown in Fig. 3 (Gulu, 2018). Of the legumes reported in Fig. 3, soybean has the highest protein (36.5%) and fat (19.9%) as well as the lowest carbohydrate content (30.2%). BGN protein is rich in the essential amino acids, methionine (3%) and lysine (2%) (Murevanhema and Jideani, 2013). It has a higher leucine, isoleucine, lysine, methionine,

Fig. 2. Colour online. Different varieties of Bambara groundnut seeds: (a) cream black-eye, (b) cream brown-eye, (c) brown, (d) red, (e) speckled/spotted, (f) cream no-eye, (g) black, (h) purple (Diedericks, 2014).

phenylalanine, threonine and valine composition (Table 3) than groundnut, one of the most consumed legumes (Olaleye *et al.*, 2013). The concentration of lysine makes it suitable for complementing cereals such as wheat and rice, which have a low lysine content (Murevanhema and Jideani, 2013). Furthermore, the high protein content of BGN (17–25%) makes it an excellent source of proteins for those who do not consume animal protein as well as lower socioeconomic class individuals who cannot afford meat-derived protein (Guillon and Champ, 2002; Massawe *et al.*, 2005; Bamshaiye *et al.*, 2011).

BGN also contains minerals such as potassium (1545–2200 mg/100 g), magnesium (32–335 mg/100 g), calcium (30–128 mg/100 g), iron (2–9 mg/100 g) and phosphorus (81–563 mg/100 g) (Table 4). The recommended dietary allowance for adults are also presented in Table 4.

The BGN fat is naturally cholesterol-free and low in saturated fatty acids (Shanmugasundaram, 2003) making it healthier than animal protein. The fatty acid profile of BGN makes its inclusion in diets important for aiding weight loss, reducing the risk of heart-related disease and lowering cholesterol levels. Table 5

Table 2. Proximate nutritional composition of Bambara groundnut seeds

Nutrient	Composition (g/100 g) (amino acids expressed in mg/g of protein[a])
Fat	1–12
Carbohydrates	55–71
Protein	17–26
Starch	22–50
Dietary fibre	5–12
Soluble fibre	1–24
Insoluble fibre	10–16
Sugars	2.4
Ash	3–12
Moisture	13–1
Essential amino acid[a]	67.28
Non-essential amino acid[a]	32.72

[a] Essential and non-essential amino acids expressed in mg/g of protein.
Adapted from: Murevanhema and Jideani (2013); Olaleye *et al.* (2013); Maphosa (2016); Yao *et al.* (2015); Khan *et al.* (2007); Majola *et al.* (2021).

shows the fatty acid composition of BGN. The main fatty acids in BGN are oleic (18:1 n-9), linoleic (18:2 n-6) and palmitic (16:0) representing 23, 36 and 21%, respectively (Yao *et al.*, 2015). BGN has both the omega 3-(n-3) and omega 6-(n-6) fatty acids among other polyunsaturated fatty acids (PUFA) (Okafor *et al.*, 2022) suggesting that its consumption would promote health benefits associated with these PUFA.

BGN has a high concentration of soluble dietary fibre (15–17%) (Maphosa, 2016). This content is higher than that of common legumes such as pea, broad pea and soybean which ranges between 3.3 and 13.8% (Guillon and Champ, 2002; Khan *et al.*, 2007). This further accentuates its nutritional quality, as soluble dietary fibre plays a major physiological role in reducing constipation, obesity, diabetes, heart complications, piles and some cancers (Khan *et al.*, 2007). Furthermore, soluble dietary fibre plays a role in lowering blood cholesterol, improving glucose tolerance and reducing glycaemic response by reducing glucose and cholesterol assimilation into the bloodstream (Khan *et al.*, 2007). Table 6 shows the non-starch polysaccharide composition of BGN.

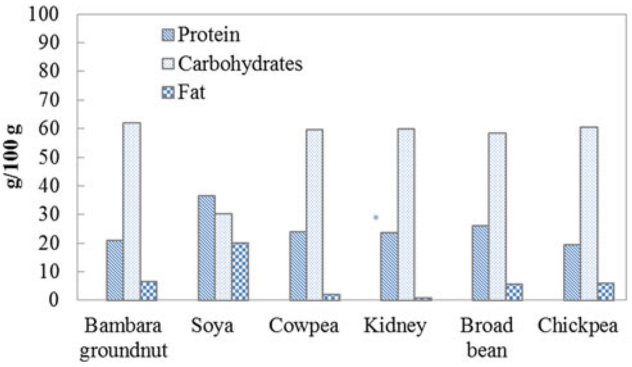

Fig. 3. Colour online. Protein, carbohydrate and fat composition of various legumes (Gulu, 2018).

Table 3. Amino acid composition of Bambara groundnut seeds

Amino acid	mg/g of crude protein
Histidine	38.6
Isoleucine	54.5
Leucine	102.1
Lysine	80.2
Threonine	44.3
Tryptophan	6.0
Valine	62.4
Methionine	6.4
Cysteine	24.1
Tyrosine	31.3
Phenylalanine	76.9
Aspartic acid	146.1
Serine	68.5
Glutamic acid	209.5
Proline	53.6
Glycine	46.5
Alanine	51.4
Arginine	74.8
Amino acid score	0.91
Sum of aromatic amino acids (phenylalanine + tyrosine)	108.2
Sum of sulphur amino acids (methionine + cysteine)	30.5

Source: Olaleye *et al.* (2013).

Table 7 shows the carotenoids, tocopherols, polyphenols and antioxidant capacity of BGN. The total polyphenolic content and ferric reducing antioxidant power of BGN are 706.9 mg CE/100 g and 0.62 mmol of Fe^{2+}/100 g, respectively (Olaleye *et al.*, 2013). Antioxidant compounds have the capacity to react with free radicals forming stable or non-reactive radicals thereby reducing inflammation in the human body, as well as providing anti-cancer and anti-ageing benefits (Maphosa and Jideani, 2016).

The presence of antinutrients, such as condensed tannins, interferes with the digestion and bioavailability of nutrients. Condensed tannins are polyphenolic compounds present in many legumes and range from 0.01 to 2.37 mg/m in BGN (Harris *et al.*, 2018; Okafor *et al.*, 2022). They inhibit protein digestion by inhibiting the proteolytic activity and forming indigestible complexes with protein, consequentially reducing the bioavailability of amino acids. Trypsin inhibitors inhibit the activity of digestive enzymes. Processing and pre-processing methods such as cooking, roasting, germination and soaking significantly reduce the tannin content in BGN seeds (Olaleye *et al.*, 2013; Yao *et al.*, 2015).

Uses of Bambara groundnut

BGN is mainly cultivated for food purposes (Table 8) and is consumed mostly at household level with little or no trading taking place. Apart from food applications, some cultures believe that BGN has medicinal properties and can be used in traditional

Table 4. Mineral composition of Bambara groundnut and corresponding recommended daily allowances for adults

Mineral	Composition (mg/100 g of seed)	Recommended daily allowance for males[a] (mg/day)	Recommended daily allowance for females[b] (mg/day)
Potassium	1545–2200	3500–4700	3500–4700
Magnesium	32–335	260	220
Calcium	30–128	800–1000	1000–1300
Sodium	16–25	2200–2300	2200–2300
Iron	2–9	11–14	24–29
Phosphorus	81–563	800–1200	800–1200
Zinc	11–40	15	12

[a] Males (weight = 65 kg, age = 19–65 years).
[b] Females (weight = 55 kg, age = 19–65 years).
Adapted from: Majola *et al.* (2021); Maphosa (2016); Yao *et al.* (2015); Murevanhema and Jideani (2013); Olaleye *et al.* (2013); Khan *et al.* (2007); FAO (2001).

ceremonies such as funerals, weddings, rituals and gift exchanges (Gerrano *et al.*, 2013). The fresh or dry seeds are boiled, fried, steamed or roasted and consumed on their own or are incorporated in other dishes such as soups, gravies and relish (Table 8). A probiotic beverage and yoghurt from BGN were found to have potential as alternatives for lactose-free milk in the market (Murevanhema and Jideani, 2013). The probiotic beverage was characterized by a high phenolic and flavonoid content suggesting the presence of antioxidant properties (Jideani and Murevanhema, 2013). Sensory evaluation indicated that the probiotic beverage and yoghurt would be widely accepted in the market by all age groups. Notable is the work of Jideani and Murevanhema (2013) who patented a process to produce a prebiotic beverage from BGN flour.

Table 5. Fatty acid composition of lipid extract from Bambara groundnut seeds

Fatty acid	Composition (g/100 g)
Palmitic acid	20.6
Palmitoleic acid	0.30
Margaric acid	0.70
Stearic acid	7.12
Oleic acid	22.6
Linoleic acid	35.9
α-linolenic acid	1.30
Arachidic acid	2.00
Gadoleic acid	0.55
cis-11.14-eicosadienoic acid	0.07
Arachidonic acid	0.05
Behenic acid	5.41
Lignoceric acid	1.86
Total saturated fatty acids	37.9
Total monounsaturated fatty acids	23.5
Total polyunsaturated fatty acids	37.3
Total n-3 fatty acids	1.30
Total n-6 fatty acids	36.0

Source: Minka and Bruneteau (2000); Olaleye *et al.* (2013); Yao *et al.* (2015).

The addition of boiled BGN to fermented maize dough increased its protein content from 10 to 16.4% (Hillocks *et al.*, 2012). BGN flour can be utilized by the cereal and baking industry as a wheat replacement in biscuit and flat cakes (Hillocks *et al.*, 2012). Insoluble fibres from BGN black-eye, brown-eye, red and brown varieties significantly increased the dietary fibre content of white bread, lowered the specific loaf volume and had positive textural effects especially on crumb softness (Diedericks, 2014). As such, BGN insoluble fibres would make good ingredients and fortifying agents in the baking industry. Jideani and Diedericks (2014) patented the extraction of dietary fibre from BGN seeds using the enzymatic-gravimetric method. The effect of BGN flour on the stability and rheology of oil-in-water emulsions was studied (Adeyi, 2014) and was shown to positively influence the stability as well as the time-dependent, time-independent and oscillatory characteristics of the studied oil-in-water emulsions. BGN flour is a better emulsifier than BGN starch as it significantly reduces the migration rate of oil droplets and reduces oil droplet size resulting in higher stability (Gabriel *et al.*, 2013). This is because BGN flour has proteins and dietary fibre, in addition to the starch, which contributes to its emulsifying and stabilizing power (than groundnut, one of the most consumed legumes) (Olaleye *et al.*, 2013; Maphosa, 2016).

Maphosa and Jideani (2016) extracted and studied BGN-soluble and insoluble dietary fibre, reporting many desirable physicochemical properties of both. Soluble dietary fibre proved to be a good orange oil beverage emulsion stabilizer. Maphosa *et al.* (2022) produced a nanocomposite from BGN starch and soluble dietary fibre and used it to stabilize beverage emulsions at significantly lower concentrations than BGN-soluble dietary fibre.

However, despite these potential and diverse uses and benefits, BGN is often neglected as a consumable legume due to its

Table 6. Non-starch polysaccharide composition of Bambara groundnut seeds

Non-starch polysaccharides	Composition (g/100 g)
Acid detergent fibre	16–66
Neutral detergent fibre	6–84
Acid detergent lignin	15–68
Cellulose	5–86
Hemicellulose	3–90

Source: Olaleye *et al.* (2013).

Table 7. Carotenoids, tocopherols, total polyphenols and total antioxidant capacity of Bambara groundnut seeds

Component	Composition
α-Tocopherol (mg/100 g)	0.38
Total polyphenols (mg CE/100 g)	706.9
Ferric reducing antioxidant power (FRAP) [mmol of $Fe^{2+/}$100 g]	0.62
Trolox equivalent antioxidant capacity (TEAC) [mmol Trolox/100 g]	2.20
γ-Tocopherol	ND
δ-Tocopherol	ND
β-Tocopherol	ND
Carotenoids	ND

CE, catechin equivalents; ND, not detected.
Source: Olaleye *et al.* (2013); Yao *et al.* (2015).

hard-to-cook phenomenon and the lack of sufficient knowledge on ways of utilizing the seeds (Murevanhema and Jideani, 2013). Fresh BGN seeds are preferred to dry seeds by a majority of consumers because they do not require large amounts of time and energy to cook (Mubaiwa *et al.*, 2016).

Production constraints

The average growth period of BGN is 110–150 days (Basu *et al.*, 2007). During the growth period, a range of production constraints limit production, but there is scope to use modern approaches to improve and overcome these production barriers. Biotic stresses, that is, diseases caused by fungi, bacteria and viruses; insect pests; and nematodes, affect productivity as well as overall yield and quality (Majola *et al.*, 2021). However, some of the diseases can be controlled using crop protection chemicals and good agronomic management practices such as crop rotation, burning of previous season's debris and the application of ash on storage seeds. The diseases commonly identified in BGN were extensively reviewed by Majola *et al.* (2021) and they are mostly caused by fungi, viruses, insects and nematodes. Fungal diseases of BGN include leaf spot (*Cercospora canescens*) (Ellis and Martin), leaf blight (*Colletotrichum graminicola* [Ces.] G.W. Wils), Fusarium wilt (*Fusarium oxysporum* Schlechtend f.sp. *voandzeia*), and rust (*Puccinia graminis* f.sp. *Tritici*) and dieback disease (*Lasiodiplodia theobromae* [Pat.] Griff. & Maubl). Phomopsis sp., Aspergillus genera and *Sclerotium rolfsii* (Sacc.) also cause diseases in BGN. The common viral diseases are cowpea aphid-borne mosaic virus, black-eye cowpea mosaic virus, peanut mottle potyvirus, cowpea mottle comovirus, cowpea yellow mosaic virus and Rosette virus disease. The pests that affect BGN include root-knot nematode [*Meloidogynae javanica* Treub], leafhoppers [*Hilda patruelis* (Stal) and *Empoasca facialis* (Jacobi), Aphids, groundnut jassid (*Empoasca kerri* Pruthi)] as well as brown leaf beetles (*Ootheca mutabilis* Schönherr). After harvest the postharvest storage insect pests often encountered are cowpea weevil (*Callosobruchus maculatus* F.) and Bruchids (*Callosobruchus maculatus* Boh.). Diseases can affect seed germination, physiological processes, crop growth, seed quality and may result in production of mycotoxin which is harmful to both humans and livestock when the grain or straw is consumed.

Major abiotic constraints to BGN production include erratic rainfall, temperature extremes (very high and low), altitude and poor soils (Gerrano *et al.*, 2013). In addition to potentially shifting seasonal conditions, climate change can also alter the epidemics and threats of plant pests and diseases (West *et al.*, 2012). The effects of predicted climatic changes are expected to be dire and might shift the rainfall season causing a disruption to the planting

Table 8. Various food uses of Bambara groundnut

Form	Uses	References
Mature, fresh or dry seeds	Eaten as pulse	Brink *et al.* (2006)
Dried seeds (whole or split)	Boiled with maize or plantains	Lim (2012)
Dried seeds (ground)	Added to maize flour for porridge	Brink *et al.* (2006)
Soaked and ground seeds	Paste for fried or steamed dishes	Brink *et al.* (2006)
Boiled salted seeds	Appetizers	Lim (2012)
Dried seeds	Commercially canned in gravy	Lim (2012)
Dried and boiled	Used in soups	Murevanhema and Jideani (2013)
Crushed, roasted seeds	Relish	Lim (2012)
Milk derived from seeds	Yoghurt beverages	Murevanhema and Jideani (2013)
Testa-free fresh seeds	Consumed as a complete meal by cooking with seasoning	Jideani and Diedericks (2014)
Dry seeds	Boiled and crushed seeds used to form cakes/balls followed by frying and adding to stews	Jideani and Diedericks (2014)
Fresh green nuts	Steamed or grilled and served as titbits	Khan *et al.* (2007)
Flour	Porridge, bread, flat cakes, soup, coffee substitute, used as a thickener, dumpling	Mazahib *et al.* (2013) Hillocks *et al.* (2012)
Brewed gel from slurry	Okpa or Moi-Moi	Khan *et al.* (2007)

calendar of subsistence farmers who are reliant on rainfall patterns (Aliyu *et al.*, 2016; Pasipanodya *et al.*, 2022).

Furthermore, most subsistence farmers are farming on poor and depleted soils in marginal lands. Stresses can occur simultaneously or have contrasting effects, for example, heat and drought stress (or salinity and drought) tend to occur co-concurrently and can be under similar or same genetic control mechanisms (Tricker *et al.*, 2018). BGN is largely considered to be a drought resilient crop (Mayes *et al.*, 2019), though drought affects a range of its traits and physiological processes (Table 9).

It requires an average rainfall of about 600–700 mm during the growing season to maximize yield, though later research has estimated the minimum rainfall requirement of the crop to be around 300 mm (Majola *et al.*, 2021). Plant response to drought involves avoidance, escape or tolerance (Mayes *et al.*, 2019) and all the three mechanisms have been observed in BGN to varying levels (Jorgensen *et al.*, 2010; Mabhaudhi and Modi, 2013; Chai *et al.*, 2016). Excessive rainfall especially during maturity and/or harvest potentially causes waterlogging and affects the underground grain causing yield losses. To avoid water logging, BGN crops are planted on moulds or ridges (Gulu, 2018).

It is frost sensitive at any growth stage and warm temperatures accelerate plant development, with 19–30°C being ideal for optimal development (Masindeni, 2006). Temperatures above 30°C cause heat stress and limit yield (Majola *et al.*, 2021). Extreme temperatures (high or low) cause dying or wilting of the leaves, and reduction of biomass accumulation and ultimately yield. Fruits (grains) are below ground and thus a properly aeriated, well-drained, loose sandy loam soil is preferable as it does not damage the seeds. It is also susceptible to anoxic/hypoxic stress factors (sensitivity to flooding) (Sesay *et al.*, 2013), and thrives best in soils with a pH between 5 and 6.5.

Production improvement approaches

Co-ordinated and cross-disciplinary approaches are needed in crop improvement for BGN. These would facilitate proper and detailed environmental characterization, adoption of modern phenotyping technologies in both the field and laboratories to complement breeding approaches. Within breeding programmes, the role of landraces and wild relatives in providing genetically diverse material and potential genes of interest should be incorporated.

Table 9. Bambara groundnut traits and physiological processes affected by drought

Response	Reference
Canopy development, size and duration	Jorgensen *et al.* (2010); Mabhaudhi and Modi (2013)
Biomass accumulation and partitioning	Mabhaudhi and Modi (2013)
Phenological plasticity	Mabhaudhi and Modi (2013); Nautiyal *et al.* (2017)
Gas exchange	Mabhaudhi and Modi (2013); Chai *et al.* (2016); Nautiyal *et al.* (2017)
Osmoregulation and regulation of photosynthesis	Mabhaudhi and Modi (2013); Chai *et al.* (2016); Nautiyal *et al.* (2017)
Leaf temperature-transpiration (leaf orientation/paraheliotropism) and epicuticular wax	Nautiyal *et al.* (2017)

Environmental characterization

In controlled environments, data capture is easier compared to under field conditions. However, crops behave differently in pot experiments under controlled glasshouse conditions compared to the field where they exist as a community, and the results from controlled conditions are not easily extrapolatable to the field. Lack of detailed and accurate environmental data especially in the field can hinder production and is therefore an area that needs improvement. This includes proper soil characterization especially the rhizosphere microorganism community, accurate recording of temperature and rainfall, exact geographic location of field, weed and disease control measures, sowing time, intercropping and rotations. In drought studies, for example, proper environmental characterization, beyond recording irrigation applied or rainfall received, is important as soil moisture and/or soil holding capacity is likely to differ between environments. The concept of 'envirotyping' has been proposed as a third 'typing' technology, complementing genotyping and phenotyping (Xu, 2016). The approach encourages precise dissection of the environment through zooming into specific field plots and individual plants, as opposed to wholesome measurement of field environmental data wherein field variation would always exist (Xu, 2016). This concept can potentially be key in improving BGN productivity and quality.

Modern phenotyping technologies

The high throughput phenotyping (HTP) technology is continuously being employed extensively in agriculture and plant science research, and excellent research and reviews have discussed this concept in greater detail (White *et al.*, 2012; Araus and Cairns, 2014; Wang *et al.*, 2014; Zhou *et al.*, 2017; Sankaran *et al.*, 2018; Maphosa *et al.*, 2020) and is a promising tool for improving BGN production. In BGN, the approach has been adopted, with normalized difference vegetation index, enhanced vegetation index 2, green normalized difference vegetation index and simple ratio generated from the red-green near infrared bands shown to be correlated to grain yield in BGN using a high throughput and low-cost UAV-based remote-sensing technology (Jewan *et al.*, 2021). A detailed but non-exhaustive list of HTP technologies applicable to legumes was given by Maphosa *et al.* (2020) and thus would not be repeated in this manuscript. The approach involves application of sensor or image-based tools, to non-destructively and non-evasively measure crop traits across time and space. The screening tools can be handheld (Tracy *et al.*, 2020), airborne (Bian *et al.*, 2019), ground-based vehicles (Maphosa *et al.*, 2017), thermal and hyperspectral imagery or shovelomics (Chen *et al.*, 2017). Key production traits that can be captured include phenology, early vigour, crop growth status, water content, biomass, yield potential and grain quality (colour and size). Common approaches to measuring and/or recording these important traits are manual, laborious and time consuming, for example, biomass cuts. Also, recording phenology is largely based on subjective scales that can introduce bias especially if more than one person is involved in the scoring. With these commonly used approaches there is a limit on the number of genotypes that can be accurately screened thus necessitating adoption of rapid HTP ones.

Improved breeding

The focus of breeding programmes is to improve grain yield and nutritional quality. The BGN genome has not been fully explored, compared to other high value crops, and this presents opportunities to further explore the available germplasm and genetic variation for breeding and cultivar development (Majola *et al.*, 2021). Limited controlled breeding programmes for BGN are hampering research, improvement and release of advanced varieties. There are few known cultivars, with production still heavily reliant on landraces, and the breeding approach is not clearly defined leading to limited germplasm development progress. Research can benefit from related studies in model species through comparative genetic approaches (Aliyu *et al.*, 2014) as there often tends to be strong conserved synteny across related crop species (King *et al.*, 2013). Like most underutilized crops, BGN's pedigree structure can be defined as 'flat genetic structure' since it is composed of a mixture of genotypes with disconnected non-hierarchical populations (Aliyu *et al.*, 2014). Costs, though decreasing, remain a limitation for breeding underutilized species as they are seldom funded.

The available diversity at both phenotypic and genotypic levels is sufficient to support breeding improvement programmes. Characterization, at molecular and phenotypic level of available landraces (Masindeni, 2006; Unigwe *et al.*, 2016), can form the foundation and/or theoretical framework for improvement through identifying potential favourable parents. For promising genotypes, the original source can be tracked back and be searched for additional favourable traits (Aliyu *et al.*, 2014). The challenge with landraces, however, is that they have high heterozygosity as they often are a mixture of genotypes which complicates understanding the underlying genetic control mechanisms and overall genotype-by-environment (G × E) interactions. G × E interactions play a huge role in crop productivity (Richards *et al.*, 2020), and together with management can result in quantum leaps in yield, and closure of the yield gap. The environmental influence in G × E interactions reduces heritability, thus complicating the selection process. To advance breeding and achieve homozygosity, measures must be in place to create pure lines through single seed descent. From this seed a characterizable genotype can be developed and tested in multi environment trials.

Within a breeding programme, a range of statistical methodologies that can test genotype stability or environmental sensitivity such as GGE biplot analysis can be effectively used in selecting potential genotypes (Malosetti *et al.*, 2020). Sound agronomic genomics, an integration of agronomy with the available 'omics' to optimize gene expression (Xu, 2016), is another approach with potential to breed for enhanced crop varieties. These enable identification of adapted and environmentally stable genotypes. However, to some limited extent, BGN improvement has been aided by adopting modern genetics and genomic approaches to complement conventional breeding in the selection of favourable traits (Basu *et al.*, 2007). This would be further enhanced by the availability of the completed genome sequence. Like other crops with significant nutritional and cultural importance, BGN genetic resources (6145 accessions) are held in gene banks worldwide, with IITA-GRC – Nigeria holding the largest (2031) number collected from 25 different countries (Muhammad *et al.*, 2020; Pasipanodya *et al.*, 2022). A suite of breeding approaches were widely discussed by Maphosa *et al.* (2020) and references therein such as conventional, molecular and genomic assisted breeding, physiological, shuttle and speed breeding and these can be employed in improving BGN.

Breeding programmes have adopted several marker types as amplified fragment length polymorphism (AFLP), restriction fragment length polymorphism, simple sequence repeats (SSRs), inter sequence repeats, random amplified polymorphic DNA and genotyping by sequencing to genotype BGN (Aliyu *et al.*, 2016). Furthermore, as reviewed extensively by Pasipanodya *et al.* (2022) linkage mapping using bi-parental populations has been used to study marker trait association and identification of useful QTLs. A marker (bgPabg-596774) associated with number of pods, number of nodes, pod weight, number of seed, seed weight and biomass dry weight traits has been identified in BGN (Ahmad *et al.*, 2013). However, the availability of the draft reference genome of BGN (National Center for Biotechnology Information (NCBI) database) offers further opportunities to identify genetic regions associated with traits of interest and accelerate genetic gains. The draft genome is 535.05 Mb in size from which 31 707 protein-coding genes are predicted (Chang *et al.*, 2019). Also, environment association analysis which uses georeferenced genetic materials to model associations between genetic sequences and environmental attributes can be adopted to identify candidate genes for environmental adaptation (Rellstab *et al.*, 2015).

Conclusion and prospects

Concerted improvement of grain yield and nutritional value will increase productivity and adoption of BGN by farmers. This however must be underpinned by improvements in crop management practices, value chains and market access, as well as overall sustainable collaboration across disciplines. At farm level, this would involve the use of improved and well-characterized varieties, adoption of modern phenotyping technologies, following sound agronomic advice and management practices as well as detailed characterization of the field. Despite having nutritional advantages over other commercial legumes, BGN has not developed as a traded commodity. This could be due to insufficient demand in the formal market resulting from lack of marketing and promotion. Empirical evidence and various research outcomes support the potential of BGN both as a crop and as food. BGN deserves more publicity and increased utilization than it is currently receiving. It is a low budget, low cost, reliable crop that thrives in adverse conditions, considered too harsh for other crops. The public, especially the lower income groups, need to be educated on the nutritional value of BGN. For example, the production of a probiotic beverage from BGN flour proved to be energy saving and, thus, would result in an affordable product in the marketplace. BGN has potential to be used in different branches of the food industry. Efforts should be intensified to improve the utilization of BGN in Africa and the rest of the world. There is a considerable need for new and innovative uses of BGN. The challenge is to narrow the gap and improve food security at household level. To attract the attention of consumers, innovative ways of presenting BGN as a food or food ingredient are required. Innovation may include the production of snacks from BGN, marketing BGN as a prebiotic and extracting the constituents of BGN such as dietary fibre for inclusion in other food applications.

Author contributions. Yvonne Maphosa: substantially contributed to the conception and design of the article and interpreting the relevant literature; wrote the article. Victoria A. Jideani: supervised the writing process; critically revised the article for important intellectual content. Lancelot Maphosa:

substantially contributed to the conception and design of the article and interpreting the relevant literature; wrote the article.

Financial support. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Conflict of interest. None.

Ethical standards. Not applicable.

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