Characterisation of Bambara groundnut landraces: Nutritional and proximate composition

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Bambara groundnut (BGN) is a promising but underutilised legume, and there is limited research on its nutritional composition. In this study, we sought to assess the nutritional makeup of 70 BGN landraces, focusing on proximate, mineral, carbohydrate, amino acid, and fatty acid content. Results revealed sucrose as the predominant sugar (91%) with an average gross energy of 17.21 MJ/kg, and with fat content at 6.34% and crude protein at 19.20%. Tryptophan was the least available essential amino acid. Notable saturated fatty acids included linoleic acid (41%) and oleic acid (21%). Potassium and sodium emerged as primary macrominerals, whilst iron dominated amongst microminerals. In addition to these positive attributes, BGN was consistent in other nutritional parameters. The proximate analysis (ash, moisture, acid detergent fibre, and neutral detergent fibre content) fell within the typical ranges observed in most legumes. Of the 70 landraces, 6 (BGN 13, 23, 35, 48, 55, and 57) exhibited superior nutritional profiles. The identification of these specific landraces with superior nutritional profiles offers practical guidance for targeted cultivation efforts. That is, by strategically selecting and cultivating these landraces, it may become possible to maximise the nutritional benefits of BGN and address specific dietary deficiencies. This approach aligns with the overarching goal of ensuring food security and improving nutrition outcomes globally, and specifically on the African continent.

Significance:

- BGN holds promise for enhancing food security in sub-Saharan Africa.
- This research highlights the nutritional composition of BGN, addressing prevalent nutrient deficiencies in the region.
- Understanding the nutritional value of BGN enables informed agricultural strategies, promotes its cultivation as a sustainable nourishment source and enhances resilience against food insecurity.
- Identifying specific landraces with superior nutritional profiles offers practical insights for targeted cultivation efforts.
- Targeted cultivation can maximise the nutritional benefits of BGN.
- This research provides a tangible pathway to address dietary deficiencies and advocate for healthier, more sustainable diets.

Introduction

The production of nutritionally dense and healthy food is a pressing issue in agriculture.[1,2] This issue has arisen because of growing populations, climate change, increasing food demand and the depletion of natural resources.[3] In addition, climate-related challenges threaten the nutritional status of staple crops. In sub-Saharan Africa, more than 30 million people are reported to be malnourished as they do not have access to a healthy and nutritious balanced diet.[4] The inability to access nutritious food promotes poor health and increases food insecurity challenges in many countries. It is therefore important to consider the cultivation of nutrition-dense crops, moving towards the direction of nutrient-sensitive agriculture, which recognises the critical link between agriculture and nutrition, promoting crops, such as legumes, that provide not only calories but also essential nutrients.[5]

Legumes stand out globally as economical and sustainable alternatives to meat, constituting a crucial source of proteins, carbohydrates, amino acids, fats, and a wide range of other essential nutrients.[6] In particular, the prominence of proteins in legumes, coupled with a significant presence of the essential amino acid lysine, positions them as a nutritional powerhouse.[7] This lysine content is particularly advantageous as it effectively complements cereals, which are commonly deficient in lysine and proteins.[8,9]

Despite the nutritional significance of legumes, their optimal utilisation relies on a comprehensive understanding of their functional properties and nutritional value.[7] Unfortunately, many legumes have been overlooked, both in terms of potential improvement and consumption. Bambara groundnut (BGN), often classified as an underutilised legume, emerges as a standout example with considerable untapped potential. Recognised as a comprehensive food source, BGN seeds boast richness in various essential nutrients, rendering them a valuable dietary resource.[10-12] Expanding dietary choices to incorporate lesser-known legumes, such as BGN, presents a unique opportunity to not only enrich nutritional intake but also effectively address dietary deficiencies.[13] The multifaceted benefits of incorporating such underutilised legumes highlight the importance of broadening our perspectives on dietary diversity for enhanced overall nutrition.

Bambara groundnut is increasingly promoted for cultivation owing to its status as a low-input crop, requiring minimal external inputs for successful growth.[14,15] This classification indicates that BGN requires fewer agricultural resources (i.e. seeds, fertilisers, herbicides, etc.) to attain satisfactory yields compared to other crops, such as maize and wheat.[16,17] This makes BGN an attractive and sustainable option for farmers, particularly in regions where resources are limited or where a focus on reducing input costs is essential. Cultivating this underutilised legume can contribute to food security and improve agricultural sustainability.[18]

Bambara groundnuts are cultivated from landraces whose nutritional composition is poorly studied and documented. Siwale et al.[19] estimated the protein content, starch components as well as selected minerals and their bioavailability in 59 BGN landraces. In another study, Mbuma et al.[20] analysed 64 southern African BGN landraces for protein content, selected minerals, oil content and fatty acids, whilst Hlanga et al.[21] evaluated the mineral, protein, moisture, ash, and starch contents of 19 BGN landraces. Yao et al.[22] evaluated the fatty acid, amino acid, and mineral compositions of 10 BGN landraces from Côte d'Ivoire. Atoyebi et al.[23] assessed the mineral, total carbohydrate, amino acid, and proximate compositions of 20 BGN landraces from Nigeria, whilst Baptista et al.[24] determined the fat, fatty acid, amino acid, and protein contents of two BGN landraces from Mozambique. All these studies reported significant variation in the nutritional profiles of BGN but did not provide a full and comprehensive analysis of the nutritional profiles of all the landraces that they studied. That is, they focused only on a few nutritional parameters and did not specify which landraces were under investigation. There is also a lack of studies evaluating crude protein and amino acids, gross energy, and carbohydrates in the form of sugars.

Therefore, a comprehensive analysis of the nutritional composition of individual BGN landraces is vital to identify those landraces that are superior to others. This study fills this research gap through the evaluation of the nutritional composition of 70 BGN landraces. We determined the carbohydrate, amino acid, fatty acid, and mineral contents and proximate composition (acid detergent fibre [ADF], neutral detergent fibre [NDF], ash, crude protein, fat, gross energy, and moisture) of the 70 landraces.

Materials and methods

Sample and preparation

Bambara groundnut seeds used in this study were obtained from subsistence farmers in the Limpopo Province (23.4013°S, 29.4179°E) of South Africa. The seeds were sorted and grouped by seed coat colour/pattern, eye colour/pattern, and testa colour/pattern according to the International Plant Genetic Resources Institute's BGN identification guidelines.[25] Seventy landraces were identified (Figure 1). The nutritional content of these landraces was determined from mature seeds harvested in a soilless cultivation study that was conducted over two trial periods during the 2021/2022 and 2022/2023 planting seasons at Stellenbosch University's Welgevallen Experimental Farm (33.9427°S, 18.8664°E). Preliminary results on the nutritional analysis of seeds harvested in aeroponics and hydroponics showed no significant differences between the treatments. Therefore, the data from different replications were pooled for further analysis. At harvest, pods were dried at ambient temperature (25–30 °C), after which they were manually shelled, with only healthy seeds used in the nutrition analysis. Prior to analysis, the seeds were ground into a fine powder using a Philips HR2141/90 Daily Collection Blender. The blending was carried out for 15 min until a uniform, fine-textured powder was obtained.

Nutritional analysis

Carbohydrates in the form of sugars, amino acids, and fatty acids

Sugars, amino acids, and fatty acids were analysed using a gas chromatography–mass spectrometer (6890N, Agilent Technologies Network) coupled to an inert XL EI/CI mass selective detector (5975, Agilent Technologies Inc., Palo Alto, CA, USA).

Mineral content

Macro- and microminerals were determined using an inductively coupled plasma optical emission spectrometer (PerkinElmer, USA) according to method 999.11 of the Association of Official Analytical Chemists (AOAC).[26]

Gross energy

Gross energy was determined using the C-6000 bomb calorimeter (IKA, Staufen, Germany). The gross energy value was presented in MJ/kg.

Acid detergent fibre and neutral detergent fibre

ADF and NDF were determined using the Ankom Fibre Analyser (ANKOM200, Ankom Technology, New York, USA), according to the method of Van Soest et al.[27]

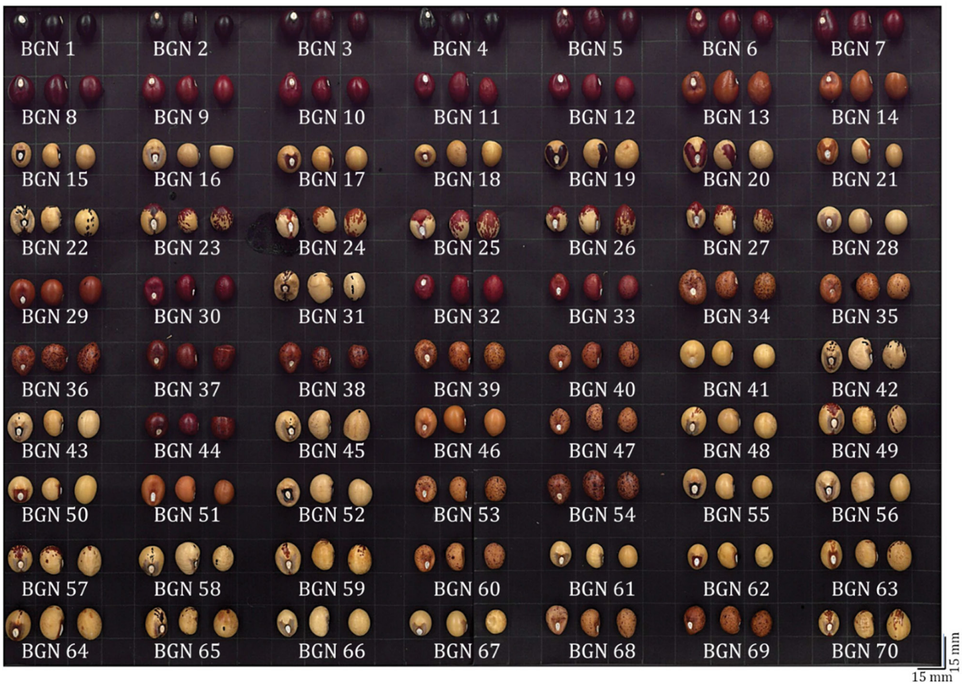

Figure 1: Bambara groundnut seeds (landraces) as used in this study. Seed separation and sorting were performed according to the International Plant Genetic Resources Institute's[25] descriptors for Bambara groundnut.

Crude protein, fat, moisture, and ash

Crude protein (method: 992.23 using the LECO 828/928 series instrument), total fat (method: 920.38), ash content (method: 942.05), and moisture content (method: 934.01) were all determined according to the methods of the AOAC.[26]

Data analysis

Data were analysed and visualised using R version 4.3.2 statistical software. Basic statistics (minima, maxima, ranges, means, standard errors [SE] and coefficients of variation) were determined for each nutritional parameter, using the *descry* function of the *summary tools* package. Principal component analysis was conducted to provide a description of the variance and covariance of landraces in relation to the nutritional parameters. This was carried out using the *prcomp* function of the *factoextra* package.

Results and discussion

Carbohydrates in the form of sugars

Carbohydrates are an excellent source of the energy required by humans for metabolic regulation. Sucrose (91%), with a mean of 2.756 mg/g (SE±0.069), was the most abundant sugar in BGN, followed by myo-inositol (2%) and D-glucose (2%) (Table 1, Supplementary table 1). Sucrose had the highest coefficient of variation, indicating that there was a large variation of this sugar between the landraces (Table 1, Supplementary table 1).

Unpublished research by Zidubule[28] also indicated that sucrose was the dominant sugar in BGN, but the values reported were much lower than those in the current study. Similarly, the sucrose, fructose, and glucose amounts found in this study (Table 1) were much higher than those reported by Apata[29] when assessing the effect of cooking methods on the available and unavailable carbohydrates of BGN landraces from Nigeria.

Compared with other landraces, BGN 23 had the highest sucrose (4.126 mg/g), D-fructose (0.090 mg/g), sorbitol (0.0972 mg/g), and glucose (0.077 mg/g) contents (Supplementary table 1), whereas BGN 3 had the lowest amounts of sucrose (0.158 mg/g), D-fructose (0.002 mg/g), sorbitol (0.001 mg/g), and glucose (0.002 mg/g) (Supplementary table 1). The abundance of sucrose, glucose, and D-fructose in the mature seeds contributes to the sweetness of BGN, with sucrose being the highest contributor (Table 1). Massawe et al.[30] reported that the sweet taste of BGN is an important trait for farmers in Botswana, Namibia and Eswatini when selecting landraces.

D-Galactose (0.015 mg/g) and mannitol (0.019 mg/g) were the least abundant sugars in the landraces (Supplementary table 1). Similar results were observed by Bravo et al.[31] who assessed the composition of underutilised Indian pulses. They reported that monosaccharides (galactose and maltose) were the least available in green gram, haricot bean, black gram, and chickpea. Oligosaccharides, such as raffinose and stachyose, were not detected in the landraces (Table 1). These sugars contribute to the indigestibility of legumes and, consequently, abdominal discomfort.[31]

Within the biplot, there were two clear groupings of sugars. Group 1 consisted of two disaccharides (D-maltose and sucrose) and one monosaccharide (myo-inositol), and Group 2 consisted of five monosaccharides (D-glucose, D-fructose, D-galactose, sorbitol, and mannitol) (Figure 2). The two principal components accounted for 64.9% of the variation in the total sugar content among the landraces (Figure 2). Dimension-1 accounted for 49.3% of the total variation and dimension-2 for 15.6% of the total variation (Figure 2). BGN 12, 20, 22, 23, 26, 27, 29, 39 and 60 were positively associated with dimension-1, showing that they contained high levels of sucrose, myo-inositol, D-galactose, D-maltose, sorbitol, and mannitol (Figure 2). Landraces in the second and third quadrants showed no association with the sugars, indicating that they contained below average quantities of all identified sugars (Figure 2). BGN 3 showed below mean values for mannitol and sorbitol and a weak association with all the sugars.

When studying the nutritional profile of cultivated and wild jute, Choudhary et al.[32] reported that genotypes that normally group alone might be highly superior and diverse from other lines in one or more nutritional parameters.

Fatty acids

There is a worldwide interest in identifying low-cost legumes that are high in essential fatty acids. The main unsaturated fatty acids found in BGN were linoleic acid (41%) and oleic acid (21%), with a mean (±SE) of 2.202±0.0709 mg/g and 1.141±0.0392 mg/g, respectively (Table 2, Supplementary table 2). The linoleic acid content varied from 1.355 mg/g to 4.892 mg/g, with a range of 3.457 mg/g, whilst the oleic acid content varied from 0.686 mg/g to 2.301 mg/g (Table 2, Supplementary table 2). The high accumulation of linoleic and oleic acids in the landraces quantifies BGN as a major source of essential fats required by humans.

BGN 13 contained the highest linoleic acid (4.892 mg/g), which was higher than the total average of 3.58 mg/g reported by Yao et al.[22] in BGN, Grelaap and Giinterb[33] in field peas (2.100 mg/g), and Rybiński et al.[34] in white lupins (2.029 mg/g). Overall, the mean linoleic acid (4.892 mg/g) and oleic acid (2.301 mg/g) of BGN 13 were comparable to that of soybean (5.4 mg/g and 2.3 mg/g, respectively) (Supplementary table 2).

Reports have shown that fats normally found in legumes are mostly unsaturated, in contrast to animal protein that is mostly composed of saturated fats.[35] This is in agreement with our findings, with unsaturated fatty acids being the most abundant in the landraces (Table 2, Supplementary table 2). Unsaturated fats are categorised into omega 3, 6, and 9 fatty acids. The most common omega 3 fatty acid present in the landraces was alpha-linoleic acid, with linoleic acid being the most common omega 6. Oleic acid and erucic acid were the most common omega 9 fatty acids (Table 2, Supplementary table 2).

Table 1: Carbohydrates in the form of sugars identified in Bambara groundnut landraces

Sugar	Minimum (mg/g)	Maximum (mg/g)	Range (mg/g)	Mean ± SE (mg/g)	Coefficient of variation (%)
D-Fructose	0.017	0.09	0.073	0.039 ± 0.002	0.006
D-Galactose	0.012	0.024	0.022	0.015 ± 0.00042	0.0037
D-Glucose	0.021	0.073	0.052	0.035 ± 0.00091	0.0008
Mannitol	0.004	0.044	0.04	0.029 ± 0.00054	0.001
Sorbitol	0.007	0.097	0.09	0.029 ± 0.002	0.001
Myo-inositol	0.034	0.129	0.095	0.066 ± 0.0025	0.004
Sucrose	1.245	4.126	2.881	2.725 ± 0.069	1.39
D-Maltose	0.009	0.053	0.044	0.019 ± 0.0011	0.019

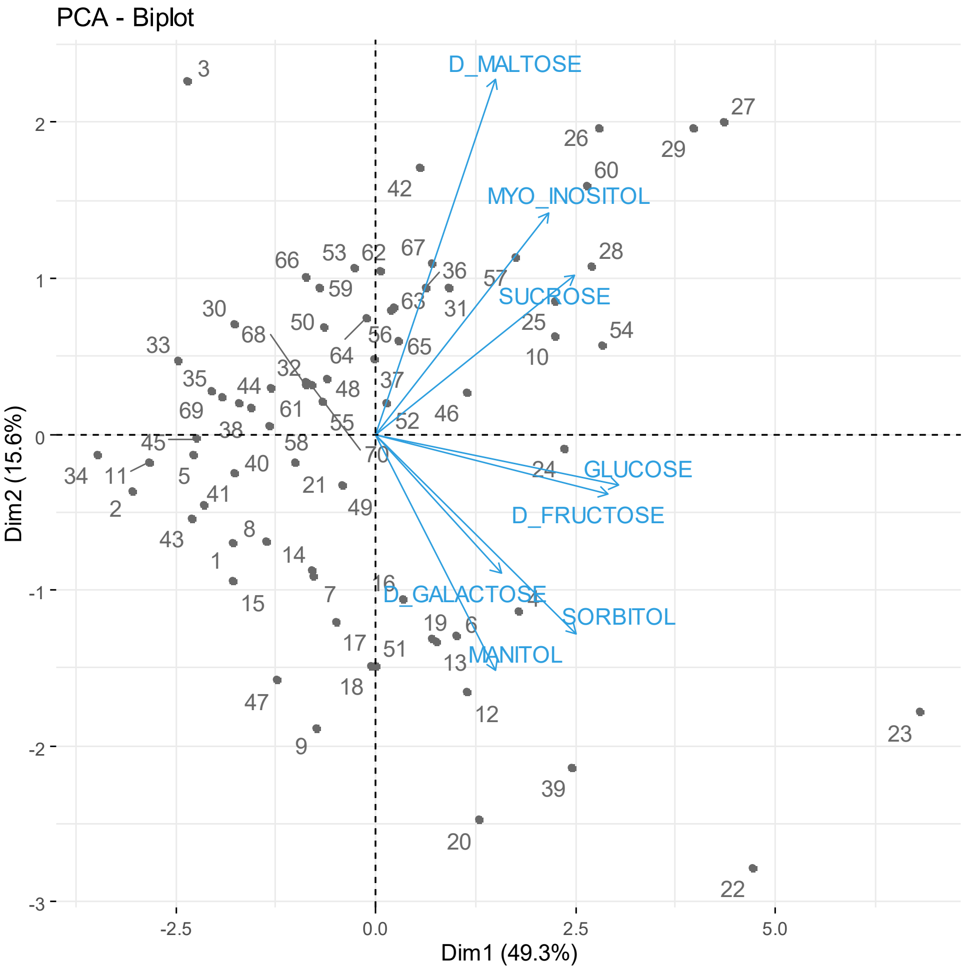

Figure 2: Principal component analysis of the landrace–trait relationship between carbohydrates in the form of sugars and Bambara groundnut landraces.

Table 2: Summary statistics of fatty acids identified in the Bambara groundnut landraces

Fatty acid	Minimum (mg/g)	Maximum (mg/g)	Range (mg/g)	Mean ± SE (mg/g)	Coefficient of variation (%)
Myristic acid (C14)	0.015	0.026	0.011	0.018 ± 0.0002	0.119
Palmitic acid (C16)	0.856	2.999	2.143	1.394 ± 0.0439	0.263
Palmitoleic acid (C16:1)	0.008	0.023	0.015	0.011 ± 0.0003	0.241
Heptadecanoic acid (C17)	0.016	0.038	0.022	0.021 ± 0.0004	0.190
Stearic acid (C18)	0.144	0.525	0.381	0.253 ± 0.0088	0.292
Oleic acid (C18:1cis)	0.686	2.301	0.381	1.141 ± 0.0392	0.287
Linoleic acid (C18:2cis)	1.355	4.892	3.547	2.202 ± 0.0709	0.268
Arachidic acid (C20)	0.031	1.120	0.081	0.053 ± 0.0020	0.315
Eicosenoic acid + alpha-linoleic acid (C20:1 + C18:3n3)	0.049	1.640	1.150	0.079 ± 0.0025	0.273
Behenci acid (C22)	0.090	0.298	0.208	0.041 ± 0.0049	0.273
Erucic acid + eicosatrienoic acid (C22:1 + C20:3n3)	0.007	0.019	0.012	0.002 ± 0.0002	0.247
Docosahexanoic acid (C22:2)	0.009	1.720	1.630	0.019 ± 0.0023	0.113
Lingoceric acid (C24)	0.065	2.140	1.490	0.019 ± 0.0036	2.762

In the biplot, the principal components accounted for 88.9% of the total variation in the fatty acid content between the landraces (Figure 3). Dimension-1 accounted for 81.6% of the total variation, and dimension-2 accounted for 7.3% of the total variation. In the second quadrant, BGN 57 and 67 were positively associated with palmitoleic acid (Figure 3). In the third quadrant, BGN 1,3, 4, and 13 were positively associated with

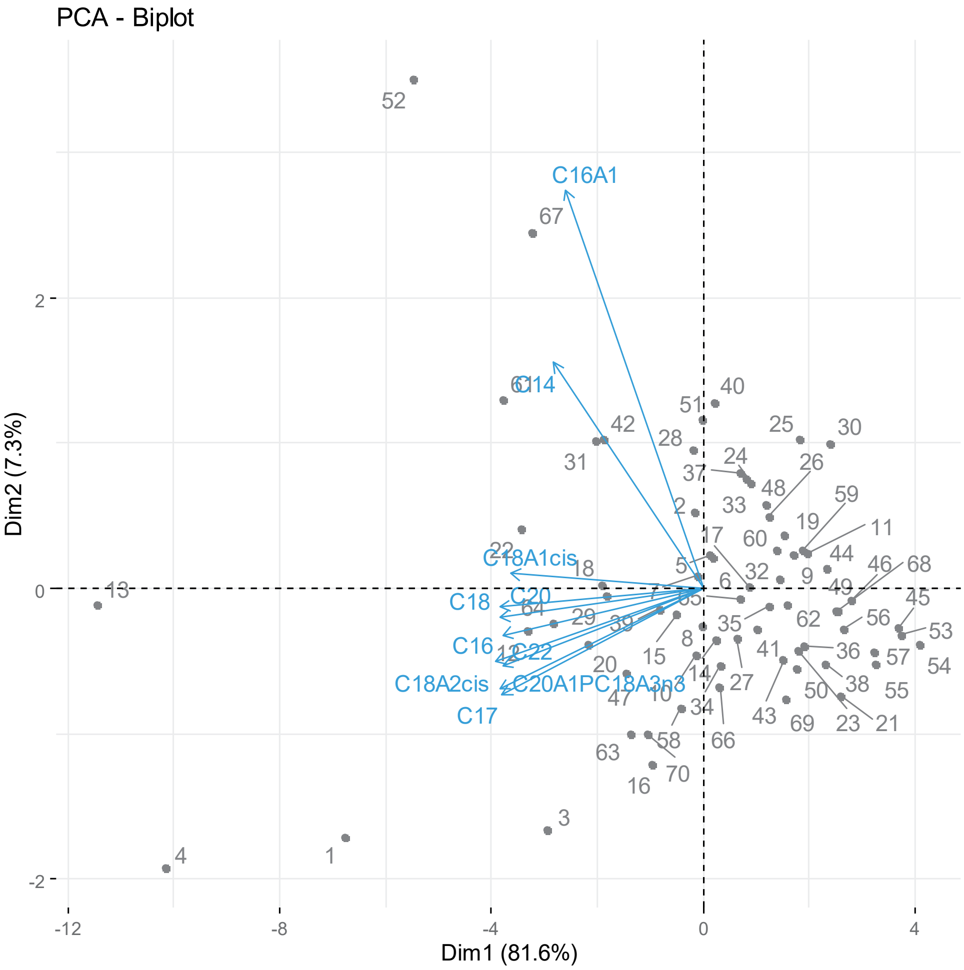

Figure 3: Principal component analysis of the landrace–trait relationship between fatty acids and Bambara groundnut landraces.

linoleic acid, arachidic acid, behenic acid, palmitic acid, heptadecanoic acid, and eicosenoic acid + alpha-linoleic acid (Figure 3). Landraces in the first and fourth quadrants showed no association with the fatty acids.

Amino acids

Essential amino acids cannot be produced by the body; therefore, they must be obtained through the diet. The studied BGN landraces are a good source of amino acids as they contain all essential amino acids in varying amounts (Table 3, Supplementary table 3). Of the essential amino acids, lysine was the most abundant (13%), with tryptophan being the least abundant (Table 3, Supplementary table 3).

Landraces in this study were low in sulfur-containing amino acids, i.e. methionine and cysteine (Table 3). Similar findings of low levels of sulfur-containing amino acids were observed by Erbersdobler et al.[36] when evaluating the nutrients and protein of lupins and faba beans.

BGN 57 showed the highest mean values for lysine (27.76 mg/g), histidine (8.42%), and methionine (2.9%). In contrast, BGN 33, 2, and 62 had the lowest mean values for methionine (0.076 mg/g), histidine (1.19 mg/g), and lysine (3.64 mg/g), respectively. Even though tryptophan was the least abundant essential amino acid, BGN 70 (0.12 mg/g) and BGN 46 (0.07 mg/g) indicated higher tryptophan mean values than all other landraces (Table 3, Supplementary table 3). Glutamic acid (35.44 mg/g) and aspartic acid (26.84 mg/g) were the most abundant non-essential amino acids (Table 3, Supplementary table 3). Yao et al.[22] and Baptista et al.[24] observed similar results when evaluating the nutritional profile of BGN.

Within the biplot, dimension-1 accounted for 73.7% of the total variation and dimension-2 accounted for 15.5% of the total variation (Figure 4). BGN 14, 19, 35, 57, 66, and 70 were positively associated with dimension-1 as they contained higher levels of lysine, histidine, valine, isoleucine, methionine, cysteine, and tryptophan. BGN 40, 54, and 55 were not in proximity to any of the amino acids, meaning that they contained the lowest amounts of all the amino acids when compared with other landraces (Figure 4).

Minerals and proximate analysis

Minerals

Whilst there have been studies on the macro- and micromineral diversity of BGN, many of these studies have not adequately addressed a representative variation of landraces. This gap in the literature highlighted the need for more comprehensive and inclusive studies that encompass a wider range of landraces to gain a more holistic understanding of their mineral composition and nutritional potential. In this study, potassium (42%), iron (13%) and sodium (12%) were the most abundant minerals in the landraces (Table 4, Supplementary table 4).

Magnesium (6%) and calcium (1%) were the least abundant macrominerals, whilst manganese (6%) and copper (2%) were the least abundant microminerals (Supplementary table 4). The high accumulation of potassium, phosphorus, magnesium, zinc, and iron in the landraces (Table 4, Supplementary table 4) makes BGN comparable with other common legumes, such as soybean, lupins, peanuts, and chickpeas.[37]

The potassium, sodium and iron contents found in this study were higher than those reported by Affrifah et al.[38] in cowpeas, namely potassium (1.112%), sodium (0.0016%), and iron (0.0083%).

BGN 55 had the highest mean percentage for potassium (2.13%), phosphorus (0.57%), sodium (0.56%), zinc (0.34%), magnesium (0.22%), and calcium (0.08%) (Table 4, Supplementary table 5). BGN 30 had

Table 3: Summary statistics of the amino acids identified in Bambara groundnut landraces

Amino acid	Minimum (mg/g)	Maximum (mg/g)	Range (mg/g)	Mean ± SE (mg/g)	Coefficient of variation (%)
Lysine*	27.76	3.64	24.12	11.87 ± 0.710	0.5
Leucine*	11.93	3.36	8.57	7.01 ± 0.245	0.29
Phenylalanine*	11.57	2.34	9.16	5.80 ± 0.276	0.39
Threonine*	9.47	2.31	7.16	4.41 ± 0.205	0.52
Valine*	8.43	1.27	7.16	3.98 ± 0.249	0.52
Histidine*	8.42	1.19	7.23	3.82 ± 0.225	0.49
Isoleucine*	7.31	0.94	6.37	3.33 ± 0.227	0.57
Methionine*	2.90	0.73	2.17	1.38 ± 0.069	0.41
Tryptophan*	0.12	0.01	0.11	0.03 ± 0.0021	0.56
Glutamic acid	34.55	11.09	23.46	21.92 ± 0.673	0.25
Aspartic acid	26.84	9.58	17.26	14.45 ± 0.475	0.27
Serine	9.23	3.14	6.09	5.32 ± 0.176	0.27
Glycine	8.28	1.34	6.94	4.30 ± 0.160	0.31
Proline	7.42	2.54	4.88	4.90 ± 0.133	0.23
Alanine	6.99	2.61	4.38	4.35 ± 0.141	0.27
Tyrosine	4.72	0.75	3.97	1.74 ± 0.109	0.38
Cysteine	5.73	0.28	5.45	1.12 ± 0.110	0.82
Cystine	1.76	0.30	1.46	0.65 ± 0.036	0.46

**Essential amino acid*

the highest mean percentage for iron (0.54%) and copper (0.06%), whilst BGN 61 had the highest mean percentage for manganese (Supplementary table 4).

Proximate composition

Proximate analyses provide crucial information on the nutritional value of food. However, information on the proximate composition related to the quality of BGN landraces is scarce. In addition, there have been no studies that report on the gross energy levels of BGN, making this study the first report. BGN contained higher amounts of crude protein (32%), NDF (30%), moisture (14%) and fat (13%) when compared to other proximate parameters (Table 4, Supplementary table 5). The mean crude protein of the landraces was 19.20%, which was higher than that reported by Anaemene and Fadupin[39] in maize (10%) and by Tasie[40] in sorghum (12%).

Amongst the BGN landraces studied, BGN 16 exhibited the highest crude protein content at 36.87%, whilst BGN 30 had the lowest at 16.44% (Table 4, Supplementary table 5). This observation emphasises the significance of BGN as a valuable source of protein. Moreover, the substantial protein content in BGN 16 and other landraces highlights the potential of BGN to alleviate protein deficiencies, positioning it as a vital plant-based protein resource in areas with restricted access to animal-derived proteins and regions where economically accessible meat-based protein sources may be limited.

The NDF content within the BGN landraces exhibited a significant variation, ranging from 10.52% to 65.09%, with a total range of 54.56%. BGN 38 displayed the highest NDF percentage at 65.08%, whilst BGN 19 had the lowest NDF percentage at 11.40% (Table 4). The ADF content ranged from 0.797% to 18.612%, with BGN 40 demonstrating the highest ADF percentage at 18.72%, in contrast to BGN 31, which had the lowest ADF content at 0.80%. This observation aligns with Eskandari et al.'s[41] findings, indicating that foods with a low ADF content tend to have higher energy and digestibility compared to those with a high NDF content (Table 4, Supplementary table 5). Consequently, BGN 38, with its higher NDF value, is considered a relatively low-energy food source, whilst BGN 31, with its lower ADF content, is considered a more energy-rich and digestible option, reflecting the nutritional diversity within BGN landraces.

The ash and moisture content of the BGN landraces displayed variations, with ash content ranging from 0.28% to 5.81% and moisture content ranging from 3.50% to 15.90% (Table 4, Supplementary table 5). Specifically, BGN 39 exhibited the lowest ash content at 0.28%, whilst BGN 34 had the highest ash content at 5.81%. These findings are in alignment with the guidelines reported by Harris and Marshall[42], suggesting that the ash content of any food should ideally fall within the range of 0–12% to be considered suitable for human consumption. Therefore, the ash content of BGN landraces falls well within this recommended range, affirming their suitability for human consumption and underlining their nutritional value and safety as a food source.

In this study, the average total fat content amongst the BGN landraces was found to be 6.35%. BGN 48 exhibited the highest fat content at 8.84%, whilst BGN 67 had the lowest fat content at 3.98% (Supplementary table 5). In general, legumes are recognised for their relatively low-fat content, with peanuts being a notable exception because of their higher fat content. This characteristic is attributed to the fact that legumes like BGN typically store low quantities of lipids and high amounts of carbohydrates in their mature, dry seeds, thereby contributing to their overall low-fat content, as reported in previous research.[43]

The principal component accounted for 56.9% of the total variation in the mineral content between the landraces. Dimension-1 accounted for 38.6% of the total variation, and dimension-2 accounted for 18.3% of the total variation (Figure 5). BGN 3, 20, 26, 30, and 55 were positively associated with dimension-1 as they contained higher amounts of potassium, phosphorus, iron, sodium, calcium, zinc, and magnesium (Figure 5). Landraces in quadrant 2 showed no association with the minerals in quadrant 4, that is, phosphorus, zinc, sodium, calcium, iron, and copper (Figure 5). Landraces in quadrant 3 were associated with manganese, indicating that those landraces had a higher mean percentage for manganese and a lower mean percentage for magnesium and potassium (Figure 5). These findings emphasise the distinct mineral profiles of different BGN landraces, highlighting the need for targeted cultivation and utilisation of specific landraces based on their nutritional attributes and mineral content.

The two principal components accounted for 43.1% of the total variation. Dimension-1 accounted for 25.7% of the variation, and dimension-2 accounted for 17.4% of the variation (Figure 6). In the first quadrant, BGN 52, 61, 68, and 69 were positively associated with moisture, indicating that these landraces had the highest moisture

Figure 4: Principal component analysis of the landrace–trait relationship between the amino acids and the 70 Bambara groundnut landraces.

Table 4: Summary statistics of the macrominerals, microminerals and proximate composition of Bambara groundnut landraces

Minerals	Minimum (mg/g)	Maximum (mg/g)	Range (mg/g)	Mean ± SE (mg/g)	Coefficient of variation (%)
Phosphorus	0.19	0.57	0.38	0.29 ± 0.6	0.18
Potassium	1.22	2.13	0.91	1.40 ± 1.4	0.09
Calcium	0.03	0.08	0.05	0.04 ± 0.09	0.18
Magnesium	0.16	0.22	0.06	0.17 ± 0.1	0.06
Sodium	0.10	0.60	0.50	0.38 ± 0.01	25.80
Iron	0.20	0.50	0.30	0.33 ± 0.006	17.30
Copper	0.03	0.07	0.04	0.05 ± 0.0007	11.60
Zinc	0.10	0.30	0.20	0.23 ± 0.002	10.50
Manganese	0.07	0.30	0.40	0.17 ± 0.005	29.00

...Table 4 continues on next page

Table 4 continued...

Minerals	Minimum (mg/g)	Maximum (mg/g)	Range (mg/g)	Mean ± SE (mg/g)	Coefficient of variation (%)
Proximate composition					
Acid detergent fibre	0.79	18.61	17.82	9.32 ± 0.581	0.52
Neutral detergent fibre	10.52	65.08	54.56	20.92 ± 0.954	0.32
Ash	0.28	5.81	5.53	3.16 ± 0.130	0.34
Crude protein	16.44	36.87	20.43	19.20 ± 0.335	0.15
Gross energy	17.10	18.31	1.21	17.63 ± 0.023	0.14
Total fat	3.89	8.84	4.94	6.34 ± 0.108	0.14
Moisture	3.50	15.90	12.40	10.96 ± 0.026	0.19

Figure 5: Principal component analysis of the landrace–trait relationship amongst the mineral elements and Bambara groundnut landraces.

content (Figure 6). BGN 38 had a higher NDF content than all other landraces; it therefore shows a strong positive association with NDF in the second quadrant (Figure 6). Landraces in quadrant 3 were closely associated with gross energy and showed no association with moisture in quadrant 1. In quadrant 4, the landraces were positively associated with ADF, ash, and crude protein.

The gross energy levels varied from 17.10 MJ/kg to 18.31 MJ/kg, with a mean±SE of 17.63±0.023 MJ/kg, indicating that there was little to no variation in the gross energy levels between the landraces (Supplementary table 5). BGN 49 demonstrated the highest gross energy level, measuring at 18.31 MJ/kg (Supplementary table 5), whereas the lowest gross energy was observed in BGN 11, with a value of 17.10 MJ/kg (Supplementary table 5). The gross energy level of BGN 49 positions it as a relatively good source of energy when compared to other landraces. The mean gross energy in the landraces was higher than that reported by Gemede and Birhanu[44] in lima beans (14.19 MJ/kg) and by Liman[45] in wild cowpea (14.40 MJ/kg) and Bosso cowpeas (15.78 MJ/kg) (Supplementary table 5). However, the mean gross energy of the studied landraces was lower than that reported by Zdunczyk et al.[46] in soybean (19.1 MJ/kg) and pumpkin seeds (21.9 MJ/kg) and by Renaudeau et al.[47] in clover (19.2 MJ/kg) and lucerne (20.5 MJ/kg).

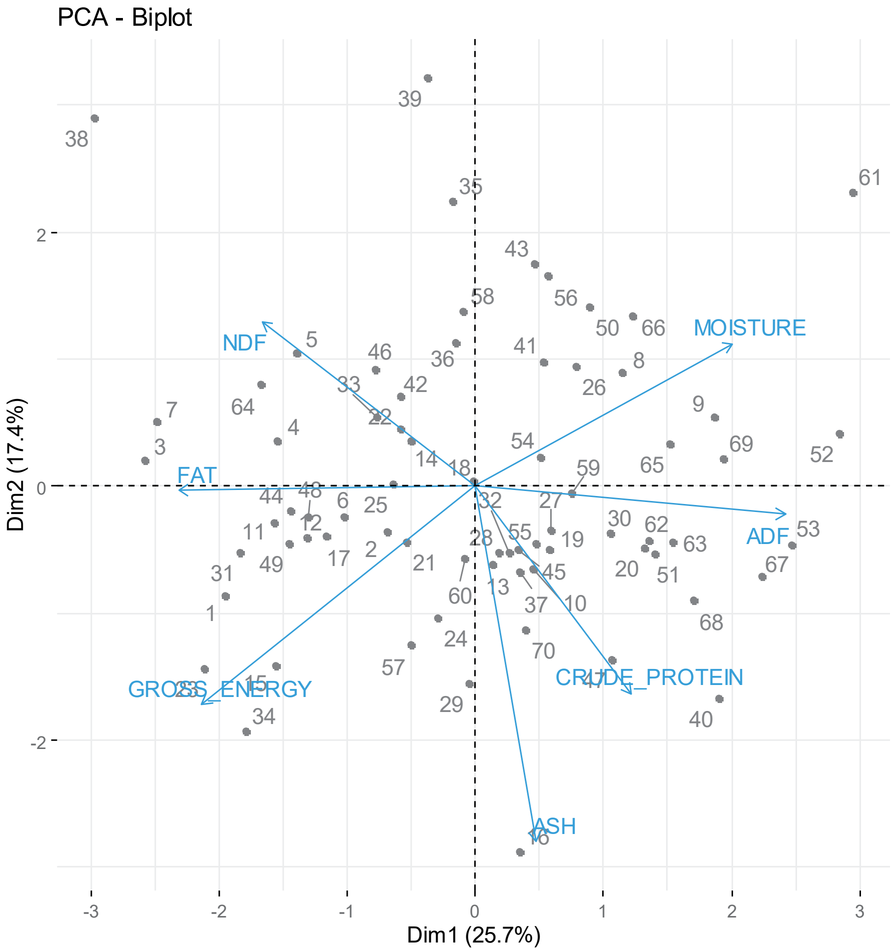

Figure 6: Principal component analysis of the landrace–trait relationship amongst the proximate composition and the 70 Bambara groundnut landraces.

Conclusion

This comprehensive study of 70 BGN landraces has provided valuable insights into the nutritional profile of this underutilised legume. BGN has been shown to be a promising crop with significant potential to address food and nutrition insecurity, particularly in sub-Saharan Africa, where malnutrition remains a critical challenge. This research identified specific landraces with superior nutritional profiles, offering the potential for targeted cultivation to address specific dietary deficiencies.

The nutritional analysis revealed the richness of BGN in essential nutrients, making it a valuable source of protein, essential amino acids, fats, and minerals. Sucrose was identified as the predominant sugar, contributing to the legume's sweetness, whilst essential fatty acids, such as linoleic acid and oleic acid, were found in substantial quantities, enhancing its dietary value. The presence of all essential amino acids, with lysine being the most abundant, highlights its potential to complement diets deficient in certain amino acids. Moreover, the mineral composition, notably high levels of potassium, iron, and sodium, emphasises its potential as a nutrient-dense crop.

In a world facing increasing food demand and climate-related challenges, diversifying diets with underutilised legumes like BGN could play a crucial role in improving nutrition and reducing food insecurity. Further research and promotion of this legume are essential to harness its full potential in addressing global nutritional needs and ensuring food security. The findings also align with the growing emphasis on nutrition-sensitive agriculture, as recommended by international organisations like the United Nations Food and Agriculture Organization.

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Data availability

The data are available upon request to the corresponding author.

Declarations

We have no competing interests to declare. We have no AI or LLM use to declare.

Authors' contributions

M.M.M.: Conceptualisation, methodology, data collection, sample analysis, data analysis, validation, data curation, writing – the original draft, writing – revisions. S.M.: Conceptualisation, student supervision, validation, writing – revisions. M.J.B.: Conceptualisation, student supervision, project management, funding acquisition, validation, writing – revisions. E.E.P.: Conceptualisation, student supervision, project leadership, project management, funding acquisition, validation, writing – revisions. All authors read and approved the final manuscript.

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