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Review Article

Nutritional composition, processing technologies, and nutraceutical potential of Bambara groundnut (*Vigna subterranea* (L.) Verdc.) and its value-added products: A comprehensive review

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Abstract: Bambara groundnut (BGN), an underutilised and climate-resilient legume indigenous to sub-Saharan Africa, has considerable potential to contribute to nutritional diversification, food security, and sustainable food systems. Although previous reviews have addressed its nutritional composition, agronomic characteristics, processing, or health-promoting properties, the relationships among BGN composition, processing technologies, value-added food development, and nutraceutical potential have received less integrated attention. This narrative review aims to provide an updated synthesis of the nutritional composition and bioactive constituents of BGN, critically examine the processing technologies used in BGN-based food production, evaluate the nutritional and functional characteristics of value-added products, and assess the available evidence for their potential health benefits. Published literature on BGN composition, processing, food applications, and nutraceutical properties was examined and synthesised, with attention to findings from in vitro, animal, and human studies. BGN has been incorporated into a range of products, including flour, plant-based milk substitutes, yoghurt, cheese analogues, and biscuits, although most value-added products remain at the laboratory or pilot scale. Processing methods, including soaking, boiling, roasting, germination, and fermentation, can reduce antinutritional factors and modify the nutritional composition, functional properties, and bioactive profiles of BGN. However, these effects vary with processing conditions, and some treatments may also result in nutrient losses or reductions in heat-sensitive compounds. Reported nutraceutical activities include antioxidant, antidiabetic, antihypertensive, anti-inflammatory, anti-obesity, and anticancer effects, which have been associated with phenolic compounds, bioactive peptides, dietary fibre, and other phytochemicals. Nevertheless, the supporting evidence is derived predominantly from in vitro and animal studies, while well-controlled human clinical trials involving BGN-based products remain scarce. By integrating evidence across nutritional composition, processing, product development, and biological activities, this review identifies key challenges in processing standardisation, bioavailability, product optimisation, and commercialisation. Further research, particularly well-designed human intervention trials and studies on the bioavailability and mechanisms of action of BGN bioactive constituents, is needed to substantiate its proposed health benefits and facilitate the wider utilisation of BGN in sustainable food systems, particularly in sub-Saharan Africa.

Keywords: Bambara groundnut, Nutraceuticals, Nutritional diversification, Underutilised legumes

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1. Introduction

Global food systems face increasing pressure to deliver sufficient, affordable, and nutritious diets to a growing and rapidly urbanising population. The world population is projected to reach approximately 9.7 billion by 2050, with sub-Saharan Africa accounting for the fastest regional growth [1]. This expansion is occurring against a backdrop of persistent hunger and malnutrition, with recent estimates indicating that around one in five people in Africa face hunger [2]. Meeting future nutritional demand sustainably will require diversifying food systems beyond a narrow set of staple crops and animal-based proteins, particularly through underutilised, climate-resilient, nutrient-dense alternative crops that smallholder farmers can produce with limited agricultural inputs [3, 4]. Bambara groundnut (BGN) (*Vigna subterranea* (L.) Verdc.) is a prominent example of such crops.

BGN (Figure 1) is a strategically important, yet underutilised legume with considerable potential as a staple for improved nutrition, food security, rural development, and the manufacture of functional foods and nutraceuticals. BGN is a low-input, climate-resilient crop that can be cultivated in suboptimal conditions where traditional staple crops perform poorly, and its nutritional value can help combat protein and micronutrient deficiencies in vulnerable groups [5-7]. These characteristics have seen BGN emerge as a favourable choice for alleviating food insecurity and supporting long-term value chain growth, especially in sub-Saharan Africa [3].

Agronomic interest in BGN is largely driven by two related qualities: its ability to thrive under limited water availability and its suitability for low-input farming systems. BGN exhibits resilience to drought and is considered a promising crop for arid and semi-arid regions, but its productivity is still negatively affected by drought [7, 8]. Furthermore, BGN is a legume that associates with multiple species of the genus *Bradyrhizobium* including *B. japonicum*, *B. elkanii*, and other phylogenetically diverse genospecies to fix nitrogen. This can improve soil fertility and reduce reliance on synthetic fertilizers, which is another key advantage for smallholder farmers, who often lack access to inputs [9]. All these characteristics make BGN an important crop increasingly considered as part of diversified and climate-smart production systems [4, 10].

Nutritionally, BGN is a rich source of plant protein, essential amino acids, and minerals. Recent studies have elaborated on its protein quality and techno-functional characteristics in processed products. While BGN is also known to contain anti-nutritional factors commonly found in legumes, processing technologies, such as sprouting, fermentation, and protein extraction, can improve its protein digestibility and bioavailability. Consequently, BGN can be used as a supplemental protein source in starchy diets [5, 11, 12]. Researchers have also observed significant diversity in nutrient and phytochemical content between geographic germplasms. This diversity can be leveraged through breeding and value chain strategies to select for nutritional traits of interest [4, 13].

In addition to its macronutrients, BGN also contains phytochemicals and peptides with antioxidant, antimicrobial, and potential metabolic activities. Some *in vitro* studies have reported the presence of phenolics, flavonoids and other compounds in BGN extracts that demonstrate antioxidant and antimicrobial activity under laboratory conditions. This evidence supports the use of BGN as a source of nutraceutical ingredients with potential antioxidant and antimicrobial properties [11]. Although clinical evidence remains limited, and most health-related claims are still based on preclinical findings, available evidence supports the continued development of BGN-based functional foods and ingredients, including protein isolates and flours with favourable functional properties and amino acid profiles [12], as well as improved antioxidant content and pasting characteristics [14].

As a promising crop for nutritional diversification, a variety of products, including flour, cheese analogue, milk substitute, yoghurt, and biscuits, have been developed using BGN either as a base or a supplement. The nutritional and nutraceutical qualities of those products have also been reported by some researchers. However, limited access to improved seed, post-harvest losses, weak market linkages, and lack of innovative processing techniques continue to hinder wider adoption, utilisation, and commercialization of BGN products [10, 15, 16].

Studies on product development also suggest that blending with other ingredients can improve nutritional and functional characteristics. For instance, BGN-maize, BGN-rice and BGN-sweet potato composites, have been reported to enhance protein, mineral, and functional properties (e.g. pasting stability). These findings suggest that BGN-based foods have potential applications in complementary feeding and nutritional interventions [17, 18]. Beyond nutritional aspects, other studies point to potential health benefits of BGN-based foods. Dietary fibre and resistant starch have been associated with lower glycaemic index, and phenolics may have antioxidant properties. But these findings are mostly based on compositional and laboratory evidence, and there is a lack of direct clinical evidence in support of these health claims [19, 20].

There are previous reviews on BGN, but the majority have concentrated on specific themes, such as its nutritional makeup, agronomic traits, processing techniques, or health-promoting qualities, with little integration of these topics into a comprehensive viewpoint. El Bilali et al.'s [10] recent bibliometric and systematic review, which examined 180 research articles on BGN in Africa, showed the crop's increasing scientific interest, as well as the expansion of research beyond agronomy to include livelihoods, food processing, value addition,



Figure 1. Different varieties of BGN seeds: (a) cream black-eye, (b) cream brown-eye, (c) brown, (d) red, (e) speckled/spotted, (f) cream no-eye, (g) black, (h) purple [21]

food and nutrition security, and climate resilience. The study also identified significant regional and theme research gaps, emphasizing the need for more thorough and multidisciplinary studies, especially in processing and marketing, health benefits, economics and social sciences, irrigation, and climate resilience. In order to support the use of BGN as a sustainable functional food and plant-based protein source [11], an updated review that incorporates these developments, critically assesses the available data, identifies knowledge gaps, and outlines future research priorities is necessary. This is especially pertinent given the recent advancements in food processing technologies, product development, functional properties, bioactive compound characterisation, and nutraceutical applications.

The objective of this review is to present a thorough and current summary of what is currently known about BGN and its value-added products. This review specifically summarizes the nutritional composition of BGN, critically examines current processing technologies and the nutritional quality of BGN-derived products, evaluates the available evidence on their nutraceutical properties while separating findings from in vitro, animal, and human studies where appropriate, and identifies existing research gaps, commercialization opportunities, and future research directions.

1.1 Chemical composition of BGN

BGN has gained recognition as a nutritionally important legume with the potential to make important dietary contributions, especially in low-resource environments. Increasing evidence shows that its use can contribute to human nutrition through its well-rounded macronutrient and micronutrient content [10, 22]. BGN is a nutrient-dense legume, containing appreciable amounts of protein, carbohydrates, dietary fibre, fat, and other nutrients [5], as well as phenolic compounds [23]. Its nutritional composition varies depending on genotype, geographical location, growing conditions, and processing

methods [5].

In addition, BGN is a source of essential nutrients, and its nutritional value supports its potential application in the development of nutritious food products [10, 20]. The balanced nutrient composition of BGN has earned it the description of being a "complete food" in plant-based diets. Crucially, BGN is a plant-based protein source with potential to support nutrition and food security in populations vulnerable to malnutrition [24].

BGN protein, comprising 1.6–2.2% of prolamins, 3.3–5.2% of glutelins, 14–71% of albumin, and 6–43% of globulin, is nutritionally well-balanced, with high levels of leucine and phenylalanine. It is also high in lysine; therefore, it can be used to supplement the lysine-deficient cereals such as maize. However, formulation and coagulation conditions can influence the physicochemical properties, texture, amino acid profile, and consumer acceptability of BGN tofu, highlighting the importance of optimising these parameters to achieve desirable product quality [25]. Protein digestibility can be enhanced through germination, as demonstrated in Bambara groundnut flours, highlighting the potential of germination to improve protein digestibility [26].

In addition to the macronutrient and micronutrient composition, BGN is also rich in bioactive phytochemicals, including polyphenols [27]. Metabolomic studies also demonstrate the existence of procyanidins and organic acid compounds, with nutritional and functional implications [28].

BGN contains phytates, tannins, trypsin inhibitors, and oxalates that lower the absorption and bioavailability of minerals, especially divalent cations - iron, zinc, and calcium. The content of these antinutrients can be reduced through soaking, dehulling, germination, fermentation, and phytate degradation by enzymes, thereby increasing the bioavailability of minerals. Specifically, fermentation can increase mineral bioavailability through organic acid production and phytase activation [29]. Mashau et al. [30] reviewed that processing techniques can lower the anti-nutritional elements in BGN, increasing the digestibility and bioavailability of nutrients. According to reports, boiling reduced tannins by 73.68%, oxalates by 81.30%, and trypsin inhibitors by 67.31%, while soaking reduced tannins by up to 99.39%, phytates by 68.25%, oxalates by 97.44%, and saponins by 63.81%. Tannins (18.92–63.74%), phytates (15.91–51.16%), and trypsin inhibitors (17.21–73.75%) were likewise successfully reduced by germination, while oxalates (59.11%), phytates (25.58%), and trypsin inhibitors (75%) were reduced by fermentation. Tannins were reduced by 73.68%, phytates by up to 49.90%, and trypsin inhibitors by 73.42% during roasting. These results show that the nutritional quality and functional potential of BGN can be improved, while its anti-nutritional effects can be mitigated through suitable processing methods.

According to Hlanga et al. [31], the nutritional content of BGN would differ among various agro-ecologies, potentially due to the interplay between genotype and environment. Variations in the nutritional value of various BGN genotypes based on germplasm, origin, or environmental conditions have been reported. The nutritional composition of the seeds is significantly influenced by genetic variation among BGN landraces. Mabitsela et al. recently evaluated 70 BGN landraces and found heterogeneity in proximate composition, mineral content, carbohydrates, amino acids, and fatty acids. This allowed for the identification of six landraces with better nutritional profiles. The observed variations represent the impact of genotype on nutrient composition and underscore the significance of choosing nutritionally superior landraces for breeding programmes, targeted cultivation, and the creation of functional food products [32]. Agroecological variables, such as climate, soil fertility, water availability, and day length, have also

Table 1. Comparative nutritional composition of BGN and selected legumes (per 100 g, dry seeds)

Nutrient	Bambara groundnut (*Vigna subterranea*)	Soybean (*Glycine max*)	Chickpea (*Cicer arietinum* L.)	Lentil (*Lens culinaris* Medik.)	Cowpea (*Vigna unguiculata*)
Protein (g)	18.80	36.49	20.47	25.80	23.53
Carbohydrate (g)	60.80	30.20	62.95	60.10	60.03
Fat (g)	1.40	19.94	6.04	1.10	1.26
Dietary fibre (g)	10.30	9.30	12.20	30.50	10.60
Calcium (mg)	30.20	277	57	56	126
Iron (mg)	8.80	15.70	4.31	7.50	1.10
Zinc (mg)	1.90	4.89	2.76	4.80	1.01

Source: Compiled from published reviews [33, 34]. Nutrient values are literature-reported values and may vary depending on cultivar, growing conditions, sample preparation, analytical methods, and moisture basis.

been linked to variations in BGN yield [5]. For instance, field drought conditions lowered BGN seed yield without influencing the nutritional value of the seed.

A comparative nutritional composition of BGN and selected legumes is presented in Table 1.

2. BGN products

Most BGN-based products discussed in this review, including milk substitutes, yoghurt, cheese analogues, and biscuits, have been developed and evaluated primarily at the laboratory or pilot scale. Although BGN flour is commercially available in some regions and through specialty markets, the commercialization of most value-added BGN products remains limited. Their production is largely confined to research settings or small-scale household preparation, highlighting the need for further product optimization and industrial-scale commercialization.

2.1 BGN flour

2.1.1 Processing of BGN flour

BGN flour is a semi-processed product from either raw or processed BGN seed that is commonly used as a complementary food and in bakery. In recent years, BGN flour has attracted more research interest due to its nutritional value and versatility, as a semi-processed food. It is being used as a functional ingredient in composite flours, plant-based beverages and functional foods [5, 30, 35]. For instance, it is used to replace wheat in bread, biscuits and snacks, and in gluten-free, protein fortified and dairy products, such as yoghurt-like beverages and plant-based sweet products. Consumer research has shown that 5–25% substitution is acceptable with optimal processing conditions.

BGN flour quality is affected by several factors. Seed coat colour and maturity affect its chemical composition and antinutritional factors [5], whereas proximate composition and antinutritional factors vary among Bambara groundnut accessions [36]. Fermentation can reduce the levels of antinutritional factors in Bambara groundnut-based flour [37]. Bioprocessing, such as germination, malting and lactic fermentation, improves the nutritional and functional properties of the flour. Germination activates amylases and proteases, decreases raffinose family oligosaccharides and phytic acid, and elevates free amino acids and soluble peptides. This enhances digestibility and functional properties for food use [38, 39]. Malting also improves amylolytic and antioxidant properties, making it suitable for use in beverages or enzyme-rich products [39]. The application of high-pressure processing (HPP) enhances extractable antioxidants, alters pasting and gelling capacities [14].

Processing methods, including germination, and roasting, influence the functional properties of BGN flour. These, in turn, affect the flour's performance in extruded products [35]. BGN flour functional properties, such as water and oil absorption, emulsification, foaming, and pasting properties, are affected by processing parameters, which also affect sensory attributes in foods [14, 38]. Germination and fermentation can also reduce antinutrients and increase mineral contents, as reported for black soybeans [40].

Micronization is an alternative rapid approach in which electromagnetism and infrared heat are applied to heat products in the near-infrared region. Due to the rapid high temperature generation, micronization influences the structural composition of biomolecules in diverse ways, affecting their functional characteristics as reported for protein derived from black gram milling by-products [41]. Ogundele et al. [42] observed a significant reduction in the pasting viscosity of whole and dehulled BGN flour, as the micronization temperature and time increased, relative to whole BGN flour. According to the authors, swelling capacity was also higher in dehulled BGN flour compared to the whole BGN flour, which could be attributed to variations in their chemical composition, such as dietary fibre.

Ultrasonication is a technique that uses high-frequency sound waves to modify the physicochemical properties and structural characteristics of food proteins, as demonstrated in chicken breast meat [43]. Mudau and Adebo [44] reported that ultrasonication altered the functional properties of BGN flour, with an increase in swelling power. The improvement in water absorption capacity and oil absorption capacity may be attributed to the exposure of proteins to the external environment by ultrasound, especially their sites with hydrophilic and hydrophobic properties, which enhances their ability to retain water and fat.

2.1.2 Nutritional composition of BGN flour

BGN is rich in protein and essential amino acids (Table 2). However, carbohydrates constitute the predominant macronutrient, generally accounting for 55–70% of the seed, with starch as the major carbohydrate and amylose accounting for 20–35% of the starch fraction [45-48]. The amylose content of BGN starch influences its pasting properties, which can be further modified by hydrothermal treatment [48, 49].

BGN flour is also a rich source of minerals, as the whole flour contains significant levels of ash that vary among accessions [36]. The ash content has been reported to increase with processing. For instance, it increased from 3.9% in the whole flour to 4.8% in the dehulled-blanched flour [27]. The level of crude fat in BGN flour ranges from 6% in raw BGN flour to 10.39% in the roasted flour [50]. The mineral composition of BGN grain has been reviewed by Ramatsetse et al. [19]. BGN products retain the high micronutrient content of the

raw seeds, being high in potassium, phosphorus, iron, and calcium. It has also been reported that adding BGN flour increases the protein content/nutritional value of composite formulations [51].

BGN protein can be considered a high-quality protein due to its amino acid composition. As presented in Table 2, BGN contains high levels of essential amino acids, including leucine, lysine, phenylalanine, valine, histidine, and isoleucine. Methionine content in BGN is low [52], and wet cooking has been reported to substantially reduce its concentration [53]. Baptista et al. reported inter-accession variation in protein composition among Mozambican pulse accessions, including Bambara groundnut, and noted that the amino acid chemical scores of the studied pulses were generally below the internationally accepted pattern, with only some common bean and cowpea accessions approaching it [54]. BGN's high protein quality, especially its rich lysine content, makes it a good complementary protein source to cereals, which are deficient in lysine but rich in methionine [5].

2.1.3 Functional properties and food applications of BGN flour

BGN flour is a possible substitute for traditional plant-based protein sources due to its functional qualities. It can be used in a variety of food compositions due to its strong water- and oil-absorption capacities, superior emulsifying and foaming abilities, and gel-forming qualities. BGN flour may be suitable for food applications where functional performance is important, as the incorporation of germinated BGN flour modifies the hydration and dough-handling properties of wheat-based formulations [38]. Its integration into baked goods, gluten-free foods, supplementary foods, snacks, pasta, composite flours, and plant-based drinks has been made easier by these useful characteristics. Additionally, BGN flour has the potential for wider use as a functional ingredient in value-

Table 2. Amino acid composition of BGN

Amino acid	Concentration (mg/g crude protein)	FAO reference (mg/g protein)	Limiting	Reference
Leucine	73.8-102.1	61	No	[52, 55]
Lysine	46.1-80.2	48	No	[52, 55]
Isoleucine	37.9-54.5	30	No	[52, 55]
Phenylalanine	51.6-76.9	-	No	[52, 55]
Tryptophan	6.0-13.2	6.6	Yes	[52, 55]
Valine	52.1-62.4	40	No	[52, 55]
Methionine	6.4-22.7	-	No	[52, 55]
Proline	33-53.6	-	No	[52, 55]
Arginine	74.8-113	-	No	[52, 55]
Tyrosine	24.7-31.3	-	No	[52, 56]
Histidine	28.9-38.6	16	No	[52, 56]
Cystine	6	-	No	[52]
Cysteine	24.1	-	No	[56]
Alanine	48.8-51.4	-	No	[52, 56]
Glutamic acid	183.1-209.5	-	No	[52, 56]
Glycine	46.5-50.6	-	No	[52, 56]
Threonine	38.6-44.3	25	No	[52, 56]
Serine	42.3-68.5	-	No	[52, 56]
Aspartic acid	82.1-146.1	-	No	[52, 56]

added food products. Further research into processing technologies is needed to facilitate the development of new food applications and address challenges associated with scaling up production [30].

2.2 BGN milk

Plant-based milk alternatives are consumed for reasons distinct from those driving demand for dairy milk; they are free of lactose and dairy protein allergens, contain no cholesterol, and typically associated with a lesser environmental impact than animal agriculture [57, 58]. However, these advantages are not exclusive to BGN, but are found in many plant-based milks. The main factors that set BGN milk apart from other well-known substitutes, such as soy, oats, or almonds, are its agronomic and environmental advantages. BGN is a drought-tolerant, nitrogen-fixing crop that smallholder farmers can grow locally on marginal, low-fertility soils [4], unlike soy, which is frequently imported into sub-Saharan African markets. As a result, BGN milk can be produced locally rather than relying on imported ingredients. BGN also possesses a distinct nutrient profile relative to soy and other legumes (Table 1), notably a lysine-rich amino acid composition that complements cereal-based staple diets.

2.2.1 Processing of BGN milk

BGN milk substitute, like other plant-based milk analogues, is a water-soluble extract of BGN produced to mimic animal milk. It is an ecofriendly, animal welfare-friendly, healthy and sustainable substitute to animal milk in human nutrition [58]. Bambara groundnut seeds contain substantial protein and dietary fibre, together with measurable amounts of fat and minerals, including iron and zinc, although their nutritional composition can be affected by processing methods [59]. Amino acid profiling shows that Bambara protein can be used to supplement restrictive amino acids in composite formulations, which is why it can be used in milk analogues and fortified beverages. In addition to its nutritional value, BGN has potential for productivity improvement through gamma irradiation, selection of superior landraces, and in vitro techniques that accelerate the breeding cycle [60]. Thus, BGN milk substitute may have potential as a functional food, in line with the antioxidant properties reported for processed BGN flour and the potential health benefits associated with plant-based milk substitutes [58, 44].

BGN milk substitute is produced by cleaning, soaking or dehulling, wet milling, extraction in water, filtration, heat treatment, and homogenisation. Critical processing stages of BGN milk substitute, such as germination, malting and high-pressure processing, play a vital role in its extractability and quality. These processing techniques can alter the functional properties, antioxidant capacity, and nutritional characteristics of BGN flour, potentially influencing its performance and quality in food applications [14, 30, 38]. The major challenge with legume milk is the presence of antinutrients (phytates, tannins, and trypsin inhibitors) that affect mineral bioavailability and protein digestibility. However, processing techniques such as germination and other bioprocessing methods have been reported to influence the antinutritional factors, nutritional composition, and functional properties of Bambara groundnut, with potential implications for its digestibility and food applications [30, 38]. Further, improving the nutritional composition and value of BGN through appropriate production and improvement strategies has been identified as an important opportunity for enhancing its nutritional potential [45].

2.2.2 Nutritional composition of BGN milk

Studies have shown that BGN milk possesses a relatively high protein content [61]. Furthermore, Maphosa et al. [45] highlighted opportunities to improve the nutritional value of BGN through production improvement strategies and better utilization of its nutritional constituents. Bambara groundnut has considerable nutritional potential, and efforts to improve its nutritional value and overall utilization are warranted [45]. This suggests the potential of BGN milk substitute as a protein-rich alternative for populations in need of affordable and accessible dairy substitutes.

2.2.3 Properties and applications of BGN milk

BGN milk has favourable functional qualities, such as a high protein content, good emulsifying ability, and palatable sensory qualities. However, some factors, such as phase separation, sedimentation, and poor storage stability, are significant barriers to product quality. It has been demonstrated that using the right homogenization, stabilization, and drying methods can increase emulsion stability and prolong shelf life. Even though processing can improve the quality and characteristics of plant-based milk alternatives, further optimisation is needed to enhance product stability, consistency, and consumer acceptability [57].

When compared to well-known plant-based beverages, such as soy, oat, almond, and pea milk, BGN milk has the advantage an underutilised, nutritious legume that can withstand drought. However, due to its large-scale production, well-established processing methods, and increased consumer awareness, soy milk continues to rule the market. While pea milk is known for its high protein content and enhanced sustainability, almond and oat milks are typically preferred for their mild flavour and sensory appeal. Plant-based yoghurt alternatives offer nutritional potential, but further optimisation of formulation and processing is needed to improve their functional properties, sensory characteristics, and nutritional value [62]. Although Bambara groundnut (BGN) has

nutritional potential, its nutritional composition and antinutrient content vary among accessions, highlighting the need for further research to better characterise its nutritional quality [36]. While *in vitro* studies indicate increased mineral solubility following processing, this has not been confirmed *in vivo*. Research on BGN milk is also geographically limited and small-scale. In terms of application, BGN milk is used for non-dairy cheese production [63]. Additional research on optimised processing, pilot-scale processing and techno-economic analysis is required to facilitate commercialisation.

2.3 BGN yoghurt

Similar to BGN milk, the benefits of BGN-based yoghurt go beyond those of plant-based fermented dairy substitutes like soy or oat yoghurt. In regions where BGN is already grown, BGN yoghurt provides an affordable alternative to the conventional yoghurt.

2.3.1 Processing of BGN yoghurt

The production of yoghurt using BGN milk substitute (Figure 2) has been the focus of wider research interest as

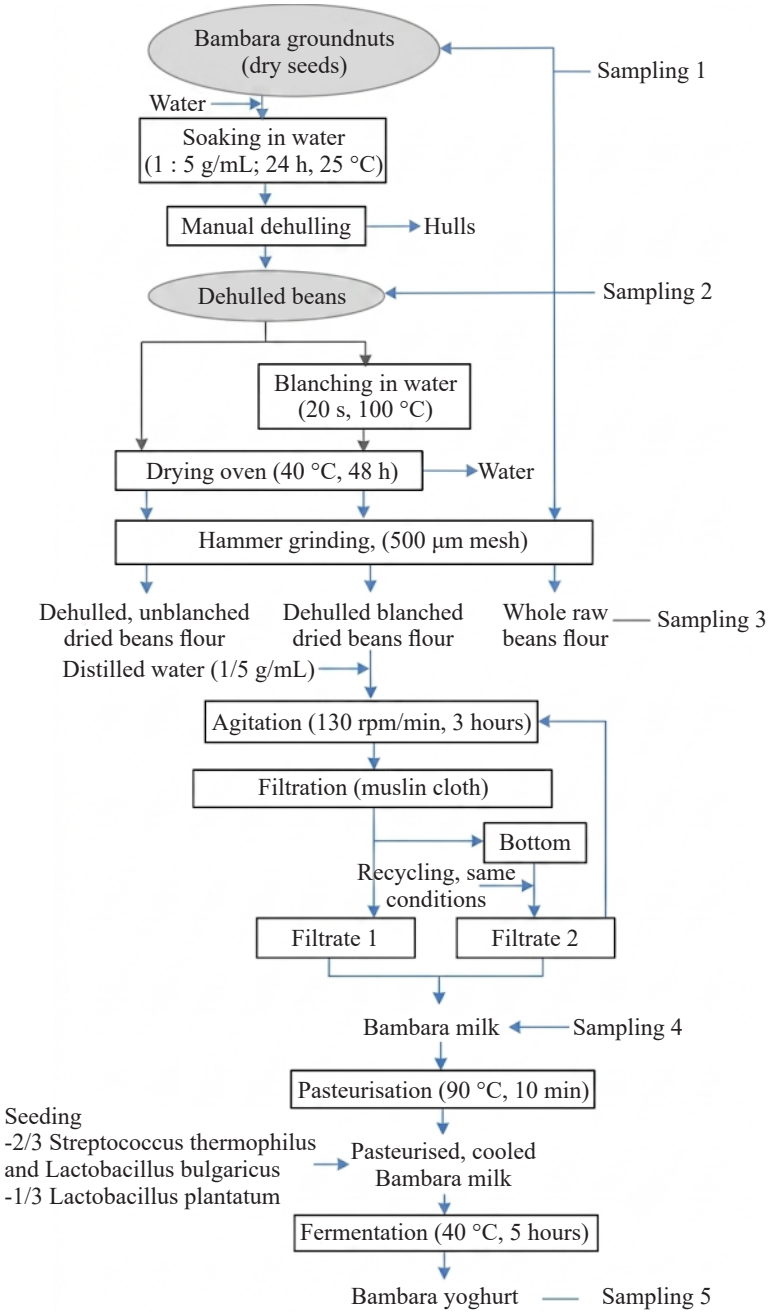

Figure 2. Flow diagram for BGN yoghurt production [27]

part of the overall work to develop plant-based fermented foods. It is formulated by either using BGN milk substitute as a base or by partially replacing cow's milk with BGN milk (0-40%), then fermented with common yoghurt cultures, including *Lactobacillus bulgaricus*, *Lactobacillus plantarum*, and *Streptococcus thermophilus* in controlled conditions [27, 64].

Lactic acid fermentation with suitable starter cultures is a promising processing method for BGN milk-based yoghurt. Fermentation increases protein digestibility [27]. Fermentation also aids in developing probiotic products, with studies demonstrating enhanced probiotic survival and product acceptability. BGN milk and yoghurt substitute development relies on viscosity, processing conditions, and starter culture selection (for yoghurt substitute), with formulation approaches, such as stabilizers and controlled heat treatment, improving texture and stability.

2.3.2 Nutritional properties of BGN yoghurt

The proximate composition of BGN yoghurt varies depending on formulation and processing conditions [27, 64]. Fermentation supports the growth of probiotic microorganisms, with viable microbial counts reported above permissible limits (> 6 log cfu/mL), increasing its potential as a functional food. Processing techniques such as foam-mat drying can enhance the stability and nutritional value of BGN yoghurt [55], while also improving its shelf life, particularly in rural areas with limited facilities for liquid yoghurt storage and preservation.

2.3.3 Physicochemical, functional and sensory properties of BGN yoghurt

The manufacture of BGN yoghurt using starting cultures of *Lactobacillus delbruieckii subspp. bulgaricus* and *Streptococcus salivarus subspp. thermophilus* was recently described by Falade et al. [65]. They discovered that soy yoghurt had a higher total solid content (10.4%) than BGN yoghurt (9.7%). Furthermore, compared to soy milk (530 Cp), the viscosity of BGN yoghurt (698 Cp) was higher but rapidly dropped during storage. Compared with spontaneous fermentation, controlled starter cultures produce more consistent product quality, enhanced safety, and improved sensory characteristics. During fermentation, a progressive decrease in pH with a concomitant increase in titratable acidity reflects normal fermentation kinetics resulting from lactic acid production by starter microorganisms. Compared to soy yoghurt, BGN yoghurt has much better sensory qualities in terms of aroma, taste, colour, and overall acceptability. These findings further demonstrated BGN's great potential for yoghurt production. Consumer acceptability studies indicate that BGN yoghurt possesses favourable sensory acceptability and can produce yoghurt of acceptable quality [65]. Legumes, including Bambara bean, are recognized as protein sources for plant-based milk and yoghurt analogues, where protein functional properties such as solubility, emulsification and foaming are required for formulation stability [66, 67]. Enzymatic or fermentative modification of protein enhances these properties, leading to better texture, mouthfeel and stability.

2.4 BGN cheese analogue

The justification for BGN-based cheese substitutes goes beyond the general advantages (lactose- and cholesterol-free, compatibility with vegan diets, and health benefits) shared by other plant-based cheese substitutes. BGN's low-input requirements, climate resilience, and suitability for smallholder production in sub-Saharan Africa make it a promising locally sourced raw material for developing plant-based cheese analogues as potential alternatives to imported dairy- or soy-based products [4].

2.4.1 Processing of BGN cheese analogue

BGN is increasingly being used as a source of plant-based dairy alternative products, especially cheese analogues, due to its high protein content and amino acid composition. Chemical analysis has consistently shown that BGN seeds generally contain high levels of protein and starch but moderate fat and mineral content. This makes it a good starting point for milk dispersions and the coagulated structures needed for cheese-making.

BGN cheese analogues are designed to enhance the availability of proteins in non-dairy products. Just like traditional cheese-making, it is produced by protein coagulation, curd formation, and dewatering. A range of coagulation methods has been used to prepare BGN cheese analogues. Acid coagulation using glucono-δ-lactone (GDL) or food-grade acid (such as vinegar) is the most commonly used method, as it results in curds with satisfactory texture and taste. Other methods, including transglutaminase and laccase crosslinking, improve BGN protein gel/hydrogel network structure, texture, encapsulation, and sustained release, and may enhance functional stability [68, 69].

2.4.2 Nutritional composition of BGN cheese analogue

Bambara-based cheese has been reported to have a favourable nutritional composition, with appreciable levels of protein, fat, carbohydrates, moisture, and ash (Table 3). These characteristics demonstrate its potential as a nutritionally valuable and low-cost protein delivery system. However, processing parameters affect the quality of the curd. The rate of coagulation and the strength of the curd are influenced by temperature, pH and divalent ions (calcium, magnesium). Processing conditions are important for the utilisation of Bambara groundnut in food production, as appropriate processing can help improve its suitability for different food applications [4].

Table 3. Comparison of different processing technologies for BGN

Processing technology	Advantages/Reported effects	Limitations/Reported effects	Food applications/ Potential uses
Roasting	Increases water absorption capacity and improves some functional properties. It also reduces some antinutritional factors. Roasted BGN flour has potential for product development, particularly in gravies, baked goods, soups and doughs.	High temperatures can cause protein denaturation, reducing foaming capacity and emulsion capacity. Roasting can also decrease some components of the proximate composition.	Useful in flour-based food products and complementary/weaning foods.
Soaking	Reduces antinutritional factors and increases water absorption, oil absorption and foaming capacity of BGN flour.	Some minerals, including calcium, iron and potassium, may decrease because of leaching into the soaking water. It can also decrease emulsion capacity and bulk density.	Useful as a processing step for improving the functional properties and nutritional quality of BGN flour.
Boiling/Cooking	Reduces trypsin inhibitors, oxalate, hydrogen cyanide, phytate and tannins. It improves protein and starch in-vitro digestibility and increases water absorption capacity.	Prolonged heating can result in loss of soluble proteins and minerals through leaching. Boiling also decreases foaming and emulsion capacities.	Suitable for preparation of cooked BGN grains and as a processing treatment for BGN flour.
Fermentation	Reduces antinutritional factors such as phytate and can improve some nutritional and functional properties. Natural fermentation has been reported to improve calcium and iron content in some studies. Fermentation also increases certain metabolites, including esters.	Effects on nutrient composition can vary according to the fermentation process. Some studies reported reductions in calcium and iron during fermentation.	Used in fermented BGN products and has applications in food products such as fermented flour and traditional foods.
Germination	Reduces antinutritional factors and improves several functional properties. It increases water absorption capacity, foaming capacity and emulsion capacity while reducing bulk density. It can also promote the formation of metabolites and phenolic compounds.	Germination changes the nutritional and functional composition of BGN and requires subsequent processing for some applications.	Has potential for ready-to-consume snack foods and nutritionally improved BGN flour.
Malting	Can reduce antinutritional factors and modify the nutritional composition and functional properties of BGN. It also affects the metabolite profile of BGN flour.	Malting can decrease some metabolites, such as esters, and change the proximate composition of the flour.	Has potential for producing value-added BGN food products.
Dehulling	Reduces antinutritional factors and results in BGN flour with higher reported protein content than whole BGN flour.	Removal of the seed coat changes the proximate composition of the flour, including reductions in carbohydrate content.	Useful for producing BGN flour with improved nutritional characteristics.
Ultrasonication	Reduces antinutritional factors and improves some functional properties of BGN flour. It can increase water absorption and other functional characteristics.	The effects depend on the processing conditions, and the treatment can alter the nutritional and functional characteristics of the flour.	Potential application in improving the functional properties of BGN flour.
Micronization	Identified as a novel processing technique for improving the nutritional quality and functional properties of BGN flour.	The article indicates that processing conditions influence the resulting characteristics of the flour.	Potential use in the production of improved BGN flour and food products.
Infrared processing	Identified as a novel processing technique that can influence the nutritional quality, functional properties and metabolites of BGN flour.	Processing can alter the metabolite profile of BGN.	Potential application in the processing of BGN flour and food products.

Source: Adapted from [7].

Cheese analogues made from BGN may provide health benefits due to their dietary fibre and bioactive components. When processed appropriately, they can provide protein and important minerals, contributing to dietary diversity. However, potential challenges include residual antinutritional factors, heat-induced unavailable lysine, and off-notes. Furthermore, potential cross-reactions with allergens from other legumes, especially soybean, pose another challenge [70].

2.4.3 Functional, rheological and sensory properties of BGN cheese analogue

The functional properties of BGN proteins play a crucial role in cheese formulation. The proteins typically have good emulsifying properties, enabling the formation of stable milk-like emulsions, but their intrinsic gelation properties are inferior to those of soy and dairy proteins. Thus, cheese formulations may involve the addition of hydrocolloids, choice of coagulant or enzyme-induced cross-linking to achieve the desired texture and consistency. Research has demonstrated that hydrocolloid blends, such as gum Arabic and sodium alginate, can improve moisture retention, texture, and consumer acceptability of Bambara groundnut tofu, potentially by enhancing the protein network and minimising syneresis [25].

The quality of BGN-based cheese analogues is strongly influenced by the quality of the extracted protein, especially its solubility and interaction with non-protein components. Thus, protein extraction is critical to the stability of the milk dispersion and the ability to coagulate. Hydrocolloids [25, 71] are often added to alter protein solubility and functionality, which in turn influence gelation and water-holding capacity of the curd. Hydrocolloids [25, 71], such as gum Arabic and sodium alginate, can modify the textural, physicochemical and rheological properties of Bambara groundnut tofu, with effects that depend on the formulation and coagulant used.

Recent formulation and processing techniques have increased the potential for scaling up BGN cheese analogues. Design of experiments, such as response surface methodology, has allowed for the formulation of products with enhanced protein, texture and sensory quality. New methods, such as enzymatic cross-linking and oxidative polymerization, are also being investigated to develop heat-stable, sliceable products similar to processed dairy cheese. However, processing methods, such as sprouting, have been reported to significantly affect the nutrient composition and physicochemical properties of BGN cheese analogues [72].

According to a study by Ariwaodo and Obasi [63], BGN cheese substitutes have good organoleptic qualities and can be compared favourably to traditional dairy cheese. Sensory panelists largely approved of cheese samples made from BGN milk; formulations with lower substitution levels had better mouthfeel, texture, flavour, and overall acceptance than formulations with higher substitution levels. The rheological and gel-forming characteristics of BGN proteins are important for formulating cheese substitutes. In contrast to soy proteins, which often result in more homogenous and persistent gel networks, Bambara proteins require higher concentrations for gel formation and form gels across a wider temperature range. Additionally, viscoelastic behaviour and the possibility of enhancing texture through enzymatic cross-linking have been demonstrated in studies on Bambara protein gels [69].

2.5 BGN biscuit

2.5.1 Processing of BGN biscuit

Biscuits are ready-to-consume energy-dense snacks conventionally produced from soft wheat flour. They are rich in sugar and fat but low protein and health-promoting bioactive constituents such as dietary fibre and phytochemicals, reflecting the compositional quality of the soft wheat flour and ingredients used for their production [73-75].

2.5.2 Nutritional properties of BGN biscuit

Studies have shown that supplementation of cereal flour with BGN flour is a viable option for enhancing the nutritional profile of cereal-based bakery products, such as biscuits [76]. Specifically, adding BGN flour can help increase lysine content and improve protein quality in biscuit formulations [77]. Substitution of wheat with BGN has been reported to increase the crude protein, fibre, and ash contents of the final biscuit [78, 79]. In addition to wheat-based biscuits, BGN has also been incorporated into germinated finger millet-based biscuits, resulting in improved nutritional quality and in vitro protein digestibility ranging from 80.52 to 89.20% [76].

2.5.3 Physicochemical and sensory properties of BGN biscuit

Evidence abounds for the replacement of wheat flour with underutilised legumes and cereals in the production of nutrient-rich and healthy biscuits [74, 80]. For instance, Irondi et al. [75, 81] formulated biscuits from biofortified yellow maize-cowpea composite flour and evaluated the biscuits' qualities, including the bioactive constituents, digestive enzyme-inhibitory, and antioxidant activities, as well as the biscuits' physicochemical, sensory, and in vitro starch digestibility properties. Other researchers have also investigated the effects of replacing wheat flour with BGN flour in composite biscuits. Okafor et al. [82] evaluated the quality and acceptability of biscuits fortified with roasted BGN. Similarly, Adefegha and Oboh [83] assessed the sensory, antioxidant and type-2 diabetes-related enzyme-inhibitory qualities of biscuits formulated from five wheat-BGN flour blends. Agu et

al. [84], on the other hand, investigated the consumer acceptability of acha-malted BGN biscuits, sweetened with date. In all these studies, the consensus conclusion was that replacement of wheat with BGN flour improved the biscuits overall quality, buttressing the versatility of BGN in nutritional diversification and a sustainable food system.

Addition of BGN flour to products, such as crackers, biscuits, and extruded products, has been reported to yield variable results in terms of their functional and physical qualities. The differences could be attributed to the varied formulations and production methods adopted, which might also account for the differences in nutritional and sensory properties among these products. In order to maximise BGN-enriched snacks potential for nutritional enhancement of the population, it is important to take local consumer preferences into consideration while developing the product [5].

Adegunwa et al. [85] formulated snacks from unripe plantain, BGN and turmeric composite flours, with the ratio of BGN in the different formulations ranging from 35% to 100%. From their findings, the different formulations had protein level ranging from 4.23% to 14.81%. Thus, the increase in protein level was dependent on the proportion of BGN added to the formulation. While larger substitution levels frequently resulted in darker colour, increased hardness, and a distinctive beany flavour that may lower overall preference, substitution levels of 10–30% BGN flour have created biscuits with good customer acceptability. The darker colour associated with increased level of BGN substitution could be due to Maillard browning during baking. BGN biscuits have been reported to absorb moisture during storage and, therefore, require appropriate packaging/storage conditions to extend their shelf life [86].

2.6 Comparison of processing technologies of BGN

Depending on the intended food application, each BGN processing method has unique benefits and drawbacks. Conventional techniques, including soaking, boiling, roasting, germination, and fermentation, lower anti-nutritional factors, as recently reviewed by Mashau et al. [30]. Roasting is a traditional processing method that reduces antinutrients and prepares grains for consumption. It might alter dietary fibre level, depending on the extent of the thermal treatment applied. Heating a food product, such as grain, during roasting leads to Maillard browning and caramelization that enhance flavour. Okafor et al. [35] observed an increase in the level of protein of roasted BGN flour, which may be attributed to nutrient enrichment by moisture reduction when roasted. Furthermore, the authors reported a reduction in moisture level, with no significant differences in fat, ash, and fibre level. The nutritional quality of soaked grains can be affected by the leaching of nutrients and anti-nutritional factors in water. Soaking, as one of the pretreatments applied to Bambara groundnut, may affect the functional and chemical properties of the resulting flour and influence the retention or loss of anti-nutritional factors and nutrients [87]. Usually, BGN grains are cooked in a large volume of water until the required level of softness is achieved. Some factors, including diversity in gene frequencies, grain maturity, physical and chemical qualities, and storage temperatures may affect the processing time of the required finished products. Legume processing involving application of heat to water results in protein denaturation, starch swelling and gelatinisation, and cell separation [88]. Ndidi et al. [89] documented a reduction in the ash, protein, fat, and carbohydrate contents of BGN grains due to boiling. On the other hand, fermentation is traditionally a less advanced processing technique for legumes that influences the nutrient composition of BGN grains. Adebiyi et al. [90] reported that fermentation improves the levels of protein and essential amino acids in *dawadawa* produced from the flour of BGN, with and without hulls. Improvement in protein level may be ascribed to the release of proteins from antinutrients during fermentation. According to Aremu et al. [91], roasting and boiling

Table 4. Comparative proximate composition across BGN products

Product Type	Protein (g/100 g)	Fat (g/100 g)	Carbohydrate (g/100 g)	Energy (kcal/100 g)	Crude fibre (g/100 g)	Ash (g/100 g)	Moisture (g/100 g)	Reference
Flour	17.70	6.58	60.1	370.4	3.50	4.22	7.7	[92]
Milk	5.42	1.92	17.1	57.3	0.3	1.25	73.92	[93]
Yoghurt	2.6	–	3.1	–	–	2.4	90.1	[27]
Cheese	3.44	1.65	48.37	209.1	2.16	4.38	40.00	[63]
Wheat-BGN biscuit	7.42–9.20	17.70–20.56	65.44–66.30	–	1.15–1.60	1.04–1.82	3.20–4.17	[78]

Ranges for the wheat-BGN biscuit reflect six blend formulations reported within a single study: three using BGN flour (15–47.5% substitution) and three using BGN protein isolate (15–47.5% substitution).

Table 5. Amino acid composition of BGN-based processed products (g/100 g protein)

Amino acid (g/100 g protein)	BGN milk substitute	Wheat–BGN biscuit[2]
Essential amino acids		
Histidine	2.5	–
Isoleucine	3.8	–
Leucine	7.0	4.28–6.24
Lysine	2.9	3.02–6.88
Methionine	2.8	1.29–3.09
Phenylalanine	4.8	–
Threonine	2.6	–
Valine	4.1	–
Tryptophan	–	–
Non-essential amino acids		
Alanine	3.9	–
Arginine	5.0	3.83–6.32
Aspartic acid	5.62	–
Cystine	0.6	–
Glutamic acid	17.2	–
Glycine	3.35	–
Proline	3.8	–
Serine	2.6	–
Tyrosine	3.5	–
Protein quality indices		
EAAI	–	37.06–76.49
PER	–	1.70–3.05
Reference	[61]	[94]

reduced the level of anti-nutritional factors in BGN.

A comparison of the processing technologies for BGN is presented in Table 3.

2.7 Comparative proximate composition across BGN product types

The nutritional quality of BGN products differs depending on the processing method, added ingredients, state of the product and/or the dry matter content - whether solid or liquid. Comparative proximate and amino compositions of different BGN products are presented in Table 4 and Table 5, respectively.

3. Nutraceutical properties of BGN and its products

BGN is considered not only as a rich source of basic nutrition but also as a wide range of bioactive compounds with health-promoting properties [23]. It is processed into multiple edible products such as BGN flour, plant-

based BGN milk and cheese analogue [95, 96]. Notably, BGN is locally used as a daily dietary therapy by diabetic patients in northern Nigeria [97]. This section reviews the bioactive constituents of BGN products and their demonstrated nutraceutical properties (antioxidant, antidiabetic, anti-inflammatory, anti-hypertensive, anti-obesity, anti-cancer), including mechanisms of action and evidence from *in vitro*, *in vivo* and clinical studies.

3.1 Bioactive compounds in BGN and its products

BGN seeds are rich in phytochemicals that underlie their nutraceutical value [23]. Key bioactive compounds include phenolic compounds (such as flavonoids and phenolic acids), tannins, saponins, alkaloids, carotenoids, dietary fibre, and bioactive peptides, among others. Phenolics, such as catechin, epicatechin, chlorogenic acid, ellagic acid, have been identified in BGN and are linked to various health benefits [23]. BGN with darker seed coats (red, brown, black) tends to have especially high phenolic and flavonoid content [98]. The extract from maroon- and black-coated BGN contains the greatest total phenolics and exhibit correspondingly high antioxidant activity [98]. Significant levels of tannins and even some alkaloids are present in BGN; Udeh et al. [11] reported BGN cultivars to contain flavonoids, tannins, and alkaloids (the latter associated with analgesic properties). According to Mashau et al. [30], BGN is a rich source of protein and amino acids. Its protein is not only high (18–25% of the seed) but is also of high quality, as it is rich in lysine, an essential amino acid. Upon processing (such as enzymatic hydrolysis or fermentation), BGN proteins can release peptides with specific bioactivities.

Notably, BGN also contains carotenoids. Though the seeds are not intensely coloured as orange vegetables, they have been reported to contain measurable quantities of lutein and β-carotene, particularly after germination [99]. According to Cele et al. [99], sprouting BGN for 48 hours increased the total carotenoid content (up to 1.5 to 1.8 mg/100 g in certain landraces) and in particular raising lutein and β-carotene levels. These carotenoids have been reported to have antioxidant and photoprotective properties. Therefore, BGN products can enrich the diet with carotenoids, which, together with phenolics and vitamins, constitute a wide array of antioxidants. BGN flour has a low glycaemic index and does not release glucose rapidly, which is beneficial for blood sugar control [100].

BGN can be made into various value-added products. An example is BGN milk (extracted from the seeds), which serves as a nutritious dairy substitute [5]. BGN milk substitute can be fermented to produce BGN yoghurt or processed into a soft BGN cheese. According to Adebanke et al. [64], replacing 10-40% of cow milk with BGN milk in yoghurt resulted in increased protein and ash (mineral) contents in the product. BGN products are rich sources of bioactive compounds and may, therefore, serve as functional foods with several health-promoting attributes.

Several processing techniques, including cooking, dehulling, malting, ultrasonication, infrared, and roasting, can influence metabolites in BGN flour. According to Oladimeji and Adebo [101], processing BGN grains may result in the production or detection of new metabolites that are absent from the raw flour. However, depending on the length of processing, certain metabolites found in raw BGN may be enhanced, eliminated, or reduced, according to the findings of Mudau et al. [102]. For instance, on days 0, 1, 2, and 3 of germination, the study also detected squalene, butylated hydroxytoluene, glycerol, and stigmasterol. Furthermore, the study reported that germination-induced metabolites in BGN flour may provide a deeper understanding of their constituents, and may be utilized to formulate functional foods.

Processing conditions affect the stability of bioactive chemicals. While controlled fermentation and germination can increase the availability of phenolic compounds and antioxidant activity through enzymatic hydrolysis and the disintegration of complex plant matrices, thermal processing, roasting, extrusion, and prolonged heating may decrease heat-sensitive phytochemicals. Therefore, maintaining the nutraceutical quality of BGN products requires careful consideration of processing techniques [103].

After being absorbed, phenolic compounds are extensively metabolized in the liver and small intestine by conjugation processes such methylation, sulfation, and glucuronidation. The gut bacteria may break down unabsorbed substances into tiny bioactive metabolites that have anti-inflammatory and antioxidant properties. The bioavailability, biological activity, and health advantages of BGN phytochemicals are all impacted by these metabolic changes [30].

3.2 Antioxidant potential of BGN and its products

Several in vitro tests, including, 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), Ferric reducing antioxidant power (FRAP), and Oxygen radical absorbance capacity (ORAC), which measure antioxidant capacity through different mechanisms, have been used to assess the antioxidant activity of BGN. ABTS assay examines radical scavenging activity in both aqueous and lipid systems, making it applicable to a wider spectrum of antioxidant chemicals, whereas the DPPH assay evaluates antioxidants' capacity to scavenge stable free radicals in organic media. On the other hand, the ORAC assay assesses the ability of antioxidants to inhibit peroxyl radical-induced oxidation and is thought to be more representative of physiological antioxidant activity, whereas the FRAP assay determines the ferric reducing

antioxidant power of a sample by measuring its capacity to reduce ferric (Fe^{3+}) to ferrous (Fe^{2+}) ions [104].

Several in vitro and in vivo studies have reported the antioxidant potential of BGN and its products. The antioxidant activity of BGN is primarily attributed to its rich phenolic content (flavonoids, phenolic acids, tannins) which can scavenge free radicals and chelate pro-oxidant metal ions, thereby preventing oxidative damage to cells [23]. Phenolic compounds according to Chouikh et al. [105] donate electrons or hydrogen atoms to neutralise reactive oxygen species, interrupting free-radical chain reactions. BGN also contains phenolic compounds with demonstrated antioxidant activity [98]. Separately, peptides and amino acids may contribute by upregulating endogenous antioxidant enzymes, and carotenoids such as lutein and β-carotene are known to quench singlet oxygen and stabilize radicals. Collectively, these mechanisms reduce oxidative stress in biological systems.

BGN has demonstrated strong antioxidant capacity in numerous *in vitro* assays. Extracts from BGN (especially from the seed coat/testa) show high free-radical scavenging activity. Okafor et al. [23] found that BGN seed coat fractions had significantly higher total polyphenol and flavonoid content than the cotyledon or whole seed, and correspondingly exhibited the greatest antioxidant power in ferric reducing antioxidant power (FRAP), 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) and oxygen radical absorbance capacity (ORAC) assays. This implies that BGN seed contains potent natural antioxidants, largely due to its polyphenol profile.

BGN products have also demonstrated antioxidant potential in vitro. Irondi et al. [106] reported that a plain, dehydrated, ready-to-consume BGN milk substitute scavenged free radicals ($DPPH^*$ and $ABTS^{*+}$), with a $DPPH^*$ SC_{50} of 350.71 µg/mL, and reduced Fe^{3+} to Fe^{2+}. According to the authors, the antioxidant activity of the BGN milk substitute increased due to supplementation with ginger rhizome and bullock leaf powder. Similarly, a condiment formulated from fermented BGN seed scavenged OH and DPPH radicals with an EC_{50} of 0.29 and 2.25 mg/mL, respectively [107]. Further, in a recent study, Chuyeh-Nforba et al. [108] affirmed the antioxidant property in terms of $DPPH^*$-scavenging activity and ferric reducing antioxidant power (FRAP) of plant-based cheese analogue produced from the blend of BGN seed and *Cucumeropsis mannii* seed kernel milks under optimised processing conditions. The antioxidant activity of the optimised plant-based cheese analogue increased significantly as the BGN milk proportion in the cheese analogue increased, with an IC_{50} of 871 µg/mL for $DPPH^*$ and FRAP of 54.04 mmol $FeSO_4$/g DM for a proportion of 4 : 2 (*Cucumeropsis mannii* seed kernel milk : BGN seed milk, v/v).

Animal studies have also confirmed BGN's antioxidant benefits in biological systems. In diabetic rat models, diets supplemented with BGN have been shown to ameliorate oxidative stress. Olanipekun et al. [109] examined the effect of BGN consumption on biomarkers of oxidative stress in alloxan-induced diabetic Wistar rats. Specifically, diabetic rats on a BGN-enriched diet had significantly higher activities of superoxide dismutase (SOD) and glutathione peroxidase (GSH-Px) in their plasma and tissues, approaching or even exceeding the levels in non-diabetic control [109]. Concurrently, the levels of oxidative damage (lipid peroxidation) decreased, suggesting that BGN intake improved the rats' antioxidant defense mechanism. The study concluded that the BGN diet moderated and decreased oxidative stress in diabetic animals.

Due to variations in extraction solvents, extraction techniques, cultivar or genotype, geographic origin, maturity stage, processing conditions, and the analytical principles underpinning each assay, antioxidant levels reported for BGN differ significantly among investigations. However, due to variations in bioavailability, metabolism, and interactions within biological systems, the antioxidant effects of BGN observed in vitro can only provide helpful preliminary information on its antioxidant potential but may not accurately reflect in vivo antioxidant activity.

3.3 Antidiabetic activity of BGN and its products

BGN and its products are prominent for their antidiabetic activity, exhibited through various mechanisms. Their low glycaemic index and high fibre content slow down the carbohydrate digestion and glucose uptake, preventing the rise in blood sugar levels following the meal [110]. The soluble fibre in BGN forms viscous gels that delay gastric emptying and enzymatic access to carbs, thereby improving glycaemic control. Phenolic-rich extracts from BGN have also been shown to inhibit α-amylase and α-glucosidase, which catalyse the breaking down of starch into absorbable monosaccharides [111]. By suppressing these enzymes, BGN polyphenols reduce glucose release and absorption, blunting blood sugar elevations (a mechanism analogous to that of acarbose, a pharmacological α-glucosidase inhibitor).

BGN contains bioactive peptides that influence glucose metabolism [112]. Saetang et al. [113] identified dipeptidyl-peptidase IV (DPP-IV) inhibitory peptides in BGN protein hydrolysates. DPP-IV is an enzyme that degrades incretin hormones (like GLP-1); inhibiting DPP-IV prolongs insulin secretion and improves glycaemic control [114]. Thus, BGN-derived peptides acting as natural DPP-IV inhibitors could enhance insulin action similarly to anti-diabetic DPP-IV inhibitor drugs. Additionally, BGN's high magnesium and polyunsaturated fatty acid content may improve insulin sensitivity, and its antioxidants alleviate oxidative stress in pancreatic β-cells. Overall, these mechanisms - enzyme inhibition, fibre-mediated glucose modulation, and insulinotropic peptide activity collectively contribute to BGN's anti-diabetic

effects.

The enzyme-inhibitory potential of BGN has been demonstrated in laboratory assays. Oyende et al. [115] prepared a protein isolate from BGN and tested its ability to inhibit α-amylase (carbohydrate-digesting enzyme) and pancreatic lipase. At 1 mg/mL, the BGN protein isolate achieved approximately 91% inhibition of α-amylase activity (with an IC_{50} of 0.40 mg/mL), which was even more potent than acarbose, a standard starch-digesting enzymes inhibitor, under the same conditions. This indicates a strong starch-blocking activity inherent in BGN peptides.

Furthermore, *in silico* and *in vitro* analyses of BGN protein hydrolysates by Saetang et al. [113] have found specific peptide sequences that bind to the DPP-IV enzyme. These authors identified peptides (sequences like YKDGLYSPHW and EPWWPK) from BGN, which showed high-affinity docking with DPP-IV's active site, effectively inhibiting its activity. Such dual enzyme inhibition (α-amylase/α-glucosidase and DPP-IV) suggests that BGN components can reduce glucose release and enhance insulin effectiveness.

The antidiabetic effect of BGN has also been confirmed in some animal studies, such as Uro-Chukwu et al. [116]. Mhya and Mohammed [97] also found that diabetic rats after 28 days of feeding diets composed of BGN flour (56 percent addition) exhibited a significant decrease in fasting blood glucose when compared to diabetic controls. It was found that blood glucose of diabetic rats fed on BGN slowly decreased to normal levels during the study period, as opposed to untreated diabetics who were found to be hyperglycaemic. The lipid profile of diabetic rats treated with BGN improved: total cholesterol was reduced, as well as triglycerides, and the HDL levels became more favourable, indicating that BGN could also help to alleviate diabetic dyslipidaemia.

Furthermore, Oguntuase et al. [117] demonstrated that the intake of bread supplemented with BGN and sweet orange peel attenuated type-2 diabetes complications in rats. Another study by Nwajiobi et al. [118] found that a combined diet of BGN and yam effectively lowered blood glucose in alloxan-induced diabetic rats, further confirming BGN's hypoglycaemic action. Intake of finger millet, BGN, and 'Khain' (*Lecaniodiscus cupanioides*) flour blend was also reported to reduce blood glucose level in diabetic rats [119]. Dietary supplementation with fermented BGN has been shown to ameliorate hyperglycaemia in streptozotocin-induced diabetic Wistar rats [120]. The possible mechanisms underpinning the hypoglycaemic effects of BGN include enhancement of glucose uptake and/or activation of the insulin-secreting capacity of pancreatic β-cells. Other mechanisms include inhibition of starch-hydrolysing enzymes (α-amylase and α-glucosidases). These hypoglycaemic effects could be ascribed to the bioactive components in BGN seed, especially the phenolic compounds.

3.4 Anti-inflammatory properties of BGN and its products

Available evidence has shown that the bioactive constituents of BGN can modulate inflammatory pathways and mediators [121]. Polyphenols, such as flavonoids and phenolic acids, in BGN are known to exert anti-inflammatory effects by down-regulating the production of pro-inflammatory cytokines and enzymes [122]. These compounds have been reported to inhibit key signaling pathways like NF-κB and mitogen-activated protein kinases, which are involved in upregulating inflammatory genes [122, 123]. Additionally, some BGN peptides and saponins could have anti-inflammatory roles (as seen in other legumes, bioactive peptides can modulate immune cell function or opioid receptors to reduce inflammation). Dietary fibre from BGN may promote an anti-inflammatory gut environment by fostering short-chain fatty acid production [124]. Overall, BGN's anti-inflammatory mechanism is multifactorial: scavenging free radicals, inhibiting inflammatory enzyme activity, and regulating cytokine release are principal modes.

The anti-inflammatory activity of BGN extracts has been demonstrated in vitro. Oyeyinka et al. [98] compared the *in vitro* anti-inflammatory properties of hot-water extracts from different BGN landraces. The results showed that maroon BGN had the highest total phenolic content, while the total phenolic, flavonoid, and antioxidant properties varied among the different landraces. Another similar study by Olanipekun et al. [125] found that BGN condiment extract (BGNCE) achieved substantial reductions in the concentration of pro-inflammatory markers (TNF-α and NF-κβ) in castor oil-induced diarrhoeal rats. BGN extract treatment was linked with reduced levels of tumor necrosis factor-alpha (TNF-6) and interleukin-6 in cell lines, relative to untreated controls. These *in vitro* results indicate that the phytochemicals of BGN can have a direct effect on disrupting the inflammatory processes. Although the anti-inflammatory potential of BGN has not been as extensively researched in vivo as certain medicinal plants, the available evidence from in vitro studies suggests a significant anti-inflammatory potential that can be attributed to its bioactive compounds. These bioactive compounds, including polyphenols, can modulate some key inflammatory signaling pathways. However, to avoid exaggerating the evidence, it should be mentioned that these effects are mostly deduced from the known biological activities of polyphenols and other phytochemicals reported in related plant systems, as there are few direct mechanistic studies that investigated the anti-inflammatory mechanism of BGN.

3.5 Anti-hypertensive activity of BGN and its products

Angiotensin I-converting enzyme (ACE) is an essential part of the renin-angiotensin-aldosterone system (RAAS), which controls fluid balance and blood pressure. Angiotensinogen is converted to angiotensin I by renin, which is released from the kidneys when blood pressure reduces. ACE then transforms angiotensin I into angiotensin II, a strong vasoconstrictor that raises the peripheral vascular resistance, causing the adrenal cortex to secrete aldosterone. Aldosterone increases the kidneys' reabsorption of water and salt, which raises blood pressure and blood volume [126]. Furthermore, bradykinin, a vasodilatory peptide that encourages the release of prostacyclin and nitric oxide, is broken down by ACE. As a result, ACE inhibition lowers angiotensin II production while maintaining bradykinin levels, which causes vasodilation and lessens water and salt retention, ultimately lowering the blood pressure [127].

BGN-derived products may have potential blood pressure-regulating effects through the ACE-inhibitory activity of bioactive peptides [113]. Proteins in BGN contain amino acid sequences that, upon hydrolysis, yield peptides (usually 2–12 amino acids in length) capable of binding to the ACE active site and blocking its activity [113]. Saetang et al. [113] found that peptide fractions with molecular weight > 10 kDa had the highest ACE-inhibitory activity, whereas the 5–10 kDa peptide fraction displayed the strongest DPP-IV-inhibitory activity after enzymatic hydrolysis. These peptides likely act as competitive inhibitors of ACE, reducing angiotensin II production, and ultimately alleviating hypertension. Another mechanism is through DPP-IV inhibitory peptides, which indirectly benefit blood pressure by improving endothelial function [128].

The ACE-inhibitory potential of BGN has been clearly demonstrated in vitro. Arise et al. [129] reported that protein hydrolysates of BGN, especially the low-molecular weight peptide fractions (< 1 kDa), exhibited high ACE inhibition. In another recent study, Saetang et al. [113] reported that BGN protein isolate, digested with Flavourzyme and fractionated, showed ACE-inhibitory activity, with the > 10 kDa fraction exhibiting the strongest activity. Specific peptide sequences from BGN (such as *YKDGLYSPHW*, *LPVSTPGKF*) were identified via LC-MS/MS and shown through molecular docking to bind ACE's catalytic residues (such as His^387 and Glu^411) with high affinity. These peptides effectively plug the active site, preventing ACE from converting angiotensin I to II. The binding free energies *in silico* were comparable to known antihypertensive peptides from other sources, highlighting BGN as a promising source of natural ACE inhibitors. Notably, the *in vitro* ACE-inhibitory activity of BGN peptides pattern is dose-dependent and, in some cases, quite potent. Arise et al. [129] reported that the low-molecular-weight (< 1 kDa) peptide fractions derived from BGN protein hydrolysates exhibited the highest inhibitory activity against angiotensin-converting enzyme (ACE).

Furthermore, because many ACE-inhibitory peptides from BGN are resistant to gastrointestinal digestion (as per simulated digestion studies), they could remain active in the bloodstream after oral intake. Beyond ACE, the dual inhibition of DPP-IV by the same peptide mixtures suggests that BGN hydrolysates could address metabolic syndrome comprehensively [113], targeting both hypertension and hyperglycaemia. Besides the seed extracts, BGN dairy alternative supplemented with bullock leaves and ginger rhizome powder inhibited ACE, demonstrating its anti-hypertensive potential [106]. Thus, *in vitro* evidence strongly supports that BGN contains bioactive constituents capable of inhibiting ACE, providing a biochemical basis for its blood-pressure-lowering potential. However, the promising ACE-inhibitory activity demonstrated by BGN peptides in *in vitro* studies notwithstanding, evidence from human intervention trials is currently lacking.

3.6 Anti-obesity activity of BGN and its products

Proteins are one of the most satiating macronutrients; hence, high-protein foods are an essential part of a diet designed to reduce the overall intake of calorie and enhance weight control. BGN flour is one of the plant-based protein sources that provides these benefits due to with its protein level ranging from 18% to 24%. When consumed, dietary proteins stimulate the release of hormones, such as cholecystokinin (CCK), peptide YY (PYY), and glucagon-like peptide-1 (GLP-1), which signal a state of fullness to the brain, thereby promoting satiety and reducing feelings of hunger for longer periods [130]. In addition, dietary fibre is prominent for the key role it plays in satiety. It has been reported that soluble fibre can delay food digestion and nutrient absorption by forming a gel-like substance in the digestive tract, thereby extending the duration of fullness after food intake [131].

BGN could help prevent obesity and control body weight through certain mechanisms. The high dietary fibre and protein contents in BGN make it satiating, reducing total calorie intake, which is essential for weight control [100]. BGN has a relatively low-to-moderate glycaemic index, which is partly ascribed to its dietary fibre, complex carbohydrates, and resistant starch content. These attributes may retard its postprandial glucose release, thereby improving blood glucose regulation [132]. BGN also contains phytochemicals that influence lipid metabolism by retarding dietary fat digestion and absorption through pancreatic lipase inhibition. Moreover, BGN could activate fat oxidation and the functionality of adipocytes due to its polyphenols, including flavonoids, such as quercetin. It can also trigger the activity of AMPK in tissues, promoting energy consumption and lipid

breakdown [133]. Additionally, the antioxidant and anti-inflammatory actions of BGN could mitigate obesity-associated oxidative stress and chronic inflammation within the adipose tissue, thereby promoting body weight maintenance. Therefore, through a decrease in caloric uptake, enhanced satiety, and metabolic fitness, BGN could mitigate obesity by balancing energy and metabolism.

The strongest evidence for BGN's anti-obesity potential comes from enzyme assays demonstrating lipase inhibition. Available evidence has shown that BGN protein isolate displayed potent inhibition of pancreatic lipase *in vitro* [115], buttressing its propensity to interfere with fat digestion. Furthermore, BGN's capacity to inhibit α-amylase and α-glucosidase, as discussed in the previous section, is also relevant to obesity, as it may lower the glycaemic load of meals and reduce de novo lipogenesis (conversion of excess carbohydrates to fat). An *in vitro* enzyme inhibition study by Oguntuase et al. reported that adding BGN flour to high-starch foods reduced the rate of starch breakdown [134], suggesting that BGN may attenuate the insulin response and the consequent fat storage in a real meal.

Another *in vitro* aspect is the antioxidant effect: by protecting against oxidative stress, BGN compounds could prevent oxidative damage that contributes to adipocyte dysfunction. Bioactive compounds in BGN, including dietary fibre and polyphenolic compounds, may contribute to metabolic health. BGN flour contains dietary fibre, while food bioactive constituents such as dietary fibre and polyphenols have been discussed in relation to obesity management and metabolic regulation [92, 135]. These mechanisms, however, are mostly deduced from the physiological effects of the bioactive components, as well as data from animal and laboratory research. Further study is necessary to validate these suggested processes and prove their clinical relevance, as there are currently few direct mechanistic investigations and human clinical trials assessing the anti-obesity effects of BGN.

3.7 Anti-cancer activity of BGN and its products

BGN's anti-cancer properties are attributed to several mechanisms, largely driven by its phytochemicals. The rich antioxidant content, including phenolic acids and flavonoids, has been suggested to contribute to cancer chemoprevention in laboratory studies [23]. Phenolic compounds have been reported to induce apoptosis and inhibit the proliferation of cancer cells in *in vitro* studies [136]. Additionally, BGN's alkaloids might have cytotoxic effects on cancer cells, as many plant alkaloids are known to possess chemopreventive property [137].

Okafor et al. [23] investigated the cytotoxic and antiproliferative effects of BGN extracts on human colon cancer cell lines (HT-29 and Caco-2). They found that BGN extracts, especially those from the seed coat, inhibited the growth of colon cancer cells in a dose-dependent manner. This aligns with the higher phenolic content of the seed coat, suggesting that these compounds may have contributed to the observed antiproliferative activity. The study also noted induction of apoptosis morphological changes in treated cancer cells, indicating that BGN extracts may trigger programmed cell death in tumor cells. In terms of potency, the IC_{50} values for growth inhibition of HT-29 cells by BGN seed coat extract were in the low hundreds of μg/mL range. BGN extract has also demonstrated *in vitro* anti-genotoxic potential as reported for pBR322 plasmid DNA [138]. Although these findings highlight the potential anti-cancer properties of BGN, the available evidence is derived predominantly from *in vitro* studies, with limited animal studies and no human clinical trials currently available.

4. Overall discussion, future trends, limitations, and conclusion

4.1 Overall discussion

This review shows that BGN is an underutilised, nutrient-dense legume with significant potential for use in nutraceuticals and functional foods. Variations in BGN's nutrient composition and functional qualities exist due to differences in genotype, geographical origin, processing methods, and analytical techniques. However, the majority of studies consistently identified high protein, dietary fibre, and bioactive chemical contents in it. Similarly, processing techniques, such as germination, fermentation, roasting, and enzymatic hydrolysis, typically improve the nutritional quality and diminish anti-nutritional elements. BGN products, such as flour, yoghurt, cheese alternatives, milk substitutes, and biscuits, provide rich and diversified plant-based sources of protein. Studies on acceptable substitution levels and product quality, however, vary, suggesting the need for optimal formulations that provide a balance among desirable sensory, functional qualities, and nutritional enhancement.

Antioxidant, antidiabetic, anti-inflammatory, antihypertensive, anti-obesity, and anticancer capacities are among the promising nutraceutical qualities of BGN. However, there are comparatively few human clinical studies, as the majority of the currently available evidence comes from in vitro and animal research. Since the results of these two study models (in vitro and animal studies) could not necessarily translate into clinical efficacy, there must be caution when interpreting these results. Therefore, to strengthen the scientific evidence supporting the use of BGN as a sustainable functional food and nutraceutical ingredient, future research should concentrate on standardised processing techniques, carefully planned and executed clinical trials, and mechanistic studies.

4.2 Future trends

Future studies on BGN should adopt sophisticated methods that promote its sustainable use, going beyond traditional nutritional and functional characterisation. Precision nutrition techniques customised to each person's dietary requirements could be made possible by emerging technologies like metabolomics and nutrigenomics, which could enhance the understanding of the connections between BGN's bioactive chemicals, metabolic pathways, and health impacts. The development of superior BGN cultivars with increased nutritional quality, stress tolerance, and yield can also be accelerated by advances in genome editing and artificial intelligence (AI)-assisted breeding.

The development of functional food ingredients and value-added products that satisfy consumer and industrial demands should also receive more attention. To validate the potential health-promoting effects of BGN observed in laboratory and preclinical investigations, future research should prioritise carefully planned human clinical trials.

4.3 Limitations

Due to limited clinical trials on the health benefits of BGN products, this review was predominantly based on in vitro and animal studies.

4.4 Conclusion

BGN is a nutrient-dense, climate-resilient legume that has the potential to significantly improve food and nutrition security due to its rich nutritional quality and intriguing nutraceutical qualities. Products made from BGN, such as flour, milk alternatives, yoghurt, and cheese analogues, are rich in vital nutrients and bioactive substances that have shown antioxidant, antidiabetic, antihypertensive, anti-inflammatory, and anticancer properties, especially in preclinical and laboratory studies. The bioavailability of its bioactive components, underlying molecular mechanisms, and long-term health implications in humans, however, are still largely unknown. To enable broader food applications of BGN, standardised processing techniques, large-scale product development, and commercialisation strategies also need to be further optimised. Therefore, to bolster the evidence base and facilitate the conversion of BGN into functional food ingredients and economically viable products, future research should prioritise well-designed clinical trials, mechanistic investigations, and new processing technologies. Additionally, adoption of cutting-edge techniques, such as metabolomics, nutrigenomics, precision nutrition, and sustainable production methods, would unleash BGN's potential as a resilient crop with valuable nutritional and nutraceutical qualities.

Human ethics and consent to participate

This study did not involve a clinical trial or any research involving human participants or animals.

Consent for publication

All the authors agreed to publish this research in the Journal of Food, Nutrition and Diet Science.

AI disclosure statement

The authors declare that ChatGPT (OpenAI) was used during the preparation of this manuscript.

AI assistance was limited to the following purposes: language improvement, formatting assistance, and literature search support. All AI-assisted outputs were critically reviewed, verified, and revised by the authors.

Generative AI was not used to replace the authors' scientific judgment, generate unsupported scientific claims, independently interpret research results, or assume responsibility for any part of the research. The authors remain fully responsible for the originality, accuracy, integrity, and ethical compliance of the manuscript.

Author contributions

Emmanuel Anyachukwu Irondi: conceptualization, manuscript reviewing; Oluwapelumi Semipe Aina: writing original draft; Babatunde Joshua: writing original draft; Abdulazeez Olamilekan Elemosho: writing original draft, manuscript reviewing; Funmilayo Ayoola: writing original draft.

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Data availability

The datasets are all reported in the paper and are available from the corresponding author on request.

Conflict of interest

Authors declare there is no conflict of interest.

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