Food and Humanity 5 (2025) 100876

Contents lists available at ScienceDirect

Food and Humanity

journal homepage: www.editorialmanager.com/foohum/journal_overview.html

Physicochemical properties and consumer acceptability of Bambara groundnut tofu chunks

Londiwe Mary Chipeta [a], Yvonne Maphosa [b,*], Victoria A. Jideani [a]

[a] Department of Food Science and Technology, Cape Peninsula University of Technology, Cape Town, South Africa
[b] Biotechnology and Food Technology, University of Johannesburg, South Africa

ARTICLE INFO

Keywords:
Tofu
Tofu chunks
Bambara groundnut
Gum Arabic
Sodium alginate

ABSTRACT

Bambara groundnut (BGN) (*Vigna subterranea* [L.] Verdc.) is a protein-rich legume suitable for developing healthy, high-quality meat alternatives for vegetarians and health-conscious consumers. This study evaluated the physicochemical and sensory properties of tofu chunks derived from BGN tofu. A response surface I-optimal point exchange randomised design was used to determine the effect of gum Arabic (0.3, 0.4, 0.5 %) and sodium alginate (0.3, 0.4, 0.5 %) on the textural, physicochemical and rheological properties of BGN tofu. The design consisted of six models, with three lack of fit and three replicate points, giving a total of twelve runs. The interaction of gum Arabic and sodium alginate was optimal at 0.5 % and was further used to make tofu chunks. Incorporating gum Arabic and sodium alginate significantly ($p < 0.05$) enhanced the colour characteristics and protein content of the chunks. Bambara groundnut tofu chunks were a good source of essential amino acids, with leucine (4.34–4.94 %) and phenylalanine (4.61–5.62 %) being the most abundant. Samples with 0.6 % glucono-lactone (GDL) had higher lysine (3.76 %) and alanine (2.65 %) content than others. Chunks prepared with vinegar + 0.5 % gum Arabic + 0.5 % sodium alginate had the highest protein content (53.09 %), while those with 0.6 % GDL had the lowest (42.70 %). Tofu chunks made with 0.6 % GDL had the highest carbohydrate content (43.10–47.38 %) and significantly ($p < 0.05$) increased bulk density, particularly in ground samples. Chunks formulated with 0.6 % GDL, gum Arabic, and sodium alginate received the highest sensory evaluation scores for appearance, colour, taste, texture and overall acceptability. Bambara groundnut tofu chunks are a promising candidate for novel, sustainable, legume-based meat analogues, with functional ingredient selection offering opportunities to optimise product quality and consumer appeal.

1. Introduction

Tofu, a traditional soybean-based food, is widely consumed in Asia and has gained global popularity due to its nutritional benefits and versatility (Xin et al., 2024). Building on this trend, producing tofu chunks (dried tofu) from Bambara groundnut (BGN) tofu offers an opportunity to diversify tofu-based products while promoting sustainability (Tan et al., 2020). Bambara groundnut tofu chunks can develop a firm, chewy, mince-like texture with a pale brown colour and a delicate nutty flavour, offering a soy-free alternative that adapts well to various cooking methods. When rehydrated with water, BGN chunks absorbs moisture and expand, taking on a more meat-like appearance with a texture resembling minced meat. This innovation leverages the nutritional richness and functional properties of BGN, making it a promising ingredient for new plant-based protein foods (Tan et al., 2020). The formation of tofu is primarily attributed to the gelation property of soybean proteins (Qin et al., 2022). Heating soy proteins exposes hydrophobic groups, causing aggregation (Zeppa et al., 2021). When a coagulant is added, these aggregated proteins further interact to form polymerised proteins with a stable three-dimensional network structure (Xin et al., 2024). Soybeans contain 35–40 % protein, with the storage globulins 11S glycinin and 7S β-conglycinin accounting for 90 % of this quantity (Singh et al., 2015). Soy proteins form gel at lower concentrations (around 4–6 %) typically at high temperatures between 70 and 80ºC (Renkema, 2001; Ma & Chen, 2023).

Tofu has nutritional advantages over other protein sources such as meat, fish, and cheese, including being cholesterol-free, rich in polyunsaturated fatty acids, and providing high-quality protein suitable for vegans as an alternative to animal-based foods (Qin et al., 2022; Xin et al., 2024). Legumes such as BGN are an excellent alternative to

* Corresponding author.
E-mail address: yvonnem@uj.ac.za (Y. Maphosa).

https://doi.org/10.1016/j.foohum.2025.100876
Received 10 July 2025; Received in revised form 14 October 2025; Accepted 28 October 2025
Available online 6 November 2025

soybeans. Bambara groundnut is an indigenous African crop that offers a well-balanced diet with significant amounts of protein (18–24 %), carbohydrates (57–63 %), and fat (5–7 %) (Ramatsetse et al., 2023). The vicilin (7S) protein fraction is the major storage protein fraction of BGN (Anjum et al., 2011; Okpuzor et al., 2010). According to Renkema (2001), soy proteins form gels at lower concentrations (4–6 %) and high temperatures between 70 and 80ºC. In contrast, BGN protein gelation occurs at higher concentrations (8–20 %) and over a wider temperature range of 40–80ºC than soy. Studies show that soy protein gels form more homogeneous and stable networks, which contribute to the desirable texture of tofu (Dang et al., 2023). On the other hand, BGN protein gels are heterogeneous and have a fractal-like structure. However, this can be improved by increasing the protein concentration to enhance protein-protein interactions.

Properties of tofu chunks such as colour attributes, nutritional profile and sensory properties are important for consumer acceptability. Evaluating these properties is crucial for producing high-quality, meat-free protein sources that meet consumer preferences and health standards. Desirable tofu chunks should possess a favourable amino acid profile, optimal texture, low bulk density, and low moisture content to ensure their marketability and consumer acceptability.

Bambara groundnut tofu was successfully produced in a preliminary study conducted as part of this research. Dried tofu, also known as tofu chunks or plant meat, is a soy-based product processed to remove moisture, resulting in a shelf-stable ingredient with a chewy texture (Huang et al., 2022). Despite dehydration, tofu chunks retain tofu's balanced nutritional profile, with protein (8–18 %), lipids (4–5 %) and carbohydrates (1–2 %) similar to conventional tofu, but with distinct textural modifications (Kim et al., 2019). They are used in plant-based food as meat alternatives because of their texture and nutritional value.

Tofu chunks exhibit a gel network formed by soy proteins coagulated by salts or acids, with hardness, cohesiveness, springiness, gumminess and chewiness as functional texture parameters. Their microstructure exhibits a cell-like gel network which can vary with the use of coagulants or hydrocolloids. Changes in network density and uniformity affect texture and water retention. The colour of tofu chunks ranges from light to yellow depending on soybean composition, processing conditions and additives (Kang et al., 2018). Tofu chunks hold water well due to their gel matrix contributing to moisture retention. Ingredient modifications can further enhance texture, improve sensory properties and support nutrient retention (Kim et al., 2019). Additionally, tofu chunks are pre-shaped, offering convenience and consistent cooking.

Rising veganism and the demand for sustainable food sources have contributed to the growing consumption of tofu (Gil et al., 2024; Nadathur et al., 2017). Therefore, exploring the production of tofu chunks from BGN tofu offers an opportunity to diversify plant-based products while promoting sustainability. However, the use of BGN for tofu and tofu chunks production has not been previously reported. As a novel product, BGN tofu chunks require sensory evaluation to guide product development and target consumers. This study developed BGN tofu chunks and assessed their physicochemical properties and consumer acceptability through sensory evaluation.

2. Materials and methods

2.1. Source of materials and equipment

All materials were sourced from South Africa; Bambara groundnuts (Triotrade, Pretoria), gum Arabic, sodium alginate and gluconolactone (GDL) (Sigma-Aldrich (Pty) Ltd), food-grade vinegar and lemon juice (Checkers, Cape Town) and equipment (Department of Food Science and Technology, Cape Peninsula University of Technology).

2.2. Bambara groundnut flour and tofu production

Bambara groundnut flour was prepared following the method of Hardy and Jideani (2020) and tofu was prepared following a modified method of Huang et al. (2022). Whole BGN seeds were cleaned, dried at 50°C for 48 h (Excalibur cabinet dryer, Model: 1069616; Geiger Klotzbucher, South Africa) and milled using a hammer mill (Trapp TRF 40, Animal ration shredder Brazil, 250 μm sieve, Three-Phase Induction Motor). To produce BGN milk, the flour was blended with water (1:10 w/v), hydrated for 2 h, filtered through three cheesecloths and boiled at 100°C for 15 min. Based on the optimisation studies from a preliminary study, tofu was prepared with 0.6 % GDL, 0.6 % GDL + 0.5 % gum Arabic + 0.5 % sodium alginate and 4 % vinegar + 0.5 % gum Arabic + 0.5 % sodium alginate, respectively. Gum Arabic (0.5 %) and sodium alginate (0.5 %) were added to boiling BGN milk while stirring. For the control sample (without hydrocolloids), 0.6 % GDL was added directly to boiling BGN milk. For the hydrocolloid-enriched samples, either 0.6 % GDL or 4 % vinegar was added. The curds were formed immediately (±5 s) after adding the coagulant onto the mixture. Moreover, the resulting protein curds were transferred into polypropylene moulds (18 × 11 × 12 cm), covered with cheesecloth, and pressed at 25°C for 15 h under a 5 kg weight. Tofu was stored in the refrigerator (4°C) immediately after pressing.

2.3. Production of Bambara groundnut tofu chunks

Bambara groundnut tofu (Section 2.2) was mashed with a plastic masher into irregular pieces. A knife was use to separate mashed tofu into small pieces (±2 cm) and then dried in a dehydrator (Excalibur EXC10, NSF, USA) at 50°C for 24 h. The dried chunks were evaluated for textural, physicochemical and sensory properties.

2.4. Proximate analysis of Bambara groundnut tofu chunks

The proximate composition of BGN tofu chunks was determined using standard AOAC methods. Moisture and total ash were measured using AOAC methods 934.01 and 942.05, respectively. Protein content was determined by the Kjeldahl method and fat was measured using the Soxhlet method (AOAC 996.06). Carbohydrate content was calculated by difference where the sum of moisture, ash, protein and fat was subtracted from 100.

2.5. Amino acid profiling of Bambara groundnut tofu chunks

The amino acid composition of BGN tofu chunks was determined using the modified methods of Kowalska et al. (2022), Montevecchi et al. (2022) and Adewumi et al. (2022). Milled BGN chunks (1 g) were hydrolysed with 9 mL of 6 M HCl containing 2 mL of 10 mM DL-2-aminobutyric acid (internal standard), 0.2 g phenol (antioxidant) at 110ºC for 24 h under nitrogen. Samples were then cooled before filtration. The filtrate (5 mL) was titrated with 12 M potassium hydroxide (KOH) to pH 9 and diluted to 20 mL with distilled water. Derivatisation was performed by sequentially adding 3 μL of sample, 237 μL of 100 mmol/L borate buffer (pH 9), 30 μL of 10 mmol/L potassium cyanide (pH 9), and 30 μL of 20 mmol/L NDA in acetonitrile. Derivatisation occurred at 24ºC for 20 min. Following this, a fraction of the derivative solution was diluted five times with acetonitrile before injecting 25 μL into a high-performance liquid chromatography (HPLC), with an ACE-100 C18 column (100 ×4.6 mm ID, 3 μm particle size). The flow rate was 1.0 mL/min at 40 °C. The mobile phases consisted of trifluoroacetic acid (TFA)-acidified water (99:1) (mobile phase A) and acetonitrile (99:1) (mobile phase B), with a gradient elution from A:B = 90:10–10:90 over 3 min.

2.6. Water absorption capacity of Bambara groundnut tofu chunks

The water absorption capacity (WAC) of BGN chunks was determined using the methods of Ezeama and Dobson (2019) and Samard et al. (2021). Whole tofu chunks (1 g) were mixed with 10 mL of distilled water before vortexing for 5 s. The samples were allowed to stand for 30 min at room temperature (24ºC) and then centrifuged at 5ºC (Jouan, Centrifuge MR 18–12, Thermo Electron Corporation in France) at 5000 x g for 30 min. The weight of the wet sample and the volume of free water were recorded, and WAC was calculated using Eq. 1.

$$WAC\ (\%) = \frac{W_2 - W_1}{W} \tag{1}$$

Where WAC is the water absorption capacity, W is the weight of dry tofu chunks, W_1 is the weight of dry tofu chunks plus the tube and W_2 is the weight of wet tofu chunks plus the tube.

2.7. Texture profile of Bambara groundnut tofu chunks

A texture analyser (Instron System ID Number 3344K6233, USA) was used to determine the compression strength of BGN chunks following the methods of Osen et al. (2015) and Samard and Ryu (2019). Granules of chunks (10 g) with an approximate length of 2 cm were transferred into an aluminium holding cup (Cat. No: S5403A), and a compression test consisting of first and second compression cycles was performed from 80 % and 20 % compression of the original sample height. The Kramer shear cell 5-bladed/KS5 (Cat. No: S5403A) cut through the chunks at a constant speed of 1.2 mm/s until fracture. The following parameters were quantified: the maximum force required to compress the sample (N), yield strength (MPa), compressive strength (MPa) and compressive strain (mm). The results were recorded automatically on the Bluehills software.

2.8. Bulk density of Bambara groundnut tofu chunks

Bulk density measurement was carried out using the methods of George et al. (2021) and Adewumi et al. (2022). Whole tofu chunks (10 g) were transferred into a 10 mL measuring cylinder. The measuring cylinder was tapped steadily on a table surface until a constant volume was obtained. The same measurements were carried out for ground tofu chunks. Bulk density was calculated as the ratio of sample weight to the volume occupied by the sample (Eq. 2).

$$Bulk\ density(g/mL) = \frac{Weight\ of\ sample(g)}{Volume\ of\ sample(mL)} \tag{2}$$

2.9. Microstructure of Bambara groundnut tofu chunks

The microstructure of dried tofu chunks was determined using the scanning electron microscope (SEM) (Zeiss EVO MA 15 EDS/WDS SEM) following the method of Lan et al. (2021) with some modification. Small pieces of samples were freeze-dried for 24 h and then coated with gold to enhance the quality and resolution of the images. The images were obtained at 2000X magnification.

2.10. Colour characteristics of Bambara groundnut tofu chunks

The colour properties of BGN tofu chunks were determined using the method of Maphosa & Jideani (2016). The ColorFlex (HunterLab, S/N CX1668, Illuminant D65 10° Observer) spectrophotometer was calibrated using white and black standard tiles then chunks (20 g) were transferred into the glass sample cup and covered with a black lid. Lightness (L*), redness/greenness (a*) and yellowness/blueness (b*) were assessed using L*C*h* and CIE-L*a*b* colour space systems.

2.11. Sensory analysis of Bambara groundnut tofu chunks

Three BGN tofu chunks prepared with (1) 0.6 % GDL; (2) 0.6 % GDL + 0.5 % gum Arabic + 0.5 % sodium alginate and (3) 4 % vinegar + 0.5 % gum Arabic + 0.5 % sodium alginate were cooked separately for sensory evaluation. Tofu chunks (1 kg) were soaked in hot water (95ºC, 1.5 L) for 30 min until soft. Excess water was drained from the chunks and kept aside. Onions (300 g) and green pepper (300 g) were sauteed in oil (20 mL) until golden, then spices (5 g), mixed vegetables (200 g), tomatoes (150 g) and tofu chunks (990 g) were added and stirred until the mixture was well cooked. Since tofu chunks are naturally bland, seasoning and vegetables were added during preparation to mimic a soy mince dish and enhance flavour for sensory evaluation (Fiorentini et al., 2020; Yang et al., 2024).

A consumer sensory analysis with 50 untrained panellists was conducted at the sensory evaluation laboratory in the Department of Food Science and Technology, Cape Peninsula University of Technology. Participants provided informed written consent prior to the study. Cooked BGN tofu chunks were served to panellists consisting of both male and female students and staff aged 20 years and above. The racial composition included Black, White, Indian and mixed-race. Participation was voluntary and the consent process explained the purpose of the study, procedures, potential risks, and the right to withdraw at any time without penalty. The evaluation was pilot-tested with 10 participants before the main study. Each panellist was served 10 g of warm cooked chunks in clear 40 mL tub containers labelled with a three-digit random number. The samples were served with a small spoon and a serviette, all placed on black and white plastic trays. A cup of water was provided to rinse the palate before and between tasting. Each panellist received a score sheet with three coded samples and a 5-point hedonic scale, where 1 = dislike very much and 5 = like very much. The panellists were instructed to rate each sample based on its appearance, colour, taste, aroma, texture and overall acceptability.

2.12. Data analysis

The IBM Statistical Package for the Social Sciences (SPSS) version 27 (2020) was used for statistical analysis (Ezenwa & Iheme, 2022). All experiments were carried out in triplicate and results were expressed as mean ± standard deviation. Multivariate analysis of variance (MANOVA) was used to establish differences between treatments. Duncan's multiple range test was used to separate means where significant ($p \leq 0.05$) differences existed. Principal component analysis was used to identify patterns by reducing dimensionality in the data.

2.13. Ethics statement

This study was approved by the Faculty Research Ethics Committee of the Faculty of Applied Sciences of Cape Peninsula University of Technology, approval number 212280341/04/2020. All participants provided written informed consent prior to participation in the sensory evaluation.

3. Results and discussion

3.1. Proximate composition of Bambara groundnut chunks

Table 1 presents the proximate composition of BGN tofu chunks prepared with and without gum Arabic and sodium alginate. The moisture content of all BGN tofu chunks was relatively low and did not differ significantly. This was expected as tofu chunks are a relatively low-moisture product. The combination of relatively low temperature (50°C) and extended drying time (24 h) allowed sufficient moisture removal without damaging the structure of the chunks. Furthermore, extended drying time at moderate temperatures is effective in achieving low moisture content for BGN chunks because it provides enough time for moisture to undergo mass transfer out of the dense tofu matrix slowly, without overheating. This low moisture content contributes to a longer shelf-life as the chunks are less susceptible to microbial growth and spoilage.

Chunks prepared with vinegar + 0.5 % gum Arabic + 0.5 % sodium alginate had the highest ash content (0.65 %). Vinegar contributed more

Table 1
Proximate composition of Bambara groundnut chunks as affected by coagulants and hydrocolloids[1].

Tofu chunks	Moisture (%)	Ash (%)	Protein (%)	Fat (%)	Carbohydrates (%)
0.6 % GDL	0.33 ± 0.12^{a}	0.40 ± 0.09^{a}	42.70 ± 1.06^{a}	$13.46 \pm 2.14^{a,b}$	43.10 ± 1.89^{a}
0.6 % GDL + 0.5 % GA + 0.5 % SA	0.25 ± 0.10^{a}	0.50 ± 0.04^{a}	44.88 ± 0.66^{b}	7.02 ± 4.79^{b}	47.38 ± 4.25^{a}
4 % Vinegar + 0.5 % GA + 0.5 % SA	0.32 ± 0.10^{a}	0.65 ± 0.08^{b}	53.09 ± 0.81^{c}	15.21 ± 2.41^{a}	30.74 ± 2.06^{b}

[1]Mean ± standard deviation of triplicate determinations. Means within a column followed by different superscripts differ significantly.
($p \leq 0.05$). [2]GA: Gum Arabic; SA: Sodium alginate; GDL: Gluconolactone.

minerals to the tofu compared to GDL because vinegar, especially that made from fermented sources like apple cider, sugar cane or rice, contains various minerals such as potassium, magnesium and trace elements (Antoniewicz et al., 2022; Perumpuli and Dilrukshi, 2022). Therefore, when used as a coagulant, these minerals may be introduced into the tofu and contribute to its overall mineral content. Ash content in food indicates the amount of inorganic materials (minerals) remaining after organic matter has burned away (Shi et al., 2024).

All the chunks significantly ($p < 0.05$) differed from each other in protein composition. Chunks made with vinegar, gum Arabic and sodium alginate had the highest protein content (53.09 %), while tofu chunks made with 0.6 % GDL alone had the lowest (42.70 %).

The addition of hydrocolloids likely enhanced protein retention by improving curd firmness and reducing syneresis during pressing. Hydrocolloids interact with BGN proteins to strengthen the protein gel matrix through hydrogen bonding and electrostatic interactions, resulting in higher water and protein holding capacity. This firmer gel structure prevents excessive whey expulsion (syneresis) and thus retains more protein and moisture in the tofu curd. Studies have shown that a more compact protein network formed with alginate and carrageenan leads to improved gel firmness and better liquid retention, which supports higher protein content in tofu made with additives such as gum Arabic and sodium alginate compared to those without.

Gum Arabic and sodium alginate form a stable gel network through ionic cross-linking and polysaccharide-protein interaction which entrap proteins and colour compounds (Mohamed et al., 2017). The negatively charged alginate interacts with positively charged regions of BGN proteins, while the protein component of gum Arabic enhances emulsification and contributes to network formation. Coagulants influence the extent of protein aggregation and entrapment during tofu formation, which in turn affects the final protein yield (Shi et al., 2024). Given their protein content, BGN tofu chunks represent a viable high-quality alternative to soy-based textured vegetable protein (TVP).

The fat content of tofu chunks made with 0.6 % GDL and with 0.6 % GDL + 0.5 % gum Arabic + 0.5 % sodium alginate did not differ significantly. However, the latter differed significantly ($p < 0.05$) from chunks prepared with vinegar + 0.5 % gum Arabic + 0.5 % sodium alginate. Studies with paneer, a dairy product, and tofu analogues confirm that using GDL and hydrocolloids yields products with significantly reduced fat percentages without sacrificing texture or water content (Chaudhary et al., 2021). Hydrocolloids can also promote the conversion of free oil to bound oil or even expel it, leading to lower measured fat content in finished products (Peh et al., 2024). Additionally, other studies have reported that the incorporation of hydrocolloids such as gum Arabic and sodium alginate can increase the protein content and reduce the fat content of tofu, while also affecting other proximate properties depending on the specific coagulation method used. Ezeama and Dobson (2019) found that the use of different coagulants like GDL, calcium sulfate and magnesium chloride increased the protein and dietary fibre levels in tofu while decreasing fat and carbohydrate contents. Similarly, Paz-Yépez et al. (2024) found that the choice of coagulant influenced the nutritional value and *in vitro* protein digestibility of tofu. Carrageenan was found to reduce the hardness of tofu when used with calcium salts and improve water holding capacity, thus contributing to better moisture retention. The addition of hydrocolloids can modulate the greater gel hardness and thermal stability with higher β-sheet protein content. Hydrocolloids interact with soy proteins, influencing gel network formation through hydrogen bonding and hydrophobic interactions, which affect texture and gel strength. This modulation enhances the viscoelastic properties of the tofu gel, contributing to improved water-holding capacity.

Carbohydrate content was significantly influenced by the type of coagulant used ($p < 0.05$). GDL-based tofu chunks, particularly those with added hydrocolloids, showed higher carbohydrate levels compared to vinegar-coagulated tofu chunks, which had the lowest content (30.74 %). No significant difference was observed between GDL-based chunks with and without hydrocolloids.

Bambara groundnut tofu chunks are a source of protein, naturally cholesterol-free, and have a low moisture content. The findings of this study are in agreement with the reports of Bakhsh et al. (2021) and Hong et al. (2022), which noted that soy-based TVP should contain 35–40 % high-quality protein with a well-balanced amino acid profile, 15–20 % fats and 30 % carbohydrates. In this study, the choice of coagulant and the inclusion of hydrocolloids significantly influenced the nutritional properties of BGN tofu chunks.

3.2. Amino acid composition of Bambara groundnut chunks

Amino acids play a crucial role in both the nutritional benefits and sensory qualities of food. For instance, glutamic acid is a key component of umami, which enhances the flavour of food (Yamamoto & Inui-Yamamoto, 2023). Incorporating amino acids into the diet can help address issues such as excessive salt consumption, nutritional imbalances and deficiencies (Veldsman et al., 2023). Amino acids are categorised into essential and non-essential. The former are synthesised by human bodies while the latter cannot be synthesised by the body. Bambara groundnut protein is a strong complementary source suitable for meat alternative applications. Soy-based TVP contains about 6.5 g of lysine per 100 g of protein, representing a substantial level of this essential amino acid important for human nutrition (Nizkii et al., 2022). Bambara groundnut protein offers lysine levels generally slightly lower but comparable to soy, in the range 5–6 g/100 g of protein, maintaining good nutritional quality. Both soy and BGN proteins provide balanced amino acid profiles with sufficient lysine to complement other plant-based protein sources, making them valuable for meat alternatives (Hamadou & Mune, 2024).

The amino acid composition of BGN tofu chunks is given in Table 2.

In tofu chunks prepared with vinegar, gum Arabic and sodium alginate, glutamic acid had the highest concentration (11.38 g/100 g) while glycine had the lowest (1.10 g/100 g). Glutamic acid is a non-essential amino acid important for metabolism and neurotransmission (Zhang et al., 2024). Glycine is also a non-essential amino acid important for protein synthesis, collagen formation, and metabolic processes (Zhang et al., 2024). Among the essential amino acids, leucine had the highest concentration for all tofu chunks ranging above 4 g/100 g, while methionine had the lowest concentration of 1–2 g/100 g. Tofu chunks prepared with vinegar + 0.5 % gum Arabic + 0.5 % sodium alginate had the highest concentration of methionine and phenylalanine. Overall, methionine had the lowest concentration among the essential amino acids in all tofu chunks. The low methionine levels found in this study

Table 2
Amino acid (g/100 g) composition of Bambara groundnut chunks within coagulant[1].

Amino acid	0.6 % Gluconolactone (g/100 g)	+ 0.5 % Gum Arabic + 0.5 % Sodium alginate	
		0.6 % Gluconolactone (g/100 g)	4 % Vinegar (g/100 g)
Arginine[1]	3.76 ± 0.06[a]	3.66 ± 0.01[a]	4.24 ± 0.03[b]
Serine[1]	3.13 ± 0.07[a]	2.91 ± 0.01[b]	3.37 ± 0.03[c]
Glycine[1]	1.86 ± 0.02[a]	1.77 ± 0.01[b]	1.10 ± 0.01[c]
Asparagine[1]	6.79 ± 0.04[a]	6.45 ± 0.08[b]	7.55 ± 0.11[c]
Glutamic acid[1]	10.03 ± 0.01[a]	9.82 ± 0.01[b]	11.38 ± 0.05[c]
Alanine[3]	2.65 ± 0.01[a]	2.61 ± 0.04[a]	2.63 ± 0.03[a]
Proline[3]	2.17 ± 0.01[a]	2.01 ± 0.01[b]	2.41 ± 0.04[c]
Threonine[2]	2.06 ± 0.01[a]	1.85 ± 0.01[b]	2.16 ± 0.01[c]
Histidine[2]	2.21 ± 0.07[a]	2.39 ± 0.01[b]	2.59 ± 0.02[c]
Lysine[2]	3.76 ± 0.02[a]	3.63 ± 0.11[a]	3.29 ± 0.11[b]
Tyrosine[2]	2.75 ± 0.05[a]	2.59 ± 0.04[a]	3.12 ± 0.13[b]
Methionine[2]	1.65 ± 0.06[a]	1.69 ± 0.04[a]	2.01 ± 0.08[b]
Valine[2]	2.65 ± 0.06[a]	2.54 ± 0.04[a]	2.86 ± 0.04[b]
Isoleucine[2]	2.27 ± 0.04[a]	2.17 ± 0.04[a]	2.45 ± 0.03[b]
Leucine[2]	4.53 ± 0.01[a]	4.34 ± 0.06[a]	4.94 ± 0.06[b]
Phenylalanine[3]	4.82 ± 0.12[a]	4.67 ± 0.18[a]	5.62 ± 0.13[b]

[1]Values are mean ± standard deviation of triplicate determinations. Means within a row followed by the different superscript are significantly ($p < 0.05$) different. [2]Essential amino acid [3]Non essential amino acid.

are consistent with those observed in other legumes, such as soybeans (1.40 g/100 g) and chickpeas (0.11 g/100 g) (Adebowale et al., 2011; Veldsman et al., 2023).

The high lysine and low methionine content reflect the typical amino acid composition of BGN and other legumes (Adebowale et al., 2011). Tofu chunks made with GDL and vinegar had relatively high levels of phenylalanine. Furthermore, both leucine and phenylalanine were the most abundant essential amino acids across all BGN tofu chunks. The content of non-essential amino acids also varied depending on the coagulants used. Among the non-essential amino acids, glycine had the lowest concentration, while glutamic acid had the highest concentration in all BGN tofu chunks.

The amino acid content presented in Table 2 indicates that BGN tofu chunks are rich in essential amino acids such as leucine, lysine and phenylalanine. These findings agree with those of several studies, which observed that aspartic and glutamic acids are the most abundant in legumes and nuts (Adebowale et al., 2011; Adeyeye et al., 2012; Nyau et al., 2019). Furthermore, the levels of essential amino acids (isoleucine, lysine, phenylalanine and methionine) in BGN tofu chunks were within the recommendations set by the Food and Agriculture Organisation (FAO) and World Health Organisation (WHO) (Bandyopadhyay et al., 2022). When compared to the recommended dietary allowances (RDA), the levels of essential amino acids in BGN tofu chunks, such as isoleucine (2.27–2.45 g/100 g), lysine (2.90–3.76 g/100 g), methionine (1.65–2.01 g/100 g) and phenylalanine (4.67–5.62 g/100 g) meet or exceed the RDA values for adults. This suggests that BGN tofu chunks can effectively contribute to meeting dietary requirements for these essential amino acids.

The higher lysine content of BGN tofu chunks is a significant nutritional benefit, making them an excellent complementary protein source for cereals that are typically low in lysine. Additionally, arginine-rich proteins are known for their potential protective effects against heart disease, while glutamine supports the immune system (Bahadoran et al., 2016). Pairing cereals with lysine-rich foods such as legumes helps achieve a more balanced and complete protein intake. Moreover, combining cereals and legumes not only addresses the amino acid deficiency but also enhances the overall nutrient density of the food, resulting in a more well-rounded nutritional profile.

Fig. 1 illustrates the distribution of various tofu chunks along the principal components, explaining their variance in amino acid composition. Component 1 accounts for 78.9 % of the variance, while component 2 accounts for 21.1 % of the variance, indicating that component 1 is more significant in differentiating the samples. Component 1 showed a positive correlation with the tofu chunks made with 4 % vinegar +0.5 % gum Arabic +0.5 % sodium alginate, which was high in arginine, glycine, tyrosine, methionine, isoleucine, leucine and phenylalanine. In contrast, tofu chunks prepared with 0.6 % GDL had higher alanine and average levels of serine and threonine. Component 2, represented by tofu chunks prepared with 0.6 % GDL +0.5 % gum Arabic +0.5 % sodium alginate, showed high histidine content (2.39 g/100 g). Overall, BGN tofu chunks were notably rich in essential amino acids, making them a valuable dietary source for improving overall protein intake and nutritional balance.

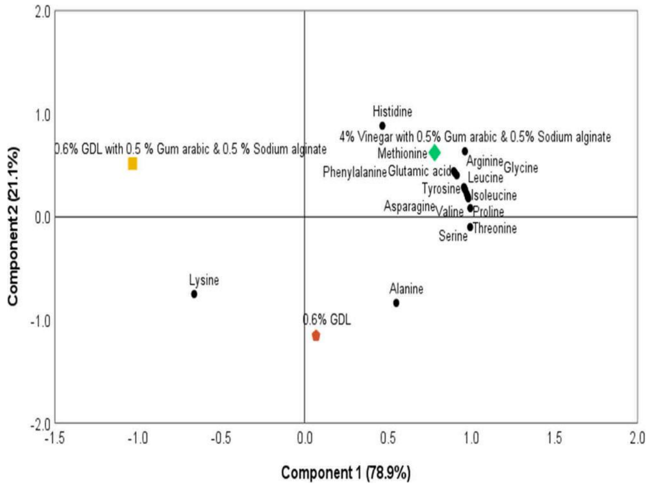

Fig. 1. Principal component analysis biplot of the amino acid profile of Bambara groundnut tofu chunks. Principal component 1 and 2 explain 78.9 % and 21.1 % of the variance, respectively.

3.3. Water absorption capacity of Bambara groundnut tofu chunks

Water absorption is the ability of a material to absorb water when immersed in it (Ezeama & Dobson, 2019). This property is crucial for retaining moisture in food. Soaking tofu chunks before cooking softens their structural proteins, making them easier to cook. Consequently, this increases their water content, which accelerates the chemical reactions during cooking and improves the texture. There was a significant difference ($p \leq 0.05$) in the WAC of tofu chunks made with GDL and those made with vinegar (Table 3). The results indicated that adding gum Arabic and sodium alginate with GDL slightly reduced WAC, suggesting that these hydrocolloids may help stabilise the matrix by reducing syneresis (water separation), improving texture, and enhancing water retention.

Conversely, the inclusion of gum Arabic and sodium alginate, along with vinegar as a coagulant, seemed to enhance the WAC of the tofu chunks. Moreover, increased water absorption may be attributed to the properties of gum Arabic and sodium alginate, which are known for their ability to bind water and contribute to the texture and stability of food products (Taheri & Jafari, 2019). Adding sodium alginate enhances strength, reduces breakage, increases water retention and stabilises the texture of tofu. Both additives contribute to improving texture, durability and shelf stability. Gum Arabic mainly contributes to stabilisation and surface properties (Lee et al., 2024).

Tofu chunks made with 0.6 % GDL + 0.5 % gum Arabic + 0.5 % sodium alginate had a lower WAC compared to those made with 0.6 % GDL without gum Arabic and sodium alginate. The differing effects of gum Arabic and sodium alginate in tofu chunks made with GDL and vinegar are a result of their distinct molecular interactions.

Gum Arabic is a complex polysaccharide with branched structures

Table 3
Effect of coagulant type and hydrocolloids on the texture, bulk density, colour and water absorption capacity of Bambara groundnut tofu chunks[1].

Formulation	Texture parameter: Maximum compression (Kgf)	Yield strength (MPa)	Compression strain extension (mm)	Compressive strength (MPa)	Bulk density (g/mL): Tofu chunks	Chunks powder	Colour parameter: Lightness (L*)	Redness/ Greenness (a*)	Yellowness/ Blueness (b*)	Water absorption capacity (%): Tofu chunks
0.6 % GDL	80.97 ± 67.96^{a}	0.01 ± 0.01^{a}	0.32 ± 0.33^{a}	0.32 ± 0.27^{a}	0.37 ± 0.01^{a}	0.69 ± 0.02^{a}	41.61 ± 0.34^{a}	6.39 ± 0.41^{a}	16.25 ± 0.79^{a}	0.91 ± 0.24^{a}
0.6 % GDL + 0.5 % GA + 0.5 % SA	42.78 ± 65.08^{a}	0.13 ± 0.21^{a}	0.45 ± 0.14^{a}	0.17 ± 0.25^{a}	0.32 ± 0.03^{b}	0.65 ± 0.01^{b}	46.49 ± 0.23^{b}	8.43 ± 0.48^{ab}	17.03 ± 1.70^{a}	0.85 ± 0.18^{a}
4 % Vinegar + 0.5 % GA + 0.5 % SA	42.87 ± 67.85^{a}	0.01 ± 0.01^{a}	0.60 ± 0.33^{a}	0.17 ± 0.25^{a}	0.29 ± 0.01^{b}	0.73 ± 0.01^{c}	39.15 ± 0.53^{c}	8.83 ± 1.93^{b}	16.66 ± 1.02^{a}	1.30 ± 0.32^{b}

[1]Values are mean ± standard deviation of triplicate analysis. Means within a column followed by different superscripts are significantly ($p \leq 0.05$) different. [2]GA: Gum Arabic; SA: Sodium alginate. GDL: Gluconolactone.

that primarily act to reduce swelling and soften the texture. Sodium alginate is a linear polysaccharide with a strong capacity to form gel through interaction with divalent cations. Thus it promotes gel strength through water binding and crosslinking interaction with protein and starch during acid-induced tofu gelation (Zhang et al., 2023a; Zhang et al., 2023b; Jing et al., 2025). This difference can be attributed to different coagulants used during the production of tofu, which influences the structure of the protein and polysaccharide complexes formed (Li et al., 2019). The lower WAC in tofu made with gum Arabic and sodium alginate leads to a firmer, more compact texture compared to tofu made with GDL alone, which could influence the mouthfeel and overall sensory perception of the product. Tofu chunks with lower WAC may be suitable in recipes that require a firmer texture or in products that need to maintain their shape during processing or handling.

3.4. Textural parameters of Bambara groundnut tofu chunks

The effect of coagulant type, gum Arabic and sodium alginate on the compression parameters of BGN tofu chunks was investigated. All BGN tofu chunks did not differ significantly in compression parameters when compared to each other (Table 3). Tofu chunks made with 0.6 % GDL alone exhibited greater force and compressive strength than those made with 0.6 % GDL + 0.5 % gum Arabic + 0.5 % sodium alginate, suggesting that tofu chunks without hydrocolloids may retain their shape better during cooking, making them more versatile in various recipes. In contrast, the addition of hydrocolloids produced a softer texture. The lack of significant effects from both coagulant and hydrocolloid type may be attributed to the inherent properties of the BGN matrix, which appear to play a dominant role in determining textural and structural characteristics, overshadowing the contribution of coagulants (Darmajana et al., 2020). It is also possible that the compression parameters measured, such as maximum compression and yield strength, may not have been sensitive enough to detect subtle differences in texture and structure. Therefore, more advanced or specialised texture analysis methods may be required to fully elucidate the impact of coagulant type on BGN tofu texture.

3.5. Bulk density of Bambara groundnut tofu chunks

Bulk density is a measure of how much mass is contained within a given volume (Pugliese et al., 2017). The bulk density of BGN tofu chunks (Table 3) indicated that coagulant type influenced density, with GDL producing denser chunks than vinegar. Ground chunks exhibited higher bulk density values compared to whole tofu chunks. Formulations containing gum Arabic and sodium alginate had lower bulk density than those prepared with 0.6 % GDL alone, suggesting that the addition of hydrocolloids had a densifying effect on the powdered tofu. The use of GDL, gum Arabic, and sodium alginate can impact the density of tofu chunks, with GDL leading to denser tofu chunks (Ibrahim & Karim, 2024). Denser tofu chunks may occupy less volume, allowing for more efficient use of space in transporting containers and storage facilities.

3.6. Microstructure of Bambara groundnut tofu chunks

Scanning electron micrographs of BGN tofu chunks at 20 μm resolution are presented in Fig. 2. The network structure appeared different in all pictures, although the surface of Fig. 2a and b exhibited a smooth texture. The microstructures of the chunks corresponded to the visually observed textures and were consistent with the results reported in Table 3. Tofu chunks coagulated with 0.6 % GDL exhibited a uniform, smooth surface with small holes. These chunks were judged to have the best compression characteristics. The chunks prepared with gum Arabic and sodium alginate displayed a clustered arrangement with round-shaped components. The micrographs also revealed two distinct layers; light grey and darker, which could be attributed to the hydrocolloid inclusions (Fig. 2a and b). The absence of holes in these images

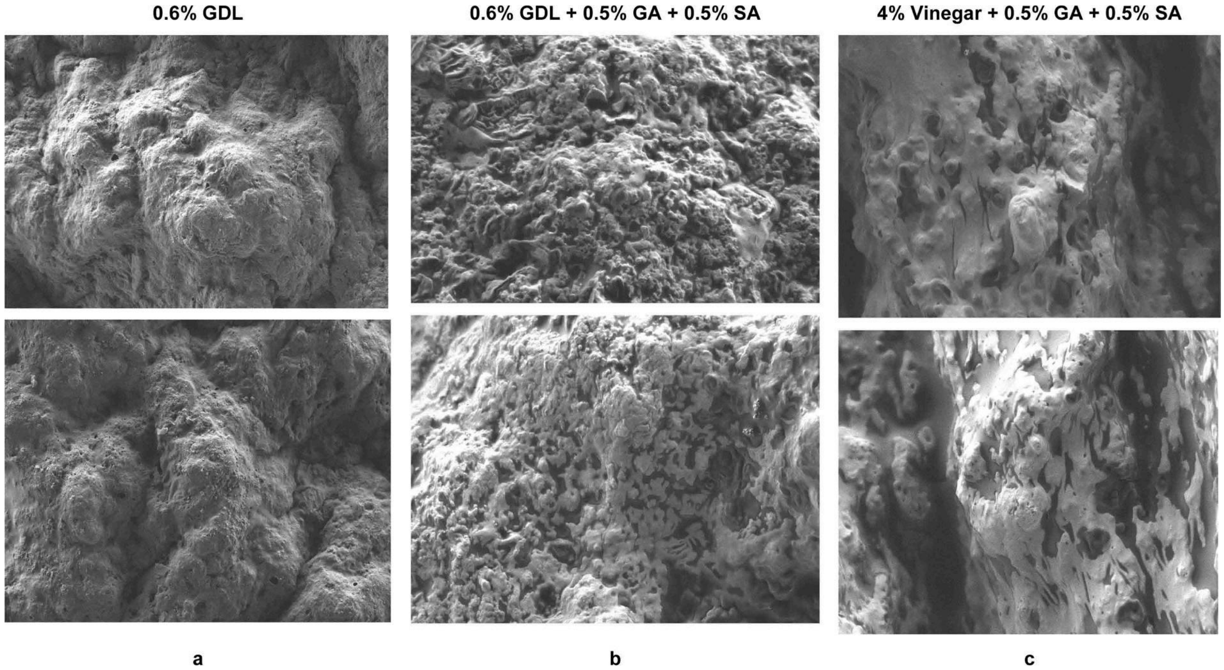

Fig. 2. Microstructure of Bambara groundnut tofu chunks prepared with (a) 0.6 % gluconolactone (GDL), (b) 0.6 % GDL + 0.5 % gum Arabic (GA) + 0.5 % sodium alginate (SA) and (c) 4 % vinegar + 0.5 % GA + 0.5 % SA. Images captured at 20 μm resolution.

suggests a more compact structure with higher protein components.

Furthermore, the network in Fig. 2b appeared more continuous and finer, which was associated with lower water absorption (Table 3). Low water absorption in tofu is indicative of a more refined internal network due to continuous protein-polysaccharide network, characterised by compactness and reduced pore size, which collectively restricts moisture uptake and enhances structural stability (Lee et al., 2024). Similar findings were reported by Zhang et al. (2023b), where GDL-coagulated tofu had the most uniform and compressible texture, while the inclusion of gum Arabic and sodium alginate resulted in a more layered and clustered microstructure that was harder, chewier and less water absorbent. This effect is likely due to the gel-strengthening properties of the hydrocolloids (Lee et al., 2024).

Sodium alginate, in particular, can enhance gel strength by cross-linking with divalent cations, contributing to increased hardness in tofu and its chunks. However, the effect depends on the specific composition and arrangement of the alginate, with higher GDL content and block structures leading to stronger gels. The addition of hydrocolloids like gum Arabic and sodium alginate increases the hardness, chewiness and cohesiveness of starch-hydrocolloid complexes similar to tofu, compared to controls without hydrocolloids (Lee et al., 2024). Gum Arabic also provides excellent thickening and stabilising properties in food systems (Lee et al., 2024).

3.7. Bambara groundnut chunks colour characteristics

The colour attributes of BGN tofu chunks were influenced by both coagulant type and the presence of hydrocolloids (Table 3). The addition of vinegar resulted in darker tofu chunks ($L^* = 39.15$) whereas the formulation with 0.6 % GDL +0.5 % gum Arabic (GA) +0.5 % sodium alginate (SA) had the lightest chunks, suggesting a brighter appearance likely due to the stabilising effect of hydrocolloids on pigment retention and curd structure. Acid coagulants such as vinegar (acetic acid) rapidly decrease pH, promoting a coarse, less-uniform protein network, and often resulting in darker tofu products due to enhanced light absorption and potential browning reactions (Geng et al., 2024). Gluconolactone promotes gradual acidification, enabling the formation of a fine, homogenous tofu gel network that reflects more light and appears lighter (Arii et al., 2021). The addition of hydrocolloids such as gum Arabic and sodium alginate increases water retention and enhances gel uniformity, contributing to lighter colour and improved optical properties in tofu (Geng et al., 2024). Recent reviews and comparative studies on tofu made with various coagulants confirm the observed differences in colour attributes due to microstructural and physicochemical effects introduced by the different coagulants and additives (Arii et al., 2021).

Redness (a^*) was highest in vinegar-based chunks, potentially due to increased Maillard browning or pigment interactions induced by vinegar (Baik & Mittal, 2003). Although yellowness (b^*) did not differ significantly across samples, all formulations displayed comparable values, suggesting similar pigment profiles or thermal reactions during processing. Tofu chunks made with 0.6 % GDL + gum Arabic + sodium alginate appeared more yellow (Figure 3).

Wet tofu chunks were initially white to light grey. However, after the drying process, the chunks turned brown. The colour change can be attributed to various chemical reactions and Maillard browning that occur when proteins and sugars are exposed to heat. The Maillard reaction starts when reducing sugars react with amino acids, forming glycosylamine. The glycosylamine then undergoes rearrangement to produce intermediate compounds (Schiff bases) (Xiang et al., 2021). Moreover, these compounds further react to form a range of complex molecules such as melanoids which contribute to colour and flavour of cooked food (Xiang et al., 2021). Tofu chunks made with vinegar + 0.5 % gum Arabic + 0.5 % sodium alginate were browner compared to those made with 0.6 % GDL (Fig. 3).

The presence of hydrocolloids, such as gum Arabic and sodium alginate, can influence the dispersion and reflection of light within the tofu matrix, leading to a visible colour change. This could be due to the ability of these hydrocolloids to interact with the proteins in the tofu, affecting light absorption and reflection properties (Zhang et al., 2023a). Additionally, the specific chemical and structural properties of gum Arabic and sodium alginate, as well as their interaction with other components in the tofu, can impact the overall colour of the BGN tofu chunks. Therefore, the use of gum Arabic and sodium alginate in tofu preparation can result in perceptible changes in the colour of the final product. Furthermore, the particle size of tofu chunks also affects their colour (Kim et al., 2019). Smaller, finer particles are more evenly

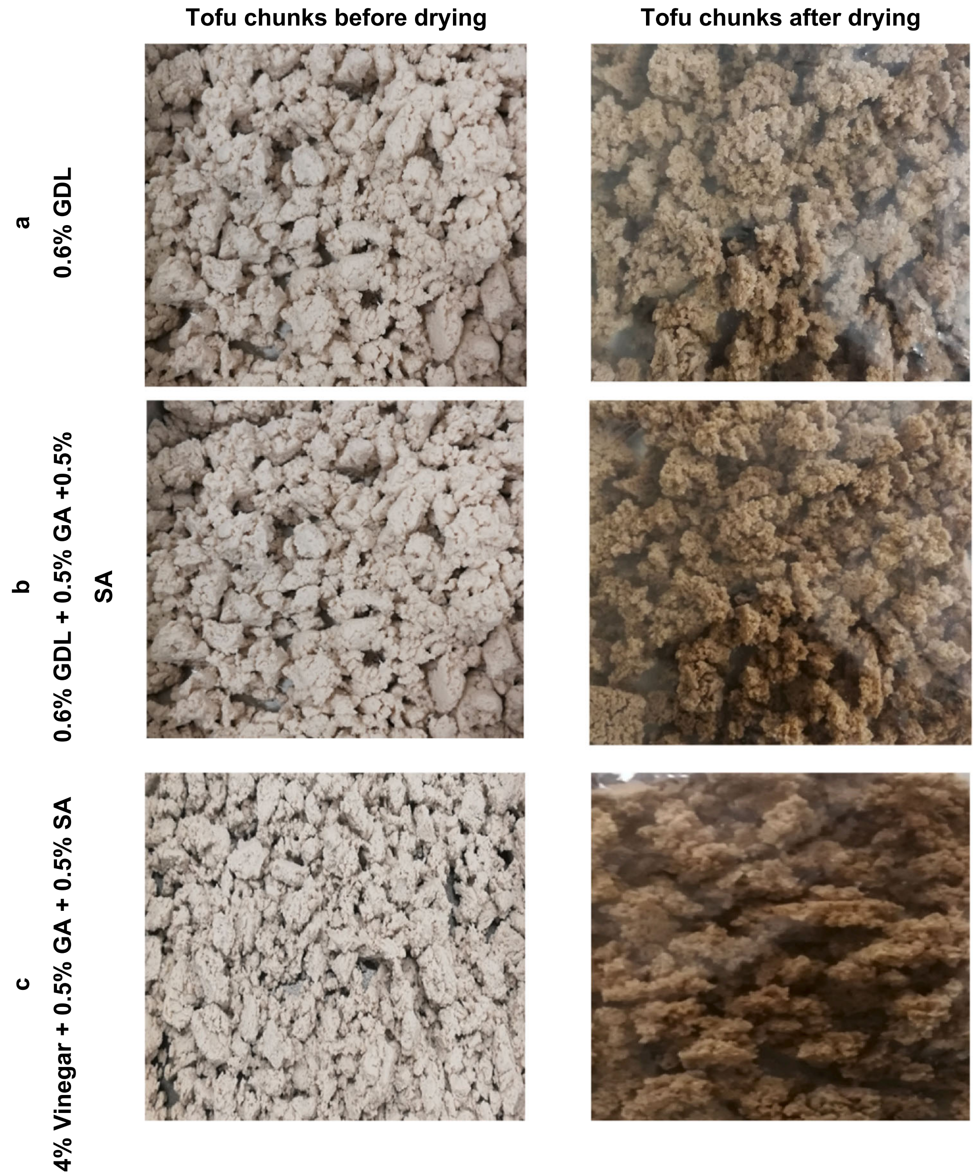

Fig. 3. Bambara groundnut tofu chunks before and after drying, prepared with (a) 0.6% gluconolactone (GDL), (b) 0.6% GDL + 0.5% gum Arabic (GA) + 0.5% sodium alginate (SA) and (c) 4% vinegar + 0.5% GA + 0.5% SA.

distributed throughout the tofu chunks matrix, causing less disruption to the overall structure and resulting in a lighter appearance. In contrast, larger, coarser particles create more heterogeneity, leading to darker spots and reduced overall lightness. Therefore, using smaller, finer particles in tofu production helps maintain a lighter colour and appearance compared to larger, coarser particles (Kim et al., 2019).

3.8. Sensory acceptability of Bambara groundnut tofu chunks

Table 4 presents the sensory scores for appearance, aroma, colour, taste, texture, and overall acceptability for BGN tofu chunks. Significant differences ($p < 0.05$) were observed for appearance, colour, taste, texture, and overall acceptability. Tofu chunks made with GDL were visually more appealing to the evaluators than those prepared with vinegar. Despite variations in other attributes, aroma remained consistent across samples, likely due to the strong acidic flavour of the

Table 4
Sensory qualities of Bambara groundnut tofu chunks as affected by coagulant, gum Arabic and sodium alginate[1].

Tofu chunks	Appearance	Aroma	Colour	Taste	Texture	Overall acceptability
0.6 % GDL	3.83 ± 0.88^{a}	3.94 ± 0.96^{a}	3.75 ± 0.84^{a}	3.56 ± 1.16^{a}	2.96 ± 1.12^{a}	3.58 ± 1.18^{a}
0.6 % GDL + 0.5 % GA + 0.5 % SA	4.26 ± 0.68^{b}	4.09 ± 0.96^{a}	4.21 ± 0.89^{b}	3.89 ± 1.07^{a}	3.34 ± 1.18^{a}	3.92 ± 0.96^{a}
4 % Vinegar + 0.5 % GA + 0.5 % SA	3.43 ± 1.20^{c}	3.98 ± 0.97^{a}	3.57 ± 1.17^{a}	3.58 ± 1.20^{a}	3.28 ± 1.29^{a}	3.55 ± 1.23^{a}

[1]Values are mean ± standard deviation of triplicate analysis. Means within a column followed by different superscripts are significantly ($p \leq 0.05$) different.
GA: 0.5 % gum Arabic; SA: 0.5 % sodium alginate.
Sensory evaluation rating: Dislike very much (1); Dislike moderately; (2), Neither Like or Dislike (3); Like moderately (4); Like very much (5).

coagulants. Therefore, rinsing curds before the pressing stage may reduce this effect. Overall, the BGN tofu chunks were moderately liked. The addition of gum Arabic and sodium alginate was well-accepted but it did not significantly improve the overall acceptability of the tofu chunks. The tofu chunks made with 0.6 % GDL + 0.5 % GA + 0.5 % SA received the highest ratings for all sensory attributes. This aligns with Yasin et al. (2019), who reported a positive correlation between texture, taste, and overall acceptability of tofu.

4. Conclusions

The investigation of Bambara groundnut (BGN) tofu chunks formulated with various coagulants and hydrocolloids demonstrated that both ingredient choice and processing conditions significantly influence the nutritional, functional, and sensory properties of the final product. BGN tofu chunks are a viable, protein-rich alternative to soy-based textured vegetable protein (TVP), offering a balanced amino acid profile that meets or exceeds dietary recommendations for key essential amino acids. Differences in protein, ash, carbohydrate, and moisture content arise from coagulant type and hydrocolloid inclusion, with gum Arabic and sodium alginate enhancing protein retention and gel strength through polysaccharide-protein interactions. High levels of lysine, leucine, and phenylalanine in BGN tofu make it suitable as a complementary protein source alongside cereals. Water absorption capacity and texture were also coagulant-dependent, with hydrocolloids improving gel stability and firmness, although not always perceptibly altering compression parameters. Vinegar-based formulations produced darker chunks due to enhanced browning reactions, while the addition of GDL, gum Arabic, and sodium alginate yielded lighter, more appealing products, mediated by pigment retention and microstructural uniformity. Bulk density and microstructural studies confirmed the densifying effects of GDL and the moderating influence of hydrocolloids on gel matrix arrangement. Sensory panel results demonstrated general acceptability of BGN tofu chunks, with formulations containing GDL, gum Arabic, and sodium alginate receiving the highest ratings for appearance, texture, and taste. The findings highlight BGN tofu chunks as a promising candidate for novel, sustainable, legume-based meat analogues, with functional ingredient selection offering opportunities to optimise product quality and consumer appeal.

CRediT authorship contribution statement

Jideani Victoria A: Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Yvonne Maphosa:** Writing – review & editing, Supervision, Project administration. **Londiwe Mary Chipeta:** Writing – original draft, Methodology, Investigation.

Funding

The research study was funded by the National Research Foundation (NRF), South Africa.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Victoria Jideani reports financial support was provided by Cape Peninsula University of Technology. Yvonne Maphosa reports a relationship with University of Johannesburg that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Not applicable

References

Adebowale, Y. A., Schwarzenbolz, U., & Henle, T. (2011). Protein isolates from Bambara groundnut (*Voandzeia Subterranean* L.): Chemical characterization and functional properties. *International Journal of Food Properties, 14*, 758–775.

Adewumi, O. O., Felix-Minnaar, J. V., & Jideani, V. A. (2022). Functional properties and amino acid profile of Bambara groundnut and Moringa oleifera leaf protein complex. *Processes, 10*, 3–5.

Adeyeye, E., Ekiti, A., & Olaleye, A. (2012). Amino acid composition of Bambara groundnut (*Vigna subterranea*) seeds: Dietary implication. *International Journal of Chemistry and Science, 5*, 152–155.

Anjum, F. M., Naeem, A., Khan, M. I., Nadeem, M., & Amir, R. M. (2011). Development of texturised vegetable protein using indigenous sources. *Agricultural and Food Sciences, 21*, 33–44.

Antoniewicz, J., Jakubczyk, K., Kupnicka, P., Bosiacki, M., Chlubek, D., & Janda, K. (2022). Analysis of selected minerals in homemade grape vinegars obtained by spontaneous fermentation. *Biological Trace Element Research, 200*, 910–919.

Arii, Y., Sano, Y., & Nishizawa, K. (2021). Direct comparison of the tofu-like precipitate formation by adding different coagulants: magnesium chloride and glucono-δ-lactone. *Heliyon, 7*(6), Article e07239.

Baik, O. D., & Mittal, G. S. (2003). Kinetics of tofu colour changes during deep-fat frying. *LWT, 36*, 43–48.

Bahadoran, Z., Mirmiran, P., Tahmasebinejad, Z., & Azizi, F. (2016). Dietary L-arginine intake and the incidence of coronary heart disease: Tehran lipid and glucose study. *Nutrition Metabolism, 13*, 23.

Bakhsh, A., Lee, S., Lee, E. & Hwang, Y. (2021). Evaluation of rheological and sensory characteristics of plant-based meat analog with comparison to beef and pork, **41**, 983–996.

Bandyopadhyay, S., Kashyap, S., Calvez, J., Devi, S., Azzout-Marniche, D., Tomé, D., Kurpad, A. V., & Gaudichon, C. (2022). Evaluation of protein quality in humans and insights on stable isotope approaches to measure digestibility - A review. *Advances in Nutrition, 13*, 1131–1143.

Chaudhary, M., Pinto, S. V., Dharaiya, C. N., & Paul, P. (2021). Preparation of low-fat paneer using Glucono delta-lactone as an acidulant. *Indian Journal of Dairy Science, 74*(1).

Dang, Y., Ren, J., Guo, Y., Yang, Q., Liang, J., Li, R., Zhang, R., Yang, P., Gao, X., & Du, S. K. (2023). Structural, functional properties of protein and characteristics of tofu from small-seeded soybeans grown in the Loess Plateau of China. *Food Chemistry: X, 18*, Article 100689.

Darmajana, D., Afifah, N., & Indrait, A. (2020). The effect of extraction method and types of coagulants on the results and physicochemical properties of tofu. *Journal of Food Science and Technology, 40*, 677–682.

Ezenwa, H. C., & Iheme, G. (2022). Nutrient properties and sensory evaluation of tofu prepared using different cooking methods. *Nigerian Journal of Nutritional Sciences, 43*, 3.

Ezeama, C. F., & Dobson, G. N. (2019). Effect of coagulants on the physicochemical properties of fresh tofu. *African Journal of Food Science, 13*, 287–296.

Fiorentini, M., Kinchla, A. J., & Nolden, A. A. (2020). Role of sensory evaluation in consumer acceptance of plant-based meat analogs and meat extenders: A scoping review. *Foods (Basel, Switzerland), 9*(9), 1334.

Geng, Y., Du, X., Jia, R., Zhu, Y., Lu, Y., Guan, X., Hu, Y., Zhu, X., & Zhang, M. (2024). Research progress on tofu coagulants and their coagulation mechanisms. *Foods (Basel, Switzerland), 13*(21), 3475. https://doi.org/10.3390/foods13213475

George, T. T., Oyenihi, A. B., Rautenbach, F., & Obilana, A. O. (2021). Characterization of Moringa oleifera leaf powder extract encapsulated in maltodextrin and/or gum Arabic coatings. *Foods, 10*, 4.

Gil, M., Rudy, M., Duma-Kocan, P., Stanisławczyk, R., Krajewska, A., Dziki, D., & Hassoon, W. H. (2024). Sustainability of alternatives to animal protein sources: A comprehensive review. *Sustainability, 16*, 7701.

Hamadou, M., & Mune, M. A. (2024). Investigating Bambara bean (*Vigna subterranea* (Verdc.) L.) protein and hydrolysates: A comprehensive analysis of biological and biochemical properties. *Applied Food Research, 4*, 2–4.

Hardy, Z., & Jideani, V. A. (2020). Functional characteristics and microbiological viability of foam-mat dried Bambara groundnut (*Vigna subterranean*) yoghurt from reconstituted Bambara groundnut milk powder. *Food Science Nutrition, 8*, 5239–5240.

Huang, Z., Zhou, P., Jiang, Q., He, W., Zhou, X., Chen, H., Zhou, X., Li, M., Liu, B., Zhou, J., & Zhao, L. (2022). Study on the quality change and deterioration mechanism of leisure dried tofu under different storage temperature conditions. *LWT-Food Science and Technology, 172*, 2.

Hong, S., Shen, Y., & Li, Y. (2022). Physicochemical and functional properties of texturized vegetable proteins and cooked patty textures: Comprehensive characterization and correlation analysis. *Foods, 11*, 3–5.

Ibrahim, S. G., & Karim, R. (2024). Full factorial design of the effects of coagulants and processing variables on the physicochemical quality and texture profile analysis of kenaf seed tofu. *Exploration of Foods and Foodomics, 2*, 223–235.

Kang, S. W., Rahman, M. S., Kim, A. N., Lee, K. Y., Chun, J., Kerr, W. L., & Choi, S. G. (2018). Yield and physicochemical properties of low fat tofu prepared using supercritical carbon dioxide treated soy flours with different fat levels. *Journal of Food Science and Technology, 55*(7), 2712–2720.

Kim, Y. N., Muttakin, S., Jung, Y. M., Heo, T. Y., & Lee, D. U. (2019). Tailoring physical and sensory properties of tofu by the addition of jet-milled, superfine, defatted soybean flour. *Foods, 8*(12), 617.

Kowalska, S., Szłyk, E., & Jastrzębska, A. (2022). Simple extraction procedure for free amino acids determination in selected gluten-free flour samples. *European Food Research and Technology, 248*, 507–517.

Lan, Q., Lin, Z., Dong, H., Wu, D., Qin, W., Liu, J., Yang, W., & Zhang, Q. (2021). Influence of okara with varying particle sizes on the gelling, rheological, and microstructural properties of glucono-δ-lactone-induced tofu. *Journal of Food Science and Technology, 58*, 520–531.

Lee, G. Y., Jung, M. J., Kim, B. M., & Jun, J. Y. (2024). Effects of sodium alginate on the physical properties and storage stability of freeze-dried tofu coagulated with crab shell extract. *Foods, 13*, 74.

Li, X., Liu, X., Hua, Y., Chen, Y., Kong, X., & Zhang, C. (2019). Effects of water absorption of soybean seed on the quality of soymilk and the release of flavour compounds. *RSC Advances, 9*, 2906–2918.

Ma, Y., & Chen, F. (2023). Plant protein heat-induced gels: Formation mechanisms and regulatory strategies. *Coatings, 13*(11), 1899.

Mohamed, H. N., Mustafa, S., Fitrianto, A., & Manap, Y. A. (2017). Development of alginate-gum Arabic beads for targeted delivery of protein. *Biomolecular Research Therapeutics, 6*, 2–6.

Montevecchi, G., Santunione, G., Licciardello, F., Köker, Ö., Masino, F., & Antonelli, A. (2022). Enrichment of wheat flour with Spirulina. Evaluation of thermal damage to essential amino acids during bread preparation. *Food Research International, 157*, 1–10.

Nadathur, S. R., Wanasundara, J. P. D., & Scanlin, L. (2017). Proteins in the diet: Challenges in feeding the global population. *Sustainable protein sources*. Elsevier Inc.

Nizkii, S., Kodirova, G., & Kubankova, G. (2022). Lysine - an absolutely essential amino acid in soybean proteins from the Russian selection. *International Journal of Pharmaceutical Research and Allied Sciences, 11*, 54.

Nyau, V., Mwelwa-Zgambo, L., Chirwa-Moonga, T., Nthani, D., Prakash, S., Rodrigues, J., & Farrant, J. (2019). Some nutritional and physical properties of different Zambian market classes of Bambara groundnut (*Vigna subterranea*). *Journal of Food Research, 9*, 34.

Okpuzor, J., Ogbunugafor, H. A., Okafor, U., & Sofidiya, M. O. (2010). Identification of protein types in Bambara nut seeds: Perspectives for dietary protein supply in developing countries. *EXCLI J, 9*, 17–28.

Osen, R., Toelstede, S., Eisner, P., & Schweiggert-Weisz, U. (2015). Effect of high moisture extrusion cooking on protein-protein interactions of pea (*Pisum sativum L.*) protein isolates. *International Journal of Food Science and Technology, 50*, 1390–1396.

Paz-Yépez, C., Gavilanes-Tomalá, M., Palmay-Paredes, J., Medina-Galarza, G., Guerrero-Luzuriaga, S., & Velázquez Martí, B. (2024). Effects of organic acid coagulants on the textural and physical–chemical properties of tofu. *Applied Sciences, 14*, 8580.

Peh, F. Z. W., Zhao, L., Chia, Y. Y., Ng, C. K. Z., & Du, J. (2024). Texture improvement and *in vitro* digestion modulation of plant-based fish cake analogue by incorporating hydrocolloid blends. *Current Research in Food Science, 8*, Article 100775.

Perumpuli, P. A. B. N., & Dilrukshi, D. N. M. (2022). Vinegar: A functional ingredient for human health. *International Food Research Journal, 29*, 560.

Pugliese, A., Cabassi, G., Chiavaro, E., Paciulli, M., Carini, E., & Mucchetti, G. (2017). Physical characterization of whole and skim dried milk powders. *Journal of Food Science and Technology, 54*, 3334.

Qin, P., Wang, T., & Yangchao Luo, Y. (2022). A review on plant-based proteins from soybean: Health benefits and soy product development. *Journal of Agriculture and Food Research, 7*, 1–8.

Ramatsetse, K. E., Ramashia, S. E., & Mashau, M. E. (2023). A review on health benefits, antimicrobial and antioxidant properties of Bambara groundnut (*Vigna subterranean*). *International Journal of Food Properties, 26*, 1–17.

Rankema, J. M. S. (2001). Formation, structure and rheological properties of soy protein gels. *Ph.D. thesis*. The Netherlands: Wageningen University.

Samard, S., & Ryu, G. H. (2019). Physicochemical and functional characteristics of plant protein-based meat analogs. *Journal of Food Processing and Preservation, 43*, 1–11.

Samard, S., Maung, T. T., Gu, B. Y., Kim, M. H., & Ryu, G. H. (2021). Influences of extrusion parameters on physicochemical properties of textured vegetable proteins and its meatless burger patty. *Food Science and Biotechnology, 30*, 395.

Shi, W., Zhang, T., Xie, H., Xing, B., Wen, P., Ouyang, K., Fangjie Xiao, F., Qing Guo, G., Hua Xiong, H., & Zhao, Q. (2024). Characterization and in vitro digestibility of soybean tofu: Influence of the different kinds of coagulant. *Food Chemistry, 450*, 5–6.

Singh, A., Meena, M., Kumar, D., Dubey, A. K., & Hassan, M. I. (2015). Structural and Functional Analysis of Various Globulin Proteins from Soy Seed. *Critical Reviews in Food Science and Nutrition, 55*, 1491–1502.

Tan, X. L., Azam-Ali, S., Goh, E., Von, Mustafa, M., Chai, H. H., Ho, W. K., Mayes, S., Mabhaudhi, T., Azam-Ali, S., & Massawe, F. (2020). Bambara groundnut: An underutilized leguminous crop for global food security and nutrition. *Frontiers in Nutrition, 7*, 1–16.

Taheri, A., & Jafari, S. M. (2019). Gum-based nanocarriers for the protection and delivery of food bioactive compounds. *Advances in Colloid and Interface Science, 269*, 277.

Veldsman, Z., Pretorius, B., & Schonfeldt, H. C. (2023). Examining the contribution of an underutilized food source, Bambara Groundnut, in improving protein intake in Sub-Saharan Africa. *Frontiers in Sustainable Food System, 7*, 01–09.

Xiang, J., Liu, F., Wang, B., Chen, L., Liu, W., & Tan, S. (2021). A literature review on Maillard reaction based on milk proteins and carbohydrates in food and pharmaceutical products:Advantages, disadvamtages and avoidance strategies. *Foods, 10*, 1–18.

Xin, Y., Yan, X., Shi, X., Xiong, L., Xiao, X., Liu, K., & Chen, F. (2024). Impact of a Mg2+ Emulsion Coagulant on Tofu's Gel Characteristics. *Journal of Food Engineering, 387*, 5.

Yamamoto, T., & Inui-Yamamoto, C. (2023). The flavor-enhancing action of glutamate and its mechanism involving the notion of kokumi. *Nature Partner Journal of Science, Food, 7*, 3.

Yang, B., Zhang, W., Wang, H., Wang, S., Yan, J., Dong, Z., Zhao, P., Ren, F., & Chen, L. (2024). Comparative analysis of texture characteristics, sensory properties, and volatile components in four types of marinated tofu. *Foods, 13*(13), 2068.

Yasin, U. A., Horo, J. T., & Gebre, B. A. (2019). Physicochemical and sensory properties of tofu prepared from eight popular soybean [*Glycine max* (L.) Merrill] varieties in Ethiopia. *Scientific African, 6*, Article e00179.

Zeppa, G., Tedesco, M., Bertolino, M., & Çilek Tatar, B. (2021). Grape pomace as a new coagulant for tofu production: Physicochemical and sensory effects. *Foods, 10*(8), 1857.

Zhang, D., Hua, Z., & Li, Z. (2024). The role of glutamate and glutamine metabolism and related transporters in nerve cells. *CNS Neuroscience and Therapeutics, 30*, Article e14617.

Zhang, X., Zhang, K., Yang, N., Xiao, Y., Peng, Y., Han, Z., Su, W., Sun, G., & Wang, J. (2023a). Effect of natural gums on pasting, rheological, structural and hydrolysis properties of kudzu starch. *Current Research in Food Science, 7*, 1–8.

Zhang, L., Zhang, J., Wen, P., Xu, H., Cui, G., & Wang, J. (2023b). Effect of high-intensity ultrasonic time on structural, mechanical, and physicochemical properties of β-conglycinin (7S)- Transglutaminase (TGase) composite edible films. *Ultrasonics Sonochemistry, 98*, Article 106478.