

Research Article

Physicochemical, pasting and proximate properties of optimized orange-fleshed sweet potato gluten-free flour supplemented with bambara groundnut flour

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Abstract - Gluten-free (GF) food development is driven by rising celiac disease cases, healthy diet demand, and wheat costs. However, most GF flours are nutrient-poor, calorie-dense, and low in functional quality, making the production of high-quality GF food challenging. In this study, GF flour was formulated from optimized orange-fleshed sweet potato flour (OSPF) supplemented with bambara groundnut flour (BGF) at a proportion (30.31:19.50) obtained using the Design Expert software. Refined wheat flour was used as the reference flour. The physicochemical, pasting and proximate properties of the flours were then evaluated. The results revealed that the flours' physicochemical, pasting, proximate, and carbohydrate properties varied significantly ($p < 0.05$). The swelling index, water absorption capacity, oil absorption capacity, starch, and sugar contents of the OSPF reduced ($p < 0.05$) when supplemented with BGF (1.67 ± 0.09 to 1.63 ± 0.05 , 249.48 ± 1.52 to $201.55 \pm 1.77\%$, 132.34 ± 0.04 to $119.90 \pm 0.52\%$, 63.05 ± 0.37 to $56.48 \pm 0.49\%$ and 7.32 ± 0.07 to $6.78 \pm 0.12\%$, respectively). In contrast, its bulk density and ash, fiber, fat and protein contents increased significantly ($p < 0.05$) from 0.63 ± 0.01 to 0.69 ± 0.01 g/mL, 2.32 ± 0.11 to $2.61 \pm 0.07\%$, 0.51 ± 0.01 to $1.80 \pm 0.02\%$, 0.66 ± 0.02 to $3.03 \pm 0.01\%$ and 1.09 ± 0.01 to $11.71 \pm 0.02\%$, respectively. The amylose contents of 100% OSPF ($18.75 \pm 0.42\%$) and OSPF-BGF (30.31:19.50) ($17.80 \pm 0.35\%$), as well as their corresponding

amylopectin contents ($81.25 \pm 0.42\%$ and $82.20 \pm 0.35\%$, respectively), were statistically comparable ($p > 0.05$). Therefore, supplementation of OSPF with bambara groundnut flour improved the proximate quality of OSPF with a significant effect on its physicochemical and pasting properties. Consequently, BGF can be used as a suitable flour to improve the nutrient quality of orange-fleshed sweet potato gluten-free flour.

Keywords: Underutilized crops, nutrient, legume, refined wheat flour, sweet potato

1. Introduction

The rising cost of refined wheat flour, growing consumer interest in healthy foods, and the increasing prevalence of celiac disease have stimulated research into the formulation of gluten-free (GF) flours for the development of GF products (Imam et al., 2024). Consequently, food technologists and researchers have been motivated to formulate GF flours using gluten-free ingredients from various sources, including GF cereals, additives, pseudocereals, legumes, tubers, fruits and hydrocolloids (Abdulrazaaq et al., 2024; Filipcev et al., 2021; Mir et al., 2016; Irondi et al., 2021; Irondi et al., 2022a). These flours have been used to produce GF foods like pasta, extruded snacks, bread, noodles, dough, cake, batter (e.g., *akara*), and numerous baked products (Affrifah et al., 2023). However, many of these GF ingredients have less nutritional value, functional qualities, and health advantages (Affrifah et al., 2023; Foschia et al., 2017; Irondi et al., 2021; Irondi et al., 2022a). This subsequently affects their GF products such that they are characterized by low protein, calorie-dense, and high-fat contents (Belorio & Gómez, 2020).

Therefore, production of high-quality GF products will require GF flours with remarkable functional and nutritional properties. To enhance the quality of GF foods, supplementing GF flours with underutilized nutrient-rich legumes, like Bambara groundnut, is being explored. This present study explored the physicochemical, pasting and proximate properties of optimized, orange-fleshed

sweet potato gluten-free flour supplemented with bambara groundnut flour (an underutilized legume).

Sweet potato (*Ipomoea batatas* (L.) Lam.) is an essential tuber crop in Latin America, Africa, and Asia. In addition to serving as an essential source of starch for both the food and non-food sectors, it is also rich in dietary fiber, minerals, vitamin C, iron, and provitamin A and is frequently utilized as an energy source in human diets (Guo et al., 2019; Zhao et al., 2024). Distinct genetic backgrounds result in differently colored root tubers; for example, sweet potatoes are available in orange, white, red, purple, and yellow varieties owing to variations in the pigments and phenolic compounds present in the tubers (Wang et al., 2018; Zhao et al., 2024). Starch is the principal constituent of sweet potato root tubers, and its structural and functional properties largely determine its quality and applicability in both the food and non-food sectors (Guo et al., 2019).

In recent years, orange-fleshed sweet potato (OFSP) has attracted increasing interest and demand because of its rich content of β -carotene and other non-provitamin A carotenoids. It serves as a good source of carbohydrates (20 - 30% fresh weight), dietary fiber (2 - 4%), protein (1.5 - 2.5%), negligible fat content and important vitamins such as vitamin C (2.4 - 5.0 mg/100g) and minerals like iron (0.63 - 15.26 mg/100 g), calcium (24.40 - 45.54 mg/100 g w), potassium (337 - 400 mg/100g), and magnesium (3 - 37 mg/100 g), as well as health-promoting

phytochemicals including carotenoids, flavonoids, and phenolic acids (Abong et al., 2020; Amagloh et al., 2021; Chen et al., 2019; Neela & Fanta, 2019; Oloniyo et al., 2021). The carbohydrate fraction comprises both rapidly digestible starch and resistant starch, contributing to its moderate glycemic index (GI < 55) despite its sweetness (Giri & Sakhale, 2019). Bioavailability of iron in OFSP makes it particularly valuable in preventing iron deficiency anemia when consumed regularly (Neela and Fanta, 2019; Alam, 2021). However, a large number of sweet potato cultivars, including OFSP, are lower in nutrients, and their final products, which are often composed of starch, reflect this as well (Effiong et al., 2018). Thus, supplementing orange-fleshed sweet potato flour with nutrient-rich flour like Bambara groundnut flour may enhance its nutritional qualities.

Bambara groundnut (*Vigna subterranea* (L.) Verdc) is an underutilized legume native to West Africa and is widely produced throughout sub-Saharan Africa and Southeast Asia. The crop's growth and harvest period range from four to six months, depending on its intended use and genotype, and it is capable of withstanding extreme weather conditions (Paliwal et al., 2021). Bambara groundnut (BG) is extensively grown for its seeds, which have been used and processed in several ways for human and animal use (Adegboyega et al., 2021; Mubaiwa et al., 2017). BG seed's nutritional profile makes it an extremely well-balanced diet that can increase GFF's nutritional value (Carbas et al., 2023). BG may be able to satisfy humans' dietary needs due to its varied nutritional composition (Irondi et al., 2026). It serves as a good source of protein (18-24%), fat (5 - 7%), carbohydrate (57 - 65%), and minerals such as calcium (95

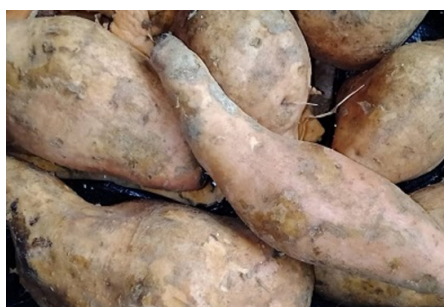
- 99 mg/100 g), potassium (1,100 - 1,900 mg/100 g), zinc (0.06 - 0.42 mg/100 g) and iron (4 - 48 mg/100 g) (Omotayo & Aremu, 2021; Irondi et al., 2026; Mayes et al., 2019; Paliwal et al., 2021). Further, dietary nutritional requirements can be met through the complementary role of legumes like BG when combined with other crops, including tubers (Imam et al., 2024; Irondi et al., 2024; Sparvoli et al., 2016). Thus, its continuous utilization could further enhance the properties of GFF as well as contribute to food security. BG flours can be used to make several GF confectionaries including snacks, cake, bread, and milk (Mayes et al., 2019). Recently, rice flour was supplemented with bambara groundnut flour and subsequently used to produce gluten-free cookies (Dzandu et al., 2023). BGF has also been used in streamed bread production (Mashau et al., 2022) as well as production of cassava-wheat-based bread (Agbara & Babagana, 2022). However, there is scarce information on the use of bambara groundnut flour (BGF) as orange-fleshed sweet potato flour (OSPF) supplement and its possible effect on the functional and nutritional qualities of OSPF. The combination of OSPF and BGF may serve as a high-quality GF flour blend for the production of GF products with improved quality. In particular, the rich nutritional composition of BGF, such as the higher protein and dietary fiber contents, can complement the nutrient limitations of OSPF. Hence, BGF may improve the functional properties of OFSP and enhance its suitability for GF products. Therefore, this study was designed to evaluate the physicochemical, pasting and proximate qualities of optimized orange-fleshed sweet potato gluten-free flours supplemented with Bambara groundnut flour.

2. Materials and methods

2.1 Plant materials

The plant (Figure 1) utilized in this study were: Bambara groundnut seeds (Voucher number: UILH/002/1791/2025), from a local agro-farmer in Itakpe, Kogi State, Nigeria; orange-fleshed sweet potatoes (Voucher number: UILH/001/1326/2025) from a local agro-farmer in

Ilorin, Kwara State, Nigeria, and refined wheat flour (*Triticum aestivum*) purchased from Mandate market, Ilorin, Kwara State, Nigeria. The plant samples were authenticated in the Herbarium unit of the Plant Biology Department, University of Ilorin. Analytical grade Sigma Chemicals (St. Louis, Missouri, USA) were used in the experimental analysis.



Orange-fleshed sweet potato tubers



Bambara groundnut pods



Orange-fleshed sweet potato chops



Bambara groundnut seeds

Figure 1. Plant materials

- 1) Whole orange-fleshed sweet potato tubers and Bambara groundnut pods
- 2) Orange-fleshed sweet potato chops and Bambara groundnut seeds

2.2 Sample preparation

2.2.1 Flour sample preparation

[Honi et al. \(2017\)](#) procedure was employed, with minor modification, to prepare the orange-fleshed sweet potatoes and bambara groundnut flours (Figure 2). Initially, the orange-fleshed sweet potato tubers were sorted and cleaned, then peeled and chopped using a stainless-steel knife. The chopped sweet potato pieces were oven-dried at 45 °C for 48 hours until a constant weight was achieved, then packed and stored in an airtight container

before milling into flour. The bambara groundnut seeds were also milled into flour. Fine flour from each sample was obtained by sieving through a 0.5 mm mesh sieve. Thereafter, the samples were individually labeled, packaged, and stored in airtight containers. Refined wheat flour (RWF) served as the reference flour. The final moisture content of OSPF, BGF and RWF were $11.48 \pm 0.06\%$, $9.09 \pm 0.01\%$ and $12.68 \pm 1.55\%$ respectively, as determined by the oven drying method ([Latimer, 2012](#)).



Figure 2. Flour materials

2.2.2 Composite flour preparation

The optimized composite flour of OSPF and BGF flour used in this study was formulated using the proportions obtained from the Response Surface Methodology Central Composite Rotatable Design of the Design Expert software (version 6.0.8, Stat-Ease Inc., USA). The experimental design was defined using flour proportion ranges adapted from [Julianti et al. \(2017\)](#), with orange-fleshed sweet potato flour varied from 30 to 60 and bambara groundnut flour from 19.5 to 29.5. These values were input into the Design Expert software and processed through Response Surface Methodology (RSM) employing a Central Composite Rotatable Design, which generated nine (9) experimental formulations, as shown in Table 1. Each ratio represents a distinct flour

combination that was thoroughly blended to form a homogeneous composite flour. The resulting composite flours were analyzed for important bioactive substances: total phenolics, flavonoids, and tannins. Optimization was performed using a desirability function to maximize phenolics and flavonoids, key bioactive compounds with important health properties, while minimizing tannin, due to its anti-nutrient and astringent properties. Subsequently, the combination with the highest desirability, as determined by Design Expert software, was used to formulate the composite flour of OSPF and BGF. The flours were mixed in a mechanical blender, labeled, and kept at room temperature in a dry, dark cupboard in airtight, moisture-resistant containers until further analysis.

Table 1. Unique Response surface central composite rotatable design runs.

Runs	Orange-fleshed sweet Potato (g)	Bambara groundnut flour (g)
1	45.00	17.43
2	45.00	24.50
3	23.79	24.50
4	66.21	24.50
5	60.00	19.50
6	45.00	31.57
7	30.00	19.50
8	30.00	29.50
9	60.00	29.50

Note: Values outside the specified range are axial (star) points from the CCRD design.

2.3 Gluten content determination

The amount of gluten in the flour samples was estimated as reported by [Ironi et al. \(2021\)](#). In a centrifuge tube, flour (20 g) was added to distilled water (10 mL) and left for 15 min. The stirrer was then used to agitate the suspension. After, the flour mixture was rolled into a ball and dipped in a beaker filled with pure water. To make sure no part was lost, this was rinsed under running water after being left to stand (30 min). Next, the resulting elastic gluten was cut into small pieces, placed in a pan, and oven-dried (Model DHG: Lemfield Medical, England) at 50°C overnight to obtain dried gluten. The percentage of gluten was then calculated by weighing the final mass.

2.4 Functional properties determination

The flour samples' functional properties: bulk density, swelling index, and water and oil absorption capacity were measured using the techniques of [Nwakaudu et al. \(2017\)](#) as described below:

2.4.1 Determination of Bulk Density (BD) of flours

The method described by [Nwakaudu et al. \(2017\)](#) was adopted to determine the Bulk Density (BD) of flour samples. A graduated cylinder 100 mL was weighed dry, and gently filled with 50 g of the flour sample. The bottom of the cylinder was then tapped gently on a laboratory bench several times. This was continued until no further diminution of the test flour in the cylinder after filling to mark was observed. The weight of the cylinder plus flour was measured and recorded. Subsequently, the bulk density was calculated as:

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

2.4.2 Determination of swelling index of flours

The procedure described by [Nwakaudu et al. \(2017\)](#) was used to quantify the swelling index of the flour sample. A clean, dry, graduated (50 mL) cylinder was filled with one (1) gram of

each flour sample. The volume was recorded after the flour samples were carefully leveled into it. Ten (10) mL of distilled water was added to every sample. The cylinder's volume (swelling) was measured as it was swirled and left to stand for sixty minutes. The sample's swelling index was computed from the formula below:

$$\text{Swelling Index} = \frac{\text{Sample Volume After Swelling (mL)}}{\text{Sample Volume before Swelling (mL)}}$$

2.4.3 Determination of Water/Oil Absorption Capacity (WAC) of flours

The WAC/OAC of flour samples was determined using the procedure described by [Nwakaudu et al. \(2017\)](#) with little modification. Sample (1 g) was weighed into a pre-weighted graduated centrifuge tube, and then mixed with 10 mL of distilled water for 30 seconds. The suspension was left for 30 min at room temperature and then centrifuged at 1500 rpm for 30 min. The supernatant was carefully decanted, and the tube containing the hydrated residue was weighed. A similar procedure was adopted for the determination of oil absorption capacity (OAC) with vegetable oil used in place of distilled water. Subsequently, WAC/OAC was calculated as:

$$\text{WAC/OAC (\%)} = \frac{\text{Weight of water/oil absorbed (g)}}{\text{Weight of sample (g)}} * 100$$

2.5 Determination of flour samples' pasting properties

In order to evaluate the flours' pasting properties, the Rapid Visco Analyzer (RVA) method was used (RVA-4, Perten Scientific, Springfield, IL model). Thermocline software was installed on the personal computer (PC) that was a component of the RVA. A suspension of the sample (3 g of flour in 25 mL of distilled water) was prepared in an

aluminum canister and loaded in the RVA machine at a constant rate (160 RPM) of stirring. The analysis was carried out using the following programme: a holding period of 5 min at 25 °C; alternating heating between 25 and 95 °C at the rate of 5 °C/minute; a 5-min holding at 95 °C; followed by a cooling to 25 °C at the rate of 5 °C/minute; and a 5-min holding at 25 °C. Employing the Thermocline software, the PC was utilized to read the pasting properties. The pasting properties measured were the peak, trough, breakdown, final, and setback viscosities (presented as Rapid Visco Analyzer Units, RVU), the peak time (min), and the pasting temperature (°C) ([Elemosho et al., 2020](#)).

2.6 Proximate composition of flour samples

The [Latimer \(2012\)](#) procedure was utilized to quantify the flour samples' proximate composition. Briefly, samples were oven-dried (105 °C) to constant weight to assess the moisture content. The Soxhlet method was used to determine the crude fat content, with petroleum ether as the extraction solvent. Ash content was determined by heating (525 °C) the sample for four hours, and the percentage ash content was calculated from the mass of the resulting residue. The Micro-Kjeldahl method was used to quantify the samples' crude protein content, and the nitrogen conversion factor was 6.25.

For the crude fiber content of the flour, two (2 g) (W_1) of the sample was weighed and put in a 1 L conical flask, then boiled for 30 minutes with 200 mL of 1.25% H_2SO_4 and filtered through a funnel. The residue was washed with boiling water until the washing was no longer acidic. The residue was boiled for another 30 min with 200 mL of 1.25% NaOH solution; filtered with hot water, neutralized by washing with 1% HCl and dehydrated by

washing with methylated spirit three times. The residue was transferred into a crucible and dried in the oven for 1 hour. The crucibles with their contents were cooled in a desiccator and then weighed (W_2). The crucibles were then taken into a furnace for ashing at 600 °C for 2 hours. The ash samples were removed from the furnace and put into the desiccator to cool and reweighed (W_3).

The percentage crude fiber was calculated as follows:

$$\% \text{Crude fibre} = \frac{W_2 - W_3 \times 100}{W_1}$$

Where:

W_1 = Weight of original sample

W_2 = Weight of crucible and residue

W_3 = Weight of final ash sample

Further, the amount of carbohydrates was calculated by deducting the percentage levels of moisture, ash, fat, fiber, and protein from 100. The metabolizable energy value was calculated using the Atwater general factor system. The percentages of available carbohydrate, crude protein, and crude fat were multiplied by their physiological fuel values of 4, 4, and 9 kcal/g, respectively.

2.7 Determination of starch and total free sugar content of flour samples

The starch and total free sugar content of the flours were quantified using the method outlined by Ironi et al. (2025). The sample (0.02 g), 80% ethanol (1 mL), 10 mL hot ethanol (80%), and distilled water (2 mL) were mixed to extract the total free sugar and starch. The mixture was centrifuged (Unigold Medical, 80-24, England) at 2000 rpm for 10 min, and the supernatant was collected. For the total free sugar analysis, an aliquot of the supernatant (0.2 mL) was combined with 5% phenol solution (0.5 mL) and 2.5 mL

of concentrated H_2SO_4 . Next, concentrated perchloric acid (7.5 mL) was used to hydrolyze the residue for an hour. The resulting hydrolysate was filtered through No. 2 Whatman filter paper and then diluted with distilled water (20 mL). Then, in a test tube, the filtrate (0.05 mL) was mixed with concentrated H_2SO_4 (2.5 mL) and 5% phenol solution (0.5 mL) to quantify the starch content. The sugar and starch reaction mixture was allowed to cool to room temperature, and the absorbance (490 nm) was read using a UV-Vis spectrophotometer (Simtronics, SE 805, India). The percentage of sugar and starch was then determined by absorbance at 490 nm from a glucose calibration curve.

2.8 Determination of amylose and amylopectin contents of flour samples

The method outlined by Ironi et al. (2021) was applied for estimating the flour samples' amylose and amylopectin contents. Initially, 95% ethanol (1 mL) and 1 N NaOH (9 mL) were mixed with 100 mg of the sample. To gelatinize the starch, the mixture was heated to 100°C for 10 min in a water bath. The extract was diluted 10 times (1:10) when it had cooled to room temperature. Next, 1N acetic acid solution (0.1 mL), 0.2 mL of iodine solution (0.2 g I_2 in 2 g KI in 100 mL of distilled water), and distilled water (9.2 mL) were mixed with the diluted extract (0.5 mL). After 20 min of color development at room temperature, the reaction mixture was shaken, and the absorbance at 620 nm was measured using a UV/visible spectrophotometer (Simtronics, SE 805, India). The amylose standard was then used to determine the samples' amylose content. The amylopectin content was evaluated using the formula below:

$$\text{Amylopectin (\%)} = 100 - \text{amylose (\%)}.$$

2.9 Data analysis

The results of the triplicate analysis (n= 3) were presented as mean ± standard deviation (SD). Statistical analyses were performed using SPSS 21 software (IBM Corporation, USA). One-way analysis of variance (ANOVA) was used to evaluate differences among samples and statistical differences were further separated using Duncan’s multiple range tests at a 95% confidence level.

3. Results and discussion

3.1 Optimization of OSPF and BGF flour for composite flour formulation

The criteria for optimizing the OSPF and BGF flour used for composite flour formulation are presented in Table 2. OSPF and BGF had constraints that were in the acceptable range. For optimization, total phenolics and total flavonoids levels were maximized, considering their health-promoting properties. However, tannin content was minimized due to its astringency. The combination outcome having the best desirability (0.698; that is, 69.8%), consisting of OSPF (30.31 g) and bambara groundnut flour (19.5 g), was then used for the OSPF-BGF composite flour formulation production.

Table 2. Criteria for optimization of the orange-fleshed sweet potato and Bambara composite flour and solution

Name	Constraint	Lower limit (g)	Upper limit (g)	Solution
Orange-fleshed sweet potato flour	Within the range	30	60	30.310
Bambara groundnut flour	Within the range	19.5	29.5	19.500
Total phenolic	Maximize	1.36	2.24	1.872
Tannins	Minimize	1.74	4.01	2.478
Flavonoids	Maximize	0.44	0.58	0.561
Desirability				0.698

3.2 Functional properties of the flour samples

The functional properties of food components determine their suitability for a specific food product. The gluten content of the flour samples is presented in Table 3. Refined wheat flour (RWF) contained measurable gluten, with wet and dry gluten contents of 30.37±0.42% and 11.61±0.28%, respectively. This was within the ranges of previous reports of Best et al. (2023) (wet gluten, 12.13-37.33% and dry gluten, 4.33-12.28%) and Bodor

et al. (2024) (wet gluten, 22.34-40.65% and dry gluten, 9.19–15.97%) for commercial wheat flours. The dry gluten level (11.61±0.28%) is higher than the 11.35% wheat flour (Maida) recorded by Rodge et al. (2012), but lower than the dry gluten content (12.8%) reported by Bodor et al. (2024) and 14.53% reported by Irondi et al. (2021). This variation may be attributed to wheat cultivar, as well as environmental and genetic factors (Irondi et al., 2021; Best et al., 2023). In contrast, no detectable gluten was observed in BGF, OSPF, and

their composite flour using the wet gluten wash method. This may indicate an absence or insufficient quantity of gluten necessary to form a functional gluten network in the OSPF and BGF. This is expected, as GF crops do not contain adequate levels of gliadin and glutenin proteins required for gluten formation (Imam et al. 2024; Irondi et al., 2021). As a result, the functionality of OSPF and BGF may be limited in baked products, whereas they could be well-suited for GF food formulations. Conversely, the presence of gluten in RWF has made it a preferred choice in the bakery industry

compared to the OFSP and BGF. This is because of its ability to form a viscoelastic network upon hydration and mixing, imparting dough with elasticity, extensibility, and excellent gas-retention capability necessary for high-quality baked products. Despite its functional benefits, the use of RWF could be constrained by health concerns such as celiac disease and gluten sensitivity, as well as economic factors such as cost, which may influence customer demand and its use in product formulations (Best et al., 2023; Imam et al., 2024).

Table 3. Gluten content of the flours.

Samples	Gluten content(%)	
	Wet gluten	dry gluten
Refined wheat flour	30.37±0.42	11.61±0.28
Bambara groundnut flour (BGF)	ND	ND
Orange-fleshed sweet potato (OSPF)	ND	ND

Note: ND, not detected.

Functional properties (bulk density (BD), swelling index (SI), water absorption capacity (WAC), and oil absorption capacity (OAC)) of the flour samples are presented in Table 4. BD ranged from 0.63±0.01 g/mL in 100% OSPF to 0.85±0.02 g/mL in 100% BGF. The BD of 100% BGF (0.85±0.02 g/mL) is lower than the BD of 100%BGF (2.15±0.13 g/mL) reported by Dzandu et al. (2023). Similarly, the BD of 100% OSPF (0.63± 0.01 g/mL) is lower than the BD of 100% orange-flesh sweet potato flour (0.71±0.00 g/mL) reported by Eke-Ejiofor et al. (2021). The SI ranged from 1.17 to 1.67 mL/mL across the samples. The SI of 100% RWF and 100%BGF are statistically comparable ($p>0.05$). Similarly, the SI of 100% OSPF and OSPF-BGF (30.31:19.50) was statistically comparable ($p>0.05$).WAC ranged from 81.87±0.21% in 100%BGF to 249.48±1.52%

in 100% OSPF. Similarly, 100%BGF (85.43±0.16%) had the lowest ($p<0.05$)OAC value while 100% OSPF recorded the highest (132.34±0.04%). Incorporation of BGF into OSPF resulted in significant ($p<0.05$) reductions in SI, WAC, and OAC. In contrast, when Bambara groundnut flour was incorporated in rice flour blends (from RB90:10 to RB75:25), the WAC and OAC increased (Dzandu et al., 2023). In this study, OSPF exhibited higher swelling and hydration capacities than Bambara groundnut flour. This behavior is expected because tuber-based flours are predominantly composed of starch, which possesses several hydroxyl groups that can establish hydrogen bonds with water molecules (Alamu et al., 2017; Eke-Ejiofor et al., 2021). The relatively low BD observed in 100% OSPF may be attributed to its loose particle structure and lower

packing efficiency. Since starch granule morphology and particle size distribution strongly influence bulk density in flour systems (Nwakaudu et al., 2017). Due to the loose starch structure, the low BD facilitates water penetration, granule swelling, and gelatinization, thereby increasing paste viscosity (Aondoakaa & Arueya, 2026). Further, since food systems use flours with BD more than 0.7 g/mL as thickeners, BGF with BD of $0.85 \pm 0.02\%$ may also be useful in this role (Aondoakaa & Arueya, 2026). The increase in BD of OSPF following BGF supplementation likely reflects the higher protein and lipid contents of the legume flour. Proteins and lipids may occupy inter-granular spaces within the starch matrix, resulting in improved particle packing and higher density. Similar observations have been reported in cereal–legume composite flours where incorporation of protein-rich legumes modifies the physical structure of starch matrices (Dzandu et al., 2023; Olaoye et al., 2018). Lower BD of OSPF-BGF (30.31:19.50) compared to the 100% RWF will make it desirable for formulating complementary foods that require a high nutrition to low bulk density (Nwakaudu et al., 2017). In addition, it will make the OSPF-BGF (30.31:19.50) easier to handle, store, and transport compared to the 100% RWF (Irondi et al., 2021). Conversely, 100% RWF with higher BD compared to OSPF-BGF (30.31:19.50) will be desirable for improved dispensability and reduced

paste thickness, thereby enhancing ease of handling and suitability in food formulations requiring lower viscosity (Nwakaudu et al., 2017).

The observed reduction in SI, OAC and WAC of OSPF when supplemented with BGF may be attributed to the compositional characteristics of BGF, which likely altered the swelling and hydration behavior of the OSPF flour matrix, thereby reducing starch granule expansion and absorption capacities in the OSPF–BGF (30.31:19.50) blends. BGF contains higher levels of protein and fiber (Table 6) but lower starch content than OSPF (Table 7). As a result, its supplementation could reduce the starch content of the OSPF, which contributes to its swelling and absorption properties (Eke-Ejiofor et al., 2021). In agreement with previous studies, legume proteins may interact with starch granules during hydration, limiting granule expansion and limiting water or oil penetration, thereby influencing the functional behavior of composite flours by restricting granule swelling and altering hydration properties (Yang et al., 2019; Dzandu et al., 2023). Further, foods' ability to absorb oil is essential since it improves flavor, mouth feel, and consistency (Dzandu et al., 2023). Consequently, the high OAC of OSPF-BGF (30.31:19.50) compared to the 100% RWF may suggest its appropriate usage in producing baked foods with enhanced sensory qualities.

Table 4. Functional Properties of orange-fleshed sweet potato and bambara groundnut flour.

Samples	BD (g/mL)	Swelling Index (mL/mL)	OAC (%)	WAC (%)
100% RWF	0.83±0.01 ^c	1.17±0.08 ^a	100.70±0.70 ^b	133.6±1.60 ^b
100% BGF	0.85±0.02 ^c	1.24±0.04 ^a	85.43±0.16 ^a	81.87±0.21 ^a
100% OSPF	0.63±0.01 ^a	1.67±0.09 ^b	132.34±0.04 ^d	249.48±1.52 ^d
OSPF-BGF (30.31:19.50)	0.69±0.01 ^b	1.63±0.05 ^b	119.90±0.52 ^c	201.55±1.77 ^c

Note: BD, bulk density; OAC, oil absorption capacity; WAC, water absorption capacity; RWF, refined wheat flour; BGF, Bambara groundnut flour; OSPF, orange-fleshed sweet potato flour. All values are mean±SD (n = 3). Values having different lowercase superscript letters along the same column differ significantly (*p*<0.05).

3.3 Pasting properties of the flour samples

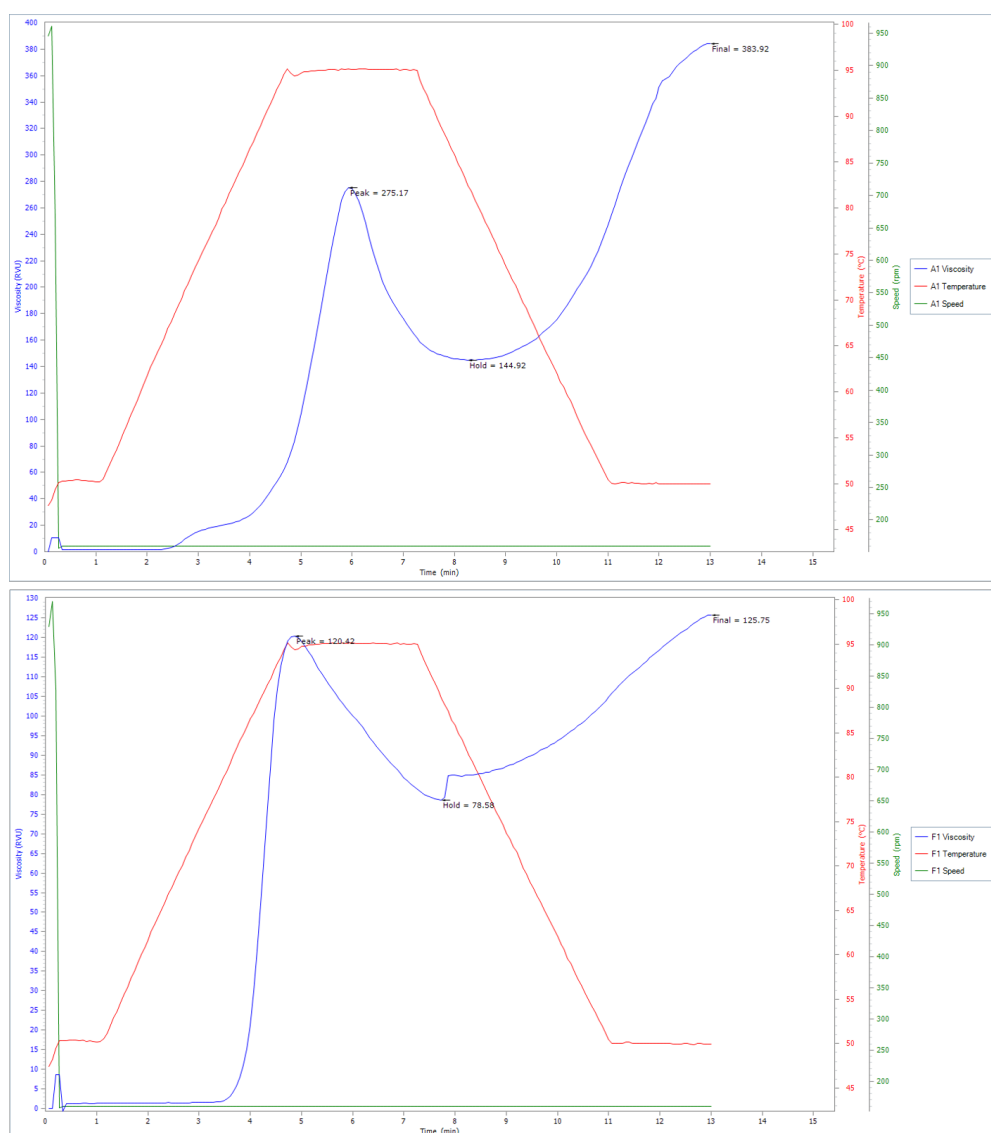
Table 5 presented the pasting properties of flour samples, including peak, trough, breakdown, final, and setback viscosities, as well as peak time and pasting temperature, while Figure 3 depicted the representative amylographs of the flours. Significant variations (*p*<0.05) were observed among the flours' pasting properties. Among the pasting properties, peak and final viscosities are the most important in the food industry (Irondi et al., 2019). Peak viscosity (PV) ranged from 110.96±13.38 RVU in OSPF-BGF (30.31:19.50) to 275.80±0.88 RVU in 100% RWF. The PV of 100% BGF (164.09±4.01 RVU) and 100% OSPF (158.75±0.50 RVU) are statistically comparable (*p*>0.05). Similarly, final viscosity (FV) values varied from 116.13±13.61 RVU (OSPF-BGF (30.31:19.50)) to 383.63±0.42 RVU (100% RWF), with 100% RWF exhibiting the highest FV value (383.63±0.42 RVU). The FV of 100% RWF (383.63±0.42 RVU)

in this study is higher than the FV of the refined wheat (159.12±1.12 RVU) reported by Irondi et al. (2024). The peak and final viscosities of OSPF reduced significantly (*p*<0.05) when supplemented with BGF. Also, the pasting temperature ranged from 84.00±1.13 °C in 100% OSPF to 94.48±0.11 °C in 100% RWF, while peak time ranged between 4.84±0.05 to 6.00±0.10 min. The pasting temperatures (84.00±1.13°C) and time (5.14±0.38 min) of 100% OSPF in this study were higher than the pasting temperatures (78 °C) and time (4 min) of orange fleshed potato flour reported by Obomeghei et al. (2020). The pasting temperature shows that 100% OFSP begins gelatinization at 84.00±1.13 °C, whereas incorporating Bambara groundnut flour (OSPF-BGF, 30.31:19.50) slightly increases the gelatinization temperature to 87.65±0.64 °C, likely due to starch-protein interactions restricting granule swelling (Irondi et al., 2022b; Yang et al., 2019).

Table 5. Pasting properties of orange-fleshed sweet potato and bambara groundnut flour.

Samples	Peak (RVU)	Trough (RVU)	Breakdown (RVU)	Final Viscosity (RVU)	Setback (RVU)	Peak Time (min)	Pasting Temp (°C)
100% RWF	275.80±0.88 ^c	146.38±2.01 ^d	129.42±1.18 ^c	383.63±0.42 ^d	237.25±2.48 ^b	6.00±0.10 ^b	94.48±0.11 ^c
100% BGF	164.09±4.01 ^b	129.55±2.65 ^c	34.54±1.36 ^a	353.71±5.48 ^c	209.17±14.04 ^b	5.73±0.00 ^b	87.35±0.00 ^b
100% OSPF	158.75±0.50 ^b	100.42±0.31 ^b	58.33±0.39 ^b	165.08±0.15 ^b	64.67±1.66 ^a	5.14±0.38 ^a	84.00±1.13 ^a
OSPF-BGF (30.31:19.50)	110.96±13.38 ^a	74.63±5.59 ^a	36.33±7.78 ^a	116.13±13.61 ^a	41.50±8.02 ^a	4.84±0.05 ^a	87.65±0.64 ^b

Note: RWF, refined wheat flour; BGF, Bambara groundnut flour; OSPF, orange-fleshed sweet potato flour. All values are mean±SD (n = 3). Values having different lowercase superscript letters along the same column differ significantly ($p < 0.05$)

**Figure 3.** Representative amylographs of flour samples.

Pasting properties, which are related to starch's ability to bind water and the expansion of its granules after heating, are crucial in starch's industrial applications, like the food sector (Irondi et al., 2024; Irondi et al., 2025; Owuno & Achinewhu, 2021). The pasting properties observed in this study reflect structural differences between starch-rich tuber flours and protein-rich legume flours. The highest PV exhibited by 100% RWF, maybe attributed to strong starch swelling and thickening potential. Because PV is a common indicator of thickening capacity of starch systems and reflects the extent of granule swelling before structural breakdown (Kareem et al., 2023). The decrease in viscosity parameters observed in the OSPF following BGF supplementation may be attributed primarily to starch dilution and interactions between starch and proteins. Legume proteins and lipids can interfere with starch gelatinization by limiting water availability and physically restricting granule swelling. During heating, proteins may form complexes with amylose molecules, thereby reducing the release of soluble starch components into the continuous phase (Irondi et al., 2022b; Yang et al., 2019). Furthermore, breakdown viscosity is a measure of how easily swollen starch granules can break down when heated and sheared (Kareem et al., 2023). The lower breakdown values exhibited by OSPF-BGF (30.31:19.50) may suggest improved paste stability compared to the 100% OSPF. This action could be explained by the surrounding protein matrices' structural support of the starch granules (Eke-Ejiofor et al., 2021).

Final viscosity and setback viscosity are indicators of gel formation and retrogradation during cooling. The relatively high final viscosity observed in 100% RWF is consistent with the presence of gluten proteins that contribute to

viscoelastic network formation during heating and cooling (Cappelli et al., 2020; Irondi et al., 2022a; Parenti et al., 2020). Since a lower pasting temperature required the least cooking energy (Elemosho et al., 2020), this showed that less energy is required to cook OSPF-BGF (30.31:19.50) compared to 100% RWF. Additionally, OSPF-BGF (30.31:19.50) will be easier to cook compared to 100% RWF. Since lower pasting temperature demonstrated ease of flour cooking (Obomeghei et al., 2020). The lowest pasting temperature of the 100% OSPF compared to the other flours may be related to the large granule size and high swelling ability of potato starch. Previous studies of Eke-Ejiofor et al. (2021) and Zhuang et al. (2022) reported that potato starch determines and promotes its gelatinization and viscosity development during heating. Similarly, the lower pasting temperature of OSPF-BGF (30.31:19.50) may result from starch dilution and interactions with proteins and lipids from BGF, which weaken starch structure and promote earlier gelatinization (Yang et al., 2019; Mukwevho & Emmambux, 2024). Specifically, the variations in starch composition may be responsible for the variations in pasting properties of the flour samples (Kareem et al., 2023; Ortiz et al., 2019). Additionally, endogenous proteins and lipids in the wheat matrix may affect the rheology of flours by preventing starch granule expansion during gelatinization and postponing amylopectin retrogradation (Irondi et al., 2022b). The pasting properties of OSPF-BGF (30.31:19.50) could further imply that supplementation of OSPF with BGF may produce functional characteristics suitable for specific food applications where these properties are beneficial (Aondoakaa & Arueya, 2026). Therefore, compared to 100% OSPF, OSPF-BGF (30.31:19.50) may

be more suitable for use in pasta, cereal bars, noodles, and extruded snacks.

3.4 Proximate composition of flour samples

The proximate compositions of the flours are presented in Table 6. Significant differences ($p < 0.05$) were observed among the samples for moisture, ash, crude fiber, fat, protein, and carbohydrate contents. The 100% OSPF contained substantially higher carbohydrate levels ($83.94 \pm 0.02\%$). The carbohydrate content of 100% OSPF ($83.94 \pm 0.02\%$) obtained in this study is higher than the values of 72.09% reported for 100% OSPF by Olugbuyi et al. (2024). In contrast, 100%BGF showed the highest protein ($30.61 \pm 0.04\%$), fat ($10.13 \pm 0.04\%$), and fiber ($3.00 \pm 0.03\%$) contents. The protein content of BGF in this study is higher than that reported by Dzandu et al. (2023) (21.99%) and Olaoye et al. (2018) (16.21%) for BGF. Incorporation of BGF into sweet potato flours significantly ($p < 0.05$) increased the protein, ash, fiber, and fat contents of the OSPF while reducing the carbohydrate content. This agrees with the previous study of Dzandu et al. (2023) and Olaoye et al. (2018), where BGF has a similar effect on rice flour and wheat flour.

The proximate composition results highlight the complementary nutritional

roles of sweet potato and Bambara groundnut in composite flour systems. The observed nutritional contents in the flours can render important physiological functions (Elemosho et al., 2020; Ironi et al., 2024). The higher carbohydrate content of 100% OSPF demonstrated that it's a rich source of carbohydrates, while Bambara groundnut, due to its observed proximate composition, will contribute substantial amounts of protein, dietary fiber, and minerals (Neela and Fanta, 2019; Carbas et al., 2023). A previous study of Olugbuyi et al. (2024) reported that sweet potato flour is predominantly composed of carbohydrates with relatively low protein and ash contents. The OSPF–BGF blend (30.31:19.50) has lower fat content than 100% RWF, suggesting a potential dietary benefit of OSPF–BGF products, as consumption of low-fat foods has been associated with improved weight control, cardiovascular health, and reduced risk of chronic diseases (Mozaffarian, 2019). The low moisture content of the OSPF–BGF blend (30.31:19.50) implies better storage stability relative to 100% RWF and 100% OSPF, as lower moisture levels are effective in controlling microbial (bacterial and fungal) growth on food (Ironi et al., 2024; Sarker et al., 2020).

Table 6. Proximate Compositions of orange-fleshed sweet potato and bambara groundnut flour.

Sample	Moisture content (%)	Ash content (%)	Crude Fibre (%)	Crude fat (%)	Crude protein (%)	Available carbohydrate (%)	Metabolizable energy (kcal/100g)
100% RWF	12.68 ± 1.55^d	3.60 ± 0.02^c	2.32 ± 0.08^c	7.42 ± 0.02^c	14.08 ± 0.06^c	59.90 ± 0.33^b	362.72 ± 0.90^c
100%BGF	9.09 ± 0.01^a	2.61 ± 0.01^b	3.00 ± 0.03^d	10.13 ± 0.04^d	30.61 ± 0.04^d	44.56 ± 0.01^a	391.84 ± 0.14^d
100% OSPF	11.48 ± 0.06^c	2.32 ± 0.11^a	0.51 ± 0.01^a	0.66 ± 0.02^a	1.09 ± 0.01^a	83.94 ± 0.02^d	346.05 ± 0.27^a
OSPF-BGF (30.31:19.50)	10.69 ± 0.14^b	2.61 ± 0.07^b	1.80 ± 0.02^b	3.03 ± 0.01^b	11.71 ± 0.02^b	70.15 ± 0.20^c	354.74 ± 0.73^b

Note: RWF, refined wheat flour; BGF, Bambara groundnut flour; OSPF, orange-fleshed sweet potato flour. All values are mean $\pm$ SD ($n = 3$). Values having different lowercase superscript letters along the same column differ significantly ($p < 0.05$).

The significant increase in protein content observed in the composite flours (OSPF-BGF (30.31:19.50)) confirms the potential of BGF as a protein enrichment ingredient. Legumes are well known for their high protein content; this could make BGF a promising functional ingredient for enhancing the nutritional quality of OSPF in the production of gluten-free foods (Foschia et al., 2017; Imam et al., 2024). Additionally, the high ash content observed in the OSPF-BGF (30.31:19.50) compared to 100% OSPF indicated improved mineral compositions of OSPF-BGF (30.31:19.50) relative to 100% OSPF. This can be attributed to the presence of bambara groundnut, which is known for its appreciable levels of essential minerals that can improve dietary micronutrient intake (Mayes et al., 2019). This finding is particularly important because many commercially available gluten-free products are nutritionally imbalanced and often contain excessive carbohydrates with limited protein content (Belorio & Gómez, 2020). Consequently, the formulated OSPF-BGF blend (30.31:19.50) demonstrated significantly ($p < 0.05$) nutritional quality, indicating its potential as a GF flour with enhanced nutritional quality and as a suitable alternative to RWF for the production of nutrient-rich bake products.

3.5 Carbohydrate profiles of flour samples

Table 7 presents the results of the carbohydrate profiles of flour samples in terms of starch, sugar, amylose and amylopectin contents. The starch content ranged ($p < 0.05$) from $56.48 \pm 0.49\%$ in OSPF-BGF (30.31:19.50) to $70.04 \pm 0.35\%$ in 100% RWF, sugar content ranged from $5.17 \pm 0.10\%$ (100% BGF) to $7.32 \pm 0.07\%$ (100% OSPF), amylose content ranged from $17.80 \pm 0.35\%$ (OSPF-BGF (30.31:19.50)) to $29.22 \pm 0.42\%$ (100% RWF), amylopectin ranged from 70.78 ± 0.42 (100% RWF) to

$82.20 \pm 0.35\%$ (OSPF-BGF (30.31:19.50)) while amylose/amylopectin ratio ranged from 0.22 ± 0.01 (OSPF-BGF (30.31:19.50)) to 0.41 ± 0.01 (100% RWF). The starch ($58.81 \pm 0.44\%$), sugar ($5.17 \pm 0.10\%$) and amylopectin ($76.42 \pm 0.50\%$) content of BGF in this study were lower than starch ($82.59 \pm 0.01\%$), sugar ($6.04 \pm 0.08\%$), and amylopectin ($79.80 \pm 0.06\%$) of Bambara flour reported by Eke-Ejiofor et al. (2022), while the amylose ($23.58 \pm 0.50\%$) is higher than their reported amylose ($20.20 \pm 0.06\%$). The variation may be due to cultivar, growing environment, and processing techniques (Irondi et al., 2021). There is a significant decrease ($p < 0.05$) in the amylose, sugar, and starch contents as well as the amylose/amylopectin ratio of OSPF following BGF Supplementation. This is in consonance with the previous study of Eke-Ejiofor et al. (2022) when cassava flour was blended with BGF. The amylose, amylopectin and the amylose-amylopectin ratio of 100% OSPF and OSPF-BGF (30.31:19.50) were statistically comparable ($p > 0.05$).

Further, the flours' amylopectin amounts were greater than their amylose concentrations, consistent with previous reports (Elemosho et al., 2020; Irondi et al., 2021; Kareem et al., 2023) that flours' starch included more amylopectin than amylose. Since sugar contributes to the product's sweetness (Eke-Ejiofor et al., 2021), the OSPF-BGF (30.31:19.50) ($6.78 \pm 0.12\%$) product may have sweet taste than the 100% RWF product ($5.50 \pm 0.16\%$). The blood glucose response and glycaemic index of flours and food products are affected by their amylose-to-amylopectin ratio; a higher glycaemic index is associated with lower amylose and higher amylopectin content (Elemosho et al., 2020; Irondi et al., 2021). Consequently, compared to 100% RWF, 100% OSPF, and OSPF-BGF (30.31:19.50) with lower amylose and higher amylopectin

may have a higher digestibility and a correspondingly higher glycaemic index since the human duodenum’s α-amylase

can easily digest them (Irondi et al., 2025; Kareem et al., 2023).

Table 7. Carbohydrate profiles of orange-fleshed sweet potato and bambara groundnut flour.

Samples	Starch (%)	Sugar (%)	Amylose (%)	Amylopectin (%)	Amylose/Amylopectin
100% RWF	70.04±0.35 ^d	5.50±0.16 ^b	29.22±0.42 ^c	70.78±0.42 ^a	0.41±0.01 ^c
100% BGF	58.81±0.44 ^b	5.17±0.10 ^a	23.58±0.50 ^b	76.42±0.50 ^b	0.31±0.01 ^b
100% OSPF	63.05±0.37 ^c	7.32±0.07 ^d	18.75±0.42 ^a	81.25±0.42 ^c	0.23±0.01 ^a
OSPF-BGF (30.31:19.50)	56.48±0.49 ^a	6.78±0.12 ^c	17.80±0.35 ^a	82.20±0.35 ^c	0.22±0.01 ^a

Note: RWF, refined wheat flour; BGF, Bambara groundnut flour; OSPF, orange-fleshed sweet potato flour. All values are mean±SD (n = 3). Values having different lowercase superscript letters along the same column differ significantly (*p*<0.05).

4. Conclusion

In this study, optimized, orange-fleshed sweet potato flour (OSPF) supplemented with bambara groundnut flour (BGF) at a ratio of 30.31:19.50 was used to formulate gluten-free flour. The flours evaluated in this study possess desirable physicochemical, pasting, nutritional, and carbohydrate properties. Supplementation of OSPF with BGF resulted in significant reductions in swelling index, water and oil absorption capacities, starch, and sugar contents, whereas bulk density and the ash, protein, fat, and fiber contents increased. Hence, supplementation with BGF improved the proximate composition of optimized, orange-fleshed sweet potato gluten-free flour and significantly influenced its physicochemical and pasting characteristics. Therefore, the blend of optimized, orange-fleshed sweet potato and bambara groundnut flour shows potential for producing functional and nutrient-enriched gluten-free flour for product development.

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