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Effect of soaking and high-pressure processing on antioxidant content, functional and pasting properties of Bambara groundnut (*Vigna subterranean* (L.) Verdc) flour

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Abstract

The study evaluated the effect of pre-treatment methods on the antioxidant content, functional properties and pasting profile of Bambara groundnut flour. Soaking and high-pressure processing (HPP) were used as pre-treatment methods. The results revealed that the value of crude protein, crude fat, total phenolic compounds, 2,2-Diphenyl-1-picrylhydrazyl, ferric reducing antioxidant power, dispersibility, water absorption index and swelling capacity of HPP pre-treated Bambara groundnut flour were significantly higher than the values obtained for raw and soaked pre-treated Bambara groundnut flour. The application of HPP pre-treatment to Bambara groundnut flour resulted in notable improvements in dispersibility, water absorption index, and swelling power. The pasting curve revealed increased peak viscosities in both soaked and HPP pre-treated samples, particularly highlighting the potential for products requiring enhanced gel strength. Additionally, the HPP pre-treated flour exhibited the shortest peak time, suggesting faster cooking and underscoring its versatility in various applications.

1. Introduction

Bambara groundnut is among the important leguminous crops native to Africa (Majola *et al*., 2021). The majority of Bambara groundnut is produced in Sub-Saharan Africa whereas a small amount is produced in Southeast Asia. Redjeki *et al.* (2020) studied the genetic relationships between Indonesian Bambara groundnut landraces and investigated their origins. Bambara groundnuts are significant as a source of dietary supplements because they are inexpensive and simple to store (Ayorinde *et al.*, 2019). Bambara groundnut survives best in direct sunlight and can withstand severe weather conditions than several crops (Sanusi *et al*., 2018). Bambara groundnut comprises 5.77% moisture, 3.00% ash, 18.37% crude protein, 4.44% crude fat, 5.02% crude fibre and 69.18 % carbohydrate (Bala and Rano, 2022). Bambara groundnut comprises significant amounts of protein, vitamins, and minerals such as iron, calcium and phosphorous that are essential for human nutrition (Ola and Adewole, 2019). Bambara groundnut has been classified as a source of a complete and balanced diet (Majola *et al*., 2021). Bambara groundnut has the potential to address future food shortages and malnutrition issues as a result of its high protein content (Khan *et al*., 2021). Bambara groundnut is still considered to be an underutilised crop despite having a high nutritional composition (Diedericks *et al*., 2020). The lack of knowledge regarding improved seed systems, farming systems, processing methods and utilisation are among the restrictions on the utilisation of Bambara groundnut (Tan *et al*., 2020). Pre-treatment is a crucial step in the processing of legumes into flour and other food products. Pre-treatment may be necessary for raw materials to enable or improve extraction, improve nutritional composition, enhance sensory properties, and/or get rid of off-flavours (Reyes-Jurado *et al*., 2021). Several pre-treatments have been reported to reduce the hard-to-cook and hard-to-mill problems of Bambara groundnut by researchers in the literature. Some of the common pre-treatment methods applied for the

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processing of Bambara groundnut into flour include soaking, boiling, autoclaving, roasting, sprouting and fermentation. However, it should be noted that soaking is the most widely used method of pre-treatment for the Bambara groundnut. Foods that have been processed at pressures up to thousands of atmospheric pressures are referred to as HPP or high hydrostatic pressure (Balakrishna *et al.*, 2020). Currently, there is an increase in the application of HPP to foods especially as a pre-treatment of legumes and its several benefits have been highlighted. HPP has been demonstrated to be a viable option for improving the safety, and palatable quality, particularly retaining the nutritional composition, and functional and sensory qualities of foods (Shao *et al.*, 2022; Zhang *et al.*, 2023). However, HPP has been applied to some legumes by several researchers, for instance, HPP has been applied for mung bean (Jiang *et al.*, 2015), white beans (Linsberger-Martin *et al.*, 2013), red beans (Lee *et al.*, 2018), common beans (Belmiro *et al.*, 2020; Lin and Fernández-Fraguas, 2020), lentil/faba beans (Ahmed *et al.*, 2019; Hall and Moraru, 2021), chickpeas (Alsalman and Ramaswamy, 2020; Chatur *et al.*, 2022), grass pea (Buta *et al.*, 2019), kidney pea (Ahmed *et al.*, 2018), peas (Chao *et al.*, 2018; Linsberger -Martin *et al.*, 2013) and soybean (Zhong *et al.*, 2015; Wu *et al.*, 2023). However, there is a paucity of information on the application of HPP as pre-treatment in the processing of Bambara groundnut into flour. Thus, the study aims to evaluate the effect of HPP on the antioxidant, functional properties and pasting profile of Bambara groundnut flour.

2. Materials and methods

2.1 Materials

Bambara groundnut (Cream colour local variety) used in the study was purchased from a farmer in Gombe, Gombe state, Nigeria.

2.2 Preparation of flour samples

2.2.1 Preparation of raw Bambara groundnut flour

All foreign objects were removed from Bambara groundnut, milled with a Medicine disk mill (Orimas DF -25, China) using 0.50 mm sieve mesh to produce raw Bambara groundnut flour and then packaged in ziplock nylon.

2.2.2 Preparation of soaked pre-treated Bambara groundnut flour

The method described by Okudu and Ojinnaka (2017) with minor modifications was used for the production of Bambara groundnut flour. All foreign objects were removed from Bambara groundnut. Then, Bambara groundnut was washed and soaked in distilled water at a ratio of 1:3 (weight: volume) for 12 hrs. After 12 hrs, water was drained and soaked Bambara groundnut was dehulled manually by scrubbing the grains between two palms of the hand and the hull was separated from the grains. The dehulled Bambara groundnut was dried in a dryer at 55°C for 24 hrs, milled with a Medicine disk mill (Orimas DF-25, China) using 0.50 mm sieve mesh to produce soaked pre-treated Bambara groundnut flour and packaged in ziploc nylon.

2.2.3 Preparation of high pressure processing pre-treated Bambara groundnut flour

The method described by Belmiro *et al.* (2020) with minor modification was used for the production of HPP pre-treated Bambara groundnut flour using high-pressure equipment (Hiperbaric 55, Spain) with 55 litre (14.50 gallons) vessel and internal (200 mm) and external (620 mm) diameter, weight 4,50 tan with a length of 2000 mm. Soaked Bambara groundnut (12 hrs) about 400 g was packaged in a plastic bottle, 100 mL of distilled water was added and procedures were run in triplicate for 15 mins at 600 MPa. After HPP, the packages were opened, water was drained off, and the Bambara groundnut was dehulled manually by scrubbing the grains between two palms of hand and the hull was separated from the grains. The dehulled Bambara groundnut was dried in a dryer at 55°C for 24 hrs, milled with Medicine disk mill (Orimas DF-25, China) using 0.50 mm sieve mesh to achieve 10%w.b. flour moisture content and packaged in ziploc nylon.

2.3 Preparation of Bambara groundnut extract

Bambara groundnut extract was prepared by the method described by Ghandehari Yazdi *et al.* (2021) with slight modifications. A total of 0.2 g of flour was mixed with 2 mL of methanol/acetic acid/distilled water (50:8:42) and vortexed for 1 min, centrifuged at 6000 rpm for 5 mins and the supernatant was filtered.

2.4.1 Determination of the proximate composition of flour

The methods described by AOAC (2012) were used to determine the moisture, ash, crude protein, crude fat, and crude fibre contents of Bambara groundnut flour samples while carbohydrate content was calculated by subtracting the total percentage contents of moisture, ash, crude protein, crude fat, and crude fibre from 100.

2.4.2 Determination of total phenolic contents of flour

Total phenolic content was determined by the method described by Oyeyinka *et al.* (2021b).

2.4.3 Determination of 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay and ferric reducing antioxidant power assay of flour

2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay was determined by the method described by Oyeyinka *et al*. (2017) while the Ferric reducing antioxidant power (FRAP) assay was determined by the method described by Oyeyinka *et al*. (2021b).

2.4.4 Determination of functional properties of flour

The bulk density of the sample was determined by the method described by Arise *et al*. (2020) while the method described by Kumari *et al*. (2018) and Kulkarni *et al*. (1991) was used to determine water activity and dispersibility respectively. The water absorption index, water solubility index and swelling power of the samples were determined by the methods described by Heo *et al*. (2014) while the method described by Kumari *et al*. (2018) and Ayorinde *et al*. (2019) was used to determine oil absorption index and swelling capacity of flour samples respectively. The colour parameter of samples was determined by the method described by Oyeyinka *et al*. (2021b).

2.4.5 Determination of the pasting profile of flour

The pasting properties of samples were measured by the method described by Jongsutjarittam and Charoenrein (2014).

2.5 Statistical analysis

The data obtained from the analyses were subjected to an analysis of variance (ANOVA) and Duncan's multiple range test was used to separate the means from the data when there was a significant difference ($p < 0.05$). The statistical analysis was done using SPSS version 25.0 software.

3. Results and discussion

3.1 Proximate composition of Bambara groundnut flour

Table 1 shows the proximate composition of Bambara groundnut flour with values ranging from 6.85 – 7.67%, 3.86 – 4.03%, 19.51 – 21.93%, 6.62 – 7.73%, 3.62 - 4.93% and 55.47 – 57.40% for moisture, ash, crude protein, crude fat, crude fibre and carbohydrate content respectively. There are significant differences ($p < 0.05$) in the moisture content of raw, soaked and HPP-pre-treated Bambara groundnut flour. The range of moisture content (6.85 – 7.67%) obtained for raw, soaked and HPP pre-treated Bambara groundnut flour samples were lower than the ranges of 8.10 - 9.70% and 8.65 – 11.96% reported for raw and pre-treated Bambara groundnut flour by Pahane *et al*. (2017) and Elochukwu (2020) respectively whereas the range of moisture content obtained for Bambara groundnut flour were within the moisture content (5.77 - 13.23%) reported for raw and pre-treated Bambara groundnut flour by Bala and Rano (2022). The values of 6.85% and 7.22% obtained for soaked and HPP pre-treated Bambara groundnut flour respectively were lower than the ranges of moisture content of 8.49 – 13.23% reported by Bala and Rano (2022) for soaked, steamed, boiled, roasted and sprouted pre-treated Bambara groundnut flour. The low moisture content of soaked and HPP Bambara groundnut flour indicated that the flour could have a stable shelf life as Usman (2021) revealed that food samples with less moisture may have the added benefit of extending the products' shelf life. There is no significant difference ($p > 0.05$) in ash content of raw, soaked and HPP pre-treated Bambara groundnut flour samples. The range of ash content (3.86 – 4.03%) obtained for Bambara groundnut flour samples was comparable the ranges of 3.90 – 4.80% and 3.90 – 4.40% reported for raw and pre-treated Bambara groundnut flour by Pahane *et al*. (2017) and Abdulrashid and Hassan (2021) respectively whereas the range of values obtained for Bambara groundnut flour samples were higher than the range of 2.69 – 3.05%, 1.96 – 2.72% and 2.89 – 3.78% reported for raw and pre-treated Bambara groundnut flour by Ndidi *et al*. (2014), Elochukwu (2020) and Bala and Rano (2022) respectively. The value obtained for soaked and HPP pre-treated Bambara groundnut flour were higher than the ranges of ash content of 2.69 – 2.91%, 3.58 – 3.85% and 2.89 – 3.78% reported by Ndidi *et al*. (2014), Okafor *et al*. (2014) and Bala and Rano (2022) respectively for soaked, steamed, boiled, roasted and sprouted pre-treated Bambara groundnut flour whereas the value obtained for soaked and HPP pre-treated Bambara groundnut flour were

Table 1. Proximate composition (%) of Bambara groundnut flour.

Sample	Moisture	Ash	Crude protein	Crude fat	Crude fibre	Carbohydrate
RB	7.67±0.11^{a}	3.86±0.09^{a}	19.51±0.05^{c}	6.62±0.04^{c}	4.93±0.31^{a}	57.40±0.17^{a}
SB	6.85±0.05^{c}	3.94±0.18^{a}	21.58±0.06^{b}	7.46±0.12^{b}	3.83±0.12^{b}	56.34±0.16^{b}
HPB	7.22±0.11^{b}	4.03±0.08^{a}	21.93±0.14^{a}	7.73±0.13^{a}	3.62±0.03^{b}	55.47±0.28^{c}

Values mean±SD of triplicate measurements. Values with different superscripts within the same column are statistically significantly different ($p < 0.05$). RB: Raw Bambara groundnut flour, SB: Soaked pre-treated Bambara groundnut flour, HPB: High pressure processing pre-treated Bambara groundnut flour.

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lower than the range of ash content (4.40 – 4.80%) reported by Pahane *et al*. (2017) for soaked and blanched pre-treated Bambara groundnut flour. Ash content provides a clue as to whether a food sample contains minerals (Ogunmuyiwa *et al*., 2017). The amount of ash in the composite flour and consequently baked foods was significantly increased by Bambara groundnut (Awolu and Olokunsusi, 2017). Since HPP pre-treated Bambara groundnut flour comprises appreciable ash content, then it could be useful for composite flour with other carbohydrate-based flour. There are significant differences ($p < 0.05$) in crude protein content of raw, soaked and HPP pre-treated Bambara groundnut flour. The range of crude protein content (14.50 – 18.37%) of raw, soaked, steamed, boiled and roasted Bambara groundnut flour reported by Bala and Rano (2022) was lower than the range of crude protein content (19.51 – 21.93%) obtained for Bambara groundnut flour. The crude protein content obtained for Bambara groundnut flour showed that the lowest crude protein content (19.51%) was observed in raw Bambara groundnut flour whereas the highest crude protein content (21.93%) was observed in HPP pre-treated Bambara groundnut flour. The crude protein content obtained for soaked pre-treated Bambara groundnut flour (21.58%) and HPP pre-treated Bambara groundnut flour (21.93%) were within the range of crude protein content of 19.70 – 25.50% and 19.50 – 22.80% reported for soaked and blanched pre-treated Bambara groundnut flour samples by Pahane *et al*. (2017) and Abdulrashid and Hassan (2021) respectively. The crude protein content of HPP pre-treated Bambara groundnut flour was higher than the range of crude protein content (17.44 – 19.02%) reported for HPP pre-treated chickpea flour by Chatur *et al*. (2022). However, the value of protein contents obtained from soaked and HPP pre-treated Bambara groundnut flour was higher than the value of crude protein obtained from raw Bambara groundnut flour and this is in line with the finding of Chatur *et al*. (2022) reported higher in crude protein content of HPP pre-treated chickpea flour than the raw chickpea flour. Thus, HPP could be utilized to increase the protein content in the food system. Protein is one of the most important macronutrients for the growth and maintenance of the human body (Mulla *et al*., 2022). Bambara groundnut could serve as a cheap source of protein which assists in many nutritional benefits as Mathew *et al*. (2014) revealed that the high protein content of Bambara groundnut can be used as a source of proteins that promote cell maintenance and growth. There are significant differences ($p < 0.05$) in crude fat content of raw, soaked and HPP pre-treated Bambara groundnut flour. The range of crude fat content (6.62 – 7.73%) obtained for Bambara groundnut flour samples was within the ranges of 5.75 – 8.87% and 6.50 – 7.80% reported for raw and pre-treated Bambara groundnut flour by Elochukwu (2020) and Abdulrashid and Hassan (2021) respectively whereas the range of values of flour samples were higher than the range of 5.10 - 6.50% and 3.89 – 4.44%, reported for raw and pre-treated Bambara groundnut flour by Pahane *et al*. (2017) and Bala and Rano (2022) respectively. The values of 7.46% and 7.73% of crude fat content obtained for soaked and HPP pre-treated Bambara groundnut flour respectively were higher than the ranges of crude fat content of 4.41 – 5.28%, 6.73 – 7.33%, 5.10 – 5.50 and 3.89 – 4.19% reported by Ndidi *et al*. (2014), Okafor *et al*. (2014), Pahane *et al*. (2017) and Bala and Rano (2022) respectively for soaked, steamed, boiled, roasted, blanched and sprouted pre-treated Bambara groundnut flour. The range of crude fat content obtained showed that Bambara groundnut is a low-fat crop, unlike soybean and groundnut which are high-fat content legumes. Dietary fat produces essential fatty acids and energy that transport fat-soluble vitamins and aid in their absorption (Adeleke *et al*., 2018). Since Bambara groundnut flour comprises an appreciable amount of fat content, it could serve as a cheap source of fat-soluble vitamins. There are significant differences ($p < 0.05$) in crude fibre content of raw, soaked and HPP pre-treated Bambara groundnut flour samples. The range of crude fibre content (3.68 – 4.67%) reported for raw and pre-treated Bambara groundnut flour by Ndidi *et al*. (2014) was within the range of 3.62 - 4.93% obtained for Bambara groundnut flour samples whereas the range of values obtained for Bambara groundnut flour samples were lower than the range of 14.00 – 17.20% reported for raw and pre-treated Bambara groundnut flour by Abdulrashid and Hassan (2021). The value of 3.83% and 3.62% of crude fibre content obtained for soaked and HPP pre-treated Bambara groundnut flour respectively were higher than the range of crude fibre content (3.21 – 3.60%) reported by Okafor *et al*. (2014) for roasted and sprouted Bambara groundnut flour whereas the value obtained for HPP pre-treated Bambara groundnut flour was lower than the ranges of 3.68 – 4.00% and 4.20 – 4.98% reported by Ndidi *et al.* (2014) and Bala and Rano (2022) respectively for soaked, steamed, boiled and roasted pre-treated Bambara groundnut flour. The crude fibre contents of soaked and HPP pre-treated Bambara groundnut flour were lower than the crude fibre content of raw Bambara groundnut flour and this is in line with the finding of Bala and Rano (2022) who reported that there is a decrease in crude fibre content of soaked, steamed, roasted and boiled Bambara groundnut flour when compared with crude fibre content of raw Bambara groundnut flour. There are significant differences ($p < 0.05$) in carbohydrate content of raw, soaked and HPP pre-treated Bambara groundnut flour. The range of carbohydrate content (55.47 – 57.40%) obtained for raw,

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soaked and HPP pre-treated Bambara groundnut flour was lower than the range of carbohydrate content (60.10 – 62.00%) of raw, soaked and blanched Bambara groundnut flour reported by Pahane *et al.* (2017) whereas the range of carbohydrate content obtained was higher than the range of carbohydrate content (51.00 - 55.00%) of raw and soaked Bambara groundnut flour reported by Okudu and Ojinnaka (2017). Bambara groundnut could be utilized as a carbohydrate food since it comprises high carbohydrates. Thammarat *et al*. (2015) disclosed that Bambara groundnut can be used as an energy source due to its high carbohydrate content, which also indicates that it has a high energy content. The carbohydrate content obtained for Bambara groundnut flour showed that the highest carbohydrate content was observed in raw Bambara groundnut flour whereas the lowest carbohydrate content was observed in HPP pre-treated Bambara groundnut flour. The result showed that HPP led to more reduction in the carbohydrate content of Bambara groundnut flour and this signifies that HPP can be utilized in the reduction of carbohydrate content of Bambara groundnut and other legumes and this is in line with Chatur *et al*. (2022) who reported that HPP may be used to lower the starch content of other high-starch grains and pulses to create lower-calorie substitutes.

3.2 Total phenolic content and antioxidant properties of Bambara groundnut flour

Table 2 shows the total phenolic content and antioxidant properties of Bambara groundnut flour. There are significant differences ($p < 0.05$) in the values of Total Phenolic Content (TPC), DPPH and FRAP ranging from 10.14 - 14.72 GAE/100g, 58.82 – 70.59% and 20. 65 – 29.03 μmole AAE/g respectively. The highest value of TPC was observed in raw Bambara groundnut flour whereas the lowest value was observed in soaked pre-treated Bambara groundnut flour. The decrease in the TPC of soaked and HPP pre-treated Bambara groundnut flour could be attributed to the dehulling of Bambara groundnut during processing as Oyeyinka *et al*. (2017) reported that total phenolic content of legume grains was reduced by dehulling or roasting. However, the colour of the Bambara groundnut seed coat (hull) influences the total phenolic content as Ramatsetse *et al*. (2023) disclosed that the amount of total phenolic and flavonoid compounds in Bambara groundnut grains depends more on the colour of their coat. There are no significant differences ($p > 0.05$) in TPC contents of soaked and HPP pre-treated Bambara groundnut flour samples but the TPC of HPP pre-treated Bambara groundnut flour was higher than soaked pre-treated Bambara groundnut flour which could be linked to the effect of HPP as Kurek *et al*. (2022) revealed that the amount of phenolic compounds is increased under pressure. The range of TPC (31.70 - 52.32 GAE/100 g) reported for HPP cooked chickpea by Chatur *et al*. (2022) was higher than the TPC (10.35 GAE/100 g) obtained for HPP pre-treated Bambara groundnut flour. However, this could be related to the type of legume, pre -treatment of Bambara groundnut, pressure and time used for the HPP. The high TPC content of soaked and HPP pre-treated Bambara groundnut flour showed that Bambara groundnut, especially HPP pre-treated Bambara groundnut flour could be useful in the production of value-added products as Olagunju *et al.* (2018) disclosed that Bambara groundnut contains significant amounts of TPC and can be used to enhance the polyphenolic compounds in products with added value, which enhance the health of consumers. The highest value of DPPH was observed in raw Bambara groundnut flour whereas the lowest value was also observed in soaked pre-treated Bambara groundnut flour. There are no significant differences ($p > 0.05$) in the DPPH content of soaked and HPP pre-treated treated Bambara groundnut flour samples. The value of DPPH (70.59%) obtained for raw Bambara groundnut flour was higher than the DPPH of 65 - 68% and 26.58% reported by Oyeyinka *et al*. (2017) and Olagunju *et al*. (2018) respectively for raw Bambara groundnut flour. The decrease in the DPPH of soaked and HPP pre-treated Bambara groundnut flour could be attributed to the dehulling of Bambara groundnut during processing as Okafor *et al*. (2021) reported that antioxidant activity of the seed coat (hull) was noticeably higher than other parts of Bambara groundnut. The range of FRAP obtained for raw, soaked and HPP pre-treated Bambara groundnut flour was lower than the range of FRAP (34.50 - 84.40 μmole AAE/g) reported for Bambara groundnut flour by Adedayo *et al*. (2021). The highest value of FRAP was observed in raw Bambara groundnut flour whereas the lowest value was observed in soaked pre-treated Bambara groundnut flour. The decrease in the FRAP of soaked and HPP pre-treated Bambara groundnut flour could be attributed to the dehulling of Bambara groundnut. The values of DPPH and FRAP of HPP pre-treated Bambara groundnut were higher than the DPPH and FRAP of soaked pre-treated

Table 2. Total phenolic content and antioxidant properties of Bambara groundnut flour.

Sample	TPC	DPPH (%)	FRAP
RB	14.72±0.95^{a}	70.59±1.24^{a}	29.03±0.30^{a}
SB	10.14±1.66^{b}	58.82±6.32^{b}	20.65±0.24^{c}
HPB	10.35±0.95^{b}	59.24±5.79^{b}	21.73±0.13^{b}

Values mean±SD of triplicate measurements. Values with different superscripts within the same column are statistically significantly different ($p < 0.05$). RB: Raw Bambara groundnut flour, SB: Soaked pre-treated Bambara groundnut flour, HPB: High pressure processing pre-treated Bambara groundnut flour.

Bambara groundnut flour and this demonstrates that the HPP process preserved phenolic compounds more than the soaking process.

3.3 Functional properties of Bambara groundnut flour

Table 3 shows the functional properties of Bambara groundnut flour. There are significant differences ($p < 0.05$) in the values of bulk density, water activity, dispersibility, water absorption index, water solubility index and swelling power. The values of bulk density, water activity, dispersibility, water absorption index, water solubility index, oil absorption index, swelling power and swelling capacity ranged from 0.42 - 0.63 g/mL, 0.26 - 0.45, 76.83 - 80.50%, 1.10 - 2.43 g/g, 28.67 - 34.33%, 1.91 - 1.95 g/g, 1.49 – 2.29 g/g and 0.55 - 0.71 respectively. The bulk density of 0.48 g/mL and 0.62 g/mL reported by Oyeyinka *et al*. (2021b) and Eltayeb *et al*. (2011) respectively for Bambara groundnut flour were within the values obtained for Bambara groundnut flour samples while 0.85 g/ml reported by Musah *et al*. (2021) for Bambara groundnut flour was higher than the values obtained for Bambara groundnut flour samples. However, the range of values (0.64 – 0.80 g/mL) reported by Adegunwa *et al*. (2014) for Bambara groundnut flour were higher than the values obtained for Bambara groundnut flour samples. The highest bulk density was observed in raw Bambara groundnut flour whereas the lowest value was observed in HPP pre-treated Bambara groundnut flour. HPP pre-treated Bambara groundnut flour could be useful in numerous food formulations due to low bulk density as Mbaeyi-Nwaoha and Uchendu (2016) revealed that the flour with low bulk density is appropriate for high-nutrient density food formulations. The values obtained for water activity in all of the Bambara groundnut flour were low. Water activity in the flour affects microbial and fungal contamination, and the higher the water activity in flour, the more contamination and spoilage (Olagunju *et al*., 2018). Since the values for the water activity for all Bambara groundnuts were low, this signifies that the flour could have a stable shelf life. The range (76.83 - 80.50%) of dispersibility obtained for the Bambara groundnut flour samples was within the range (73.00 – 80.67%) of dispersibility of Bambara groundnut flour reported by Adegunwa *et al*. (2014). The highest dispersibility was observed in HPP pre-treated Bambara groundnut flour whereas the lowest value was observed in raw Bambara groundnut flour. Dispersibility measures how easily flour can be reconstituted in water and how well its constituent parts can disperse and blend within the aqueous medium (Arinola and Omowaye-Taiwo, 2020). The higher the dispersibility, the better the degree of reconstitution of the flour, so the higher dispersibility of pre-treated HPP Bambara groundnut flour could give the easier reconstitution of the flour with a smooth paste. The highest water absorption index was observed in HPP pre-treated Bambara groundnut flour whereas the lowest value was observed in raw Bambara groundnut flour. The starch of HPP pre-treated Bambara groundnut flour is likely to be more digestible than raw and soaked pre-treated Bambara groundnut flour as Mbaeyi-Nwaoha and Uchendu (2016) stated that high water absorption suggests that the starch is highly digestible. The value of the water solubility index (29.70%) of Bambara groundnut flour reported by Ogundele *et al*. (2017) was within the range (28.67 - 34.33%) obtained for the Bambara groundnut flour samples. The values of the water solubility index of flour samples (soaking and HPP) were higher than the raw Bambara groundnut flour, which could be attributed to pre-treatment (especially soaking and dehulling) of the seeds prior to the production of flour. The highest oil absorption index was observed in soaked pre-treated Bambara groundnut flour whereas the lowest value was observed in raw Bambara groundnut flour. The low oil absorption index obtained for all Bambara groundnut flour samples is expected as Adeleke *et al*. (2018) revealed that the low levels of hydrophobic proteins which exhibit higher lipid binding, could be the cause of the low oil absorption of Bambara groundnut flour. The value of swelling power (2.00 g/g) of Bambara groundnut flour reported by Ogundele *et al*. (2017) was within the range obtained for the Bambara groundnut flour samples. The highest swelling power was observed in soaked pre-treated Bambara groundnut flour whereas the lowest value was observed in raw Bambara groundnut flour. The values of swelling power of soaked and HPP Bambara groundnut flour samples were higher than the raw Bambara

Table 3. Functional properties of Bambara groundnut flour.

Sample	Bulk density (g/cm^3)	Water activity	Dispersibility (%)	Water absorption index (g/g)	Water solubility index (%)	Oil absorption index (g/g)	Swelling power (g/g)	Swelling capacity
RB	0.53 ± 0.06^b	0.39 ± 0.01^b	77.23 ± 0.06^b	1.10 ± 0.04^c	28.67 ± 1.15^b	1.91 ± 0.02^a	1.49 ± 0.05^b	0.55 ± 0.13^a
SB	0.63 ± 0.01^a	0.26 ± 0.00^c	76.83 ± 1.61^b	1.75 ± 0.08^b	34.33 ± 2.52^a	1.95 ± 0.07^a	2.29 ± 0.60^a	0.60 ± 0.03^a
HPB	0.42 ± 0.023^c	0.45 ± 0.00^a	80.50 ± 0.50^a	2.43 ± 0.05^a	32.00 ± 2.00^{ab}	1.92 ± 0.03^a	2.14 ± 0.03^{ab}	0.71 ± 0.02^a

Values mean±SD of triplicate measurements. Values with different superscripts within the same column are statistically significantly different ($p < 0.05$). RB: Raw Bambara groundnut flour, SB: Soaked pre-treated Bambara groundnut flour, HPB: High pressure processing pre-treated Bambara groundnut flour.

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groundnut flour, which could be attributed to pre-treatment (dehulling) of the seeds prior to the production of flour as Ogundele *et al*. (2017) revealed that the higher values of swelling observed in the flour made from dehulled Bambara groundnut may be due to the absence of the seed coat (hull). The swelling capacity (0.94) of Bambara groundnut reported by Oyeyinka *et al*. (2021b) was higher than the values of swelling capacity obtained for the Bambara groundnut flour samples. All the values of swelling capacity obtained for Bambara groundnut flour were low with HPP pre-treated Bambara groundnut flour having the highest value and raw Bambara groundnut flour having the lowest value. However, Tan *et al*. (2020) revealed that the low value of swelling capacity of Bambara groundnut flour might be explained by its comparatively high amylose content, which results in a more rigid granular structure and thus limits swelling.

3.4 Colour properties of Bambara groundnut flour

Table 4 shows the colour properties of Bambara groundnut flour. The values of L*, a* and b* ranged from 81.21 - 90.40, 1.16 - 1.37 and 10.27 -12.55 respectively. The value of L* (81.67) of Bambara groundnut flour reported by Oyeyinka *et al*. (2021a) was within the range (81.21 - 90.40) obtained for the Bambara groundnut flour whereas the value of L* (91.00) of Bambara groundnut flour reported by Olagunju *et al*. (2018) was higher than the values obtained for the Bambara groundnut flour. The highest L* values observed in raw Bambara groundnut flour might be due to the hull (seed coat) contained in the flour. The brightness (L* value) obtained for pre-treated HPP Bambara groundnut flour was lighter than the ranges of L* values reported for HPP pre-treated red bean powder (70.89 – 71.90) and HPP pre-treated chickpeas flour (32.50 - 54.30) reported by Lee *et al*. (2018) and Alsalman and Ramaswamy (2020) respectively. However, the lower L* value obtained for HPP pre-treated Bambara groundnut flour in comparison with raw Bambara groundnut flour was in line with lower L* values reported for HPP pre-treated red bean powder in compared with raw red bean powder by Lee *et al*. (2018). The values of 0.67 and -2.89 reported for a* by Olagunju *et al*. (2018) and Oyeyinka *et al*. (2021a) respectively for Bambara groundnut flour were lower than the range (1.16 - 1.37) obtained for the Bambara groundnut flour. The redness (a* value) obtained for HPP pre-treated Bambara groundnut flour was lower than the ranges of a* value reported for HPP pre-treated red bean powder (2.28 – 2.75) and HPP pre-treated chickpeas flour (2.00 – 6.80) by Lee *et al*. (2018) and Alsalman and Ramaswamy (2020) respectively. Also, the higher a* value obtained for HPP pre-treated Bambara groundnut flour in comparison with raw Bambara groundnut flour was in line with higher a* values reported for HPP pre-treated red bean powder by Lee *et al*. (2018). However, the value of b* (20.26) reported for Bambara groundnut by Oyeyinka *et al*. (2021a) was higher than the range (10.27 - 12.55) obtained for the Bambara groundnut flour whereas the value of b* (10.41) reported for Bambara groundnut by Olagunju *et al*. (2018) was within the range obtained for the Bambara groundnut flour. The yellowness (b* value) obtained for HPP pre-treated Bambara groundnut flour was within the range of b* value (8.90 – 31.20) reported for HPP pre-treated chickpeas by Alsalman and Ramaswamy (2020) whereas b* value obtained for HPP pre-treated Bambara groundnut flour was higher than the range of 8.26 – 8.8.38 reported for HPP pre-treated red bean powder by Lee *et al*. (2018).

Table 4. Colour properties of Bambara groundnut flour.

Sample	L*	a*	b*
RB	90.40 ± 0.13^{a}	1.28 ± 0.03^{ab}	10.27 ± 0.04^{c}
SB	89.91 ± 0.63^{a}	1.16 ± 0.06^{b}	11.93 ± 0.15^{b}
HPB	81.21 ± 1.87^{b}	1.37 ± 0.09^{a}	12.55 ± 0.42^{a}

Values mean±SD of triplicate measurements. Values with different superscripts within the same column are statistically significantly different ($p < 0.05$). RB: Raw Bambara groundnut flour, SB: Soaked pre-treated Bambara groundnut flour, HPB: High pressure processing pre-treated Bambara groundnut flour.

3.5 Pasting properties of Bambara groundnut flour

Table 5 shows the pasting properties of Bambara groundnut flour. There are significant differences ($p < 0.05$) in the values of peak viscosity, trough viscosity, breakdown viscosity, final viscosity, setback viscosity, peak time and pasting temperature which ranged from 1266.00 - 1960.67 cP, 1130.33 - 1651.33 cP, 96.00 - 674.00 cP, 1660.67 - 2612.33 cP, 530.33 - 1292.00 cP, 4.64 - 6.99 min and 83.35 - 84.75°C respectively. The peak viscosity (100.83 – 159.92 cP), trough viscosity (94.92 -106.25 cP), breakdown viscosity (5.92 – 53.67 cP), final viscosity (145.25 -171.75 cP) and setback viscosity (50.33 – 65.50 cP) of Bambara groundnut flour reported by Abiodun and Adepeju (2011) were lower than the peak viscosity, trough viscosity, breakdown viscosity, final viscosity and setback viscosity obtained for Bambara groundnut flour. However, the peak time (5.13 - 6.73 min) of Bambara groundnut flour reported by Abiodun and Adepeju (2011) was within the range of peak time obtained for Bambara groundnut flour whereas pasting temperature (93.65 - 95.00°C) of Bambara groundnut flour reported by Abiodun and Adepeju (2011) were higher than pasting temperature obtained for Bambara groundnut flour. The values obtained for peak viscosities of soaked and HPP pre-treated Bambara

Table 5. Pasting properties of Bambara groundnut flour.

Sample	Peak viscosity (cP)	Trough viscosity (cP)	Breakdown viscosity (cP)	Final viscosity (cP)	Setback viscosity (cP)	Peak time (Min)	Pasting temperature (°C)
RB	1266.00±88.61[b]	1170.00±91.00[b]	96.00±6.25[c]	2462.00±72.11[b]	1292.00±21.93[a]	6.99±0.00[a]	84.75±0.05[a]
SB	1960.67±106.50[a]	1651.33±79.32[a]	309.33±31.82[b]	2612.33±90.58[a]	961.00±22.07[b]	5.35±0.03[b]	84.12±0.46[a]
HPB	1804.33±58.29[a]	1130.33±31.47[b]	674.00±28.52[a]	1660.67±39.15[c]	530.33±9.07[c]	4.64±0.04[c]	83.35±0.39[b]

Values mean±SD of triplicate measurements. Values with different superscripts within the same column are statistically significantly different ($p < 0.05$). RB: Raw Bambara groundnut flour, SB: Soaked pre-treated Bambara groundnut flour, HPB: High pressure processing pre-treated Bambara groundnut flour.

groundnut flour showed no significant difference ($p > 0.05$) but were significantly higher than raw Bambara groundnut flour. High peak viscosity may be appropriate for products that need a high level of gel strength and elasticity (James *et al*., 2018). Thus, the soaked and HPP -pre-treated Bambara groundnut flour could be useful in food systems that require a high degree of elasticity and gel strength. The highest trough viscosity was observed in soaked Bambara groundnut flour whereas the lowest was observed in HPP pre-treated Bambara groundnut flour. The high values of trough viscosity of soaked pre-treated and HPP Bambara groundnut flour signify that the flour may continue to have high paste stability while cooking. The highest breakdown viscosity was observed in HPP pre-treated Bambara groundnut flour whereas the lowest value was observed in raw Bambara groundnut flour. The highest breakdown viscosity of HPP pre-treated Bambara groundnut flour could lower its capacity to withstand heat and shear stress during cooking as Arise *et al.* (2020) revealed that the low breakdown viscosity implies that flour can withstand breakdown during heating and shearing. Final viscosity reflects the capacity of the material to form a viscous paste which is heavily reliant on retrogradation of soluble amylose during cooling (Yeboah-Awudzi *et al*., 2018). The highest final viscosity was observed in soaked pre-treated Bambara groundnut flour whereas the lowest was observed in HPP pre-treated Bambara groundnut flour. Setback viscosity is an indicator of retrogradation of linear starch molecules when cooling (Adegunwa *et al*., 2014). The soaked and HPP pre-treated Bambara groundnut flour may exhibit minimal retrogradation of viscous paste during cooling due to high setback viscosity. The highest peak time was observed in raw Bambara groundnut flour whereas the lowest was observed in HPP pre-treated Bambara groundnut flour. Peak time suggests simplicity in cooking (Arinola and Omowaye-Taiwo, 2020). This signifies that HPP pre-treated Bambara groundnut flour could cook faster than soaked pre-treatment Bambara groundnut flour and raw Bambara groundnut flour. Pasting temperature is the lowest temperature needed to cause swelling of the granule and subsequent rupture of the starch granules after gelatinization (Yeboah-Awudzi *et al*., 2018). The highest pasting temperature was observed in raw Bambara groundnut flour whereas the lowest was observed in HPP pre-treated Bambara groundnut flour. The pasting analysis of Bambara groundnut flour highlighted distinct properties in the soaked and HPP pre -treated samples. Both pre-treatments showed higher peak viscosities which suggests potential for products requiring increased gel strength. The observed high trough viscosity in both treatments indicates improved paste stability during cooking. However, the HPP pre-treated flour displayed the highest breakdown viscosity, potentially affecting its heat resistance. Minimal retrogradation during cooling was noted in both soaked and HPP pre-treated flour. Notably, HPP pre-treated flour exhibited the shortest peak time, indicating faster cooking.

4. Conclusion

The study showed that HPP retained more phenolic compounds and antioxidant properties with better functional properties. Also, the HPP pre-treated flour exhibited the shortest peak time, suggesting faster cooking and underscoring its versatility in various applications. These findings offer valuable insights into the diverse applications of Bambara groundnut flour based on its unique functional and pasting properties.

Conflict of interest

The authors declare no conflict of interest.

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