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High-intensity ultrasound processing of baobab fruit pulp: Effect on quality, bioactive compounds, and inhibitory potential on the activity of α-amylase and α-glucosidase

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ABSTRACT

Effect of high-intensity ultrasound (HIU) compared with thermal treatments on baobab fruit pulp (BFP) quality and bioactive properties were investigated. HIU treatments, particularly at intensities of 687.5 W/cm^2 for 5 min, and 344 W/cm^2 for 15 min significantly ($p < 0.05$) increased the cloudiness index, ascorbic acid (AA) retention, total phenolic and flavonoid contents, and antioxidant capacity besides a more potent α-amylase and α-glucosidase inhibition relative to thermally treated samples. Moreover, the physicochemical parameters, colour index, and browning index were maintained with HIU besides lower 5-hydroxymethylfurfural values than thermal processing. HPLC analysis revealed that the content of most phenolic compounds was the highest in HIU treatments besides a 235–256% increase in procyanidin C_1 compared with control samples. The AA retention following HIU treatments was 87.62–102.86% compared to 30.47–61.90% in thermally treated samples. Our analyses portrayed ultrasound as a feasible alternative to conventional thermal processing of BFP.

1. Introduction

Diabetes mellitus (DM) is the 6th most common cause of high morbidity and mortality rate in young and middle-aged groups. As a growing public health problem, the prevalence of DM has quadrupled, and 439 million people are forecasted to be affected by 2030 (Mukhopadhyay & Prajapati, 2015). Based on recent information, 1 in 11 adults are affected by DM globally, and 90% have type 2 diabetes mellitus [T2DM]) (Chaari, Abdellatif, Nabi, & Khan, 2020). Therefore, currently, researchers have intensified their effort to find new medications from natural sources to manage T2DM and prevent the side effects of the drugs currently in use (Mukhopadhyay & Prajapati, 2015).

Natural plant polyphenols have gained considerable interest recently for their antidiabetic potentials and possess more advantages of being natural, cheap, and with fewer side effects. Plant polyphenols' antidiabetic potential is measured by their inhibitory activity against enzymes such as α-glucosidase and α-amylase involved in carbohydrates digestion. The inhibition of these enzymes' activity leads to reduced postprandial blood glucose spikes, which has become an essential strategy for glycemic control in T2DM (da Silva et al., 2019; Luyen et al., 2019).

The baobab (*Adansonia digitata* L.) fruit belongs to Africa's most famous tree existing over immense savannas and savanna woodlands areas. It is nicknamed 'the Chemist tree' or 'the small pharmacy tree' because of its enormous importance in nutrition, traditional medicine, cosmetics applications, and as a raw material for novel functional foods production (Ismail, Pu, Guo, Ma, & Liu, 2019; Ismail et al., 2020). The baobab fruit pulp (BFP) has been regarded as a good source of ascorbic acid (vitamin C), and its richness in numerous compounds of pharmacological importance, including phenolic acids, flavonoids, and their glycosides, has been widely reported (Braca et al., 2018; Ismail, Pu, Guo et al., 2019; Russo et al., 2020; Tembo, Holmes, & Marshall, 2017). The BFP has a strong potential for being a functional food, and previous studies have shown its ability for glycemic response reduction and the inhibition of carbohydrate hydrolysing enzymes (Braca et al., 2018; Coe, Clegg, Armengol, & Ryan, 2013; Ismail, Pu, Fan et al., 2019). Currently,

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BFP is a novel food ingredient in Europe and had been given a Generally Recognised as Safe (GRAS) status in the US (Russo et al., 2020).

The BFP is commonly processed to make products such as baobab juice, baobab yoghurt and can also be used as an additive in many foods. BFP juice has become a popular drink thanks to its nutritional and bioactive potentials. It contributes significantly to an ever-growing global juice market driven by consumers' growing interest in a healthy and nutritionally rich diet. Over 36 billion litres of fruit juice and nectars were consumed worldwide in 2017 alone (Kahraman & Feng, 2021).

For food processing, the priority is to ensure the product's microbial safety, and as such thermal processing techniques are commonly used. These techniques effectively destroy spoilage and pathogenic microorganisms. However, a significant detrimental effect on the nutritional and sensory properties has been reported. In BFP, for instance, several bioactive compounds, including flavonoids and phenolic acids, were reported to be negatively affected by thermal treatment in addition to the significant loss of the high ascorbic acid content in the final product (Tembo et al., 2017). There is also a concern that 5-hydroxymethyl-2-furfural (HMF), a potentially toxic compound, can be generated during thermal treatment resulting in loss of quality. The determination of HMF concentration in foods is specifically essential for the food industry (Önür et al., 2018).

The high-intensity ultrasound (HIU) technology had received growing attention in response to the demand for meeting the dual objective of achieving microbial safety and maintaining the original attributes and nutritional quality of foods. Moreover, it presents a unique potential as a non-thermal food preservation method that can sufficiently destroy microorganisms without the common aftereffects associated with conventional heat treatments (do Amaral Souza et al., 2019; de Araújo et al., 2021; Guimarães et al., 2019; Monteiro et al., 2020). Furthermore, HIU offers several other advantages, including shorter processing times, low costs of water and energy, improved food quality and shelf life, and lower production of toxic compounds and residual effluents (de Araújo et al., 2021; Ismail, Guo et al., 2019). Besides, HIU treatments have been reported to significantly improve the colour, bioactive constituents, and antioxidant capacity of several fruit pulps and juices (de Araújo et al., 2021; Oladunjoye, Adeboyejo, Okekunbi, & Aderibigbe, 2021; Wang, Wang, Vanga, & Raghavan, 2020).

In this regard, previous studies have shown the effects of conventional thermal treatments on quality attributes of BFP, particularly on ascorbic acid and a few selected bioactive compounds (Tembo et al., 2017). In our previous studies, ultrasound-assisted extraction, purification, and enrichment of baobab phenolics were carried out (Ismail et al., 2019, 2020). However, the use of HIU as a non-thermal treatment to process BFP and the effect on its quality and bioactive properties have yet to be explored. There is currently no consensus on the HIU parameters that could be applied for the processing of foods. Therefore, we hypothesise that HIU might be applied to preserve the quality and bioactive properties of BFP. Thus, the current study aimed to determine the effect of different HIU power intensities (115–687.5 W/cm^2) compared to the conventional thermal processing (63 °C/30 min, and 70 °C/5 min) on the abovementioned properties of BFP.

2. Materials and methods

2.1. Materials

Raw BFP powder from South Africa was obtained from MRM superfoods, USA. Phenolic standards were purchased from two companies. Gallic acid, caffeic acid, chlorogenic acid, (+)-catechin, (−)-epicatechin, rutin, quercetin, and protocatechuic acid were obtained from Sigma-Aldrich (St. Louis, MO). 5-hydroxymethylfurfural (HMF), procyanidin B_1, B_2, and C_1, kaempferol, and proanthocyanidin were purchased from Yuanye Biotechnology Ltd (Shanghai, China). All chemicals and reagents were of analytical grade.

2.2. Sample preparation and treatments

The BFP was prepared according to the protocol described by Tembo et al. (2017). Briefly, 1L distilled water was added to a 100 g BFP and homogenised in a domestic blender for 10 min at a medium speed. After that, the homogenised sample was transferred into 50 mL tubes and centrifuged at 4000 rpm for 20 min at 4 °C. The juice was collected as the supernatant, filtered through a muslin cloth, degassed, and kept under refrigeration at 4 °C before different treatments. For the high-intensity ultrasonic treatment, a 900 W power, 22 kHz frequency probe sonicator (JY92-IIDN, Ningbo Scientz Biotechnology Co., Ningbo, China) equipped with ultrasonic power and time digital controls were used. A 10-mm-diameter sonotrode was used for the ultrasound processing. Samples were treated with different power intensity and time combinations of 115 W/cm^2 for 30 min, 344 W/cm^2 for 15 min, and 687.5 W/cm^2 for 5 min, labelled as LPI, MPI, and HPI, respectively. These parameters were selected following analysis of single-factor experiments and response surface methodology of ultrasound technology reported in our previous studies (Ismail, Guo et al., 2019; Ismail et al., 2020). A 25 mL sample was treated in a 50 mL tube with the sonotrode dipped 1.5 cm in the sample to introduce the ultrasonic field. HIU treatments using pulse duration of 2 *sec* on and 2 *sec* off, 30 °C were carried out in a low-temperature thermostatic water bath (DC-1006, Safe Corporation, Ningbo, China), with the temperature maintained at 30 °C. Moreover, a temperature probe was used to monitor the temperature fluctuations in the treated samples. The power intensity (PI, W/cm^2) dissipated from the tip of the sonotrode with radius r used were calculated using Eq (1) below:

$$\text{Power intensity(PI)} = \frac{\text{Input power (W)}}{\pi r^2\ (cm^2)} \quad (1)$$

Similarly, a portion of BFP was also submitted for domestic batch thermal treatments at 63 °C for 30 min, and 70 °C for 5 min for comparison with the ultrasound treated samples. These treatment conditions were previously employed for the thermal processing of BFP and other fruit pulps and juices (Branco et al., 2016; Tembo et al., 2017). Treated samples were immediately chilled and stored at −18 °C until subsequent experiments.

2.3. Physicochemical analysis

The total soluble solids (TSS) measurements expressed as °Brix were taken with a digital hand refractometer. The titratable acidity (TA) was determined following the method described by Sadler and Murphy (2010). To be exact, 5.00 mL BFP was mixed with 20 mL distilled water and titrated to an endpoint of pH 8.2 using 0.1 mol L^{-1} sodium hydroxide (NaOH). TA was then calculated based on the amount of NaOH consumed. The results were expressed in mg citric acid/100 g sample. A digital pH meter (S210, Mettler Toledo, Shanghai, China) was used to record the pH value for all samples.

2.3.1. Colour parameters

The colour changes in treated BFP samples were measured at room temperature using a colorimeter (HunterLab Colorflex-EZ, USA) designed with CIE LAB system. The L* (lightness), a* (redness/greenness), and b* (yellowness/blueness) readings were taken. The chroma (C), hue angle (h) colour index (CI), yellow index (YI), the total colour difference (ΔE) and were determined using Eqs. (2) to (6) (de Araújo et al., 2021; Kahraman & Feng, 2021).

$$C = \sqrt{(\Delta a^{*2} + \Delta b^{*2})} \quad (2)$$

$$h = tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (3)$$

$$CI = \frac{(180 - h)}{(L - C)} \quad (4)$$

$$YI = \frac{(142.86 \times b^*)}{(L^*)} \quad (5)$$

$$\Delta E = \sqrt{(\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})} \quad (6)$$

The browning index (BI) depends on L*, a*, and b* colorimetric parameters. Hence, BI was determined using Eq. (7) (Klimczak & Gliszczyńska-Świgło, 2017).

$$BI = \frac{[100(x - 0.31)]}{0.172} \quad (7)$$

where $x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 0.3012b^*)}$

The cloudiness index was also determined according to Oladunjoye et al. (2021). To be exact, 10 mL BFP was centrifuged at 3500×*g* for 20 min. The supernatant was collected, and its absorbance was measured at 660 nm with a UV–vis spectrophotometer.

2.4. Determination of ascorbic acid content

To determine the ascorbic acid content in the BFP samples, the Tillmans Method was employed as described by Nielsen (2017). To be exact, 2 mL BFP was mixed with 5 mL metaphosphoric-acetic acid solution and titrated with an indophenol dye solution. The endpoint was reached with >5 s persistence of light but distinct rose-pink colour. Using ascorbic acid (AA) as the reference standard, the results were expressed as mg AA/100 g DW sample.

2.5. Total phenolics (TPC), total flavonoids (TFC), and antioxidant capacity

The TPC and TFC of different samples were determined according to (Ismail et al., 2021). Obtained results were expressed as mg standard equivalents/g DW sample. The antioxidant capacity by ferric reducing antioxidant power (FRAP), 2,2-Diphenyl-1-picrylhydrazyl (DPPH), and 2,2′-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid (ABTS) radical scavenging activity assays was determined following the procedure described by Ismail et al. (2021). The results were calculated as mg Trolox/100 g DW.

2.6. HPLC analysis of the phenolic compounds

The analysis of phenolic compounds was carried out according to Ismail et al. (2021). "An LC-20AD Prominence Ultra-Fast Liquid Chromatograph (Shimadzu, Japan) designed with a photodiode array detector (PAD) was used. A Capcell PAK C18 column (4.6mmID. × 250) maintained at 40 °C was used. The UV-absorption of the HPLC eluates was recorded at 200–400 wavelength to monitor peak intensity in real-time. The mobile phase comprised acetonitrile (eluant B) and 0.1% phosphoric acid (eluant A). 1 mL min^{-1} was the flow rate, and 10 μL as the injection volume. The gradient elution system was: 0.01 min, 5% of B; 32 min, 30% of B; 36 min, 80% of B; 37 min, 5% of B and 46 min, 5% of B". For the identification and quantification of compounds, the retention time and peak areas of samples are matched, respectively, against those of the standards. Briefly, a known quantity of each standard was dissolved in methanol and further diluted to a ratio of 1:1 (v/v) with mobile phase A. The standards were maintained at 10 μg mL^{-1} concentration and injected using the procedure described above".

2.7. Biological potentials

2.7.1. α-amylase inhibition

The α-amylase inhibitory activity was determined following a previously described procedure (da Silva et al., 2019). "Briefly, in a 96 well plate 20 μL of phosphate buffer (PPBS, 100 mM, pH 7), 10 μL of α-amylase (2 units mL^{-1} in PPBS) and 50 μL sample or acarbose (positive control) at varying concentrations (0.1–0.5 mg mL^{-1}) were pre-incubated for 20 min at 37 °C. After that, 20 μL of the substrate (1% soluble starch in PPBS) was added and further incubated for 30 min at 37 °C. Then, 100 μL of the DNS (3,5-Dinitrosalicylic acid) colour reagent was added to stop the reaction, and the samples were boiled for 10 min. A plate reader (1510, Thermo Fisher, USA) was used after that to measure the absorbance at 540 nm. The experiments were repeated in triplicates, and the results were expressed as a percentage of inhibition calculated using Eq. (8):

$$\text{Inhibitory activity } (\%) = \left(\frac{A_{\ sample} - A_{-ve\ control}}{A_{-ve\ control}}\right) \times 100$$

where $A_{\text{-ve control}}$ is the absorbance of the negative control."

2.7.2. α-Glucosidase inhibition

The α-glucosidase inhibition activity was measured according to Ismail, Guo et al. (2019). "Briefly, 40 μL sample and acarbose (positive control) at varying concentrations (0.1–0.5 mg mL^{-1}), 130 μL potassium phosphate buffer (PBS, 100 mM, pH 7) and 60 μL of the substrate (5 mM 4-nitrophenyl α-D-glucopyranoside in PBS) were added in a 96 well plate. The initial reading (T_0) was recorded at 405 nm. To initiate the reaction, 20 μL of the stock solution of the α-glucosidase enzyme (1 unit mL^{-1} in PBS) was added followed by incubation at 37 °C for 10 min. Then, the final reading (T_{10}) was determined again at 405 nm. Blank PBS subjected to the described procedure above without sample extracts was used as a negative control. The percentage of inhibitory activity was calculated using Eq. (9):

$$\text{Inhibitory activity } (\%) = \left(1 - \frac{A_{\ sample}(T_{10} - T_0)}{A_{-ve\ control}(T_{10} - T_0)}\right) \times 100$$

where A-ve control is the absorbance of the negative control."

2.8. Statistical analysis

The sample size was 100 g BFP, and all experiments and treatments were carried out in triplicates. The experimental data were expressed as mean ± SE and were further subjected to the analysis of variance (ANOVA) using SPSS 22 (IMB, NY, USA). The separation of the means was achieved using by Duncan posthoc test at $p \leq 0.05$. Pearson's correlation test was also performed between the bioactive constituents and antioxidant capacity.

3. Results and discussion

3.1. Physicochemical properties of BFP

The physicochemical properties of BFP samples subjected to HIU and thermal treatments were evaluated. Both HIU and thermal treatments induce no significant changes in the pH, total soluble solids (TSS), and titratable acidity (TA) of BFP samples (Table 1) compared with the control. This suggested that the molecular structures of high molecular weight compounds related to the physicochemical properties were not affected by the ultrasound and thermal treatments. Thus, the pH (3–3.06), TSS (7.1–7.4 *Brix), and TA (1921.2–1959.62 mg CA/100 g sample) were within the acceptable levels obtained in fresh BFP. Similar results regarding the stability of physicochemical properties following ultrasound and thermal treatments were reported in cranberry juice (Gomes et al., 2017) and hog plum juice (Oladunjoye et al., 2021). Previous studies reported a pH ranging from 3.11 to 3.33 in fresh BFP (Coe et al., 2013; Tembo et al., 2017); therefore, agreeing with the values obtained in this study. The high titratable acidity observed could be ascribed to BFP's high ascorbic acid content (Tembo et al., 2017).

Table 1
Physicochemical properties of BFP under high-intensity ultrasound and thermal treatment.

Treatment	Time (min)	Final temperature (°C)	Power intensity (W/cm^2)	pH	Soluble solids (°Brix)	Titratable acidity (mg CA/100 g sample)
Control	-	-	-	3.02 ± 0.52^a	7.3 ± 0.05^a	1921.2 ± 1.34^a
PS63	30	63	-	3.00 ± 0.00^a	7.4 ± 0.01^a	1945.14 ± 0.96^a
PS70	5	70	-	3.03 ± 0.01^a	7.4 ± 0.02^a	1936.47 ± 0.38^a
HPI	5	47	687.5	3.02 ± 0.10^a	7.2 ± 0.00^a	1959.62 ± 0.38^a
MPI	15	50	344	3.03 ± 0.20^a	7.3 ± 0.06^a	1925.14 ± 0.96^a
LPI	30	42	115	3.06 ± 0.10^a	7.1 ± 0.10^a	1959.62 ± 0.38^a

Values were expressed as a mean ± standard error (n = 3). Means within each column with different superscripts differ significantly ($p < 0.05$). Control: Untreated BFP; *P*63: Thermal treatment at 63 °C for 30 min; P70: Thermal treatment at 70 °C for 5 min; HPI: BFP treated at 687.5 W/cm^2 for 5 min; MPI: BFP treated at 344 W/cm^2 for 15 min; LPI: BFP treated at 115 W/cm^2 for 30 min.

3.2. Colour, cloudiness, and browning indices

Colour is an important attribute used to assess food quality and whether it can satisfy consumer requirements. Hence, maintaining a desirable colour in foods after processing is necessary to increase their overall acceptability (Wang et al., 2020). The colour, cloudiness, and browning indices of BFP samples were presented in Table 2. Differences were observed between HIU and thermal treatments regarding the effects on colour attributes. For instance, the L* values for all treated samples significantly decreased relative to the control samples. However, the redness/greenness (a*) index was not affected by both treatments except for thermal treatment at 63 °C for 30 min (*P*63). The results indicated that HIU treatments maintained the colour index (CI) and hue angle (h) of BFP compared to the control. However, HIU treatments resulted in a significant reduction in yellowness (b*), chroma (C), and yellow index (YI), while the total colour difference (ΔE) increased significantly compared to the thermal treatment. In contrast, thermal treatments maintained a small ΔE but increased the h, CI, and YI values compared to the HIU treatments and control samples. Dark compounds may be formed following thermal treatments due to ascorbic acid degradation or the Maillard reaction, which could result in the observed colour changes (do Amaral Souza et al., 2019). The decrease in L*, b*, h, and C values in HIU treated samples suggests that BFP's visual colour was more intense, probably due to the Maillard reaction induced by sonication. Furthermore, the pinkish colour of BFP is generally influenced by natural pigments such as anthocyanins. Hence, the shift in colour following ultrasound treatment might also be attributed to the breakdown of anthocyanins caused by sonication (Aadil, Zeng, Han, & Sun, 2013). HIU treatment can cause the release of intracellular compounds by cellular disruptions, affecting the product's final colour (Wang, Wang, Ye, Vanga, & Raghavan, 2019). The ΔE represents the magnitude of the colour difference between treated and control samples categorised as very different ($\Delta E > 3$), different ($1.5 < \Delta E < 3$), and small difference ($\Delta E < 1.5$) (Bellary, Indiramma, Prakash, Baskaran, & Rastogi, 2016). In the current study, the ΔE for the thermal treatments were 1.46 ± 0.10 and 1.08 ± 0.05 for *P*63 and P70, respectively. Since these values were <1.5, this indicates a small colour difference. In contrast, the colour change by HIU treatments irrespective of the different amplitudes visually more perceptible since ΔE values were >1.5, although these are below the level that can affect the consumer acceptance or rejection of a product (do Amaral Souza et al., 2019).

The hue angle (h) reflects the samples' visual colour based on a* and b* values. In the current study, h values increased significantly ($p < 0.05$) following thermal treatment compared with the control. On the other hand, the h value of the HIU treated BFP, and the control did not vary significantly, indicating the positive effect of ultrasound in developing and maintaining redness in treated samples (Gouma, Álvarez, Condón, & Gayán, 2020). The decrease in h and YI values following ultrasound treatments can be attributed to the rupturing of cell well in BFP in response to the cavitation effect or the generation of hydroxyl radicals. This phenomenon causes an increase in phenolic content in the samples and consequently changing the visible spectrum area from yellow to yellow–red, thereby reducing the YI in the samples (Ordóñez-Santos, Martínez-Girón, & Arias-Jaramillo, 2017).

Despite the variation in the colour attributes in the treated samples, the browning index was found to be within the range obtained in the control samples (Table 2). However, thermal treatments significantly increased the 5-hydroxymethylfurfural (HMF) concentration relative to HIU treaments and control. Interestingly, HMF concentration was maintained in the HIU treated samples (Fig. 1). HMF has been considered a potential carcinogen generated by cooking and thermal processing, and it is commonly used as an indicator of food quality. It is therefore not surprising that HMF increased significantly in the thermally treated samples. Lower HMF values than thermal treatments have been reported in HIU treated Turkish honey types (Önür et al., 2018).

Cloudiness favourably affects the aroma and colour of fruit pulps, reflects turbidity, and the level of suspended particles such as proteins, lipids, pectin, cellulose, and hemicelluloses (do Amaral Souza et al.,

Table 2
Effect of high-intensity ultrasound and thermal treatments on the colour attributes of BFP.

Sample	L*	a*	b*	C	h	CI	YI	TCD	Cloudiness	Browning Index
Control	54.51 ± 0.40^a	8.86 ± 0.03^a	30.11 ± 0.10^a	31.28 ± 0.52^a	73.59 ± 0.01^b	4.66 ± 0.10^b	79.23 ± 0.23^b	NA	0.38 ± 0.01^b	16.96 ± 0.22^a
PS63	51.84 ± 0.05^b	8.01 ± 0.10^b	30.76 ± 0.10^a	31.90 ± 0.10^a	75.29 ± 0.60^a	5.24 ± 0.40^a	84.95 ± 0.25^a	1.46 ± 0.10^b	0.42 ± 0.00^b	16.89 ± 0.01^a
PS70	52.43 ± 0.00^b	8.62 ± 0.02^a	30.72 ± 0.02^a	31.92 ± 0.20^a	74.32 ± 0.20^a	5.16 ± 0.10^a	83.76 ± 0.50^a	1.08 ± 0.05^c	0.43 ± 0.03^b	17.38 ± 0.03^a
HPI	52.83 ± 0.01^b	8.68 ± 0.02^a	28.32 ± 0.02^b	29.63 ± 0.05^b	72.95 ± 0.07^b	4.6 ± 0.12^b	76.59 ± 0.70^c	1.76 ± 0.12^a	0.55 ± 0.1^a	16.84 ± 0.75^a
MPI	52.90 ± 0.02^b	8.71 ± 0.02^a	28.37 ± 0.01^b	29.70 ± 0.12^b	72.93 ± 0.34^b	4.61 ± 0.21^b	76.64 ± 0.15^c	1.72 ± 0.20^a	0.51 ± 0.1^a	16.86 ± 0.02^a
LPI	52.38 ± 0.13^b	8.81 ± 0.3^a	29.28 ± 0.14^b	30.31 ± 0.10^b	73.24 ± 0.72^b	4.87 ± 0.10^b	78.29 ± 0.35^b	1.62 ± 0.40^a	0.53 ± 0.12^a	17.33 ± 0.15^a

Values were expressed as a mean ± standard error (n = 3). Means within each column with different superscripts differ significantly ($p < 0.05$). Control: Untreated BFP; *P*63: Thermal treatment at 63 °C for 30 min; P70: Thermal treatment at 70 °C for 5 min; HPI: BFP treated at 687.5 W/cm^2 for 5 min; MPI: BFP treated at 344 W/cm^2 for 15 min; LPI: BFP treated at 115 W/cm^2 for 30 min.

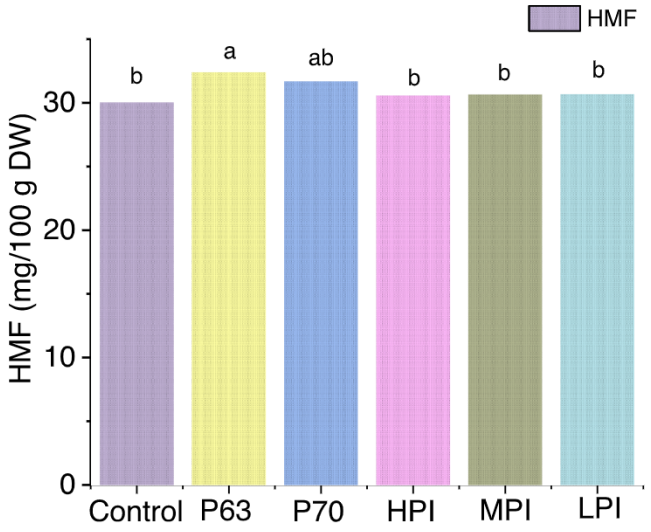

Fig. 1. 5-Hydroxymethylfurfural (HMF) concentration in different treated BFP samples. Values are presented as means ± SE with different letters (a, b), indicating a statistically significant difference ($p < 0.05$). Control: Untreated BFP; *P*63: Thermal treatment at 63 °C for 30 min; P70: Thermal treatment at 70 °C for 5 min; HPI: BFP treated at 687.5 W/cm^2 for 5 min; MPI: BFP treated at 344 W/cm^2 for 15 min; LPI: BFP treated at 115 W/cm^2 for 30 min.

2019; Oladunjoye et al., 2021). In this study, the cloudiness values (Table 2) increased significantly ($p < 0.05$) following HIU treatment (0.51–0.55) in comparison with thermally treated samples (0.42–0.43) and the control (0.38). The increase in cloudiness in HIU treated samples can be attributed to physicochemical reactions such as conformation and structural changes of protein and the inactivation of enzymes related to cloudiness, particularly pectin methylesterase (Wang et al., 2020). Moreover, ultrasound can lead to the breakdown (sonolysis) of suspended particles during bubble cavitation, contributing to increased cloudiness and improved consistency in food products (Aadil et al., 2013; Oladunjoye et al., 2021).

3.3. Ascorbic acid content

Vitamin C (ascorbic acid) is an essential contributor to the nutritional quality and antioxidant capacity of foods. Ascorbic acid (AA) protects cells from damages induced by free radicals and significantly prevents the onset of several diseases, including cancer and cardiovascular diseases (Wang et al., 2019). BFP is an excellent source of ascorbic acid (67–500 mg/100 g), which recent analyses reported to be 8-fold higher than in oranges and lemon juice (Tembo et al., 2017). However, AA is highly unstable and degrades quickly by exposure to heat and oxygen. Hence, several variables need to be controlled to preserve its content in food products. The AA content in treated and control samples were presented in Table 3. Conventional thermal treatments resulted in a significant reduction in the AA content than the control and HIU treated samples. The AA loss was 61.90% and 30.47% for conventional thermal treatments at 63 °C for 30 min and 70 °C for 5 min, respectively. In comparison, HIU treatment achieved better AA retention with a slight increase obtained under HPI ultrasound (500.31 ± 19.32 mg AA/100 g) than the control (486.41 ± 31 mg AA/100 g). Moreover, the AA loss in other HIU treatments was <15%. The ability of ultrasound to significantly maintain the AA content in foods has been reported previously (Aadil et al., 2013; de Araújo et al., 2021). Ultrasound can achieve significant retention of AA by several mechanisms, including the removal of dissolved oxygen, which promotes AA stability during processing and low degradation at low temperature (Aguilar, Garvín, Ibarz, & Augusto, 2017; Oladunjoye et al., 2021), while the degradation effect of elevated temperatures significantly reduced the AA content in thermally treated BFP (Tembo et al., 2017). The degradation reaction of AA leads to the formation of different products, including dehydroascorbic acid, 2-furoic acid, 2-furaldehyde, 2,3-diketogulonic acid, and 3-deoxypentosone. Other low molecular weight compounds are also produced due to the opening of the lactone ring. While some reactions are reversible, like dehydroascorbic acid formation, others such as lactone ring-opening are not. These compounds' generation leads to flavour and colour changes because they can polymerise under anaerobic conditions to form coloured compounds such as 5-hydroxymethylfurfural (HMF) (Tembo et al., 2017). Thus, it is not surprising that the HMF concentration in thermally treated samples was higher than in other samples. Hence, here we show that using HIU treatment could benefit consumers by ensuring a stable AA content in BFP.

3.4. Total phenolic content (TPC), total flavonoids content (TFC), and antioxidant capacity

3.4.1. TPC and TFC

The BFP is a good source of phenolic compounds (Ismail et al., 2020), a group of bioactive antioxidants; their dietary intake has been linked to the prevention of several physiological and degenerative diseases, including cancer and cardiovascular disease (Guimarães et al., 2019). The TPC in BFP treated with HIU varied from 749.47 to 814.29 mg GA/100 g DW, which is significantly higher than in control and thermally treated samples (Table 3). Under HIU, the TPC increases significantly with HPI treatment and decreases with LPI treatment. Similarly, the TFC follows the same trend with the values ranging from 3750.28 to 3897.63 mg RE/100 g DW for HIU treated samples (Table 3). In general, a significant reduction was observed in TPC and TFC following thermal treatments, perhaps due to the loss of heat-labile phenolic compounds. The lowest TPC (671.99 ± 6.74 mg GA/100 g DW) and TFC (3504.81 ± 8.97 mg RE/100 g DW) were observed under thermal treatment at 70 °C for 5 min (P70).

The results point out that TPC and TFC in BFP increased with increased ultrasonic power and reduced treatment time. This implies that shorter ultrasonic time contributed to improved efficiency; this is important as it also will significantly reduce operation costs. Several mechanisms could explain the increase in the TPC and TFC following HIU treatment; the greater release of the compounds from the cell wall

Table 3
Effect of high-intensity ultrasound and thermal treatments on Total Phenolic Content (TPC), Total Flavonoid Content (TFC) and antioxidant capacity of BFP.

Sample	Vitamin C (mg AA/100 g)	TPC (mg GA/100 g DW)	TFC (mg RE/100 g DW)	FRAP (mg Trolox/100 g DW)	DPPH (mg Trolox/100 g DW)	ABTS (mg Trolox/100 g DW)
Control	486.41 ± 31^{a}	728.91 ± 6.74^{b}	3795.79 ± 7.25^{ab}	5030.59 ± 522.33^{b}	2190.93 ± 35.85^{ab}	2211.80 ± 53.78^{ab}
PS63	148.20 ± 46.33^{d}	714.68 ± 5.39^{bc}	3584.83 ± 72.32^{bc}	4288.33 ± 525.77^{d}	1883.13 ± 102.52^{c}	2089.25 ± 89.82^{b}
PS70	301.11 ± 15.44^{c}	671.99 ± 6.74^{c}	3504.81 ± 8.97^{c}	4510.67 ± 434.44^{c}	1606.60 ± 66.81^{d}	2044.05 ± 67.50^{b}
HPI	500.31 ± 19.32^{a}	814.29 ± 28.31^{a}	3897.63 ± 4.56^{a}	6388.96 ± 543.86^{a}	2297.55 ± 7.39^{a}	2456.39 ± 103.4^{a}
MPI	440.09 ± 30.88^{ab}	765.28 ± 8.10^{ab}	3828.47 ± 29.10^{ab}	6263.73 ± 276.08^{a}	1949.1 ± 90.86^{bc}	2171.45 ± 43.08^{ab}
LPI	426.19 ± 14.44^{ab}	749.47 ± 5.39^{b}	3750.28 ± 32.21^{ab}	5064.07 ± 203.25^{b}	1983.35 ± 118.59^{bc}	2112.92 ± 168.10^{ab}

Values were expressed as a mean ± standard error (n = 3). Means within each column with different superscripts differ significantly ($p < 0.05$). Control: Untreated BFP; *P*63: Thermal treatment at 63 °C for 30 min; P70: Thermal treatment at 70 °C for 5 min HPI: BFP treated at 687.5 W/cm^2 for 5 min; MPI: BFP treated at 344 W/cm^2 for 15 min; LPI: BFP treated at 115 W/cm^2 for 30 min.

due to cavitation collapse in the colloidal particles surroundings, hydroxyl radicals addition to the aromatic ring of polyphenolics during sonication, and their consequent hydroxylation in the ortho-, meta- and para- positions (Tomadoni, Cassani, Viacava, Moreira, & Ponce, 2017). Also, phenolic compounds existing in plants are in free and bound forms, and when acoustic cavitation in the form of shock waves, water jets, and high shear forces is introduced, this results in the rupturing of plant cells, which leads to the release of bound phenolics to the juice (; Kahraman & Feng, 2021). A similar increase in TPC and TFC following HIU treatment was reported in several food products, including araçá-boi pulp (de Araújo et al., 2021), apple-carrot juice (Kahraman & Feng, 2021), carrot-grape blend (Nadeem, Ubaid, Qureshi, Munir, & Mehmood, 2018), and prebiotic soursop whey beverage (Guimarães et al., 2019).

3.4.2. Antioxidant capacity

The antioxidant capacity of foods depends on the antioxidants content possessing different mechanisms of action (Tomadoni et al., 2017). In the current study, the antioxidant capacity in BFP samples were determined using FRAP, DPPH, and ABTS free radical assays. From the results presented in Table 3, it is clear that ultrasound positively impacted BFP's antioxidant capacity compared with the thermal treatments and in line with the TPC and TFC results. The antioxidant capacity increases with increasing ultrasonic power and a decreasing treatment time. In contrast, the thermally treated samples significantly reduced the antioxidant capacity ($p < 0.05$) compared with control and HIU treated samples. This reduction may be linked to the high temperature used during treatment (Kahraman & Feng, 2021). It can be pointed out from the results that the FRAP assay revealed a significant variation in the antioxidant capacity between ultrasound and thermally treated samples, which was not observed with the DPPH and ABTS assays. This can be attributed to the structural characteristics of the phenolic constituents in BFP and the different mechanisms of the antioxidant assays (Shahidi & Zhong, 2015). The antioxidant capacity of fruits and vegetables is generally associated with the contents of phenolic compounds and AA (Tembo et al., 2017). Contrasted with AA, which exerts its antioxidant capacity via the hydrogen atom transfer (HAT) mechanism (Liu, Liu, & Li, 2020), phenolic compounds use their redox potential, enabling them to act as hydrogen donors, reducing agents, and singlet oxygen quenchers (Shahidi & Zhong, 2015). Besides, a strong positive correlation has been established between the antioxidant capacity of BFP and its phenolics and AA contents (Ismail, Pu, Guo et al., 2019; Tembo et al., 2017). Several studies have also reported an increased antioxidant capacity of fruit pulps and juices subjected to ultrasound attributed to the increased contents of phenolic compounds resulting from cavitation produced during sonication (Aadil et al., 2013; de Araújo et al., 2021; Wang et al., 2019). On the other hand, the reduction in the antioxidant capacity following thermal treatments could be attributed to the loss of bioactive constituents, particularly ascorbic acid and thermally labile phenolics, and the formation of melanoidins pro-oxidants (Tembo et al., 2017).

3.5. Analysis of individual phenolic constituents

Individual phenolic compound contents in treated BFP samples and control were analysed by HPLC analysis. Thirteen authentic standards were employed based on the previously identified phenolic compounds in BFP. The phenolic standards used for qualitative and quantitative analysis of the samples consist of four phenolic acids and nine flavonoids. The results expressed as mg respective phenolic standard/100 g DW were presented in Table 4. The chromatographs and chromatographic information of the compounds in treated samples and external standards were presented in Fig. S1(a-b) and Table S1.

The results showed a significant variation in the contents of the selected phenolics in different samples. The contents of the twelve phenolics were the highest in HPI treatment, followed by MPI and LPI. In general, all HIU treated samples showed significantly higher phenolic contents ($p < 0.05$) than thermally treated samples. Additionally, the individual phenolic contents in HPI and MPI treatments were significantly higher than in control. However, phenolic content in both LPI and control treatments were not significantly different. Despite this, the procyanidin C_1 contents increased by 256.60%, 227.96%, and 235.14% in HPI, MPI, and LPI, respectively, compared with control samples. Moreover, the total phenolic chromatographic index (TPCI) decreased in the order: HPI (1635.34 ± 45.89 mg/100 g DW) > MPI (1498.14 ± 56.84 mg/100 g DW) > control (1376.12 ± 42.86 mg/100 g DW) > LPI (1352.09 ± 73.49 mg/100 g DW) > *P*63 (1281.16 ± 51.59 mg/100 g DW) > and P70 (1267.61 ± 41.98 mg/100 g DW), respectively. In comparison, thermal treatments result in significantly lower ($p < 0.05$) individual phenolic contents than the HIU treated samples and control in line with the other results. These results reaffirm the effectiveness of HIU treatment in retaining the bioactive constituents of foods and improving their contents. The higher content of phenolic compounds in HIU-treated samples can be attributed to the mechanical effect of ultrasonic waves based on the cavitation activities (high shear forces, shockwaves, and water jets) that can disrupt the plant cell wall and intensify the mass transfer of bound phenolics to the juice (Kahraman & Feng, 2021; Nadeem et al., 2018). The increase in catechin, gallic acid, and ellagic acid has been reported in strawberry juice subjected to ultrasound (Wang et al., 2019). It can be pointed out from the results that flavonoids, particularly proanthocyanidins, dominated the phenolic

Table 4
Representative phenolic compounds in BFP samples determined by HPLC.

Phenolic compound	Concentration (mg/100 g DW)					
	Control	*P*63	P70	HPI	MPI	LPI
Gallic acid	4.49 ± 0.56^{b}	3.93 ± 0.02^{bc}	3.27 ± 1.08^{d}	4.85 ± 1.13^{a}	4.35 ± 0.56^{b}	4.11 ± 0.12^{b}
Chlorogenic acid	13.95 ± 1.12^{c}	5.46 ± 0.09^{d}	5.57 ± 0.01^{d}	22.86 ± 0.85^{a}	20.79 ± 0.15^{b}	12.86 ± 3.54^{c}
Protocatechuic acid	6.57 ± 0.25^{c}	9.43 ± 2.90^{b}	9.6 ± 1.19^{b}	11.41 ± 1.02^{a}	11.43 ± 0.96^{a}	7.43 ± 1.09^{c}
Caffeic acid	37.27 ± 0.17^{c}	36.92 ± 0.17^{c}	35.9 ± 4.44^{cd}	42.87 ± 1.15^{a}	39.29 ± 2.43^{b}	32.9 ± 3.87^{d}
D- (+)-Catechin	43.59 ± 2.02^{d}	52.9 ± 1.23^{b}	52.71 ± 1.12^{b}	60.17 ± 2.89^{a}	60.26 ± 2.45^{a}	48.97 ± 6.21^{c}
(−)-Epicatechin	185.76 ± 5.98^{a}	154.14 ± 4.51^{b}	134.62 ± 1.19^{c}	121.00 ± 4.35^{d}	111.19 ± 10.20^{e}	96.12 ± 17.90^{f}
Procyanidin C_1	130.13 ± 11.12^{c}	77.61 ± 5.90^{e}	113.81 ± 7.05^{d}	333.91 ± 1.17^{a}	296.65 ± 5.13^{b}	305.99 ± 7.25^{b}
Procyanidin B_1	28.77 ± 2.91^{e}	31.39 ± 3.00^{d}	32.32 ± 1.23^{d}	44.05 ± 0.01^{a}	39.6 ± 0.89^{b}	36.4 ± 1.90^{c}
Procyanidin B_2	524.46 ± 12.35^{c}	534.31 ± 18.9^{d}	516.04 ± 9.87^{c}	584.34 ± 12.13^{a}	536.24 ± 20.42^{b}	487.9 ± 22.09^{d}
Proanthocyanidin	281.2 ± 3.45^{c}	269.31 ± 8.21^{d}	264.42 ± 6.80^{d}	308.19 ± 12.56^{a}	290.94 ± 5.49^{b}	238.61 ± 4.55^{e}
Rutin	45.39 ± 1.13^{b}	45.2 ± 1.78^{b}	43.96 ± 4.50^{c}	48.47 ± 8.5^{a}	45.15 ± 4.56^{b}	44.62 ± 2.32^{b}
Quercetin	64.09 ± 0.75^{a}	49.55 ± 2.14^{b}	43.87 ± 1.23^{b}	39.77 ± 0.03^{c}	28.61 ± 2.54^{e}	23.21 ± 1.76^{d}
Kaempferol	10.45 ± 1.05^{d}	11.01 ± 0.60^{c}	11.52 ± 2.27^{c}	13.45 ± 0.10^{a}	13.64 ± 1.06^{a}	12.97 ± 0.89^{b}
TPCI	1376.12 ± 42.86^{c}	1281.16 ± 51.59^{d}	1267.61 ± 41.98^{d}	1635.34 ± 45.89^{a}	1498.14 ± 56.84^{b}	1352.09 ± 73.49^{c}

Values were expressed as a mean ± standard error (n = 2). Means within each row with different superscripts differ significantly ($p < 0.05$). Control: Untreated BFP; *P*63: Thermal treatment at 63 °C for 30 min; P70: Thermal treatment at 70 °C for 5 min; HPI: BFP treated at 687.5 W/cm^2 for 5 min; MPI: BFP treated at 344 W/cm^2 for 15 min; LPI: BFP treated at 115 W/cm^2 for 30 min; TPCI: Total phenolic chromatographic index.

profile of all the BFP samples. Several studies have highlighted BFP as a promising source of proanthocyanidins, contributing significantly to its antioxidant capacity (Ismail, Pu, Guo et al., 2019; Russo et al., 2020). BFP has been reported to contain a significantly higher proanthocyanidin content than blueberries, cranberries, plums, apples, and strawberries (Tembo et al., 2017). The myriad health-promoting and disease-preventing properties of proanthocyanidins have been reported, including immune-stimulating, hypoglycemic, free radical reducing, anti-inflammatory, antiviral, anticancer activities (Unusan, 2020).

There were statistically significant ($p < 0.05$) correlations between TPC, TPC, and antioxidant assays (Table S2). Moreover, the AA contents showed a positive but non-significant correlation with the TPC, TFC, and antioxidant capacity. This suggested that the phenolic constituents play a more significant role in the antioxidant capacity of BFP. Regarding the individual phenolic contents, it is clear from the results that gallic acid, chlorogenic acid, procyanidins B_1 and B_2, and rutin seem to have impacted the TPC in BFP, while proanthocyanidins showed a significant correlation with the TFC. In general, a positive correlation was found between the individual phenolic content and the antioxidant capacity assays consistent with the previous reports (Tembo et al., 2017).

3.6. Biological potentials of BFP

The glycemic response reduction and α-glucosidase and α-amylase inhibitory activity of BFP has previously been reported (Braca et al., 2018; Coe et al., 2013; Ismail, Guo et al., 2019). However, to our knowledge, the effects of HIU and thermal treatments on these inhibitory activities have not been evaluated thus far. Hence the inhibitory activity against α-glucosidase and α-amylase of BFP subjected to HIU and thermal treatments was determined and compared with acarbose (positive control) at the same concentration (0.1–0.5 mg mL^{-1}). The result presented in Fig. 2a indicated that all BFP samples, irrespective of the treatments, significantly inhibited α-amylase with higher potency than acarbose. However, HIU treated samples showed significantly higher activity than thermally treated samples, probably due to the cavitation effect of HIU in increasing the availability of phenolic compounds or altering their primary structure leading to a significant inhibitory effect (Rasouli, Hosseini-Ghazvini, Adibi, & Khodarahmi, 2017). Significant recoveries of phenolic compounds such as chlorogenic acid, catechin, epicatechin, proanthocyanidin C_1 were achieved with HIU treatments. These compounds were reported to exert strong α-amylase inhibition. For instance, chlorogenic acid is a potent

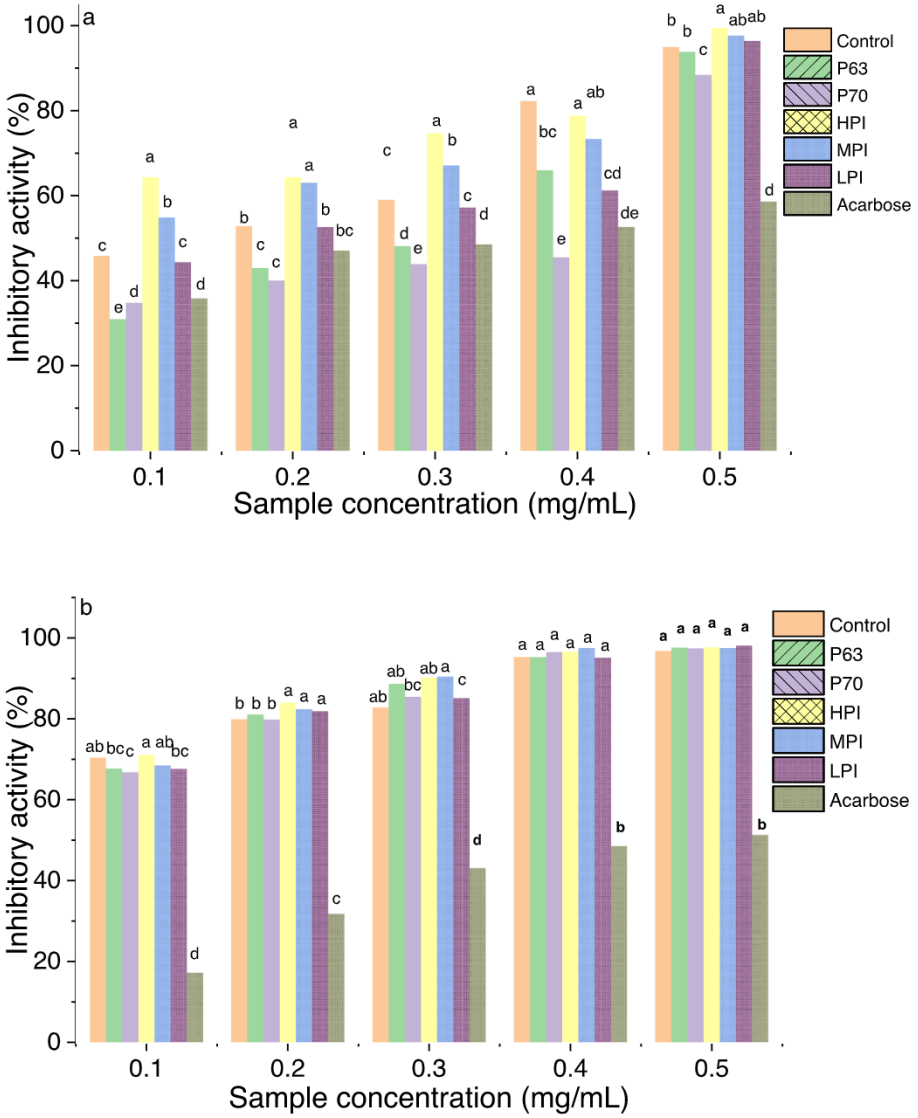

Fig. 2. Inhibitory activity of BFP subjected to different treatments against (a) α-amylase and (b) α-glucosidase Values are presented as means ± SE with different letter s(a-d), indicating a statistically significant difference ($p < 0.05$). Control: Untreated BFP; P63: Thermal treatment at 63 °C for 30 min; P70: Thermal treatment at 70 °C for 5 min; HPI: BFP treated at 687.5 W/cm^2 for 5 min; MPI: BFP treated at 344 W/cm^2 for 15 min; LPI: BFP treated at 115 W/cm^2 for 30 min.

α-amylase inhibitor and exerts its effect by altering the enzyme's secondary structure through hydrogen bonds (Zheng et al., 2020). The strong α-amylase inhibitory activity of catechin, epicatechin and proanthocyanidins has also been reported (Rasouli et al., 2017). Given the key role of α-amylase in carbohydrate metabolism, its inhibition may be useful for regulating postprandial hyperglycaemia in diabetic patients and related disorders (Rasouli et al., 2017; Zheng et al., 2020). It can be pointed out that the inhibitory activity in HIU treated samples was higher in HPI than in other treatments, which is in line with the other results. The IC_{50} (mg mL^{-1}) values of different samples were presented in Table S3. The IC_{50} (mg mL^{-1}) values for α-amylase inhibitory activity were; control (0.24), *P*63 (0.28), P70 (0.32), HPI (0.22), MPI (0.24) and LPI (0.26), while that of acarbose was 0.40.

Similarly, BFP exhibited the most potent effect against α-glucosidase (Fig. 2b). Moreover, similar inhibitory activity against α-glucosidase was observed in all BFP samples. Consequently, an IC_{50} value of 0.20 mg mL^{-1} was obtained for treated samples and control compared with 0.42 mg/mL for acarbose. The IC_{50} values of acarbose for α-amylase and α-glucosidase inhibitions reported in the current study were similar to those reported in previous studies. For instance, da Silva et al. (2019) reported 0.465 mg mL^{-1} as the IC_{50} for acarbose against α-amylase, while Luyen et al. (2019) reported 0.45 mg mL^{-1} as the IC_{50} of acarbose against α-glucosidase. Moreover, a dose-dependent inhibitory activity against the enzymes was observed in both BFP samples and acarbose. The modulatory actions of BFP in this disease condition are attributed to its bioactive components, particularly phenolic compounds. Moreover, previous studies reported baobab phenolic compounds' effectiveness in inhibiting α-glucosidase and α-amylase activity and reducing glycemic response (Braca et al., 2018; Coe et al., 2013). Moreover, this modulatory activity is dependant on phenolic compounds' mechanism of action, binding affinity, and the presence of active sites (da Silva et al., 2019).

4. Conclusions

HIU treatment of BFP improved the quality parameters and lower 5-hydroxymethylfurfural (HMF) values compared with the thermal treatment. Moreover, the ascorbic acid and phenolic compounds' profiles were significantly improved, resulting in a significantly higher antioxidant capacity and more potent inhibition of α-amylase and α-glucosidase. Thermal treatments led to lower ascorbic acid retention and detrimentally affected the phenolic composition and antioxidant capacity. It also leads to higher HMF values besides a significantly lower inhibition of α-amylase and α-glucosidase enzymes relative to control and HIU-treated samples. Therefore, based on these results, HIU could be an alternative non-thermal processing technology to be employed for preserving and improving the quality, bioactive constituents, and biological potentials of BFP. Yet, the changes in quality, microbial safety, bioactive compounds, and biological potentials during storage remain to be further explored.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Aadil, R. M., Zeng, X.-A., Han, Z., & Sun, D.-W. (2013). Effects of ultrasound treatments on quality of grapefruit juice. *Food Chemistry, 141*(3), 3201–3206. https://doi.org/10.1016/j.foodchem.2013.06.008.

Aguilar, K., Garvín, A., Ibarz, A., & Augusto, P. E. D. (2017). Ascorbic acid stability in fruit juices during thermosonication. *Ultrasonics Sonochemistry, 37*, 375–381. https://doi.org/10.1016/j.ultsonch.2017.01.029.

Bellary, A. N., Indiramma, A. R., Prakash, M., Baskaran, R., & Rastogi, N. K. (2016). Anthocyanin infused watermelon rind and its stability during storage. *Innovative Food Science and Emerging Technologies, 33*, 554–562. https://doi.org/10.1016/j.ifset.2015.10.010.

Braca, A., Sinisgalli, C., De Leo, M., Muscatello, B., Cioni, P. L., Milella, L., & Sanogo, R. (2018). Phytochemical profile, antioxidant and antidiabetic activities of *Adansonia digitata* L. (Baobab) from Mali, as a source of health-promoting compounds. *Molecules, 23*, Article 3104. https://doi.org/10.3390/molecules23123104.

Branco, I. G., Moraes, I. C. F., Argandoña, E. J. S., Madrona, G. S., dos Santos, C., Ruiz, A. L. T. G., … Haminiuk, C. W. I. (2016). Influence of pasteurization on antioxidant and *in vitro* anti-proliferative effects of Jambolan (*Syzygium cumini* (L.) Skeels) fruit pulp. *Industrial Crops and Products, 89*, 225–230. https://doi.org/10.1016/j.indcrop.2016.04.055.

Chaari, A., Abdellatif, B., Nabi, F., & Khan, R. H. (2020). Date palm (*Phoenix dactylifera* L.) fruit's polyphenols as potential inhibitors for human amylin fibril formation and toxicity in type 2 diabetes. *International Journal of Biological Macromolecules, 164*, 1794–1808. https://doi.org/10.1016/j.ijbiomac.2020.08.080.

Coe, S. A., Clegg, M., Armengol, M., & Ryan, L. (2013). The polyphenol-rich baobab fruit (*Adansonia digitata* L.) reduces starch digestion and glycemic response in humans. *Nutrition Research, 33*(11), 888–896. https://doi.org/10.1016/j.nutres.2013.08.002.

do Amaral Souza, F. D. C., Gomes Sanders Moura, L., de Oliveira Bezerra, K., Paiva Lopes Aguiar, J., Moreira Mar, J., Sanches, E. A., … Campelo, P. H. (2019). Thermosonication applied on camu–camu nectars processing: Effect on bioactive compounds and quality parameters. *Food and Bioproducts Processing, 116*, 212–218. https://doi.org/10.1016/j.fbp.2019.06.003.

de Araújo, F. F., de Paulo Farias, D., Neri-Numa, I. A., Dias-Audibert, F. L., Delafiori, J., de Souza, F. G., … Pastore, G. M. (2021). Influence of high-intensity ultrasound on color, chemical composition and antioxidant properties of araçá-boi pulp. *Food Chemistry, 338*, 127747. https://doi.org/10.1016/j.foodchem.2020.127747.

Gomes, W. F., Tiwari, B. K., Rodriguez, Ó., de Brito, E. S., Fernandes, F. A. N., & Rodrigues, S. (2017). Effect of ultrasound followed by high pressure processing on prebiotic cranberry juice. *Food Chemistry, 218*, 261–268. https://doi.org/10.1016/j.foodchem.2016.08.132.

Gouma, M., Álvarez, I., Condón, S., & Gayán, E. (2020). Pasteurization of carrot juice by combining UV-C and mild heat: Impact on shelf-life and quality compared to conventional thermal treatment. *Innovative Food Science and Emerging Technologies, 64*, 102362. https://doi.org/10.1016/j.ifset.2020.102362.

Guimarães, J. T., Silva, E. K., Ranadheera, C. S., Moraes, J., Raices, R. S. L., Silva, M. C., … Cruz, A. G. (2019). Effect of high-intensity ultrasound on the nutritional profile and volatile compounds of a prebiotic soursop whey beverage. *Ultrasonics Sonochemistry, 55*, 157–164. https://doi.org/10.1016/j.ultsonch.2019.02.025.

Ismail, B. B., Guo, M., Pu, Y., Çavuş, O., Ayub, K. A., Watharkar, R. B., … Liu, D. (2021). Investigating the effect of in vitro gastrointestinal digestion on the stability, bioaccessibility, and biological activities of baobab (*Adansonia digitata*) fruit polyphenolics. *LWT - Food Science and Technology, 145*, 111348. https://doi.org/10.1016/j.lwt.2021.111348.

Ismail, B. B., Guo, M., Pu, Y., Wang, W., Ye, X., & Liu, D. (2019). Valorisation of baobab (Adansonia digitata) seeds by ultrasound assisted extraction of polyphenolics. Optimisation and comparison with conventional methods. *Ultrasonics Sonochemistry, 52*(2018), 257–267. https://doi.org/10.1016/j.ultsonch.2018.11.023.

Ismail, B. B., Pu, Y., Fan, L., Dandago, M. A., Guo, M., & Liu, D. (2019). Characterizing the phenolic constituents of baobab (*Adansonia digitata*) fruit shell by LC-MS/QTOF and their in vitro biological activities. *Science of the Total Environment, 694*, 133387. https://doi.org/10.1016/j.scitotenv.2019.07.193.

Ismail, B. B., Pu, Y., Guo, M., Ma, X., & Liu, D. (2019). LC-MS/QTOF identification of phytochemicals and the effects of solvents on phenolic constituents and antioxidant activity of baobab (*Adansonia digitata*) fruit pulp. *Food Chemistry, 277*, 279–288. https://doi.org/10.1016/j.foodchem.2018.10.056.

Ismail, B. B., Yusuf, H. L., Pu, Y., Zhao, H., Guo, M., & Liu, D. (2020). Ultrasound-assisted adsorption/desorption for the enrichment and purification of flavonoids from baobab (*Adansonia digitata*) fruit pulp. *Ultrasonics Sonochemistry, 65*, 104980. https://doi.org/10.1016/j.ultsonch.2020.104980.

Kahraman, O., & Feng, H. (2021). Continuous-flow manothermosonication treatment of apple-carrot juice blend: Effects on juice quality during storage. *LWT-Food Science and Technology, 137*, 110360. https://doi.org/10.1016/j.lwt.2020.110360.

Klimczak, I., & Gliszczyńska-Świgło, A. (2017). Green tea extract as an anti-browning agent for cloudy apple juice. *Journal of the Science of Food and Agriculture, 97*(5), 1420–1426. https://doi.org/10.1002/jsfa.2017.97.issue-510.1002/jsfa.7880.

Liu, Y., Liu, C., & Li, J. (2020). Comparison of vitamin C and its derivative antioxidant activity: Evaluated by using density functional theory. *ACS Omega, 5*(39), 25467–25475. https://doi.org/10.1021/acsomega.0c0431810.1021/acsomega.0c04318.s001.

Monteiro, S. H. M. C., Silva, E. K., Guimarães, J. T., Freitas, M. Q., Meireles, M. A. A., & Cruz, A. G. (2020). High-intensity ultrasound energy density: How different modes

of application influence the quality parameters of a dairy beverage. *Ultrasonics Sonochemistry, 63*, 104928. https://doi.org/10.1016/j.ultsonch.2019.104928.

Mukhopadhyay, P., & Prajapati, A. K. (2015). Quercetin in anti-diabetic research and strategies for improved quercetin bioavailability using polymer-based carriers-a review. *RSC Advances, 5*(118), 97547–97562. https://doi.org/10.1039/C5RA18896B.

Nadeem, M., Ubaid, N., Qureshi, T. M., Munir, M., & Mehmood, A. (2018). Effect of ultrasound and chemical treatment on total phenol, flavonoids and antioxidant properties on carrot-grape juice blend during storage. *Ultrasonics Sonochemistry, 45*, 1–6. https://doi.org/10.1016/j.ultsonch.2018.02.034.

Nielsen, S. S. (2017). *Food Analysis Laboratory Manual(3rd ed)*. Springer (Chapter 15).

Oladunjoye, A. O., Adeboyejo, F. O., Okekunbi, T. A., & Aderibigbe, O. R. (2021). Effect of thermosonication on quality attributes of hog plum (*Spondias mombin* L.) juice. *Ultrasonics Sonochemistry, 70*, 105316. https://doi.org/10.1016/j.ultsonch.2020.105316.

Önür, İ., Misra, N. N., Barba, F. J., Putnik, P., Lorenzo, J. M., Gökmen, V., & Alpas, H. (2018). Effects of ultrasound and high pressure on physicochemical properties and HMF formation in Turkish honey types. *Journal of Food Engineering, 219*, 129–136. https://doi.org/10.1016/j.jfoodeng.2017.09.019.

Ordóñez-Santos, L. E., Martínez-Girón, J., & Arias-Jaramillo, M. E. (2017). Effect of ultrasound treatment on visual color, vitamin C, total phenols, and carotenoids content in Cape gooseberry juice. *Food Chemistry, 233*, 96–100. https://doi.org/10.1016/j.foodchem.2017.04.114.

Rasouli, H., Hosseini-Ghazvini, S.-B., Adibi, H., & Khodarahmi, R. (2017). Differential α-amylase/α-glucosidase inhibitory activities of plant-derived phenolic compounds: A virtual screening perspective for the treatment of obesity and diabetes. *Food and Function, 8*(5), 1942–1954. https://doi.org/10.1039/C7FO00220C.

Russo, M., Ronci, M. B., Vilmercati, A., Gionfriddo, M., Fanali, C., Dugo, L., … De Gara, L. (2020). African baobab (*Adansonia digitata*) fruit as promising source of procyanidins. *European Food Research and Technology, 246*(2), 297–306. https://doi.org/10.1007/s00217-019-03342-9.

Sadler, G. D., & Murphy, P. A. (2010). pH and Titratable Acidity. In S. S. Nelson (Ed.), *Food Analysis Laboratory Manual* (pp. 227–232). Boston, MA: Springer.

Shahidi, F., & Zhong, Y. (2015). Measurement of antioxidant activity. *Journal of Functional Foods, 18*, 757–781. https://doi.org/10.1016/j.jff.2015.01.047.

da Silva, C. P., Soares-Freitas, R. A. M., Sampaio, G. R., Santos, M. C. B., do Nascimento, T. P., Cameron, L. C., … Areas, J. A. G. (2019). Identification and action of phenolic compounds of Jatobá-do-cerrado (Hymenaea stignocarpa Mart.) on α-amylase and α-glucosidase activities and flour effect on glycemic response and nutritional quality of breads. *Food Research International, 116*(2018), 1076–1083. https://doi.org/10.1016/j.foodres.2018.09.050.

Tembo, D. T., Holmes, M. J., & Marshall, L. J. (2017). Effect of thermal treatment and storage on bioactive compounds, organic acids and antioxidant activity of baobab fruit (*Adansonia digitata*) pulp from Malawi. *Journal of Food Composition and Analysis, 58*, 40–51. https://doi.org/10.1016/j.jfca.2017.01.002.

Luyen, N. T., Binh, P. T., Tham, P. T., Hung, T. M., Dang, N. H., Dat, N. T., & Thao, N. P. (2019). Wedtrilosides A and B, two new diterpenoid glycosides from the leaves of Wedelia trilobata (L.) Hitchc. with α-amylase and α-glucosidase inhibitory activities. *Bioorganic Chemistry, 85*, 319–324. https://doi.org/10.1016/j.bioorg.2019.01.010.

Tomadoni, B., Cassani, L., Viacava, G., Moreira, M. D. R., & Ponce, A. (2017). Effect of ultrasound and storage time on quality attributes of strawberry juice. *Journal of Food Process Engineering, 40*(5), 1–8. https://doi.org/10.1111/jfpe.12533.

Unusan, N. (2020). Proanthocyanidins in grape seeds: An updated review of their health benefits and potential uses in the food industry. *Journal of Functional Foods, 67* (February), Article 103861. https://doi.org/10.1016/j.jff.2020.103861.

Wang, J., Wang, J., Vanga, S. K., & Raghavan, V. (2020). High-intensity ultrasound processing of kiwifruit juice: Effects on the microstructure, pectin, carbohydrates and rheological properties. *Food Chemistry, 313*(2019). https://doi.org/10.1016/j.foodchem.2019.126121.

Wang, J., Wang, J., Ye, J., Vanga, S. K., & Raghavan, V. (2019). Influence of high-intensity ultrasound on bioactive compounds of strawberry juice: Profiles of ascorbic acid, phenolics, antioxidant activity and microstructure. *Food Control, 96*(2018), 128–136. https://doi.org/10.1016/j.foodcont.2018.09.007.

Zheng, Y., Yang, W., Sun, W., Chen, S., Liu, D., Kong, X., & Ye, X. (2020). Inhibition of porcine pancreatic α-amylase activity by chlorogenic acid. *Journal of Functional Foods, 64*(2019). https://doi.org/10.1016/j.jff.2019.103587.