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Ultrasound-IR combination improves physicochemical and antioxidant properties of Mushk budji rice

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The present study examines the impact of ultrasound assisted infrared (IR) drying on physicochemical, nutritional, and thermal characteristics of Mushk budji rice, an aromatic rice variety locally grown in Kashmir. The effects of ultrasonic pretreatment (2–6 h) and IR drying (35–55 °C) on starch composition (amylose amylopectin ratio), antioxidant activity, vitamin retention and thermal and pasting properties were measured. The outcome showed that ultrasound led to a relative increase in amylopectin content (maximum 84.87%) and a decrease in amylose due to leaching from swollen starch granules. The best result was observed in moderate ultrasonication (4 and 5 hours) with maximum thiamine (0.00627 mg g^{-1}), riboflavin (0.08863 mg g^{-1}), and niacin (0.0689 mg g^{-1}) at low drying temperatures (35 °C). Likewise, the maximum total phenolic content (4.64 mg GAE g^{-1}), total flavonoid content (5.77 mg g^{-1}) and antioxidant activity (DPPH, 68.9%) were observed at 4 h of ultrasonication and declined with increasing exposure or drying temperature, which is an indication of oxidative degradation of bioactives. The analysis of pasting properties and DSC showed that ultrasonic samples had lower peak viscosity and gelatinization temperature, suggesting that the granules were disrupted and their water absorption was enhanced. The outcome also showed that the parameters related to antioxidants (total phenols, flavonoid and DPPH activity) and water-soluble vitamins (thiamine, riboflavin and niacin) were more sensitive to processing conditions compared with starch-related components. Altogether, the use of ultrasound-assisted IR drying showed a significant positive effect on the nutrient and antioxidant activity and starch functionality of Mushk budji rice, which can be considered a promising method for processing rice in terms of high quality and low energy consumption.

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Sustainability spotlight

The combination of ultrasound-assisted infrared (IR) drying in rice processing also provides the sustainable alternative to usual practices by saving considerable drying time and energy use while maintaining the nutritional and functional attributes of the product. The given environmentally friendly technique reduces the loss of nutrients and improves the antioxidant activity, which leads to the creation of high-quality rice with fewer environmental effects. The process helps to ensure sustainable food processing by maximizing the ultrasonication time and drying temperature, which are in line with energy conservation and value addition objectives of local aromatic rice such as Mushk budji.

Introduction

Rice (*Oryza sativa* L.) is one of the most significant staple foods in the world, contributing over one-fifth of the global caloric intake and serving as a crucial source of carbohydrates, proteins, vitamins, and bioactive compounds. The physicochemical and nutritional properties of rice are predetermined by the composition of starch (and, in particular, the amylose and amylopectin ratio) and the preservation of antioxidants, phenols, flavonoids, and vitamins during processing.[1] Mushk budji rice is an aromatic variety with a great cultural and economic value in the Kashmir region of India due to its unique aroma, creamy texture, and high eating quality.[2] Nevertheless, there is a lack of research offering an explanation of how the modern processing methods affect the structural, thermal, and nutritional properties of Mushk budji rice. The conventional processing techniques including soaking, steaming, and drying may have an immense influence on the starch morphology, nutrient stability and functional properties of rice grains.[3]

The gelatinization, disruption of crystalline regions, and degradation of heat-sensitive nutrients such as vitamins and antioxidants may occur because of high temperature and long drying periods.[4] Such restrictions have promoted the

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application of more sophisticated non-thermal or mild-intensity physical processing techniques that will help to enhance the quality of rice as well as maintain nutritional integrity.[5] One such new technology is ultrasound-assisted parboiling, which is also a powerful pretreatment that increases mass transfer, hydration and diffusion of nutrients by the process of acoustic cavitation.[6] Breaking microbubbles during ultrasonication creates localized zones of high-temperature and pressure that enhance the penetration of water and alter the structure of starch granules.[7]

Studies have shown that ultrasound can be used to change the structure of amylose and amylopectin, enhance the antioxidant retention and alter the thermal and pasting characteristics of rice starch.[8,9] After pretreatment with ultrasonic soaking, infrared drying is also a quick and energy-efficient method for removing moisture from foods and does not harm the nutritional value of food. The IR radiation enters the substance and offers homogeneous volumetric heating, which reduces oxidative degradation of thermo-sensitive compounds including phenolics and vitamins.[10,11] IR drying could greatly decrease the drying duration, preserve the microstructure of grains, and increase the rehydration characteristics as compared to convective drying.[12]

Ultrasound and IR drying can be synergistic with each other – ultrasound pretreatment of food enables redistribution of internal water and structural loosening, which enhances faster and more uniform drying by IR and retention of bioactive compounds.[13] Although there is an increasing amount of evidence on the individual advantages of ultrasound and IR drying, the combined (synergistic) effect of ultrasound-assisted soaking followed by infrared drying on aromatic rice, particularly Mushk budji, has not been reported in previous literature. Moreover, no study has simultaneously examined such a comprehensive set of parameters (starch composition, antioxidant activity, vitamin profiling, and pasting/thermal behaviour) in a single investigation.

Thus, the current research was aimed at determining the synergies of ultrasound-aided soaking and infrared drying of Mushk budji rice. The aims were to determine (i) alteration in starch composition (amylose and amylopectin), (ii) the difference in antioxidant activity and vitamins and (iii) pasting and thermal properties. The results expected to be obtained are to offer some insight into the structure–function–nutrient associations of Mushk budji rice under new processing conditions.

Materials and methods

Preparation of samples

Local indigenous aromatic rough rice (*Oryza sativa* var Mushk budji) was collected from MRCFC Khudwani Kulgam (Kashmir). The grains were manually cleaned to remove foreign materials and flawed grains and stored for analysis at room temperature (25 ± 3 °C). For the traditional method, paddy rice (Mushk budji) was soaked in distilled water in the proportion of one : two at 25 °C for 24 hours. After that, the water was drained, and the paddy rice was steam-cooked for 15 minutes and was then dried at different temperatures (35, 45 and 55 °C). Drying using the traditional method was carried out using the same infrared (IR) dryer as described for the ultrasonic-assisted parboiling treatment. After drying, the ultimate moisture content was maintained at 13% (w.b.). These samples were then dehusked and polished to obtain white rice, which was then stored in polyethylene bags at 25 °C for further investigation. For ultrasonic-aided parboiling, paddy rice samples (Mushk budji) were soaked for different time periods (2–6 h). The ultrasonic bath was carried out at 40 kHz. The temperature of the soaking medium was carefully kept lower than the gelatinization temperature of rice (*i.e.* lower than 55 °C) during sonication to avoid any untimely starch gelatinization; the range of working temperature was kept between 25 and 35 °C. Each batch of soaking contained 500 g of paddy rice. The samples were soaked, after which they were steamed (15 min). Infrared drying was performed on the grains that were steamed, followed by setting the temperature of the grains to 35, 45 and 55 °C, with an IR dryer having a heating power of 1000 W, temperature control accuracy of ±1 °C and a constant radiation distance of 12 cm. The drying was continued until the final moisture content was 13 percent (w.b.), which was determined on a moisture analyzer. All the samples were then dehusked, polished, cooled and stored under similar conditions to those used in traditional parboiling.

Physico-chemical characteristics

Amylose content. The amount of amylose in the samples (AC) was calculated with the assistance of a spectrophotometer in accordance with the procedure outlined in ref. 14. A total of 100 mg of rice sample was wetted with 1 ml of 95% ethanol to which 9 ml of 1 N NaOH was added. The mixture was boiled in a boiling water bath for 10 min and then cooled down. A 5 ml volume of the solution was put in a volumetric flask to which 1 ml of 1 N acetic acid and 2 ml of iodine solution were added. The amount of solution was adjusted to 100 ml using distilled water to which it was shaken and left to rest after 20 min. The UV-vis spectrophotometer was used to measure the absorbance of the solution at 620 nm (Labtronics, India). AC of the samples was calculated using a standard curve prepared using potato amylase (Sigma Aldrich).

Amylopectin percentage. The amylopectin percentage was calculated using the below mentioned equation. The equation was explained in ref. 15. The average value of amylose % obtained from the equation, based on total starch, was considered for the calculation.

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

Vitamin profiling. Vitamin B1, B2 and B3 estimation according to ref. 16 and photometric measurement were performed using a spectrophotometer. Although spectro-photometric methods provide reliable comparative estimation of vitamins, they are comparatively less specific than chromatographic techniques such as HPLC. Therefore, the obtained values represent approximate estimates of vitamin content rather than highly precise compound-specific measurements.

Thiamine (vitamin B1). The samples of rice (5.0 g) were homogenized with ethanol sodium hydroxide (50 ml). Sodium-hydroxide (4.2 gm) was dissolved in 5 ml DH_2O, and 1 L ethanol (aldehyde free) was added to it. The solution was allowed to stand in a tightly capped bottle for 24 h, after which the clear liquid was decanted into another suitable bottle. Filtering was carried out using a 100 ml flask. And the colour was developed by adding 10 ml of 0.1 N potassium dichromate. The absorbance was measured at 360 nm. A thiamine standard curve was used to determine the thiamine content.

Riboflavin (vitamin B2). The samples (5.0 g) were chopped and treated with 100 ml of 50% ethanol solution. The samples were placed in a shaker for 1 h, and then filtered into a flask. Extracted samples of 10 ml were pipetted and placed into a volumetric flask. Then 10 ml of potassium permanganate (5%) was added, followed by 10 ml of 30% H_2O_2, and the mixture was allowed to stand over a hot water bath for about 30 min. 2 ml of sodium sulphate (40%) was added. This solution was made up to the 50 ml mark and absorbance was measured at 510 nm using a spectrophotometer. The riboflavin content was calculated from a riboflavin standard curve.

Niacin (vitamin B3). The samples were chopped and 5.0 g was taken for niacin estimation. The samples were treated with 50 ml of 1 N H_2SO_4 and shaken for 30 min. 3 drops of ammonia solution were added to the sample and filtered. The filtrate (10 ml) was pipetted into a 50 ml volumetric flask and 5 ml potassium cyanide (0.5 g KCN dissolved in 100 ml cold DH_2O kept in a refrigerator) was added. This was acidified with 5 ml of 0.2 N H_2SO_4 and absorbance was measured at 470 nm wavelength. The niacin content was calculated from a niacin standard curve.

Antioxidant properties

Sample extraction. 2 g of homogenised rice was mixed with 50 ml of 70% methanol. The sample was centrifuged at 2500 rpm for 20 minutes at ambient temperature to extract antioxidants. The decanted supernatant was kept at 4 °C to determine the TPC, TFC, and antioxidant activity (DPPH) of the rice samples.

Total phenolic content. The amount of total phenolics (TPC) was determined using the FC reagent, according to ref. 17. 2 ml of FC reagent (ten times diluted with double-distilled water) was combined with 300 μL of extract and allowed to remain at 25 °C for five mins. The mixture was then mixed with 2.5 ml of sodium carbonate solution. A spectrophotometer was used to measure absorbance at 725 nm after 90 minutes at room temperature. Gallic acid equivalents (mg GAE g^{-1}) in 1 g of dried material were used to express the results.

Total flavonoid content. The colorimetric approach, which was slightly modified from ref. 17, was employed to determine the flavonoids (TFC). In a glass tube, 2.5 ml of distilled water and 0.55 milliliter of the extract were combined. 0.15 milliliters of a 5 percent sodium nitrite solution and 1.0 milliliter of 1 M sodium hydroxide were then added and allowed to stand for six minutes. After six minutes, 0.4 milliliters of a 10 percent aluminum chloride hexahydrate solution were added and the resulting mixture was allowed to rest for an additional five minutes. After that, a vortex mixer was used to mix the mixture, and a spectrophotometer was used to detect absorbance right away at 510 nm. Quricetin equivalents per gram of dried material (milligram of quricetin equivalents per gram) were used to express the results.

DPPH radical scavenging activity. DPPH radical scavenging activity of the sample was assessed using the methodology outlined in ref. 18 with minor adjustments. 1.9 milliliters of a 0.1 millimolar 2,2-diphenyl-1-picrylhydrazyl in ethanol mixture was combined with 0.1 ml of sample extract. After vortexing the mixture for one minute and allowing it to remain at room temperature in the dark for thirty minutes, the absorbance of the mixture was measured at 517 nm. The inhibitory activity percentage was computed as:

$$\mathrm{DPPH}(\%) = \frac{A_1 - A_2}{A_1} \times 100$$

where A_1 is the absorbance without extract and A_2 is the absorbance with extract.

Pasting properties. The rice was first milled into rice flour, and its pasting qualities were tested using a rapid visco analyser (RVA Starch TM, New Port, Scientific Warrie Wood, Australia). The sample consisted of 3 g of rice flour with 12% moisture (on a wet basis) and 25 ml of deionised water, using the method followed by ref. 19. The slurry was cooked according to a specified heating and cooling regime: initially, it was heated from 50 to 95 °C at a rate of 6 °C min^{-1}, then it was kept at 95 °C for 2.7 minutes, then cooled from 95 to 50 °C at a rate of 6 °C min^{-1}, and finally it was held at 50 °C for 2 minutes. Pasting temperature and duration, peak-viscosity, final viscosity, breakdown viscosity and setback viscosity were among the parameters noted.

Thermal properties. The thermal properties of the isolated starch were examined using a differential scanning calorimeter (DSC) (PerkinElmer Co. Ltd, model DSC-7, Norwalk, USA). A 2 mg sample and distilled water (1 : 4 ratios) were put into an aluminum pan. After sealing, the pan was equilibrated for 1 h at room temperature and heated from 20 to 130 °C at a rate of 5 °C min^{-1}. The onset (T_o), peak (T_p), and conclusion temperatures (T_c), as well as gelatinization enthalpy (ΔH (J g^{-1})), were measured.[20]

Statistical analysis. All experiments were conducted three times, and the findings are recorded as the mean of the replicates. The analysis of data was performed using one-way analysis of variance (ANOVA) at a 95% confidence level using SPSS Statistics software (version 16). Duncan multiple range test was used to make post hoc comparisons in order to establish statistical significance at $p = 0.05$.

Results and discussion

Amylose percentage

The amylose content of the untreated control sample was 21 percent. For the two techniques, the amylose content of Mushk budji rice reduced with an increase in drying temperature. It was 20.4 percent at 35 °C and 19.55 percent at 55 °C for traditional soaking, as represented in Table 1. This loss of amylose is

Table 1 Effect of traditional parboiling on the physico-chemical properties of aromatic Mushk budji rice[a]

Physico-chemical properties of rice	Control	Simple soaking for 24 hours and drying temperature		
		35 °C	45 °C	55 °C
Phenolic content (mgGAE g^{-1})	2.87 ± 0.03	3.27 ± 0.03[a]	3.25 ± 0.03 [a]	3.21 ± 0.02[b]
Flavonoid Content (mgQE g^{-1})	3.35 ± 0.0	5.59 ± 0.05[a]	5.01 ± 0.2[b]	4.4 ± 0.3[c]
DPPH (%)	45.2 ± 0.02	61.2 ± 0.04[a]	53.7 ± 0.05[b]	49.7 ± 0.3[c]
Amylose (%)	21.5 ± 0.03	20.4 ± 0.04[a]	20.01 ± 0.04[b]	19.55 ± 0.05[c]
Amylopectin (%)	78.5 ± 0.01	79.6 ± 0.04[c]	79.99 ± 0.01[b]	80.8 ± 0.03[a]
Thiamine (mg g^{-1})	0.00404 ± 0.002	0.00505 ± 0.004[a]	0.00433 ± 0.003[b]	0.00407 ± 0.004[c]
Riboflavin (mg g^{-1})	0.02175 ± 0.04	0.03634 ± 0.02[a]	0.02575 ± 0.02[b]	0.02491 ± 0.01[c]
Niacin (mg g^{-1})	0.0207 ± 0.03	0.0461 ± 0.03[a]	0.03153 ± 0.01[b]	0.0246 ± 0.043[c]

[a] Values are expressed as mean ± standard deviation ($n = 3$). Different superscript letters (a–c) within the same row indicate significant difference ($p \leq 0.05$). GAE: gallic acid equivalent; QE: quercetin equivalent.

also the reason behind the ensuing increase in the proportion of amylopectin, which is an increase relative to amylopectin loss and not to the formation of amylopectin. The amylose content rose gradually and maximized at 17.97 percent for 4 hours of ultrasonic soaking at 35 °C drying temperature (Fig. 1a), owing to ultrasonic cavitation that led to starch granule swelling and greater release of amylose chains. However, this value was lower than that observed in the traditional method even at 55 °C, which may be attributed to greater leaching and possible depolymerization of amylose during ultrasonic treatment. There was however a slight decline at longer periods of soaking (5–6 hours) perhaps as a result of breakdown or depolymerization of the leached amylose under long periods of sonication. This is also explained by the increased drying temperatures, which cause the thermal rearrangement of the starch molecules and the appearance of starch–protein complexes that prevent the process of iodine binding. The highest decrease in amylose occurred at 55 °C, and this signifies a high thermal effect. These findings are consistent with those of ref. 21, which reported up to 59.9 percent decrease in amylose content in Chakhao Poireiton rice after ultrasonication-assisted parboiling, due to starch–protein interactions during steaming that hinder iodine–amylose complex formation.

Amylopectin percentage

The amylopectin content of the control sample was 79 percent. With an increase in the drying temperature, the amylopectin content of Mushk budji rice increases for both methods. Traditional parboiling (as shown in Table 1) resulted in amylopectin contents ranging from 82.13 to 82.55 percent between 35 and 55 °C during soaking and steaming, respectively, because of amylose leaching. As amylose decreases during processing due to leaching, the comparative change of amylopectin is more of a proportional change rather than an absolute increase. The amylopectin level gradually increased with sonication time, and the highest level was 84.87 percent after 6 hours (Fig. 1b). Initially, ultrasonic cavitation promotes the release and leaching of amylose from starch granules, leading to a reduction in measurable amylose content. This disruption of starch granules reduces the proportion of amylose in the starch fraction, thereby resulting in a relative increase in amylopectin percentage rather than the actual formation of new amylopectin. Nevertheless, with shorter ultrasonication time (2 hours) and low IR drying (IR 35 °C), the content of amylopectin was not significantly different than that of traditionally parboiled samples, indicating that the low conditions did not

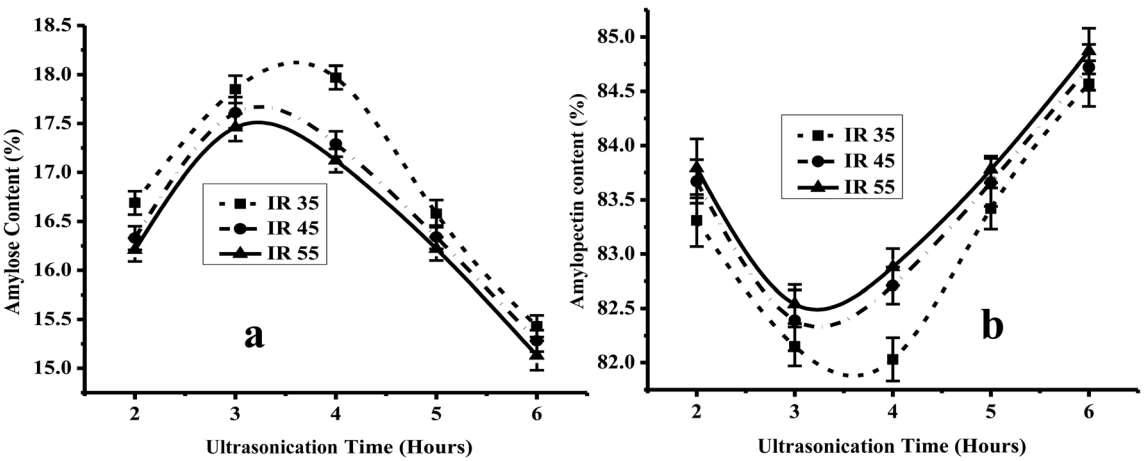

Fig. 1 Effect of ultrasonic soaking time and infrared drying temperature on the amylose (a) and amylopectin content (b) of aromatic rice (Mushk budji).

disrupt it greatly. It is also possible that the increase in the levels of amylopectin with higher temperature is because of the gelatinization and rearrangement of starch during drying thus stabilizing the amylopectin-rich regions. These findings are also similar to the research results of ref. 22 and 23, which reported that parboiling reduces amylose through leaching, thereby relatively increasing amylopectin in rice starch fractions. Thus, the observed increase in amylopectin should be interpreted as a proportional rise due to amylose loss, not the synthesis of new amylopectin.

Vitamin B1 (thiamine). In this study, ultrasonic-assisted parboiling positively influenced thiamine retention in rice. The treatment helped preserve B1 at lower IR drying temperatures, minimizing thermal degradation. The amount of thiamine in the present study was 0.00404–0.00627 mg g^{-1}. The lowest value was in the control sample (0.00404 mg g^{-1}). Both methods show a decline in thiamine content with the rise in the temperature in the drying process. In conventional soaking (as shown in Table 1), the values ranged between 0.00505 in 35 °C and 0.00407 mg g^{-1} at 55 °C. It was found that thiamine content increased gradually with the sonication time (as shown in Fig. 2a) to a peak of 0.00627 mg g^{-1} in 4 hours. But after this, a decrease was observed at 5 and 6 hours. This drop can be explained by the long exposure of ultrasonic waves, which results in local heating and possible oxidative deterioration of this heat labile vitamin. In comparison to the literature values, germinated brown rice of FARO 44 (GBR-24) has 0.0034 mg g^{-1}, FARO 57 (GBR-35) has also 0.0034 mg g^{-1} and NERICA-8 (GBR-35) has 0.0035 mg g^{-1}, which are very low compared to the amount of thiamine found in our experiment. The increase in thiamine concentration at reduced drying temperatures can however be credited to the cavitation effect caused by ultrasound, increasing the rate of diffusion of vitamin B1 into endosperm, which eventually does not go to waste during milling. Conversely, the reduction at elevated temperatures of drying is probably caused by the fact that thiamine is heat-sensitive, and its degradation occurs during heating. This trend agrees with the study reported in ref. 24, which also observed significant vitamin loss in milled rice due to bran and embryo removal and emphasized that mild processing conditions better retain water-soluble vitamins.

Vitamin B2 (riboflavin). In this study, parboiling of rice with the help of ultrasonic showed a positive impact on riboflavin (vitamin B2) retention in rice. The treatment was suitable to maintain the B2 content under lower infrared (IR) drying conditions through minimizing thermal degradation. The concentration of riboflavins in the current work was in the range of 0.02175 to 0.08863 mg g^{-1}, with the minimum value of 0.02175 (mg g^{-1}) observed in the control sample. As with thiamine, the drying temperature of IR caused a progressive decrease in riboflavin content in both soaking and drying methods. Table 1 demonstrates that in traditionally soaked samples, the amount of riboflavin concentration decreased from 0.03634 mg g^{-1} at 35 °C, to 0.02491 mg g^{-1} at 55 °C. It was found that the concentration of riboflavin increased with the increase in the period of ultrasonication (as shown in Fig. 2b),

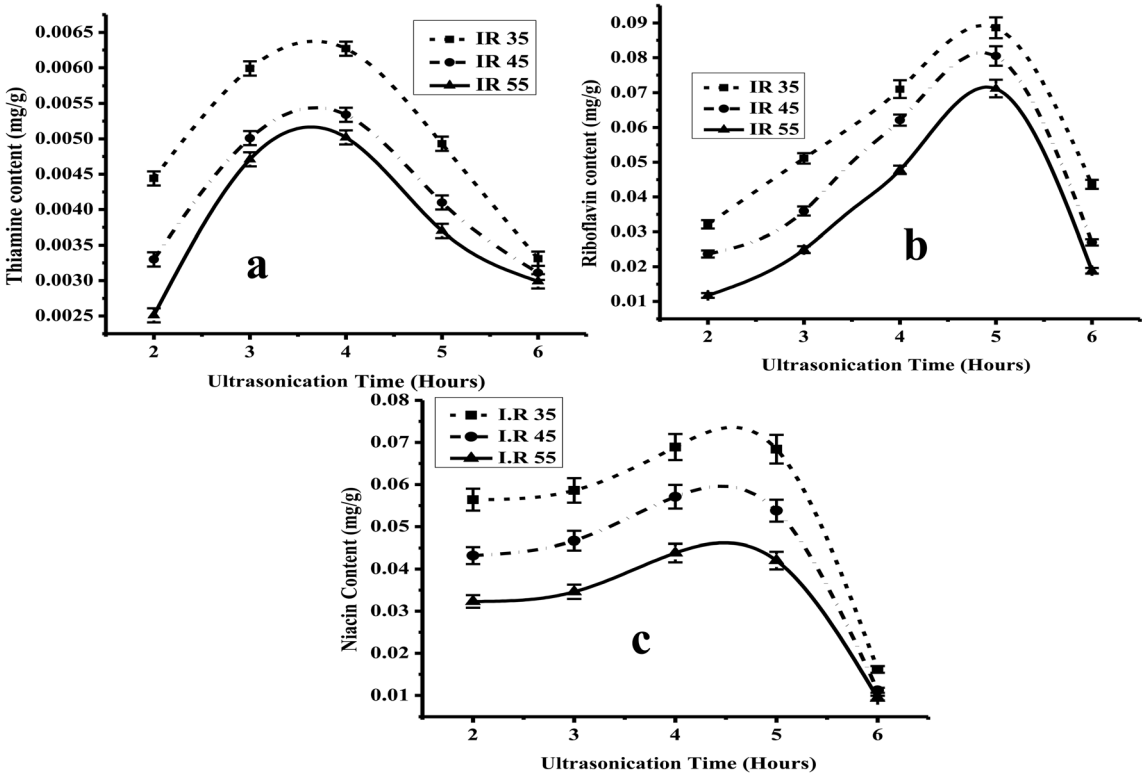

Fig. 2 Effect of ultrasonic soaking time and infrared drying temperature on the thiamine (a), riboflavin (b) and niacin content (c) of aromatic rice (Mushk budji).

with the highest concentration of 0.08863 mg g^{-1} at 5 hours (35 °C). Nevertheless, a decrease was observed after this period *i.e.* 6 hours, which was probably because of the accumulation of the ultrasonic energy and the concentration of local heat, resulting in the loss of this vitamin with the heat. Comparatively, FARO 44 (GBR-24 h) has 0.0269 mg g^{-1}, FARO 57 (GBR-35) has 0.0292 mg g^{-1} and NERICA-8 (GBR-35) has 0.0298 mg g^{-1}, which are all lower than the riboflavin content that was found in our study, which confirms better B2 retention for ultrasonic-assisted parboiling. This improvement can be explained by the fact that the cavitation effect caused by ultrasound results in the increased permeability and deeper diffusion of vitamin B2 into the grain interior, thereby reducing its loss during post-processing. In contrast, high drying temperatures must have been involved in the decomposition of riboflavin since it is thermolabile. These results are in agreement with the findings in ref. 24, which also obtained significant losses of vitamins during harsh processing and advised mild thermal processing as a better preservation technique for water-soluble vitamins.

Vitamin B3 (niacin). It was also discovered that ultrasound-assisted parboiling has a significant impact in improving the retention of niacin (vitamin B3) in rice. The optimal concentration of niacin was observed in lower temperatures of IR drying, indicating the usefulness of the combined method in preserving this relatively stable vitamin at high temperatures. The amount of niacin in the present case ranged between 0.0207 and 0.0689 mg g^{-1}. The lowest level (0.0207 mg g^{-1}) was recorded in the control group. For both methods, the content of niacin declines with the drying temperature. A significant increase of 0.0461 mg g^{-1} was noted in conventional parboiling samples dried at IR 35 °C. The niacin content decreased with an increase in the drying temperature and thus the values were 0.0461 mg g^{-1} at 35 °C and 0.0246 mg g^{-1} at 55 °C, as shown in Table 1. There was a steady rise in the amount of niacin with increasing sonication time (as demonstrated in Fig. 2c), reaching the maximum at 4 hours (0.0689 mg g^{-1}). Nonetheless, some reduction was found at 5 and 6 hours, which could be explained by the protracted exposure during which oxidation or external migration took place. In comparison to the literature, FARO 44 (GBR-24) contains 0.0099 mg g^{-1}, FARO 57 (GBR-35) contains 0.0086 mg g^{-1} and NERICA-8 (GBR-35C) contains 0.0090 mg g^{-1}, far lower than the niacin values determined in this study, indicating better B3 retention. Although niacin exhibits greater thermal stability compared to thiamine and riboflavin, excessive infrared (IR) drying temperatures can still promote its volatilization or oxidative degradation. The elevated retention of niacin under lower IR conditions must also be because of the cell disruption caused by ultrasonication, which allows increased diffusion and integration of niacin into the rice kernel. These results align with those in ref. 24, which reported enhanced niacin levels in germinated and less-processed rice varieties, stressing the importance of gentle processing to preserve vitamin integrity.

Antioxidant properties

Phenolic content. Ultrasonic-assisted soaking and infrared drying had a strong effect on the phenolic content of Mushk budji rice (Fig. 3a). The control sample had 2.87 mg GAE g^{-1} whereas in traditional parboiling, it increased marginally (3.21–3.41 mg GAE g^{-1}). The values in ultrasonic-assisted parboiling were between 3.62 and 4.64 mg GAE g^{-1}, and this was determined by the time of soaking and the temperature of drying. An obvious upward trend was observed up to 3–4 hours of ultrasonication beyond which a slowdown was evident. The maximum values were obtained at IR 35 °C where drying at a high temperature 45 °C and 55 °C gave rise to significant decreases, which showed the thermal degradation of thermozoic phenolic compounds. The decrease in TPC at higher IR temperatures and prolonged sonication may also be attributed to oxidation, structural breakdown of phenolic compounds, and their possible leaching into the soaking medium due to extended exposure. The TPC experienced some slight growth during the ultrasonic hydration, which can be sufficiently explained by the shorter ultrasonic hydration processing time that reduces leaching into the hydration medium and the degradation of heat-sensitive compounds in the phytochemicals.[5,25] Another cause of the use of UH (Ultrasonic Hydration) is the enhanced preservation of bioactive compounds. The results of the study in ref. 26 ensure that the use of ultrasound-aided hydration entails reduced processing time, decreased energy consumption, and increased nutrient retention.

Flavonoid content. The control sample was found to contain a Total Flavonoid Content (TFC) of 3.35 mg QE g^{-1}. TFC in traditionally parboiled samples (Table 1) varied with drying temperature, with a definite decrease in TFC at higher drying temperatures, resulting in a range of 4.4 at 55 °C down to 5.59 mg QE g^{-1} at 35 °C. The flavonoid content exhibited a positive response to soaking time under ultrasonic soaking with a highest content of 5.77 mg QE g^{-1} and a lowest content of 5.01 mg QE g^{-1} at 4 hours (35 °C) and 6 hours (55 °C), respectively (Fig. 3b). This shows that intermediate ultrasonication (3–4 hours) provided better retention of flavonoid because of cavitation that helps in cell rupture and better release of bioactive compounds. Nonetheless, the extended time of ultrasonication (more than 4 h) and an increase in the temperature of drying decreased TFC due to the thermo-sensitive nature of flavonoids as a group, which degrades under the influence of thermal and ultrasonic stress. The results of our study align with previous studies[27] that have found a marked increase in flavonoid content following ultrasonic treatment due to the improvement in the ability to extract the substance through the plant cell walls. A decrease at higher temperatures is facilitated,[28] which emphasized that flavonoids can be easily degraded during the heat treatment.

DPPH. The lowest DPPH value was found in the control (45.2%). Antioxidant activity decreased with an increase in drying temperature from 35 to 55 °C for both the methods. For the traditional parboiling method, antioxidant activity decreased from 61.2% at 35 °C to 49.7% at 55 °C because of thermal degradation of phenolic compounds (Table 1). However, ultrasonic-assisted soaking yielded significantly better results than traditional parboiling, where DPPH values continued to rise with increasing soaking time and peaked at 4 h. Higher percentages were achieved with 68.9% (at 35 °C),

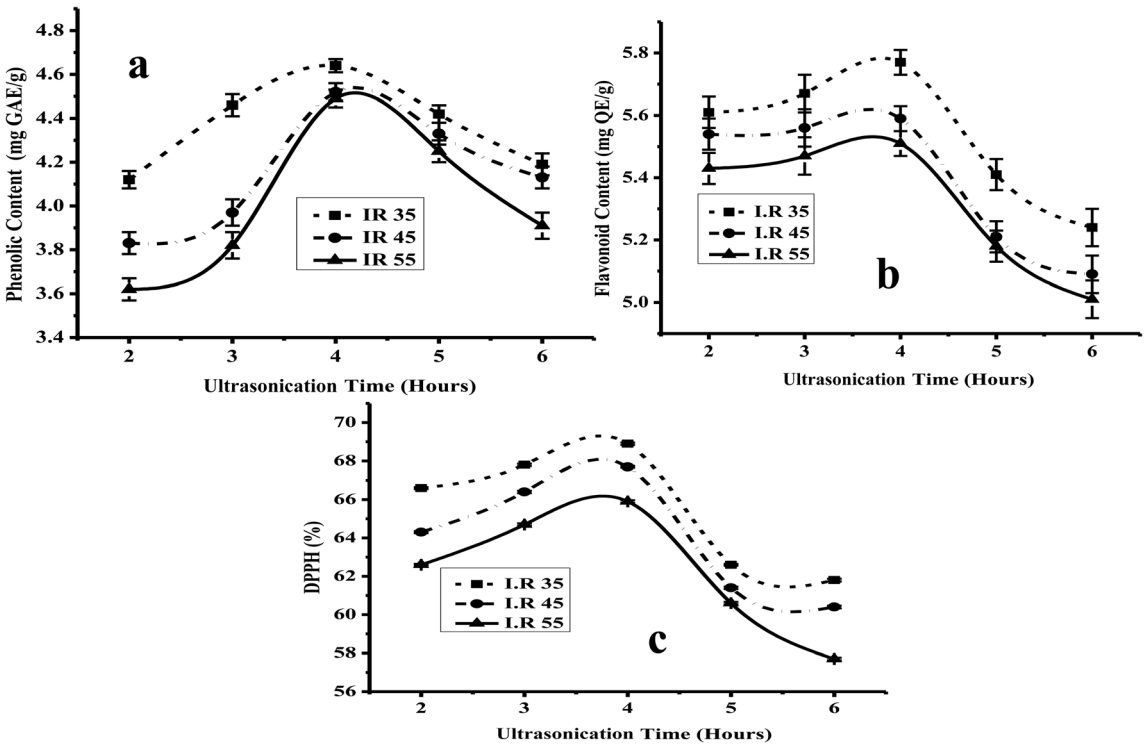

Fig. 3 Effect of ultrasonic soaking time and infrared drying temperature on the phenolic content (a), flavonoid content (b) and DPPH (c) of aromatic rice (Mushk budji).

67.7% (at 45 °C), and 65.9% (at 55 °C) (as shown in Fig. 3c), followed by a slight decrease after 4 h, presumably due to an excessive exposure that negatively affects the stability of antioxidants. The DPPH values for all samples varied from 49.7 to 68.9%, indicating that lower drying temperatures and shorter ultrasonication times improved antioxidant activity. It is possible that the cavitation produced during ultrasound breaks the cell wall, releasing more phenols and therefore enhancing antioxidant capability. Athoi *et al.*[21] similarly noted greater antioxidant activity in ultrasonically treated parboiled rice than in untreated or raw rice. Additionally, other studies[29,30] have demonstrated similar effects on retaining antioxidants using ultrasound.

Pasting properties. Peak Viscosity (PV) is the capacity of starch to expand because of increasing temperature prior to its physical disintegration. Table 2 presents the highest viscosity at 27.75 P, which was the highest swelling capacity of the native starch granules. The highest viscosity was between 19.326 and 23.122 P to ensure moderate gelatinization to maintain swelling capacity in the case of traditional parboiling. Compared to the control, traditionally parboiled samples exhibited lower peak viscosity values. Peak viscosity in ultrasonic soaking, as illustrated in Table 2, was dependent on soaking time and drying temperature, with the viscosity values ranging from 6.103 to 22.7 P at 35 °C, 5.89 to 21.39 P at 45 °C, and 7.595 to 15.78 P at 55 °C, indicating that ultrasound alters the integrity of starch granules and does not allow maximum swelling, and the stronger the sonication intensity, the greater the disruption of the starch structure, leading to a reduction in peak viscosity. In general, the ultrasonic samples had a lower peak viscosity than the control and traditionally parboiled samples. The drop in peak viscosity suggests decreased swelling capacity and water-binding capacity of starch grains caused by some gelatinization during soaking and sonication, leading to thinner pastes, which could be advantageous in products that demand reduced paste thickness and smoother cooking properties.[31,32]

Breakdown viscosity (BD) implies the stability of the starch paste to heat and shear. The control sample had a BD of 18.331 P, which indicates the inherent paste stability. Traditional parboiling samples had BD values of 1.963 to 1.970 P, indicating moderate shear resistance. Breakdown viscosity values in traditionally parboiled samples were lower than the control. The ultrasonic soaking technique showed a significant variation in the breakdown viscosity with the time of soaking and drying temperature with values of 3.988 to 16.33 P at 35 °C, 3.05 to 18.62 P at 45 °C, 4.321 to 11.17 P at 55 °C. Compared to the control, ultrasonicated samples generally exhibited reduced breakdown viscosity values, indicating that ultrasound disintegrates the starch granules and exposes them to shear effects, which lead to the thinning process. A decrease in breakdown viscosity of ultrasound-treated samples is an indication that ultrasound-treated samples have a lower chance of maintaining stability in hot-paste but at the expense of mechanical shear and heating stress resistance during the cooking process, which can affect processing behaviour and texture of the end product.[33]

Setback Viscosity (SV) is the retrogradation tendency of starch during the cooling process. The SV of the control sample was 74.35 P, whereas in traditional parboiling, the setback

Table 2 Effect of traditional parboiling and ultrasonic soaking time at different infrared drying temperatures on the pasting properties of aromatic Mushk budji rice[a]

Ultrasonication time (h)	Drying temp (°C)	Peak viscosity (P)	Peak time (min)	Pasting temp (°C)	Breakdown viscosity (P)	Final viscosity (P)	Setback viscosity (P)
2	35	22.7 ± 0.03^{a}	8.50 ± 0.02^{a}	64.54 ± 0.03^{c}	16.33 ± 0.02^{a}	79.02 ± 0.03^{a}	74.35 ± 0.04^{a}
3		15.91 ± 0.03^{b}	8.50 ± 0.02^{a}	72.81 ± 0.03^{a}	11.12 ± 0.04^{b}	77.35 ± 0.02^{b}	73.33 ± 0.03^{b}
4		15.62 ± 0.02^{b}	8.48 ± 0.03^{a}	72.77 ± 0.02^{a}	10.93 ± 0.02^{b}	76.67 ± 0.03^{c}	73.28 ± 0.02^{b}
5		7.32 ± 0.03^{c}	8.50 ± 0.02^{a}	69.52 ± 0.04^{b}	3.995 ± 0.03^{c}	75.64 ± 0.02^{d}	70.85 ± 0.03^{c}
6		6.103 ± 0.02^{d}	8.50 ± 0.03^{a}	66.43 ± 0.02^{c}	3.988 ± 0.03^{c}	73.79 ± 0.02^{e}	6.90 ± 0.03^{d}
2	45	21.39 ± 0.03^{a}	8.50 ± 0.02^{a}	64.35 ± 0.03^{c}	18.62 ± 0.04^{a}	72.03 ± 0.02^{a}	67.53 ± 0.03^{a}
3		20.28 ± 0.02^{b}	7.50 ± 0.03^{b}	66.90 ± 0.03^{b}	17.78 ± 0.02^{b}	68.68 ± 0.03^{b}	63.55 ± 0.04^{b}
4		18.84 ± 0.04^{c}	8.50 ± 0.02^{a}	71.24 ± 0.02^{a}	13.71 ± 0.03^{c}	65.86 ± 0.02^{c}	61.63 ± 0.03^{c}
5		13.30 ± 0.02^{d}	8.50 ± 0.02^{a}	70.09 ± 0.04^{a}	8.798 ± 0.03^{d}	64.47 ± 0.03^{d}	59.84 ± 0.02^{d}
6		5.89 ± 0.03^{e}	8.50 ± 0.03^{a}	69.92 ± 0.03^{a}	3.050 ± 0.02^{d}	57.71 ± 0.03^{e}	52.65 ± 0.03^{e}
2	55	15.78 ± 0.03^{a}	8.50 ± 0.02^{a}	71.18 ± 0.03^{a}	11.17 ± 0.03^{a}	85.32 ± 0.02^{a}	80.72 ± 0.03^{a}
3		14.62 ± 0.02^{b}	8.50 ± 0.03^{a}	65.68 ± 0.03^{b}	10.23 ± 0.04^{b}	79.50 ± 0.03^{b}	75.11 ± 0.04^{b}
4		13.06 ± 0.03^{c}	8.50 ± 0.02^{a}	70.08 ± 0.03^{a}	8.881 ± 0.03^{c}	72.87 ± 0.03^{c}	65.87 ± 0.02^{c}
5		8.37 ± 0.03^{d}	8.50 ± 0.02^{a}	71.13 ± 0.03^{a}	5.27 ± 0.03^{d}	68.97 ± 0.03^{d}	62.69 ± 0.03^{d}
6		7.595 ± 0.02^{d}	8.50 ± 0.02^{a}	65.74 ± 0.03^{b}	4.321 ± 0.02^{e}	61.12 ± 0.03^{e}	57.85 ± 0.02^{d}
Traditional parboiling	35°C	23.122 ± 0.02^{a}	8.5 ± 0.015^{a}	71.22 ± 0.02^{c}	1.9701 ± 0.02^{a}	81.144 ± 0.02^{a}	80.8522 ± 0.02^{a}
	45°C	22.215 ± 0.02^{b}	8.5 ± 0.01^{a}	72.15 ± 0.02^{b}	1.9691 ± 0.02^{a}	80.732 ± 0.02^{b}	80.632 ± 0.02^{b}
	55°C	19.326 ± 0.01^{c}	8.44 ± 0.01^{b}	73.26 ± 0.01^{a}	1.9631 ± 0.02^{a}	80.413 ± 0.02^{b}	80.307 ± 0.02^{c}

[a] Values are expressed as mean ± standard deviation ($n = 3$). Different superscript letters (a–e) within the same column indicate significant differences ($p \leq 0.05$).

viscosity ranges from 80.307 to 80.852 P, indicating a higher retrogradation tendency than the control. Thus, setback viscosity in traditionally parboiled samples was comparable to or slightly higher than the control. For the ultrasonic soaking procedure, setback viscosity was between 6.90 and 74.35 P at 35 °C, between 52.65 and 67.53 P at 45 °C and between 57.85 and 80.72 P at 55 °C. In comparison to the control, ultrasonicated samples generally showed lower setback viscosity values, indicating that the ultrasound tended to decrease retrogradation though a few higher temperature treatments exhibited some partial recovery of the SV. The lower setback viscosity suggests that amylose retrogradation has a lower tendency during the cooling process and can lead to a less firm texture and better storage properties of cooked rice.[32]

Final Viscosity (FV) is the strength of the starch paste during cooling. FV of the control sample was 79.02 P, whereas parboiling samples that used traditional samples had a range between 80.413 to 81.144 P, which showed good gel formation. Final viscosity of traditionally parboiled samples was comparable to or slightly higher than the control. The samples under ultrasonic conditions were found to have FV values between 73.79 and 79.02 P at 35 °C, 57.71 and 72.03 P at 45 °C and 61.12 and 85.32 P at 55 °C. Overall, final viscosity values of ultrasonicated samples were generally lower than the control, which demonstrated that gel forming capacity tended to be lower under ultrasound and it differed as a result of soaking time and temperature. Reduced final viscosity indicates a reduced gel strength, which can affect the firmness of cooked rice and can be beneficial to products where it is desirable to have a soft texture and reduced rigidity after cooling.[33]

Generally, ultrasonic soaking led to low pasting properties (peak, breakdown, setback and final viscosities) when compared to traditional parboiling and control samples, which is the indication of the disruptive impact of ultrasound on the starch granules. In general, the changes in the pasting parameters indicate altered paste-thickness, stability, retrogradation behaviour and gel strength, which are customisable for certain food applications based on preferred specific texture and cooking characteristics. The findings are consistent with those found in the studies in ref. 7 and 34, which established that traditional parboiled rice showed better PV, BD, and SV, exhibiting reduced shear-thinning with cooking, and ultrasound-assisted parboiling reduced pasting properties with extension of ultrasonic soaking time. In the same manner, our findings are consistent with those reported in ref. 35 and 36, which proved that ultrasound has a significant effect on the pasting behavior of rice starch.

Differential scanning calorimetry. The thermal analysis of Mushk budji rice starch provided precise information on the physical and chemical transformations occurring during ultrasonic-assisted and traditional parboiling treatments. The onset temperature (T_o) and peak temperature (T_p) of both ultrasonicated and traditional parboiled samples were consistently lower than those of the raw control. This indicates that the starch granules in treated rice began their phase transition at comparatively lower temperatures than the untreated grains (Table 3). Such behavior can be attributed to structural

Table 3 Effect of traditional parboiling and ultrasonic soaking time at different infrared drying temperatures on the thermal properties of aromatic Mushk budji rice[a]

Ultrasonication time	Infrared drying	T_o (°C)	T_p (°C)	T_c (°C)	ΔH (J g^{-1})
0	Control	63.5 ± 0.30	69.0 ± 0.30	74.2 ± 0.40	9.8 ± 0.20
2	35	62.0 ± 0.30^{a}	67.5 ± 0.31^{a}	72.8 ± 0.40^{a}	10.4 ± 0.20 ^{a}
3		61.5 ± 0.30^{b}	67.0 ± 0.30^{b}	72.5 ± 0.40^{b}	10.2 ± 0.20 ^{b}
4		61.2 ± 0.30^{c}	66.7 ± 0.33^{c}	72.2 ± 0.40^{c}	10.0 ± 0.20^{c}
5		61.0 ± 0.30^{c}	66.5 ± 0.30^{c}	72.0 ± 0.40^{c}	9.6 ± 0.20^{d}
6		60.8 ± 0.30^{d}	66.2 ± 0.30^{d}	71.8 ± 0.40^{d}	9.7 ± 0.20^{d}
2	45	62.5 ± 0.30^{a}	68.0 ± 0.30^{a}	73.2 ± 0.40^{a}	10.6 ± 0.20^{a}
3		62.0 ± 0.30^{b}	67.7 ± 0.30^{b}	73.0 ± 0.40^{b}	10.4 ± 0.20^{b}
4		61.8 ± 0.30^{c}	67.5 ± 0.30^{c}	72.8 ± 0.40^{c}	10.2 ± 0.20^{c}
5		61.5 ± 0.30^{d}	67.2 ± 0.30^{d}	72.5 ± 0.40^{d}	10.0 ± 0.20 ^{d}
6		61.2 ± 0.30^{e}	67.0 ± 0.30^{d}	72.2 ± 0.40^{d}	9.7 ± 0.20 ^{e}
2	55	63.0 ± 0.30^{a}	68.5 ± 0.30^{a}	73.8 ± 0.40^{a}	10.8 ± 0.20 ^{a}
3		62.5 ± 0.30^{b}	68.2 ± 0.30^{b}	73.5 ± 0.40^{b}	10.6 ± 0.20 ^{b}
4		62.2 ± 0.30^{c}	68.0 ± 0.30^{c}	73.2 ± 0.40^{b}	10.4 ± 0.20 ^{c}
5		62.0 ± 0.30^{c}	67.8 ± 0.30^{c}	73.0 ± 0.40^{c}	10.2 ± 0.20 ^{d}
6		61.8 ± 0.30^{d}	67.5 ± 0.30^{d}	72.8 ± 0.40^{d}	10.0 ± 0.20 ^{d}
Traditional parboiling	35	63.0 ± 0.30^{c}	68.5 ± 0.30^{c}	73.8 ± 0.40 ^{b}	10.0 ± 0.20 ^{a}
	45	63.2 ± 0.30^{b}	68.7 ± 0.30^{b}	74.0 ± 0.40 ^{a}	10.1 ± 0.20 ^{a}
	55	63.5 ± 0.30^{a}	68.9 ± 0.30 ^{a}	74.1 ± 0.40 ^{a}	10.2 ± 0.20 ^{a}

[a] Values are expressed as mean ± standard deviation (n = 3). Different superscript letters (a–e) within the same column indicate significant differences ($p \leq 0.05$). T_o: onset temperature; T_p: peak temperature; T_c: conclusion temperature; ΔH: enthalpy change.

modifications within the starch matrix caused by ultrasonication, which enhances water absorption and increases the mobility of starch polymers. The gelatinization enthalpy (ΔH) of the treated samples was higher than that of the control, particularly at shorter ultrasonication durations (2 hours). This suggests improved molecular rearrangement and a relatively higher proportion of amylopectin, likely due to the unavoidable leaching of amylose into the soaking medium.[37] However, prolonged ultrasonication (5–6 hours) resulted in only minimal changes in ΔH, implying partial disruption of starch granules and a decrease in overall thermal stability. The conclusion temperature (T_c), representing the completion of gelatinization, also decreased with increasing ultrasonication time. This further supports the idea that ultrasonication facilitates and accelerates the gelatinization process. Among the DSC transitions, the dominant contribution arises from amylopectin crystallites, as amylose crystallites typically melt at much higher temperatures (120–160 °C).[37] Overall, the findings demonstrate that moderate ultrasonication and parboiling enhance gelatinization energy and promote earlier phase transitions, whereas extended ultrasonication exposure leads to reduced thermal stability due to granule weakening.

Conclusion

The findings of this study indicate that combining the ultrasound-assisted soaking and infrared drying significantly enhances the physicochemical and nutritional value of Mushk budji rice. Ultrasonic cavitation improved water diffusion, starch gelatinization, as well as vitamin and phenolic compound migration into endosperm, whereas IR drying induced homogeneous and gentle removal of moisture and reduced the loss of nutrients. The combination of these effects offers a more regulated alteration of the starch structure but retains heat-sensitive compounds; therefore, the method is very appropriate to quality-conscious food processing. The most practical condition turned out to be moderate ultrasonication (3–4 h) with low IR temperature (35 °C), which conserves all vitamins (B1, B2, and B3), boosts phenolics and flavonoids, and improves antioxidant potential. This optimized combination offers food processors a balanced approach by maximizing nutritional retention without compromising structural integrity. But prolonged sonication or a higher drying temperature caused adverse consequences on bioactive retention and thermal stability of food because the structural disruption became too great. This shows a distinct trade-off: moderate processing can improve quality, but too much can cause nutrient loss and reduced starch stability. Among the examined properties, antioxidant activity and water-soluble vitamins responded more strongly to ultrasonic-assisted soaking and infrared drying conditions, whereas starch fractions primarily reflected structural changes. The ultrasound-IR combination method is thus a viable solution to the conventional method of parboiling as it is more sustainable and non-thermal, and it has the potential to preserve the nutritional and functional properties of aromatic rice varieties. Overall, these insights provide valuable guidance for designing energy-efficient, nutrient-retentive post-harvest technologies that can enhance processing quality and market value of Mushk budji rice.

Conflicts of interest

The authors declare no conflicts of interest.

Data availability

The datasets generated and/or analyzed during this study are included in this manuscript.

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