



Physico-chemical Characterisation of Ultrasound Processed Finger Millet Malt

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ABSTRACT

Background: Finger millet (*Eleusine coracana*) is recognized for its high nutritional value and potential as a staple food source across various regions. However, its widespread adoption is limited due to the presence of antinutritional factors which inhibits nutrient absorption. This study investigates the effect of sonication as an innovative processing technique on the finger millet malt's nutritional profile, antioxidant components and micronutrient bioaccessibility.

Methods: During the hydration process, finger millet grains were subjected to different sonication treatments and optimized with the help of central composite design in design expert software. Parameters like Angle of Repose, water activity, water holding capacity, moisture content, color, calcium, iron and % of bioaccessibility of calcium and iron were analyzed using standard protocols.

Result: Sonication treatment significantly improved the physical, nutritional and functional properties of finger millet malt. The angle of repose increased from 27.45 ± 0.95 to 35.52 ± 0.82 , while water activity, water holding capacity (%) and moisture content (%) enhanced from 0.544 ± 0.00 to 0.596 ± 0.00 , 201.36 ± 0.95 to 218.36 ± 1.96 and 7.27 ± 0.56 to 7.88 ± 0.48 , respectively. Nutrient content showed remarkable enhancement, like calcium (mg/100 g) and iron (mg/100 g) from 323 ± 0.13 to 341 ± 0.45 and 3.73 ± 0.54 to 7.12 ± 0.22 . Concurrently, antinutritional factors such as phenols (mg/100 g) and tannins (mg/100 g) decreased from 126.22 to 50.11 and 107.91 to 50.64, respectively, boosting mineral bioaccessibility. Calcium and iron bioaccessibility (%) improved from 0.51 to 36.54 and 1.92 to 58.26. Optimal conditions were observed at 18 min, 30°C and 100% amplitude, making finger millet malt a superior and palatable food ingredient.

Key words: Bioaccessibility, Hydration, Malting, Thermosonication, Ultrasound.

INTRODUCTION

Developing nations are primarily focusing on cereal grains to sustain their growing population, but challenges like groundwater depletion and climate change have shifted interest towards millets, known for their resilience and nutritional value (Sruthi and Rao, 2021). Millets are considered the "nutri-cereals of today and the coarse grains of yesterday." (Asawari *et al.*, 2024). In 2022, India produced 39% of the world's millet, including 26.01 million tonnes of finger millet (*Eleusine coracana*) (Pavithra, 2023). Finger millet is extensively grown in Karnataka, Tamil Nadu, Andhra Pradesh, Orissa, Maharashtra, Uttar Pradesh, Bihar, Gujarat and Madhya Pradesh (Geetha *et al.*, 2012). Nagaraja *et al.* (2022) states that it is often regarded as "Super Cereal" and serves as a staple food for low-income households in India due to its high content of dietary fiber, calcium, essential amino acids and other nutrients. It offers health benefits such as antidiabetic, anti-tumorigenic and antioxidant properties, with a unique profile of 5-8% protein, 65-75% carbohydrates and 344 mg/100 g of calcium (Devi *et al.*, 2014). Finger millet malting is common among both domestic and commercial level in India and it is extensively employed in weaning foods, beverages, infant nutrition and pharmaceutical preparations. Malting aims at producing enzymes and break down the cell walls surrounding starch granules. This enzymatic activity converts them into amino acids and soluble peptides, in addition to facilitating the degradation of the proteinaceous matrix surrounding the

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endosperm's starch granules (Andriotis *et al.*, 2016). To obtain greatest health advantages from finger millet, anti-nutrients like phytates and tannins must be eliminated. The traditional malting process is presently practiced to eliminate these anti-nutrients. However, this procedure takes a long time and yields low-quality grains (Yadav *et al.*, 2021).

Literature has reported positive results on sonication of seeds and grains by increasing hydration and germination performance. Through acoustically induced

cavitation activity, ultrasound treatment stands as a promising avenue for reducing processing time and diminishing the presence of anti-nutrients in finger millet. It also augments water binding capacity, starch solubility, starch particle size reduction and uniform dispersion (Yadav *et al.*, 2021). This study aims to evaluate the impact of malting conditions on the physical, chemical and functional properties of ultrasonicated malted flour. The primary objective is to determine optimal malting conditions that preserve the nutritional content of finger millet, which is rich in essential minerals like calcium and iron. Additionally, the research assesses the bioaccessibility of minerals in control and optimized sonicated samples using solubility and dialysis methods. This comprehensive approach aims to deepen the understanding of finger millet's nutritional significance and its potential to provide essential nutrients.

MATERIALS AND METHODS

The present research was conducted at Dr. NTR College of Agricultural Engineering, Bapatla, Andhra Pradesh, India, over a period of six months in 2023. Finger millet grains of Tirumala variety were pre-treated with ultrasonic waves for 8, 13 and 18 minutes at varying different amplitudes (40, 70, 100%) and temperatures (30, 45, 60°C) using an ultrasonic probe Sonicator (Model: DP 120). The grains were steeped, sprouted for 48 hours, dried at 50±2°C for 12 hours and then milled into flour using a Wiley mill. A grain-to-water ratio of 1:3 was maintained throughout the hydration process. Angle of repose (Zaalouk and Zabady, 2009), water activity (Make: Rotronic, HydroLab), water holding capacity (Ramashia *et al.*, 2018), colour (Magdic *et al.*, 2009), moisture (AOAC 925.10) (George, 2019), phenol (Malick and Singh, 1980) and tannin content (Schanderi, 1970) of finger millet malt flour were performed in triplicate for analysis. Calcium and iron content were determined with the help of Atomic Absorption Spectrophotometer (Model: AA8000). The study assessed the bioaccessibility of micronutrients in finger millet malt samples using solubility and dialysis method. 16 g of pepsin was suspended in 100 mL of 0.1 M HCl to prepare pepsin digestion mixture. Pancreatin-bile extract mixture was prepared by dissolving 4 g pancreatin and 25 g of bile extract in 1 litre of 0.1 M NaHCO₃. The gastric stage involved homogenizing 1 g of flour sample with 80 mL of distilled water for 5 minutes, adjusting the pH to 2.0 by adding 6 M HCl and then adding 3 mL of fresh pepsin solution. The samples were then incubated at 37°C for 2 hours, then modified to 7.5 pH with 0.5 M NaOH. The assays were placed in an ice bath for 60 minutes to halt the gastric

digestion process. The intestinal stage involved placing pepsin digest aliquots into the dialysis tube to which 5 g of pancreatin mixture was added and placed in a shaker incubator for 2 h at 37°C. The samples were then analysed for calcium and iron content using Atomic Absorption Spectrophotometer (Luten *et al.*, 1996).

Process optimization and statistical analysis

Sonicated finger millet malt flour was optimized by using Design Expert Software (Version 12.0.6.0) through response surface methodology. Model was validated by comparing experimental values with predicted ones using a central composite design (Table 1). ANOVA in Design Expert was used to assess the impact of independent variables on quality characteristics.

RESULTS AND DISCUSSION

Angle of repose for sonicated finger millet malt flour ranged from 27.45±0.95 to 35.52±0.82 (Fig 1). It was observed that increase in time duration, temperature and amplitude of sonication leads to an increased angle of repose due to the moisture content. As ultrasound waves pass through the grains they enhance liquid penetration into grains, facilitating deeper hydration. This causes the grains to swell and undergo changes in their physical properties, resulting in enhanced cohesion and reduced flowability, which indicates a more stable pile formation (Macho *et al.*, 2020). Previous studies have reported that increase in moisture content of paddy from 8 to 16% has increased the angle of repose from 27.5 to 31.2° (Bhople *et al.*, 2017). Response surface plots of angle of repose in relation to sonication time duration, temperature and amplitude are presented (Fig 1). A statistically significant difference was found ($P < 0.05$) with a quadratic model (F -value-8.19). The angle of repose model regression equation (R^2 -0.8806 and adjacent R^2 -0.7731) is presented after excluding non-significant terms and affecting process parameters.

$$\text{Angle of repose } (^{\circ}) = 31.02 + 1.29A + 1.13B + 0.6555C$$

Ultrasound treatment affects water activity by enhancing the hydration process, creating microchannels and cavities within the food matrix. This accelerates water absorption and increases the equilibrium moisture content. The pressure differences caused by acoustic waves induce inertial flow and the "sponge effect," where the food matrix alternately squeezes and relaxes, facilitating more efficient water uptake (Miano and Augusto, 2018). The water activity (a_w) of finger millet malt flour ranged from 0.544±0.00 to 0.596±0.00 (Fig 2), indicating high microbial stability as

Table 1: Range of experimental conditions obtained with the help of Central Composite Design (CCD).

Independent process parameters		Factorial and axial values				
		-α	-1	0	+1	+α
Time duration, min	Designed	05	08	13	018	021
Temperature, °C	experimental	20	30	45	060	070
Amplitude, %	conditions	20	40	70	100	120

the activity of most microorganisms would be inhibited at a water activity level below 0.6. These results closely align with kodo millet flour (Srilekha *et al.*, 2019). Response surface plots of water activity relation to sonication time duration, temperature and amplitude are presented (Fig 2). Statistically, a significant difference was found ($P < 0.05$) with a quadratic model being significant (F-value-6.40). Water activity model regression equation (R^2 -0.8521 and adjusted R^2 -0.7189) is presented below after excluding non-significant terms.

$$\text{Water activity (A}_w\text{)} = 0.5599 + 0.0061A - 0.0094B + 0.0087C^2$$

Water holding capacity of finger millet malt flour ranged from 201.36 ± 0.95 to $218.36 \pm 1.96\%$ (Fig 3), it was increased with time duration, temperature and amplitude. High shearing forces generated by ultrasound, increases water-binding capacity, leading to the formation of micro-jets that breaks down the starch granules. This process enhances water penetration and binding within the pores (Yadav *et al.*, 2021). Mechanical energy generated by ultrasound leads to the physical modification (Vela *et al.*, 2021) and it also dissociate proteins and disrupt their secondary structure,

which affects their water-binding sites (Harasym *et al.*, 2020). Similar findings were reported in finger millet (Yadav *et al.*, 2021). Response surface plots of water holding capacity in relation to sonication time duration, temperature and amplitude are presented (Fig 3). Statistically significant difference was found with a quadratic model (F-value-33.37). WHC model regression equation (R^2 -0.9678 and adjusted R^2 -0.9388) is presented after excluding non-significant terms and impacting process parameters.

$$\text{WHC (\%)} = 212.73 + 1.53A + 2.41B + 3.89C - 1.52B^2$$

Colour plays a significant role in perception of food and it is greatly influenced by overall acceptability of consumers whether to accept it or reject (Imram, 1999). An increase in lightness with respect to control was observed among all treatments, contrary to the trend reported in sonicated rice by Ding *et al.* (2018). Ultrasound treatment may have removed the surface layer of grains, resulting in a brighter surface (Oladejo *et al.*, 2017). Extent of colour change induced by ultrasound treatment appeared to be different among treatments in finger millet malt flour, as in sweet potato and wheat flour (Cui and Zhu, 2020). Largest

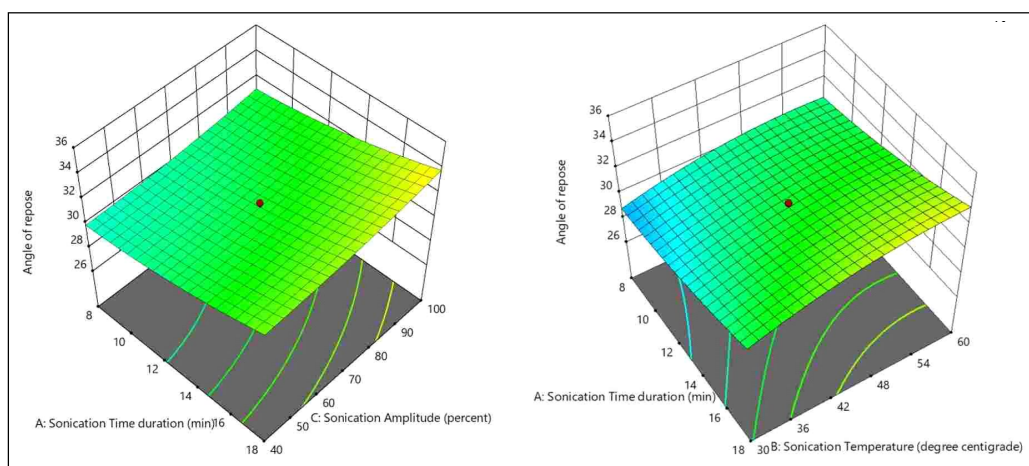


Fig 1: Effect of process parameters of thermosonication on angle of repose of finger millet malt flour.

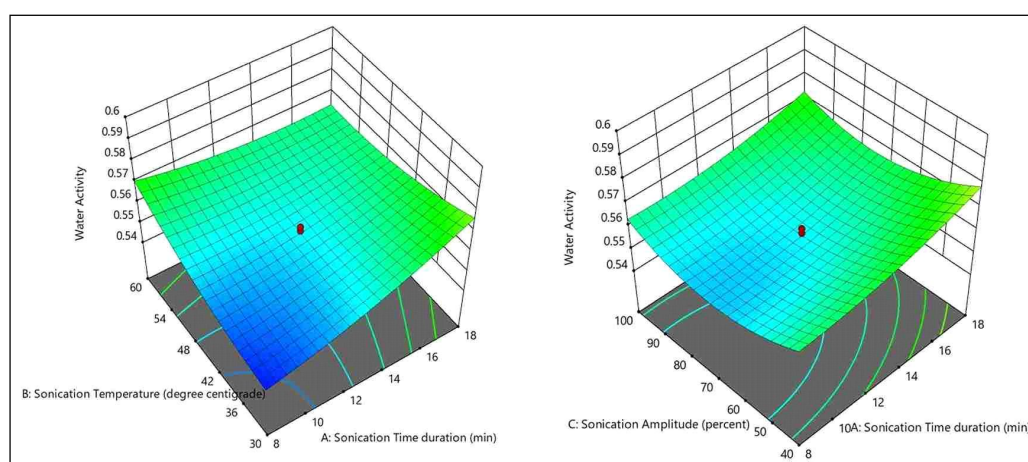


Fig 2: Effect of process parameters of thermosonication on water activity of finger millet malt flour.

ΔE was observed at sonication treatment of 18min, 60°C and 100%. Decrease in the red green value (a^*) and blue-yellow value (b^*) was observed with increase in temperature. The color changes were primarily due to the migration of colored components into the aqueous environment during incubation. Components mainly, the phenolic acids from the bran layer and carotenoids, are responsible for the dark and yellow/red hues, respectively (Xia *et al.*, 2020). Additionally, Maillard reactions might occur during ultrasound treatments, further contributing to color changes in the flour (Cui and Zhu, 2020). Response surface plots of colour difference (ΔE) in relation to sonication time duration, temperature and amplitude are presented (Fig 4). Statistically, significant differences ($P < 0.05$) were found with a quadratic model (F-value-11.15). The colour difference (ΔE) model regression equation (R^2 -0.9094 and adjacent R^2 -0.8278) is presented after deleting non-significant terms and highlighting the impact of process parameters.

$$\text{Colour } (\Delta E) = 1.95 + 0.4048A + 0.2021B + 0.6241C$$

Ultrasound treatment generates acoustic cavitation, which collapses bubbles and loosens the grain matrix in a grain-water system. This process creates micropores, increases porosity, and disrupts the cell wall, enhancing water mass transfer into the grain due to osmotic gradient difference (Bonto *et al.*, 2021). As a result, moisture content in finger millet grains increases as water from the surrounding medium is absorbed (Oladejo *et al.*, 2017) and it ranges from 7.27 ± 0.56 to $7.88 \pm 0.48\%$ (Fig 5) and it was observed that increase in sonication time duration, temperature and amplitude has increased the moisture content and these results agreed with finger millet flour (Ramashia *et al.*, 2018). Response surface plots of moisture content in relation to sonication time duration, temperature and amplitude are presented (Fig 5). Statistically significant difference ($P < 0.05$), was found with a quadratic model (F-value-13.17). Moisture content model regression equation (R^2 -0.9222 and adjacent R^2 -0.8522) is presented below after excluding non-significant terms, along with the impact of process parameters.

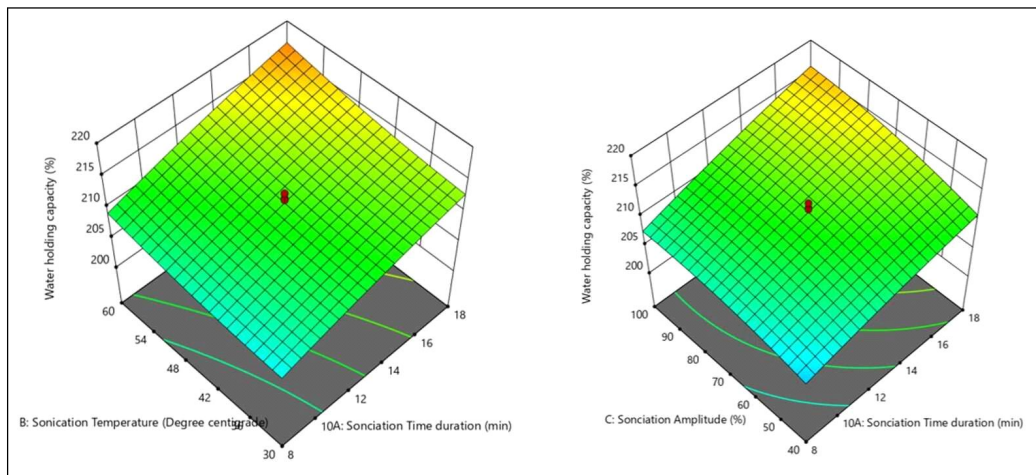


Fig 3: Effect of process parameters of thermosonication on water holding capacity of finger millet malt flour.

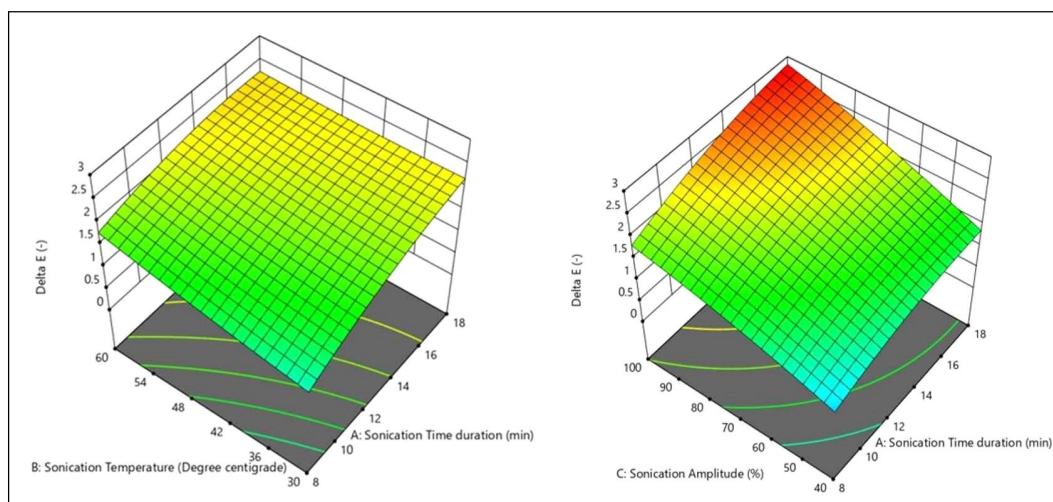


Fig 4: Effect of process parameters of thermosonication on colour difference (ΔE) of finger millet malt flour.

Moisture content (%) =

$$7.80 + 0.1272A + 0.1093B - 0.0756A^2 - 0.0756B^2$$

Total Phenol Content (TPC) of sonicated finger millet malt flour were found to be 50.11-126.22 mg/100 g (Fig 6). An extended sonication time duration increases total phenols, likely due to enhanced cell wall disruption caused by cavitation, which releases bound polyphenolic compounds. Increasing sonication amplitude and temperature has reduced phenols due to a lower grain-to-water ratio, which enhances cavitation and solvent penetration within the grain structure. This increased energy decreases the presence of galloyl moieties, leading to reduction in phenols. Yadav *et al.* (2021) has reported that increase in sonication time duration and amplitude has decreased the phenolic content in finger millet. Response surface plots of phenolic content in relation to sonication time duration, temperature and amplitude are presented (Fig 6). A statistically significant difference was found with quadratic model (F-value-10.87). Phenolic content model regression equation ($R^2=0.9241$ and adjusted $R^2=0.8558$) is presented below after deleting non-significant terms and impacting process parameters.

TPC (mg/100 g) =

$$96.03 + 5.37A - 9.32B - 9.02C + 4.79BC - 9.49B^2$$

Tannin content of sonicated finger millet malt flour ranged from 50.64 to 107.91 mg/100 g (Fig 7), against the control sample 125.45 ± 0.89 mg/100 g on dry weight basis and these results agreed with Yadav *et al.* (2021). Increased water content in the sample significantly reduces the tannin content. This reduction can be attributed to the disruptive effects of sonication on tannin molecules present in the grains which impacts the hydrolysis of ester linkages in the tannins, driven by the dissociation of water into OH^- and H^+ ions (Bhangu *et al.*, 2018). Increasing the sonication time duration and amplitude creates disruptive effects on the grains, leading to a greater reduction of tannin content. Response surface plots of tannin content in relation to sonication time duration, temperature and amplitude are presented (Fig 7). A statistically significant difference was found with quadratic model being significant (F-value-8.15). Tannin content model regression equation ($R^2=0.8800$ and adjusted $R^2=0.7721$) is presented below after excluding non-significant terms and impacting process parameters.

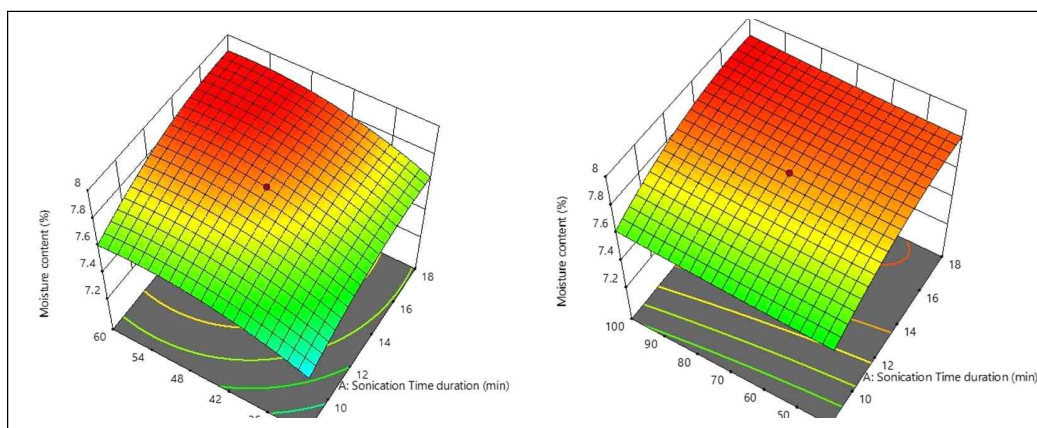


Fig 5: Effect of process parameters of thermosonication on moisture content of finger millet malt flour.

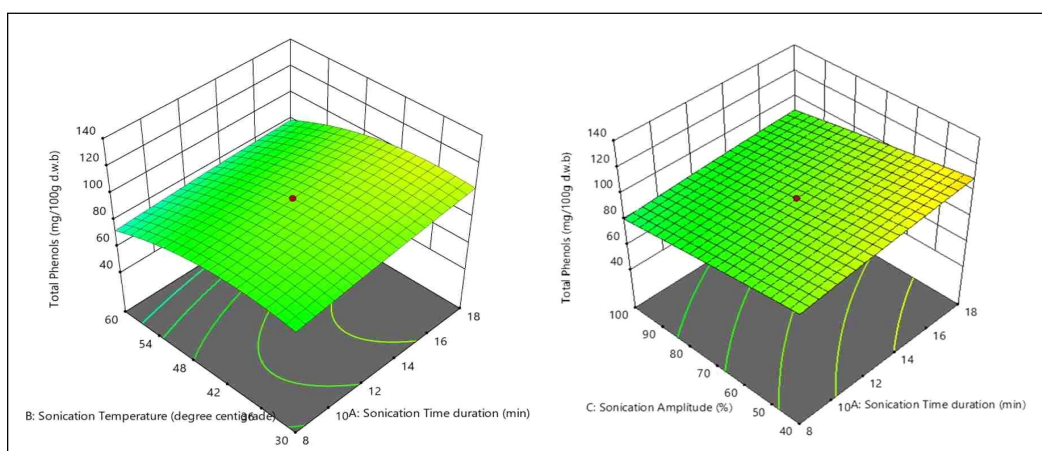


Fig 6: Effect of process parameters of thermosonication on phenolic content of finger millet malt flour.

$$\text{Tannin content (mg/100 g)} = 89.75 - 7.21A + 9.25B - 8.03B^2$$

Analysis of minerals and trace elements is essential for assessing food nutritional quality. Microelements like copper, chromium, iron and zinc are *vital* for human metabolism (Ertas, 2013), but anti-nutritional factors like phytic acid in cereals can hinder their bioavailability. The present study found that ultrasound treatment significantly increased the soluble calcium and iron content ($P < 0.05$), confirming a direct correlation between soluble minerals and bioaccessibility. Sonicated finger millet malt flour contained calcium ranging from 323 ± 0.13 to 341 ± 0.45 mg/100 g and iron from 3.73 ± 0.54 to 7.12 ± 0.22 mg/100 g (dry weight), consistent with findings by Singh and Raghuvanshi (2012). Ultrasound treatment enhances mineral composition in grains by improving germination rates, breaking seed dormancy and altering the nutritional profile and morphological structure (Gunathunga *et al.*, 2024). Cavitation plays a crucial role in altering mineral levels by mobilizing endosperm nutrients through cell wall disruption (Miano and Augusto, 2018). This process increases calcium content by breaking down divalent metal ions (calcium, iron, zinc) that bind with proteins and form

complexes with tannins, thus increasing the concentration of unbound calcium (Kassegn *et al.*, 2018). Studies have demonstrated that ultrasound treatment has reduced calcium levels in PWR variety of rice (Xia *et al.*, 2020). Additionally, sonicated finger millet malt exhibits increased iron content due to enhanced permeability of seed cell walls, promoting interaction between iron cations and polyphenols. This interaction leads to stable iron-polyphenol complexes, improving iron bioavailability and stability. Germination process further increases iron solubility by converting insoluble polyphenols into soluble forms (Xia *et al.*, 2020). This phenomenon was in accordance with the findings of PWR variety of rice who reported that ultrasound treatment has increased the iron content (Xia *et al.*, 2020). Response surface plots of calcium (Fig 8) and iron content (Fig 9) of sonicated finger millet malt flour in relation to sonication time duration, temperature and amplitude are presented. Calcium ($R^2=0.9549$ and adjacent $R^2=0.9144$) and Iron content model regression equation ($R^2=0.8812$ and adjacent $R^2=0.7742$) is presented below after excluding non-significant terms and impacting process parameters.

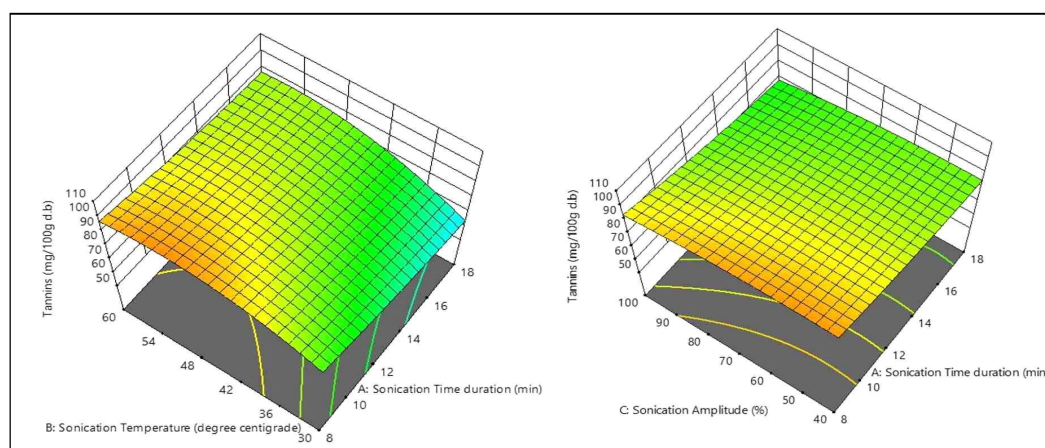


Fig 7: Effect of process parameters of thermosonication on tannin content of finger millet malt flour.

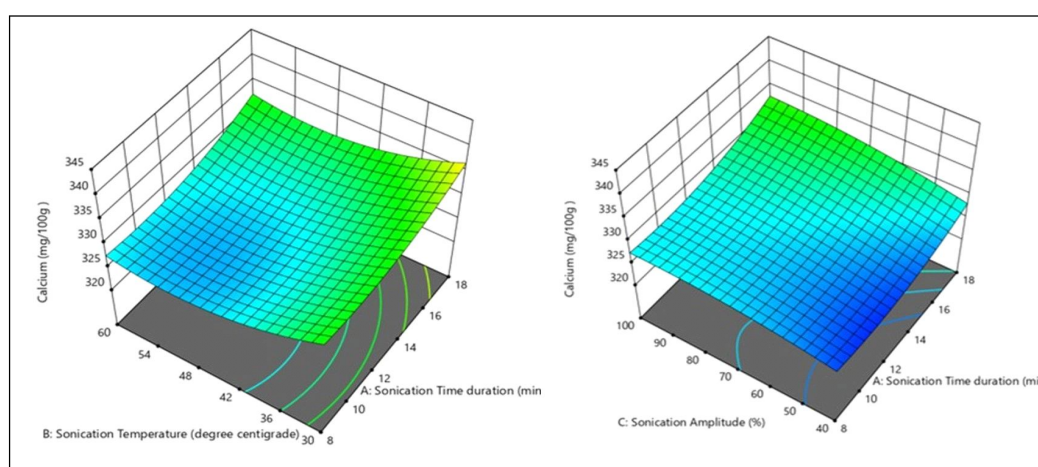


Fig 8: Effect of process parameters of thermosonication on calcium content of finger millet malt flour.

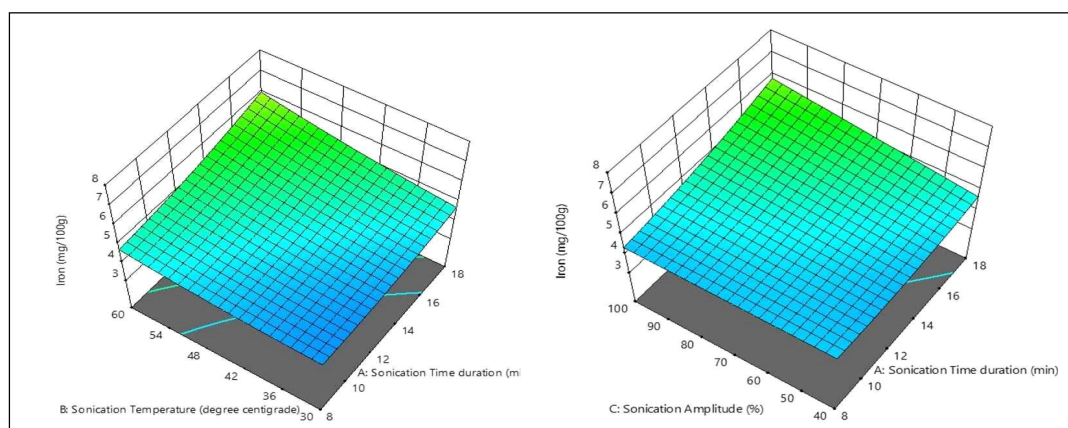


Fig 9: Effect of process parameters of thermosonication on iron content of finger millet malt flour.

Table 2: Optimized conditions for sonicated finger millet malt flour.

Variables	Target	Model optimized value	Experimental values
Treatment time (min)	In range	18	18
Temperature (°C)	Minimum	30	30
Amplitude (%)	In range	100	100
Phenols (mg/100 g)	In range	87.36	86.27
Tannins (mg/100 g)	minimize	59.30	50.64
Calcium content (mg/100 g)	maximize	329.96	323.69
Iron content (mg/100 g)	maximize	5.24	4.90
Desirability	-	0.736	-

Calcium content (mg/100 g) =

$$327.12 + 2.28A - 2.27B + 1.96C + 2.05A^2 + 3.12B^2$$

Iron content (mg/100 g) =

$$4.67 + 0.4434A + 0.4550B + 0.2874C + 0.2988AC$$

Bio-accessibility of calcium and iron in sonication-treated finger millet malt significantly improved compared to the control, with calcium bioaccessibility increasing from 0.51% to 36.54% and iron from 1.92% to 58.26%. Ultrasound treatment enhances bioaccessibility by activating the phytase enzyme during germination, which reduces phytic acid, an antinutrient that binds essential minerals, making them less available for absorption (Nkhata *et al.*, 2018). By hydrolyzing phytic acid into phosphoric acid and myoinositol, phytase releases these bound minerals, thereby increasing their bioaccessibility. The activation of hydrolytic enzymes during germination also facilitates the breakdown of carbohydrates, proteins, lipids and dietary fiber, further enhancing nutrient bioavailability (Gunathunga *et al.*, 2024). Overall, mineral bioaccessibility in plant-based foods depends on interactions between food components and the food matrix structure (Xia *et al.*, 2020). While germination and ultrasound treatment can enhance mineral availability, their effects can vary; for example, ultrasound-treated PWR variety rice showed increased calcium bioaccessibility but reduced iron bioaccessibility (Xia *et al.*, 2020). Statistically,

no significant difference was found in calcium and iron bioaccessibility percentages ($P > 0.05$), suggesting that variations in sonication time, temperature and amplitude notably influenced bioaccessibility without a specific trend.

Process optimization and validation

Ultrasound-assisted hydration was optimized for tannin removal and retention of phenolic and mineral content using the desirability function. Optimal conditions for finger millet malt were 100% ultrasound amplitude, 18 minutes soaking time and 30°C temperature. Predicted optimized values were validated through laboratory experiments, showing close alignment with actual results and confirming the accuracy of the regression model (Table 2).

CONCLUSION

This study demonstrates that sonication is an effective processing technique to enhance the nutritional profile, functional properties and bioaccessibility of micronutrients in finger millet malt. Sonication significantly improved calcium and iron content while drastically reducing antinutritional factors, such as phenols and tannins, which are known to inhibit nutrient absorption. The resultant increase in calcium and iron bioaccessibility highlights the potential of sonicated finger millet malt to address micronutrient deficiencies. Moreover, optimized conditions of 18 minutes, 30°C and 100% amplitude yielded superior results, making the malt more palatable and functional as

an ingredient in food formulations. This process offers a promising solution for tackling malnutrition and improving dietary diversity, particularly in regions where finger millet is a staple crop.

Conflict of interest

The authors declare no conflict of interest.

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