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Effect of Hydrothermal Treatment on Physical, Nutritional and Functional Properties of Pearl Millet (*Pennisetum glaucum*) Flakes

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ABSTRACT

Background: Pearl millet flakes were developed using various hydrothermal treatments to assess their impact on physical properties, nutritional composition, functional attributes and textural characteristics.

Methods: Different hydrothermal treatments, including soaking (at varying temperatures and durations) and steaming or pressure cooking, were applied before flaking. Physical properties like bulk density, color and texture were measured. Functional attributes such as water absorption, fat absorption, emulsion activity and stability were analysed. Nutritional composition, including protein, fat, fiber, minerals and phenolic content, was evaluated.

Result: Hydrothermal treatment T4 (soaking at 65°C for 30 min, followed by steaming for 20 min) produced flakes with the lowest bulk density (355 kg/m^3). Higher soaking temperatures and extended steaming times reduced lightness, while shorter durations preserved color. Water absorption index ranged from 2.20-4.10 and fat absorption capacity decreased with increasing bulk density. Nutritionally, flakes contained high energy (410-424 kcal), protein (9.41-12.89 g), fiber (4.01-6.54 g), iron (1.22-1.70 mg), calcium (25.9-34.9 mg) and phosphorus (138-305 mg) per 100 g. Pressure cooking resulted in the highest loss of phenolic content (1.59-0.59 mg GAE/ml), whereas steaming helped retain nutrients better.

Key words: Bulk density, Flakes, Functional, Nutritional, Polyphenols.

INTRODUCTION

Millets are a group of small seeded species of cereal crops belonging to Gramineae family. Millets can be grown in adverse agro-climatic conditions of arid soils, high moisture stress and atmospheric temperature. India's share of the total millet production was 12.49 MMT (80% of Asia and 20% of global production) being largest producer of pearl millet in the world . Nutritional quality of pearl millet (*Pennisetum glaucum*) is better than popular cereal crops like wheat, rice and sorghum. It is a potential source of energy, protein, fibre, B-group vitamins and micronutrients such as iron, zinc, phosphorus, magnesium *etc.* and also possesses various functional and health benefits for curing different lifestyle associated disorders. However, pearl millet is rich source of nutrients, its utilization is limited in processing sector due to various factors such as small grain size, dark colour, prolong cooking time, lack of instant products and lower shelf life (Jaybhaye *et al.*, 2014; Mahalakshmi *et al.*, 2024; Datir *et al.*, 2018). Recently, the importance of millets has been recognised as ingredient in multigrain and gluten-free cereal products. High incidence of celiac disorder in *European* population, affects approximately 1 in 100 individuals characterized as life-long autoimmune enteropathy. Such individuals develop gluten susceptibility genetically which targets the gastrointestinal tract of the individual and after ingestion of gluten an immune mediated mechanism is triggered that hamper the absorptive function of villi present in small intestine. Pearl millet is highly nutritious and excellent alternative for gluten intolerant population.

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Flaking is a process in which grains are soaked to its equilibrium moisture content followed by steaming or roasting to fully gelatinize the starch, dried, conditioned, decorticated and then flaked immediately by passing through a pair of heavy-duty rollers. Pearl millet flaking, especially after hydrothermal treatment, offers several advantages (Prashanth *et al.*, 2024). Hydrothermal treatment works by using high-pressure steam or hot water to disrupt fat structures and inhibit lipase activity, thereby preserving the quality of the grains. This process utilizes the high specific enthalpy of moist heat, carried by the steam or hot water disrupts the globular structures of fat molecules within the grains prevent the lipase enzyme from functioning effectively. By inhibiting lipase activity, hydrothermal treatment reduces the breakdown of fats, which can be crucial in improving the stability and shelf life

of grain products. Primary purpose of steam-flaking is to increase surface area and gelatinization, allows for greater digestibility and starch availability. Steam-flaking of grains increased gelatinization more than other processing methods because moisture and heat are provided in sufficient quantities to disrupt intermolecular hydrogen bonds. Acquisgrana *et al.* (2019) reported hydrothermal treatment is effective in reducing tannin levels in both wholegrain sorghum and flour. Lokeshwari *et al.* (2022) indicated that sorghum and pearl millet had a greater number of free sulfhydryl groups in proteins, thus pearl millet requires more severe heat processing. Pearl millet flakes and its convenience products may help in commercialization of food product development technologies through public and private partnerships that can enhance the large-scale adoption of pearl millet in food processing sector.

MATERIALS AND METHODS

Pearl millet variety HHB-67 was selected for preparation of flakes. It is an early maturing variety of pearl millet characterized by lustrous, bold grains with compact conical panicles sown in first fortnight of July and harvested after 70-80 days in October-November, 2020. The experiments were conducted in ICAR-Central Arid Zone Research institure, Jodhpur during 2020-2022. The grains were stored in aluminum bins. The initial moisture content of the millets used for the study was 11.00%±0.15% (w.b.) Roller flaking machine (CAZRI, Jodhpur) was used to prepare pearl millet flakes. Pearl millet grains were subjected to two types of hydrothermal treatments (soaking, steaming and drying) and (soaking, pressure cooking and drying) sequentially as shown below. The independent variables of the study included soaking temperature, soaking time and steaming time. A comprehensive evaluation of dependent variables, encompassing proximate components, physical properties, antinutrients, total phenolics content, sensory scores and textural characteristics was systematically conducted. Following Treatments were conducted:

T_1 (5 min soaking at 80°C + 5 min steaming).
T_2 (10 min soaking at 75°C + 10 min steaming).
T_3 (20 min soaking at 70°C + 15 min steaming).
T_4 (30 min soaking at 65°C + 20 min steaming).
T_5 (10 min soaking 70°C + pressure cooking for 2 min at 15 psi).
T_6 (20 min soaking 75°C + pressure cooking for 2 min at 15 psi).

Physical properties

Colour values of hydrothermally treated samples were measured using Hunter colour scale in triplicates. The values were expressed in terms of L, a, b values where parameter 'a' takes positive values for reddish colour and negative values for greenness, 'b' takes positive values for yellowish colour and negative values represents blue. 'L' is an approximate measurement of luminosity, which is the property according to which each colour can be considered as equivalent to a member of grayscale, between black and white. Total colour difference Δ E has been monitored as the modulus of the distance vector between the initial colour values and the actual colour coordinates. The measurement of bulk density was carried out by gently tapping the samples in a graduated measuring cylinder, following the procedures mentioned by Joshi and Rao (2014).

Functional characteristics

Water absorption index (WAI) and water solubility index (WSI) was estimated by the method of Bello-Perez *et al. (*2000). Oil absorption capacity (OAC) was estimated by the method of Sosulski *et al.* (1976). Emulsion activity (EA) and stability (ES) was analysed by the protocol of Yasumatsu *et al.* (1972).

Proximate composition

Moisture, ash, protein, fat, crude fibre, soluble dietary fibre, calcium, phosphorus and iron were estimated according to AOAC approved methods of AOAC (1995). Minerals were estimated in Atomic Absorption Spectrophotometer (GBC, Avanta). Total phenol content of the flakes was determined by the folin-coicalteau method of Singleton and Rossi (1965).

Textural parameters

Textural properties crispness and hardness was measured using the texture analyzer (Stable Micro Systems, Vienna, England). Sample weight was taken 2.0 g, tube diameter 20.0 mm, velocity 1 mm/sec and time taken for the measurement 7.0 sec.

RESULTS AND DISCUSSION

Pearl millets flakes developed using different hydrothermal treatments were evaluated for various physical, functional, textural and nutritional properties. Performance of flaking machine was evaluated with the variable roller clearance (0.1 to 0.5 mm) between flaking rolls. The length, width and thickness of flakes was measured by using vernier calliper and also bulk density was evaluated for the flakes obtained at different roller clearance.

Fig 1 presents the physical parameters of pearl millet flakes as the function of roller clearances. As the roller clearance increased from 0.1 to 0.5 mm, length and width of flakes decreased from 5.2 to 3.09 mm and 4.44 to 2.76 mm, respectively whereas the thickness of flakes increased from 0.50 to 1.50 mm. Bulk density of flakes (349.5-590.7 kg/m^3) was found proportional with the increasing roller clearance at the mean moisture content of 8.11±0.07 per cent. It was pertinent to note that at the lowest roller clearance of 0.1 mm 50% grains were broken. Hence, a roller clearance of 0.2 mm was found optimum.

Colour

Color analysis of hydrothermally treated pearl millet flakes revealed that lower temperatures resulted in higher L*

values (lighter color), while increased treatment temperatures reduced lightness due to thermal degradation, pigment leaching and Maillard browning. Initially, lightness increased, but prolonged steaming led to further darkening. Soaking temperature, time and steaming time significantly influenced L* values ($P<0.01$). Higher soaking temperatures negatively impacted lightness, while extended soaking and steaming initially enhanced it. Color changes were linked to phenolic polymerization and pigment reactions. The 'a' value reflected shifts in red-green tones, influenced by soaking and steaming conditions, while the 'b' value, affected mainly by steaming, indicated yellow-blue variations. The overall color difference (ΔE) increased with soaking temperature and time, highlighting greater perceptible changes due to combined chemical and physical effects.

Bulk density

Hydrothermally treated pearl millet flour was found to have lower bulk densities. Lower bulk density is desirable criteria for producing good quality flakes. It has been observed that, with the increase in the temperature of soaking and steaming time, the bulk density decreased while it increased in soaking and pressure-cooking treatments Bulk density of flakes ranged from 355-430 kg/m^3 with different pre-treatments. Soaking and steaming produced flakes with lower bulk density compared to pressure cooking. Lowest bulk density (355 kg/m^3) was observed for sample T_4 (30 min soaking at 65°C + 20 min steaming) while highest bulk density (430 kg/m^3) in flakes produced after pressure cooking in sample T6 (20 min soaking 75°C + pressure cooking for 2 min at 15 psi) of pearl millet grains.

The decrease in bulk density following prolonged steam treatment can be attributed to the process of starch gelatinization. When starch granules are exposed to heat and moisture, as in steam treatment, they absorb water and swell, disrupting their crystalline structure. This swelling increases the volume of the starch, while its mass remains unchanged, effectively lowering the bulk density of the material. Additionally, prolonged exposure to steam may cause further breakdown of the starch granules, leading to a more porous structure that contributes to the overall reduction in bulk density (Yadav *et al.*, 2012).

Functional characteristics

Functional characteristics of pearl millet instant flakes are influenced by factors like water absorption index (WAI), water solubility index (WSI) and fat absorption capacity. WAI, ranging from 2.20 to 4.10, indicates starch gelatinization and was negatively correlated with bulk density (r^2 = -0.85) but positively correlated with water solubility (r^2 = 0.59). The highest WAI (3.44±0.93) and fat absorption capacity (287.84) were observed in sample T_4. Water uptake by the endosperm during steam flaking controls gelatinization, with higher WAI in steamed flakes due to limited moisture availability. Hydrothermal treatment (soaking and steaming) resulted in higher WSI than steaming and pressure cooking. Pearl millet flakes exhibited greater water absorption capacity (287.84±3.17) than conventional rice and oat flakes, attributed to their high insoluble dietary fiber. The least cooking time (0.20 min) was found in steamed flakes. High water and fat absorption capacities enhance flavor and mouthfeel, making millet flakes suitable for food applications requiring optimal moisture or oil retention. Variability in functional attributes, as noted by Narang *et al.* (2018), is influenced by the carbohydrate/protein matrix and plasticizing effects of water, similar to interactions observed in corn and quinoa flakes.

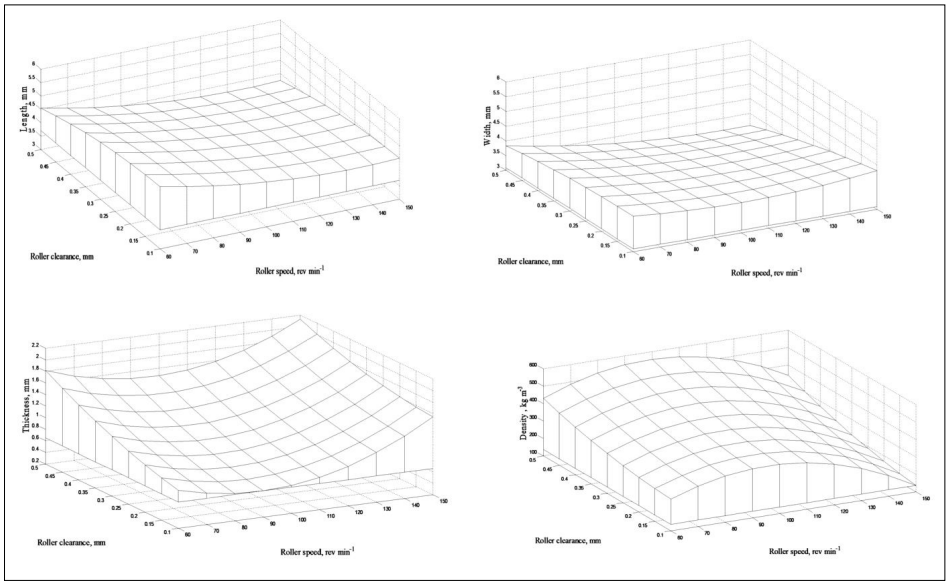


Fig 1: Physical properties of pearl millet flakes (Length, width, thickness, bulk density) as function of roller clearance.

Textural characteristics

Textural properties were measured in terms of crispness and hardness of flakes. It was observed that hydrothermal treatment, specifically (soaking and pressure cooking), resulted in flakes that require more force to break, indicating they are harder compared to flakes prepared through (soaking and steaming) treatment. This could be due to differences in the structural changes caused by the different hydrothermal treatments as depicted in Table 1. The reason behind was controlled gelatinization and starch retrogradation prior to flaking in hydrothermal treatment (soaking and pressure cooking) and also to higher dietary fiber content. Sample T_3 and T_4 reflected desired crispness. Hardness of T_4 was lowest while significantly higher values were obtained in case of T_6 and T_7. Results indicated that flakes prepared through hydrothermal treatment, which includes soaking and steaming of the grain, particularly in samples T_3 and T_4, exhibited superior textural attributes which suggests that the specific combination of soaking and steaming conditions applied to these samples positively influenced their texture. Hydrothermal treatment often enhances the textural quality of grains by modifying the starch structure, making the flakes softer, more cohesive and improving their overall mouthfeel. The improvement in texture in samples T_3 and T_4 could be due to optimized processing parameters, such as soaking duration and steaming intensity, which led to desirable changes in the grain's physical properties (Pawase *et al.*, 2019). Hydrothermal treatment involving soaking and pressure cooking appears to negatively impact the crispness of the flakes, as evidenced by a significantly higher hardness value. Pressure cooking, in particular, can lead to over-gelatinization of starch and increased moisture retention, resulting in a denser, less crispy texture. Consequently, while hydrothermal treatment can improve other qualities, it may render the product unsuitable for applications where crispness is a key requirement.

Nutritional composition

Nutrient composition of pearl millet flakes is shown in Table 2. Moisture content of pearl millet flakes ranged from 3.09-4.39%, with the lowest in T_3 and T_4 (soaking and steaming). Ash content varied between 0.1-0.5 g, with the highest in T_4. Protein content (9.41-12.89%) was higher in soaking and pressure cooking, possibly due to improved bioavailability. Energy content ranged from 410.14-421.11 Kcal, higher than other millet flakes like barnyard (277 Kcal) and oats (343 Kcal) (Takhellambam *et al.*, 2016). Fat content (5.33-5.62%) remained unaffected by hydrothermal treatment, but free fatty acids were lower (2.69%) due to lipid stabilization. Total dietary fiber decreased from native grain (16.11 g) due to fiber disintegration, with soluble fiber reducing more in soaking and pressure cooking. Crude fiber was highest in T_1. Mineral content ranged from 34.5-46.0 mg (calcium) and 138-305 mg (phosphorus), with iron levels (1.20-1.70 mg) higher in soaking and pressure

Table 1: Functional properties of pearl millet instant flakes.

Treatment	L	a	b	ΔE	Bulk density (kg/m^3)	Water absorption index	Water solubility Index	Fat absorption capacity	Emulsi-fication activity (%)	Emulsion stability (%)	Crispness (kg.sec)	Hardness (N)
T_1	62.38^a	5.16^a	11.21^a	2.79^a	367.60±0.98^a	1.11±0.18^a	2.22±0.78^a	216.68±2.07^a	10.27±1.12^a	15.87±1.02^a	0.81±0.31^a	1.70±0.22^a
T_2	64.12^b	5.30^a	13.17^b	2.86^a	358.80±0.88^b	2.82±0.98^b	2.53±0.18^a	217.42±2.47^a	11.11±1.02^b	14.04±1.01^b	0.88±0.21^a	1.59±0.35^a
T_3	65.07^b	5.41^a	13.47^b	2.69^c	355.74±0.92^b	3.44±0.93^c	2.42±0.92^a	287.84±3.17^b	12.48±1.22^c	13.52±1.02^c	0.87±0.39^a	2.32±1.17^b
T_4	62.94^a	5.61^b	14.08^c	2.89^a	392.42±0.95^c	2.12±0.12^b	2.44±0.16^a	261.09±2.57^c	12.11±1.02^c	12.50±1.12^d	0.68±0.32^a	1.52±0.24^a
T_5	55.63^c	6.17^c	9.19^d	7.02^b	426.02±0.88^d	1.27±0.16^a	1.16±0.78^b	227.95±3.27^a	15.38±1.12^d	15.82±1.08^a	0.29±0.48^b	5.61±2.61^c
T_6	52.72^c	4.30^d	9.14^d	8.81^c	430.58±0.93^e	1.01±0.10^a	1.08±0.68^b	220.49±3.78^a	15.33±1.11^d	15.46±1.17^a	0.28±0.26^b	6.07±2.51^d

Values with different superscripts in a row are significantly different, Tukey HSD ($p<0.05$).

Table 2: Nutrient composition of pearl millet instant flakes.

Treatment no.	Moisture (w.b.)	Carbohydrate (g)$	Energy (Kcal)$	Ash (g)	Protein (g)	Fat (g)	Crude Fibre(g)	Soluble dietary fibre (g)	Calcium (mg)	Phosphorus (mg)	Iron (mg)
T1	4.39±0.02^{a}	75.32±0.71^{a}	410.14±2.71^{a}	0.32±0.02^{a}	9.43±1.12^{a}	5.58±1.16^{a}	6.54±0.32^{a}	1.27±0.14^{b}	31.12±0.22^{a}	210.0±0.23^{a}	1.52±0.12^{a}
T2	4.15±0.14^{a}	76.43±0.64^{a}	414.20±0.22^{a}	0.31±0.17^{a}	*12.04±1.21^{c}	5.52±1.02^{a}	5.51±0.20^{b}	1.23±0.14^{b}	30.03±0.17^{a}	220.0±0.19^{a}	1.65±0.11^{a}
T3	3.09±0.07^{b}	76.12±0.52^{a}	414.78±3.61^{a}	1.15±0.12^{b}	*12.47±1.02^{c}	5.39±1.06$_{a}$	5.12±0.12^{c}	1.24±0.10^{b}	34.52±0.12^{b}	240.2±0.11^{a}	1.67±0.14^{a}
T4	3.15±0.16^{b}	76.79±0.51^{a}	420.04±2.26^{b}	0.30±0.03^{a}	*11.41±1.71^{b}	5.53±1.12^{a}	5.04±0.02^{c}	1.33±0.12^{b}	34.92±0.08^{b}	305.0±0.12^{b}	1.70±0.11^{a}
T5	4.21±0.17^{a}	77.82±0.60^{a}	421.11±1.17^{b}	0.22±0.02^{a}	*12.67±1.40^{c}	5.38±1.21^{a}	4.01±0.02^{d}	1.10±0.12^{b}	28.63±0.18^{c}	160.0±0.10^{c}	1.22±0.14^{b}
T6	4.24±0.07^{a}	77.42±0.05^{a}	424.21±1.42^{b}	0.20±0.23^{a}	*12.89±1.2^{d}	5.33±1.17^{a}	4.31±0.12^{d}	1.01±0.16^{a}	25.92±0.01^{c}	138.0±0.09^{d}	1.20±0.13^{b}

Values with different superscripts in a row are significantly different, Tukey HSD ($p<0.05$).

$Computed value

*Foods contain ≥10.0 g/100 g of protein classified as rich in protein.

cooking due to reduced antinutrients. Hydrothermal treatment influenced phenolic content, with steaming better for retention while pressure cooking reduced it (Rafaella *et al.* (2017). Steaming prevented polyphenoloxidase enzyme degradation, aiding phenol retention. Overall, steaming preserved more nutrients, making it a favorable method for processing pearl millet flakes.

CONCLUSION

Pearl millet flakes were prepared using a flaking machine, with dimensions of 5.0 mm (length), 4.1 mm (width) and 0.5 mm (thickness). Increased roller clearance reduced flake length and width but increased bulk density and thickness. Hydrothermal treatment (soaking and steaming) resulted in lower bulk density and higher water and fat absorption than soaking and pressure cooking. Sample T4 had the lowest bulk density (355 kg/m^3), followed by T3 (358 kg/m^3). Higher temperatures and prolonged heating caused Maillard reactions, darkening the flakes. Crispness was higher in soaked and steamed flakes. Enhanced swelling capacity made them suitable for porridges and ready-to-eat cereals. Pearl millet flakes exhibited high energy (410.14-421.11 Kcal) and protein (9.41-12.89 g) content, along with significant iron, calcium and phosphorus levels, making them nutritionally superior. Phenolic content was best retained in steaming, while pressure cooking reduced it. Overall, pre-treatment T4 produced the best quality flakes with desirable functional and nutritional properties, making flaking a valuable method for improving pearl millet's nutritional profile for direct consumption or processed products.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

All animal procedures for experiments were approved by the Committee of Experimental Animal Care and Handling Techniques were approved by the University of Animal Care Committee (Not applicable in this study).

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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