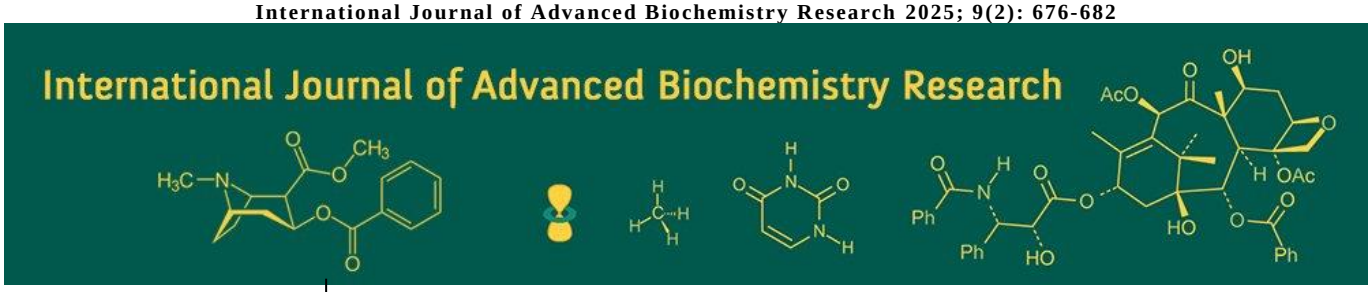

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Khumbaron Kiranbala Kabui
Department of Food Process Engineering, Centre of Excellence for Grain Sciences, National Institute of Food Technology, Entrepreneurship and Management, Thanjavur, Tamil Nadu, India

KA Athmaselvi
Department of Food Process Engineering, Centre of Excellence for Grain Sciences, National Institute of Food Technology, Entrepreneurship and Management, Thanjavur, Tamil Nadu, India

Corresponding Author:
KA Athmaselvi
Department of Food Process Engineering, Centre of Excellence for Grain Sciences, National Institute of Food Technology, Entrepreneurship and Management, Thanjavur, Tamil Nadu, India

Influence of Ohmic heating parboiling on functional and cooking characteristics of Kodo millet

Khumbaron Kiranbala Kabui and KA Athmaselvi

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Abstract
Ohmic heating (OH) has drawn interest as a new thermal method for processing food. The purpose of this study was to assess how the functional and cooking characteristics of Kodo millet were affected by Ohmic heating parboiling (OP). Millet can be used more effectively in the creation of innovative, gluten-free food products by enhancing their functional qualities. Cooking characteristics including optimum cooking time, color, gruel loss, and water uptake ratio and functional properties like swelling power, solubility, and water and oil absorption capacities were assessed and contrasted with conventional parboiling (CP). The findings showed that, in comparison to CP, OP reduces the cooking time while improving the water uptake ratio of the millet. The amount of gruel lost during cooking was reduced by 10.04% and 29.98% in CP and OP, respectively. The CP and OP showed improvements in water and oil absorption capabilities of 19.17% and 7.03%, respectively, and 27.39% and 15.62%. Additionally, it was observed that OP had an impact on the total phenolic content and antioxidant activity. OP used less energy when compared to CP. Based on these results, OP may be a viable and energy-efficient way to parboil Kodo millet, which could increase its use in a variety of culinary applications.

Keywords: Ohmic heating parboiling, cooking time, gruel loss, swelling power, antioxidant, energy

Introduction
Kodo millet (*Paspalum scrobiculatum*) is one of the world's ancient grains from tropical Africa and was domesticated 3,000 years ago in India. It is cultivated in dry and semi-arid areas of Asian and African nations. In India, Kerala, Tamil Nadu, and Uttar Pradesh are the states where it is most commonly cultivated. It contains a good amount of protein, dietary fiber, vitamins, and minerals. So, it is referred to as nutrient cereals and can be a good alternative to wheat and rice [1]. Kodo millet has substantial amounts of flavonoids, antioxidants, and polyphenols. Kodo millet offers numerous health advantages because of its abundance of nutritional components. Despite its nutritional properties, millet has limited utilization because of the presence of hard hull and its challenges in processing.

Processing of Kodo millet is necessary before consumption to remove husk. The husk is removed by manual pounding by tribal people. The technique is extremely time-consuming and tedious. The attempt at dehulling of millet showed that they may be hardened through parboiling, making them resistant to impact during milling. Compared to raw grain, parboiled grain is more resilient to breaking under friction and abrasive milling parameters. The milling yield rises as a result of less breakage when grain fissures are filled or sealed during parboiling [2]. Kodo milling results in a high breakage rate, and the byproduct husk contains fine broken, which lowers both the head grain yield and the overall recovery [3]. Such breakage may be removed by gelatinizing the starch, which would fill the cracks and fissures. Thus, parboiling and dehulling of Kodo millet could improve its prospects for product diversification.

Parboiling involves soaking the grain and steaming followed by drying. This procedure causes simultaneous modifications in the nutritional, chemical, and physical characteristics of grains, which have a significant impact on the quality of processing, drying, storage, and cooking [4]. The impact of parboiling on grains is primarily influenced by the extent of starch gelatinization and its tendency to retrograde [5]. The process results in significant variations in swelling, water absorption, and cooking properties, which makes it appropriate for various uses.

This modification improves their utility in a greater variety of products, with enhanced functional properties. The low sensory acceptance, anti-nutritional effects, storage stability, and variety of millet-based goods provide substantial hurdles in their processing and commercialization. Hence, it is essential to invest in process technologies to improve the nutritional and functional characteristics of millet for the production of numerous healthy foods [6]. Numerous research has studied the impact of parboiling on the functional and cooking characteristics of millets. Dharmaraj ***et al***. [2] reported that hydrothermal processing enhanced solubility and decreased the swelling power of the finger millet. Akhil *et al.* [7] observed that the water absorption capacity and cooking time of foxtail millet increased after parboiling. Prashanth *et al*. [8] reported that the water absorption capacity and water solubility index of pearl millet increased with soaking temperature and suggested that the functional qualities can be significantly enhanced by appropriate hydrothermal treatment, making it appropriate for a diverse range of applications. Parboiling of little millet and proso millet was also reported to have higher cooking qualities such as water uptake, swelling index, and elongation ratio [9].

However, conventional parboiling can be time-consuming and energy-intensive. Therefore, these drawbacks should be overcome using different approaches to parboiling. Ohmic heating (OH), also known as joule heating, is a novel technique that shows great potential as an alternative to conventional heat treatment. The application of OH as a pretreatment/ parboiling step on functional and cooking characteristics of Kodo millet was found to be limited. Therefore, an investigation has been done to study the effect of Ohmic heating parboiling (OP) on the functional, cooking characteristics, antioxidant, and total phenolic content of Kodo millet. The present study was also compared with the conventional approach.

Materials and Methods

Kodo millet was procured from the Centre of Excellence in Millets Athiyandal, Tiruvannamalai District, Tamil Nadu. The millet was thoroughly cleaned and then stored in airtight barrels at ambient conditions. The millet had an initial moisture content ranging from 11% to 12% (w.b).

Parboiling Parameters

Conventional Parboiling (CP)

Cleaned millet was soaked in hot water at a millet-to-water ratio of 1:2.5 at temperatures of 50°C, 60°C, and 70°C for 5 h, 2.5 h, and 1.5 h, respectively, to attain a moisture content of 30±2%. The soaking was performed in a water bath, with soaking times optimized based on hydration studies conducted at different temperatures until equilibrium moisture content was reached (Unpublished data). A perforated vessel was used to allow steam from the boiling water to pass through during the steaming process. The steaming time was optimized through multiple trials ranging from 10 to 30 min, with 20 min chosen for its highest yield in head grain during milling. The millet was then shade-dried till the moisture content attained 12-14%. The kodo millet hydrated at 70 °C °C, 60 °C, and 50 °C were designated as CP70, CP60, and CP50 respectively, while raw millet was labeled as C.

Ohmic Heating Parboiling (OP)

The time-temperature profile, representing the total time taken for the millet to reach an endpoint of 90 °C, was nearly identical for both OH and conventional heating (CH). OH, at 20 V/cm, required 50 min to reach the endpoint, while CH took 54 min. Given their similar time-temperature profiles, these two different treatments were compared.

The grains were hydrated using the same conditions in an OH chamber as those used for the conventional method. The water was drained after soaking, and the soaked millet was mixed with salt solutions at a millet and salt solution ratio of 1:0.5. The mixture was then parboiled at a voltage gradient of 14 V/cm for 20 min in the OH chamber, reaching a final temperature of 90 °C. The parboiling time remain consistent with the conventional steaming process. Kodo millet hydrated in the OH chamber at 70 °C, 60 °C, and 50 °C was named as OP70, OP60, and OP50, respectively.

Ohmic Heating Apparatus

An ohmic heating apparatus having two stainless steel 316 L electrodes positioned at both ends of a rectangular heating chamber (12.6 x 12.6 x 13.9 cm^3) was used for the study. Each treatment was conducted at a frequency of 50 Hz. An autotransformer connected to these electrodes supplied the necessary voltage for the heating process. During the treatments, the output data from the autotransformer, including voltage (V), current (A), and energy consumption (kWh), was noted after 2 min.

Dehulling and Polishing

The dehulling and polishing processes were carried out using a single-stage millet dehuller (Perfura Technologies, India) and an Emery polisher (Zaccaria Model PAZ/1-DTA, Brazil). Multiple conventional and Ohmic parboiling treatments were carried out to obtain the required quantity for milling.

Energy Consumption

The power consumption of the conventional method was determined using an energy meter. The energy consumption (kWh) of the appliance was calculated by multiplying its power consumption (kW) by the treatment time (h). The digital readout of the autotransformer was used to directly record the energy consumed by OH treatments in kWh.

Cooking Qualities

Optimum cooking time

2 g of sample was added in a 75 ml capacity tall-form beaker containing 20 ml of water. The cooked millet was pressed using the glass slides. The time taken by the grains for the disappearance of the white core or opaque in the center was considered the optimum cooking time [10].

Water uptake ratio (WUR) and Gruel loss

WUR and gruel loss were evaluated as described by Polesi *et al.* [11] and determined using the below equations:

$$\text{WUR (g/g)} = \frac{\text{Weight of cooked millet (g)}}{\text{Weight of uncooked millet (g)}} \quad (1)$$

$$\text{Gruel loss (\%)} = \frac{\text{Weight of residue in drained water (g)}}{\text{Weight of uncooked millet (g)}} \text{ x } 100 \quad (2)$$

Color

The color of the cooked millet was measured using a Hunter Lab Colorimeter (Hunter Association Laboratory, Inc., USA). According to the CIELAB system, the color values were displayed as L*, a*, b*, and ΔE were calculated using the below equation [12].

$$\Delta E = [(L_1^*-L^*)^2 + (a_1^*-a^*)^2 + (b_1^*-b^*)^2]^{1/2} \quad (3)$$

where L*, a*, and b* are the color values of the treated samples.

Functional Properties

Solubility and Swelling Power

The solubility and swelling power of the millet flour were evaluated as described by Rao *et al*. [13]. The swelling power and solubility were determined as follows:

$$\text{Solubility (\%)} = \frac{\text{Weight of dried supernatant}}{\text{Weight of sample}} \text{ x } 100 \quad (4)$$

$$\text{Swelling power (g/g)} = \frac{\text{Weight of sediment}}{\text{Weight of sample}} \quad (5)$$

Water Absorption Capacity (WAC) and Oil absorption capacity (OAC)

WAC and OAC of millet flour were investigated as described by Awolu [14] with some modifications. The WAC and OAC were determined as follows:

$$\text{WAC (ml/g)} = \frac{\text{Amount of water absorbed}}{\text{Weight of sample}} \quad (6)$$

$$\text{OAC (ml/g)} = \frac{\text{Amount of oil absorbed}}{\text{Weight of sample}} \quad (7)$$

Total phenolic content (TPC)

The TPC of the sample extracts was assessed following the methodology of Chandra *et al*. [15]. The absorbance was measured using a Shimadzu UV-1800 spectrophotometer at 765 nm. The TPC was determined using the standard calibration curve of gallic acid (mg GAE/100 g).

Antioxidant Activity

The radical scavenging activity was estimated using DPPH according to Salar and Purewal [16]. DPPH scavenging activity (%) was estimated using the below formula:

$$\text{DPPH Scavenging activity (\%)} = \frac{A0-As}{A0} \text{ x } 100 \quad (8)$$

A_0 and As are the absorbances of the control and sample, respectively.

Statistical Analysis

Analysis of variance (ANOVA) was used to examine all values, which are shown as mean±standard deviation. Statistical analysis was done using the IBM SPSS software package (Version 28.0; IBM Corp, USA). Tukey test was used to assess mean differences with a probability of $P<0.05$.

Results and Discussion

Energy Consumption

Energy consumption by CP and OP is shown in Figure 1. Treatment time is a crucial factor in the energy consumption of the parboiling process. For CP, more energy was consumed as the soaking temperature decreased due to longer treatment time at lower temperatures, with P50 having the highest and P70 the lowest. However, for OH, O70 consumed the most energy whereas O50 had the lowest energy consumption. With an increase in temperature, the electric current passing through the sample increased, which further increased the energy consumption. When the two methods were compared, OP used less energy than CP. Thus, the study indicated that the OH has a considerable energy consumption advantage over the conventional approach. The explanation was that OH is the direct heat generation process; while the conventional method generates heat by transforming electrical energy to thermal energy, which is subsequently delivered to the appliance, water, and the sample. Numerous studies that have evaluated OH with traditional heating techniques have found that the former uses less energy [19, 21].

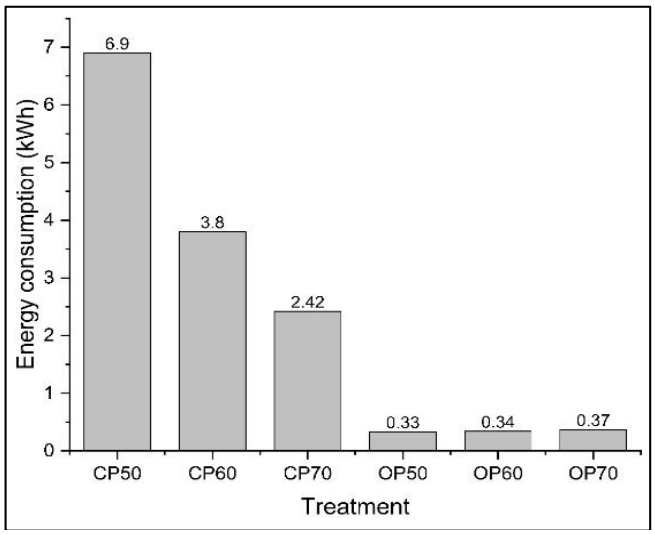

Fig 1: Energy consumption of OP and CP of Kodo millet

Cooking qualities

Cooking time

The cooking time of millet is an important characteristic as it determines the amount of energy needed to cook the millet for consumption or subsequent processing for food product development. The cooking qualities of OP and CP are displayed in Fig. 2. The hardness achieved after parboiling is the reason why parboiled millet took longer to cook. Parboiled rice requires longer to cook than non-parboiled rice due to the strong integration between endosperm cells, which causes the tightly packed starch granules to hydrate slowly and reduce in-water penetration into the grain [19]. The cooking time of the Ohmic-treated millet was found to be lower despite of higher hardness value. OP can quickly heat electroconductive materials, such as salty water, and can produce heat directly inside the materials. This reduced cooking time could be due to the greater intermolecular gaps by thermal effect facilitating easier water penetration during cooking. These findings revealed that lower cooking time by OP depends on the type of food and factors such as the electric field, voltage, and power [20]. A similar reduction of cooking time by OH was reported by Gavahian *et al*. [21].

WUR and Gruel loss

The WUR of OP and CP was higher than the untreated millet. Higher temperatures may accelerate the

gelatinization of starch by modifying the crystalline structure, breaking down hydrogen bonds, and releasing the amylopectin and amylose into the surrounding area. This increases the moisture content and size of the grains as starch granules absorb more moisture [22]. The untreated and parboiled millet cooked to a similar level of softness showed that parboiled millet absorbs more water maintaining its appearance. Another reason for higher water uptake may be due to steaming during parboiling, which influences the gelatinization of starch. Rice with a higher WUR had better cooking properties [23]. The higher WUR in the OP samples may be due to the higher heating rate and evaporation rate during the ohmic process.

Gruel loss is the quantity of solutes released during cooking from the grain into the boiling water. It was observed to decrease for both treatments when compared to the untreated sample. Parboiled millet had higher hardness and longer cooking time than untreated millet. This is the reason for lower gruel loss in the treated sample. The hardness and cooking time of rice have an adverse correlation with gruel solid loss. An increase in starch gelatinization resulted in a decrease in gruel loss and enhanced millet structure [24].

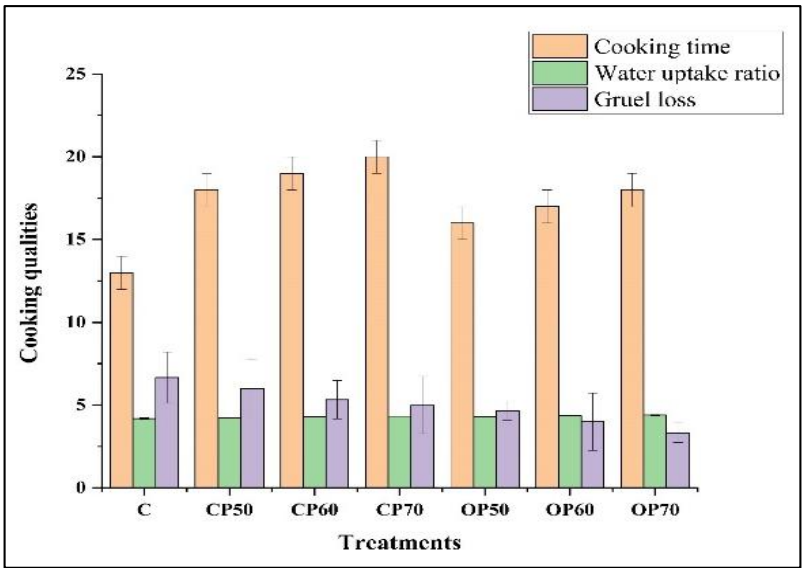

Fig 2: Cooking qualities of OP and CP of Kodo millet

Color

The color is an important parameter that increases the product's market value and improves consumer acceptance. During cooking, the water became somewhat cream color, suggesting that certain endosperm components had become soluble. It was found that the color of cooked millet changed which can be seen by the decrease in L* values (Table 1). Discoloration of parboiled millet typically has a direct correlation with market value because most consumers refuse to accept dark-colored parboiled millet. The main reason for the a* and b* values change in parboiled brown millet was the non-enzymatic browning of the Maillard type. Moreover, the fact that some nutrients from the bran constituents (lipids) leached out during parboiling indicates the contribution of pigments to the color of the parboiled millet [25]. The study showed that the L* values of cooked millet decreased for both OP and CP samples. This could explain the color differences seen in the millet grains that were treated using this method [26].

Table 1: Effect of OP and CP on the color values of cooked Kodo millet

Treatments	L*	a*	b*	ΔE
C	58.18±1.28^{a}	2.83±0.03^{a}	21.68±0.52^{a}	-
CP50	57.54±0.66^{a}	2.19±0.53^{bc}	21.13±0.16^{a}	1.87±0.52^{ab}
CP60	56.89±1.10^{ab}	2.45±0.32^{ab}	20.26±0.19^{bc}	1.57±0.25^{ab}
CP70	55.80±0.15^{b}	1.47±0.32^{de}	19.50±0.26^{d}	1.84±0.53^{ab}
OP50	57.57±0.95^{a}	1.93±0.15^{bcd}	20.53±0.20^{b}	2.19±0.68^{a}
OP60	57.03±0.94^{ab}	1.84±0.31^{cbd}	19.73±0.36^{cd}	1.72±0.85^{ab}
OP70	56.48±0.65^{ab}	1.32±0.14^{e}	19.92±0.49^{bcd}	0.86±0.26^{b}

Different superscripts of lowercase letter within the column represent significant differences between the treatments (p<0.05)

Functional properties

Solubility and swelling power

The solubility and swelling power are shown in Table 2. Solubility is a measure of starch granule dispersion after heating. Solubility of the sample increased after parboiling. Untreated starch, found in control millet, swells significantly more at higher temperatures but less at lower temperatures. This increased solubility is due to the more amylose leaching out of the starch granules when they swell during parboiling. Different chain length distributions in the starch could be the cause of the solubility difference [27]. Similarly, increased solubility was observed by Dharmaraj *et al.* [2].

Swelling power is the capacity of the starch to hydrate. The swelling power was found to be decreased after both treatments. This reduction may be due to the beginning of starch breakdown during soaking [28]. According to several studies, there is a negative association between swelling power and moisture content, meaning that as the flour absorbs more water, its swelling power decreases [29]. This result was found similar to Rao *et al.* [13].

WAC and OAC

The capability to bind water and oil molecules under restricted water and oil circumstances, respectively, is represented by the absorption capacity of water and oil [30]. The WAC and OAC of the sample increase after parboiling when compared to the raw millet. This could be due to the more damaged starch of the treated millet, which absorbs and holds more water at different temperatures. The degree of native flour granule breakdown mostly influences the

WAC, indicating that unchanged samples have poor potential absorption abilities [31]. This is due to the loss of the crystalline structure of starch and an increase in amylose leaching and solubility. High water absorbing capacity may contain more hydrophilic ingredients like polysaccharides [32]. Higher water adsorption capacity is ideal for product consistency, and bulking, and as a thickening agent for some food preparation. During ohmic soaking, the millet grains undergo hydration as they absorb water. Hydrated grains may have an increased capacity to absorb more water or oil due to their expanded and softened structure. Similar enhanced water adsorption was reported by Mir and Bosco [33].

Table 2: Effect of OP and CP on the functional characteristics of Kodo millet

Treatments	Solubility (%)	Swelling power (g/g)	WAC (ml/g)	OAC (ml/g)
C	2.67 ± 0.58^{b}	6.35 ± 0.4^{a}	0.73 ± 0.12^{a}	1.28 ± 0.23^{a}
CP50	3 ± 1^{ab}	4.8 ± 0.24^{b}	0.87 ± 0.12^{a}	1.37 ± 0.16^{a}
CP60	3.33 ± 0.58^{ab}	4.65 ± 0.22^{b}	0.93 ± 0.23^{a}	1.46 ± 0.28^{a}
CP70	4 ± 0.58^{ab}	3.78 ± 0.03^{c}	1.07 ± 0.12^{a}	1.59 ± 0.46^{a}
OP50	3.33 ± 0.58^{ab}	4.64 ± 0.14^{b}	0.93 ± 0.06^{a}	1.48 ± 0.26^{a}
OP60	4 ± 1^{ab}	4.37 ± 0.43^{bc}	1.03 ± 0.15^{a}	1.57 ± 0.07^{a}
OP70	4.67 ± 1.53^{a}	$4.25\pm0.4b^{bc}$	1.13 ± 0.31^{a}	1.64 ± 0.1^{a}

Different superscripts of lowercase letter within the column represent significant differences between the treatments ($p<0.05$)

TPC

Numerous research on cereals found that thermal treatments can either increase or decrease the phenolic content based on the type of cereal studied, the degree of heat treatment and the period of exposure [34]. TPC of all the samples are displayed in Fig.3. Untreated millet had significantly ($p<0.05$) lower TPC than the parboiled millet. This may be due to the heat treatment which could partially dissolve the ester link holding phenolics and cell walls together, causing some bound phenolics to become free phenolics [35]. There was a decrease in TPC in OP compared to CP. OH reduces the polyphenol content of the grain due to oxidative and degradation reactions, that take place due to exposure to thermal treatment. Furthermore, phenols may have migrated into the soaking and cooking water, along with the breakdown of phenolics during the processing steps, contributing to the lowering of the phenolic component. Zhang *et al.* [36] also reported a degradation of phenolics due to the thermal treatment of buckwheat flour. Chandrasekara *et al.* [37] demonstrated that the hydrothermal treatment liberated phenolic compounds from esterified and insoluble bound forms of the grain, indicating the thermal application-induced disintegration of cellular contents.

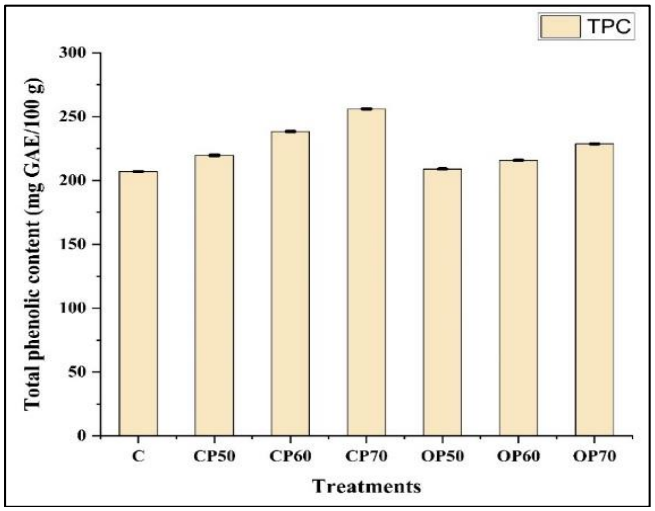

Fig 3: TPC of OP and CP of Kodo millet

Antioxidant Activity (AA)

The antioxidant activity of millet may be associated with several health advantages, including a lower risk of diabetes and cardiovascular disease depending on the variety. Fig.4 shows the AA values of Kodo millet after the treatments. OP reduced the DPPH antioxidant capacity when compared with the control sample. The findings revealed that some antioxidant compounds degraded during the treatment. This could be because the activation of enzymes like peroxidase and polyphenol oxidase causes the oxidative degradation of bioactive compounds [38] The antioxidant activity of the millet decreased as the soaking temperature increased from 50 °C to 70 °C. Higher temperatures result in the activation of oxidative enzymes, which increases the impact of degradation and lowers the antioxidant activity of the sample. Previous studies have shown that high OH-intensity conditions might accelerate the decomposition of bioactive compounds that possess antioxidant properties [42, 43]. The antioxidant capacity of pearl millet was reported to be influenced by dehulling and hydrothermal treatments [37]. The reduction in antioxidant activity is caused by the oxidation and degradation processes that take place during heat treatments such as heating, boiling, and roasting. The lower DPPH radical scavenging capacity by thermal processing may be the result of phenolics attaching to other molecules, such as phenolics or some proteins being difficult to extract during heat processing.

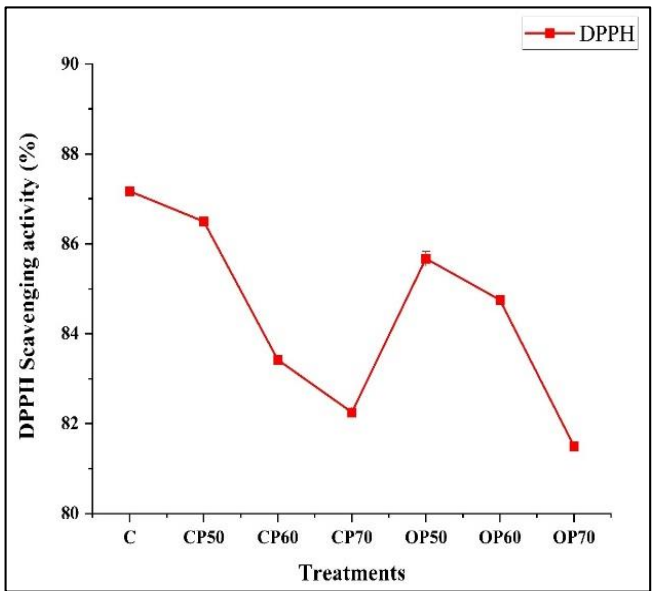

Fig 4: DPPH scavenging activity of OP and CP of Kodo millet

Conclusion

This study on the innovative parboiling of Kodo millet using OH highlights its effectiveness in improving cooking and functional properties. OP significantly reduces cooking time, enhances water and oil absorption compared to conventional methods. This process also improves the cooking quality of the millet, making it more suitable for various culinary applications. It was also found that the antioxidant activity and total phenolic content were reduced after OP. Compared to CP, OP used less energy. This study can provide new possibilities for the improved use of kodo millet in new products by demonstrating the potential use of OH treatment. This approach could pave the way for broader industrial applications and greater consumer acceptance of millet-based products.

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