BIO Web of Conferences **228**, 05003 (2026) https://doi.org/10.1051/bioconf/202622805003
Biospectrum 2025

Investigating Thermal Process-Induced Functional Changes in Little Millet: A RSM-based Comparative Insight

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Abstract. Little millet is emerging as a potential alternative staple crop with gluten-free characteristics and growing demand for health-oriented food formulations. However, the effects of contemporary thermal processing on the functional properties of little millet have yet to be fully explored. The present study investigated the effect of microwave and induction heating treatment on the key functionalities, such as water solubility index (WSI), water absorption capacity (WAC), and oil absorption capacity (OAC) of ground little millet flour, which were measured using a full factorial and response surface methodology (RSM) of little millet flour. The microwave and induction temperatures varied between 110–170°C and 120–160°C, respectively, with a time variation from 2–8 min. Due to the little millet flour exhibiting minimal thermal solubility, the WSI, which remained low and constant, showed little response to the processing treatments (0.10–0.17). However, process intensity did positively correlate with WAC, which reached values of 7.68 g/g and 6.77 g/g for induction and microwave treatments, respectively, clearly indicating increased water absorption and WAC due to starch gelatinization and the structural unfolding of the associated proteins. Further, OAC was examined with mustard and sunflower oil, and there is a clear positive correlation evident for OAC with oil type and process. Induction heat processing for mustard oil produced the most significant OAC values (0.27–7.82 g/g), while microwave processing with sunflower oil exhibited lower values (0.30–2.83 g/g). In conclusion, the study showed that the application of induction and microwave processing technologies can be employed for tailored processing to achieve the desired functional and processing attributes for little millet flour.

Keywords: little millet, thermal Processing, functional properties, response surface methodology

1 Introduction

Millets are ancient heritage grains that are cultivated on dry soils without the use of any pesticides [1]. They are high in dietary fiber, minerals, flavonoids, protein, fat, and carbohydrates [2]. The majority of these millets are utilized as staple foods and as key ingredients in a variety of traditional dishes, including bread, chakli, papads, idli, dosa, porridges, and more [3]. Millets have a brief growing season and are pest-resistant. Notably, only a small number of food crop varieties possess these qualities, which together make them the future's golden harvests. They are known as "miracle grains" because of their excellent nutritional profile with regard to the amount of fiber, gluten-free status, resistant starch, micronutrient concentration, and other phytochemicals that have potential medical uses [4]. A significant portion of India's food grain industry is made up of millet grains, which make up almost one-sixth of all food grain production. South and East Asia account for almost 60% of millet output, followed by Eurasia and Central Asia (14%), Africa (16%), and the rest of the world (10%) [5]. About 33–37% of the 28 million tonnes of millet grains produced worldwide come from India, making it the world's top producer [1, 6]. Along with several other vital minerals and phytochemicals, little millet is free of gluten and contains proteins (9.80–12.49 g/100 g), fat (2.87–5.09 g/100 g), ash (0.98–4.78 g/100 g), crude fiber (0.49–8.72 g/100 g), and carbohydrates (62.25–76.59 g/100 g) [7]. Millets are customarily consumed as a food, prepared using diverse processing methods, such as pressure cooking, roasting, and boiling. The type of pre-processing employed, the grain size, the ratio of water to grain, the duration of cooking, the mode of cooking, and the cooking temperature are only a few of the many variables that alter the characteristics of cooked grain. Microwaves are electro-heat devices that operate frequencies ranging from 300 MHz to 300 GHz to convert electrical energy into thermal energy; these are applicable in food ranging between 2.45 GHz and 915 MHz [8]. The processing technologies are very critical in defining the functional, physical, and nutritional properties of cereals and millets. Cooking in the traditional ways, like boiling or roasting, dates back centuries, but with modern-day cooking technology like microwave and induction heating, it is a more efficient method of cooking and could preserve nutrients better [9]. However, such processing methods can also induce changes in the molecular structure of starches and proteins, which affect the functional characteristics, including water absorption capacity (WAC), oil absorption capacity (OAC), and water solubility index (WSI). These changes are important in understanding how to formulate millet-based food formulation with desirable sensory and textural properties [10].

Though thermal processing techniques have been applied for longer times, the effect of modern thermal processing techniques, such as induction and microwave treatment, on the techno-functionalities WSI/WAC, and OAC of little millets has not been explored properly. Hence, the objective of the study lies in the application of modern processing techniques on the effects of techno functionalities with an integrated approach of factorial experimental design and response surface methodology (RSM).

2. Materials and Methods

2.1 Collection and preparation of raw material

Little millet was purchased in May 2025 from Paushtik Life, an organic shop in Kolkata, India. Samples were stored in a cold (5 °C) temperature until further use [8]. Further, the same sample has been used in a further study. Thermal processing of the little millet sample was conducted using a microwave and an induction oven to evaluate the functional properties. For the induction oven (Morphy Richards Chef Express 400) and microoven cooking (Whirlpool Magicook Pro 22CE), grains were added in the water in a ratio of 1:7 g/ml and processed at diverse processing conditions (**Table 1 and Table 2**). The processed sample was further dried using a tray drier at a temperature of 55 °C. After that, a mortar and pestle were used to grind the samples into flour and stored at 10 °C for further analysis. A raw sample (as a control) was also ground concurrently at room temperature. The different processing types and parameters have been coded (**Table 1 and Table 2**).

Table 1. Diverse processing conditions of little millets in microwave treatment

CODE	TIME(minutes)	TEMPERATURE (Celsius)
LMFO1	2	140
LMFO2	2	110
LMFO3	2	170
LMFO4	5	140
LMFO5	5	110
LMFO6	5	170
LMFO7	8	110
LMFO8	8	170
LMFO9	8	140

Table 2. Diverse processing conditions of little millets in induction treatment

CODE	TIME(minutes)	TEMPERATURE (Celsius)
LIFO1	2	140
LIFO2	2	120
LIFO3	2	160
LIFO4	5	120
LIFO5	5	160
LIFO6	5	140
LIFO7	8	120
LIFO8	8	160
LIFO9	8	140

2.2 Functional properties of processed flour

2.2.1 Water Solubility Index

The WSI was performed according to the methods described by Kumar *et al.* (2020) [8] with some modifications. Briefly, 0.5 g with 10 ml distilled water, 1 g with 20 ml distilled water, and 1.5 g with 30 ml distilled water have been placed in different conical flasks separately. The conical flasks were shaken or swirled to ensure appropriate mixing, and then they were left undisturbed for an hour to settle. After an hour, the water in the conical flasks was filtered and gathered in petri dishes. The filtrates were placed in petri dishes and dried in a tray drier for four hours at 65 °C. For the control of the sample, the same process has been performed (Kumar *et al.*, 2020) [8] without any heat treatment. The water solubility index was then calculated using equation 1 [11].

$$WSI = \frac{\text{Weight of the petridishes after drying the filtrate}}{\text{Weight of the blank petri dish}} \quad [1]$$

2.2.2 Water Absorption Capacity

The WAC was performed according to the methods described by Kumar *et al.* (2020) [8] with some modifications. In the conical flasks, 0.5 g of the compound was mixed with 10 ml of distilled water, 1 g was mixed with 20 ml of distilled water, and 1.5 g was mixed with 30 ml of distilled water. The conical flasks were shaken well to ensure proper mixing, leaving the mixtures undisturbed for one hour to allow settling. After an hour, the water will be separated from the solid residue. The water of the conical flask was filtered, and the weight of the solid residue was noted. For the control of the sample, the same process has been performed (Kumar *et al.*, 2020) [8] without any heat treatment. The amount of water absorbed by the little millet flour was determined using equation 2 [12].

$$WAC = \frac{\text{Weight of the solid residue}}{\text{Weight of the sample}} \qquad [2]$$

2.2.3 Oil Absorption Capacity

OAC has been employed for two types of oil: mustard and sunflower oil. The OAC has been executed in accordance with the procedure described by Kumar *et al.* (2020) [8]. Briefly, 1.5 g of the ground thermal treated sample was placed in the conical flask, 0.5 g, 1 g, 1.5 g, in three different test tubes, and 10 ml, 12 ml, 15 ml of oil were added, respectively, in the conical flasks. The mixtures were shaken to ensure there was proper mixing and followed by settling for an hour to settle. Later, the oil was separated from the solid residue portion. The weight of the solid residue that remained in the test tube and the conical flask was taken. For the control of the sample, the same process has been performed Kumar *et al.*, 2020) [8] without any heat treatment. The amount of oil absorbed by the little millet flour was calculated using equation 3 [13].

$$OAC = \frac{\text{Weight of the solid residue}}{\text{Weight of the sample}} \qquad [3]$$

2.3 Experimental Design and Statistical Analysis

A full factorial experimental design has been considered for the study with 3 levels and 2 factors, i.e., 9 runs for each type of thermal treatment. All the data were performed in triplicate (n=3) and presented as mean ± standard error (S.E.) at $p<0.05$ (95% confidence level). Further, the analytical data of WSI, WAC, and OAC were further analyzed in RSM (Design Expert software, version 13) to investigate the effect of treatment on the functional properties like WSI, WAC, and OAC of little millet flour at 95% confidence interval ($p<0.05$).

3. Results and Discussion

3.1 Water Solubility Index

Figure 1A shows that the WSI value in the induction oven was between 0.1 and 0.16. The WSI of LMFA and LMFC is constant, implying the changes in processing factors (such as time and temperature) have very little influence on the solubility of the millet flour in the ranges that were tested (Figures 1B and 1D). However, LMFB shows that WSI increases with higher temperatures and moderate cooking times, which implies solubilization of flour components under the given conditions (Figure 1C).

For the microwave, WSI was between 0.1 and 0.17 (Figure 2A). Figure 2B indicates that LMFA had a slight rise in WSI with an increase in temperature and time, whereas LMFB and LMFC had no significant rise in WSI within the range of temperatures and time (Figures 2C and 2D).

The possible reason is that little millet flour exhibited specific hydration and lipid-binding behaviors after thermal processing. This suggests that the minor variations in WSI (0.10-0.17) over the two systems indicate that the solubilisation of low molecular weight polysaccharides and proteins remained low. This was in line with the low solubility of heat- modified millet flours during heat-moisture treatment when the chief macromolecule's structural integrity was preserved [14].

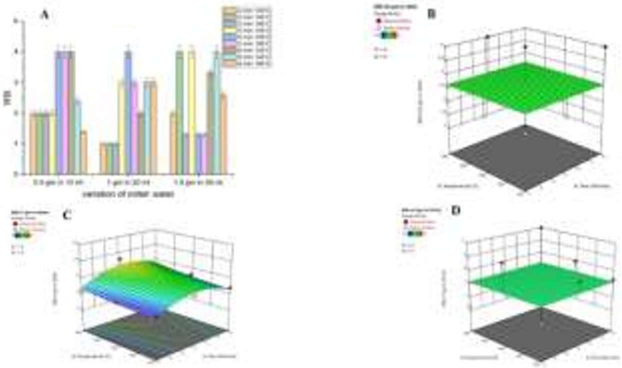


Figure 1: (A) WSI of little millet in varying condition of temperature 120-160 °C and time 2-8 minutes in induction oven, (B) Effect of thermal treatment on WSI of LMFA using induction oven (C) Effect of thermal treatment on WSI of LMFB using induction oven, (D) Effect of thermal treatment on WSI of LMFC using induction oven

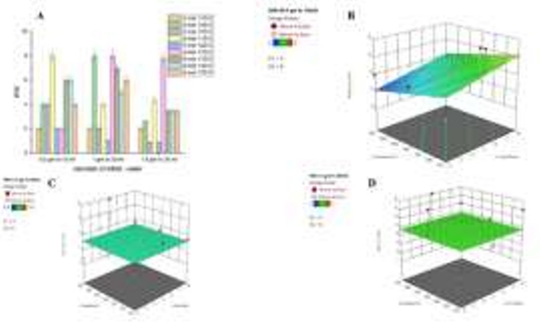


Figure 2: (A) WSI of little millet in varying conditions of temperature 110-170 °C and time 2-8 minutes in microwave, (B) Effect of thermal treatment on WSI of LMFA using microwave, (C) Effect of thermal treatment on WSI of LMFB using microwave, (D) Effect of thermal treatment on WSI of LMFC using microwave.

3.2 Water Solubility Index

The WAC of the samples cooked in the induction oven ranged from 0.17 to 7.68 g/g (Figure 3A). The WAC slightly increases with longer cooking times and higher temperatures, but overall remains relatively moderate across the tested range for LMFA (Figure 3B). LMFB test sample indicates a rapid increase in water binding ability at high temperature and long time, underlying a threshold effect, while LMFC represents a generally strong but more distributed increase in hydration potential across a wider range of processing conditions (Figure 3C & Figure 3D).

The WAC of the samples cooked in the microwave ranged from 0.04 to 6.77 g/g (Figure 4A). Across varying concentrations (LMFA, LMFB & LMFC), the 3D surface plots demonstrate that the water absorption and solubility characteristics of little millet flour generally increase with longer microwave times and higher temperatures. At the lowest concentration, WAC rises steadily under intensified processing (Figure 4B), while moderate concentrations show similar trends with even greater effects (Figure 4C). For the highest flour concentration, absorption peaks are significantly under the most intense conditions (Figure 4D).

The strong positive correlation between WAC and temperature and time corresponds to the process of gelatinizing the starch-rich granules and unfolding the proteins present in millet. This behavior parallels the above phenomena, where increased water-binding was observed in other millet species under microwave and hydrothermal treatments [15]. The increased WAC under induction is likely a result of surface heating uniformity and a decrease in evaporative losses, in contrast to microwave heating, which can produce volumetric heating gradients and differing degrees of water mobility within the matrix during treatment [16]. Overall, WAC has many functional and sensory effects on food products. Processed flours contain more binding sites than the raw samples because of the partial denaturation or dissociation of proteins and the gelatinization of carbohydrates in the heat processing [17]. Further, the proper formulation and sensory appeal of processed flour in bakery products need to be achieved through diverse formulations. However, industrial applicability remains a potential challenge considering cost, structural changes, and agro diversity of millet.

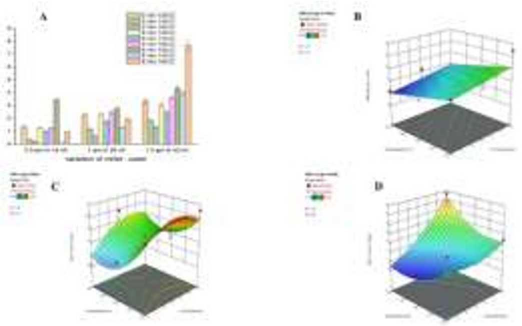


Figure 3: (A) WAC of little millet in varying condition of temperature 120-160 °C and time 2-8 minutes in induction oven, (B) Effect of thermal treatment on WAC of LMFA using induction oven (C) Effect of thermal treatment on WAC of LMFB using induction oven (D) Effect of thermal treatment on WAC of LMFC using induction oven.

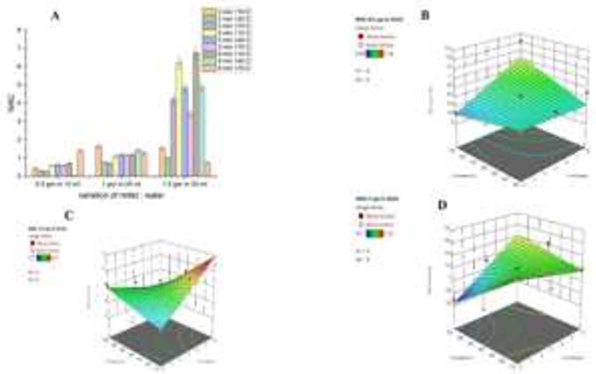


Figure 4: (A) WAC of little millet in varying conditions of temperature 110-170 °C and time 2-8 minutes in microwave, (B) Effect of thermal treatment on WAC of LMFA using microwave, (C) Effect of thermal treatment on WAC of LMFC using microwave, (D) Effect of thermal treatment on WAC of LMFB using microwave.

3.3 Oil Absorption Capacity

OAC of the induction oven samples examined in mustard oil ranged from 0.27 to 7.82 g/g (Figure 5A). The plot of LMFO1 reveals that oil absorption is high at moderate temperatures (130-150 0C) and shorter processing time (2-5 minutes), which indicates that maximum oil uptake occurs at this condition (Figure 5B). Conversely, LMFO2 and LMFO3 plots reveal a comparably constant OAC throughout the range with minor variation at elevated temperature and time (Figures 5C and 5D).

The OAC of sunflower oil was from 0.17 to 2.35 g/g (Figure 6A). At intermediate concentration, the LMFO2 graph shows that oil absorption capacity (OAC) rises significantly with an increase in temperature and time (Figure 6C). The LMFO1 plot is almost flat at low concentration, showing no or minimal influence of temperature or time on oil absorption (Figure 6B). The LMFO3 plot is also rather stable at high concentration, with little sensitivity to the processing (Figure 6D).

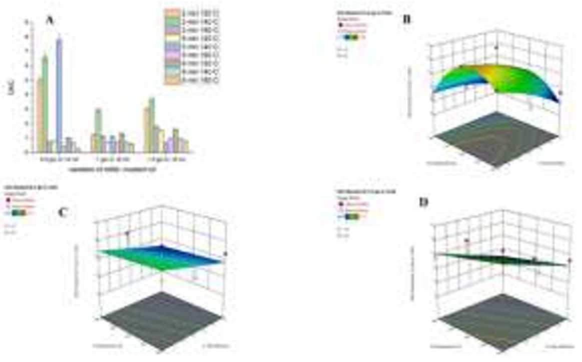
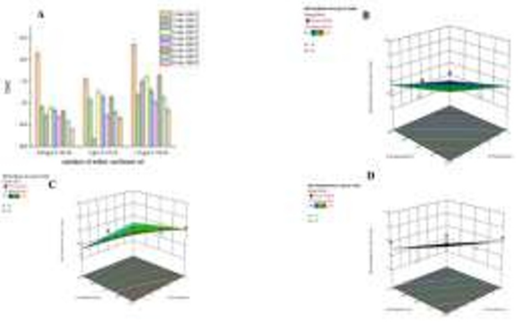


Figure 5: (A) OAC of little millet in mustard oil in varying condition of temperature 120-160 °C and time 2-8 minutes in induction oven (B) Effect of thermal treatment on OAC of LMFO1 using induction oven (C) Effect of thermal treatment on OAC of LMFO2 using induction oven (D) Effect of thermal treatment on OAC of LMFO3 using induction oven.



Figures 6: (A) OAC of little millet in sunflower oil in varying condition of temperature 120-160 °C and time 2-8 minutes in induction oven (B) Effect of thermal treatment on OAC of LMFO1 using induction oven (C) Effect of thermal treatment on OAC of LMFO2 using induction oven (D) Effect of thermal treatment on OAC of LMFO3 using induction oven

The OAC of microwave samples examined in mustard oil ranged from 0.3 to 1.6 g/g (Figure 7A).In the LMFO3plot, the surface shows a more dramatic rise toward the centre, indicating that OAC is more sensitive to temperature and time (Figure 7D). The LMFO2plot also has a noticeable peak, although it is less intense than the LMFC (Figure 7C). The surface of the LMFO1 plot becomes almost flat, and the result is generally consistent across temperature and time (Figure 7B).

The OAC of the samples in microwave in sunflower oil from 0.3 to 2.83 g/g (Figure 8A). The LMFO1 and LMFO2plot shows an almost planar surface with a gentle positive slope, suggesting weak curvature and little to no interaction where OAC increases mostly with time (Figures 8B & 8C). LMFO3 plot's surface is pyramidal/curved, rising from low OAC at short time–low temperature toward a peak at mid to high temperature and long-time (Figure 8D). This indicates both factors have strong positive main effects across most of the range.

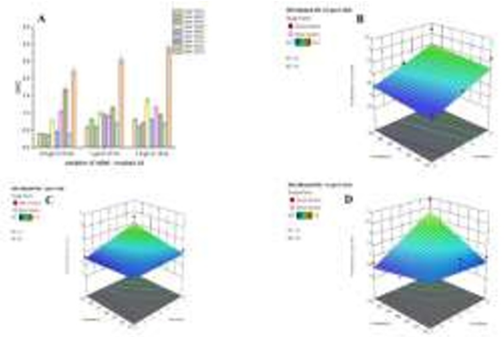


Figure 7: (A) OAC of little millet in mustard oil in varying conditions of temperature 110-170 °C and time 2-8 mins in microwave (B) Effect of thermal treatment on OAC of LMFO1 using microwave (C) Effect of thermal treatment on OAC of LMFO2 using microwave (D) Effect of thermal treatment on OAC of LMFO3 using microwave

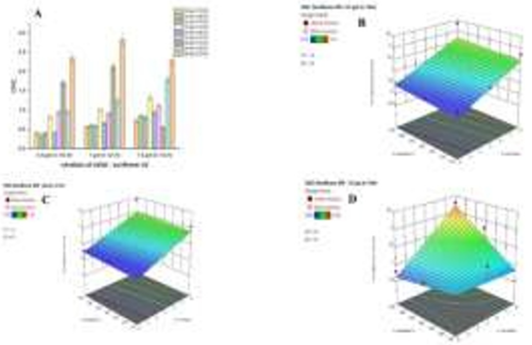


Figure 8: (A) OAC of little millet in sunflower oil in varying conditions of temperature 110-170 °C and time 2-8 mins in microwave (B) Effect of thermal treatment on OAC of LMFO1 using microwave (C) Effect of thermal treatment on OAC of LMFO2 using microwave (D) Effect of thermal treatment on OAC of LMFO3 using microwave.

High OAC implies that the flours may be applied to enhance food preparations with regard to taste and texture. Due to such properties, flour may also be used as a functional ingredient in food products (such as sausages, whipped toppings, chiffon deserts, and sponge cakes). The flour protein's ability to physically bind fat by capillary attraction is known as its OAC [8]. The factors for interaction between lipids and proteins include non-covalent bonds such as hydrophobic bond, electrostatic bond, as well as hydrogen bond, and the oil absorption especially leads to the entrapment of oil physically within the protein isolates [18].

4. Potential limitation, uncertainty, and future scope

Addressing uncertainties is important for the interpretation in this study. First, only one type of millet was employed in the study used, and starch–protein mixes can influence functional performance [19], [20]. Second, pre-thermal treatment variations in moisturization and water activity differed between batches and may impact WAC and OAC [21]. Third, the residential microwave and induction heater may not have the industrial scale and commercial-grade thermal intensity and penetration features [8], [22]. Fourth, OAC was only tested with two oils (mustard and sunflower), compared to other food matrix fats, the viscosity, polarity, and fatty acid profile of the lipids may influence fat-binding to the matrix less. Lastly, all functional experiments were performed on isolated flour systems, not on doughs or assembled matrices, so techno-functional responses in real food systems where hydrocolloids, lipids, or processing additives are significant may differ [23]. These uncertainties may account for the significant differences from the existing literature and underline the importance of further research in food formulation. Hence, the proper formulation and sensory appeal of processed flour in bakery products need to be achieved through diverse formulations. However, industrial applicability remains a potential challenge considering cost, structural changes, and agro diversity of millet [19].

Further, future studies can also focus on the rheology and structural changes to elucidate the starch protein interaction at the molecular level, and a correlation can be established with functional and structural changes. Further, inclusion of such process samples into ready foods like bakery and confectionery is needed to check the compatibility of the formulation.

Conclusion

The present study indicates microwave and induction treatments can be used to regulate hydration and lipid-binding properties of little millet flour under time-temperature conditions and loadings. While RSM based approach exhibited that WSI remained almost unchanged, WAC and OAC showed marked increases consistent with starch gelatinization and protein unfolding, showing significant temperature and time-dependent increases. With regards to oil absorption, there was marked oil type specificity, with mustard oil showing particularly elevated absorption. Such functional behaviors are consistent with the partial starch gelatinization and denaturation of proteins, causing more binding sites to be available to water and oil with little change in solubility. These results give a basis for the possible use of thermally treated little millet flour in food formulations, though practical applications and structural characterizations are needed.

Acknowledgement

The authors would like to acknowledge the instrumentation facility of the Department of Food Technology, Guru Nanak Institute of Technology, Kolkata. Further, the authors would like to acknowledge Mr. Sudip Chattopadhyay and Mrs. Ruth Chattopadhyay, Paushtik Life, Kolkata, West Bengal, and Mr. Bhairav Saiani, farmer and seed conserver, Panchal, Bankura, West Bengal, for their motivation and samples of the study.

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