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Rheological, physical, and sensory evaluation of finger millet-based instant idli premixes: Optimizing rice substitution for enhanced nutrition and consumer acceptability

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PAPER

Abstract

This study aimed to assess the rheological, physical, and sensory properties of instant idli premixes formulated with finger millet (30–70%), as a partial or full substitute for rice. The attractiveness and convenience of pre-prepared foods led the food industry to reformulate traditional, time-consuming foods into modern, ready-to-cook options. Rheological assessments revealed that incorporating finger millet significantly improved water absorption (up to 65.5%) and accelerated starch gelatinization, with the onset temperature recorded at 71.0°C for the 60% millet blend. Optimal dough stability (17.6–18.3 min) and extensibility (1638 mm) were observed at 50% millet inclusion, contributing to a soft, well-aerated texture. In contrast, higher substitution levels (70%) impaired structural integrity and increased dough resistance, indicating reduced viscoelastic performance. Physical analysis demonstrated consistent batter viscosity (~2500 cP) across formulations, while color metrics (ΔE*: 14.9–17.5) showed only minor shifts. Organoleptic properties confirmed high consumer acceptability of idlis containing 50–60% finger millet, as assessed in terms of softness, flavor, and appearance. These results highlight the potential of finger millet as a valuable, gluten-free ingredient for improving the nutritional profile of idlis without sacrificing their texture or flavor.

Keywords: finger millet; free gluten; idli; rheological properties; sensory attributes

Introduction

Idli, a widely consumed fermented steamed rice cake prepared from ground rice and urad dal (hulled black gram), is a staple breakfast in cuisines of India and its neighboring regions, with a soft texture, sour flavor, and balanced nutritional profile (Karunanithi *et al.*, 2024). As demand for convenient, ready-to-cook foods increases, instant idli premixes have become a popular alternative to the traditional fermentation method, saving preparation time while retaining the authentic taste and texture (Panigrahi *et al.*, 2025). Instant premixes were fortified with various grains, including sorghum, pearl millet, finger millet, and amaranth, to enhance the nutritional quality (Patil *et al.*,2024; Rani *et al.*, 2019).

Finger millet (*Eleusine coracana*), a micronutrient and fiber-dense grain, has gained attention as a functional food ingredient. It is rich in calcium (344 mg/100 g), iron (3.9 mg/100, 43 g), phenolic compounds, and dietary fiber (15–20%), which support bone health, digestion, and glycemic control (Nagaraja *et al.*, 2024). Additionally, its low glycemic index (~55) and gluten-free nature suit individuals managing diabetes, celiac disease, and metabolic disorders (Siroha and Bangar, 2024). However, finger millet's unique composition (high amylose (~25%) and complex protein matrix) can alter starch pasting and dough behavior, thus impacting the rheological properties of the idli batter (Bhasin *et al.*, 2024). Poor rheological properties can lead to dense textures, uneven porosity, or structural instability (Zhao *et al.*, 2025).

Though more studies concentrated on ingredient substitution for idli premixes, there is scant systematic analysis of the rheological behavior of the same. Siddique *et al.* (2024) have noted that high fiber content of millets reduces dough cohesiveness, necessitating the use of hydrocolloids for textural improvement. Further, Zhang *et al.* (2025) stated that the existence of starch–protein interactions is complex in gluten-free formulations, which modify viscoelastic properties. Failure in understanding the modifications in the rheological behavior can lead to inconsistent product quality, restricting scalability, and commercial feasibility.

This study aims to assess the rheological and pasting properties of finger millet-containing instant idli premixes through a holistic view. In response to the growing demand for functional and fortified foods, this study aimed to assess the rheological, physical, and organoleptic properties of instant idli premixes formulated with 30–70% finger millet as a partial or full substitute for rice, to improve nutritional quality while maintaining texture and taste of traditional idlis.

Materials and Methods

Materials

Polished rice (*Oryza sativa* L.), decorticated black gram (*Vigna mungo* L.), and finger millet (*E. coracana* L.) were procured from the Regional Agricultural Research Station (RARS), Dapoli, Maharashtra, India. Finger millet used in this study was sown during the early monsoon (June–July) and harvested during September and October.

Experimental treatments

Six formulations (T1–T6) of Instant Idli Premix were prepared by varying the proportions between rice, finger millet, and black gram, all set for standardization to 100 g (Figure 1). T1 had rice (50%), finger millet (30%), and black gram (20%), which is a balanced ratio. T2 and T3 gradually increased the millet content to 40 and 50%, respectively, while reducing the rice content accordingly. T4 and T5 had 60 and 70% millet, respectively, and T6 (control) consisted of 70% rice and 30% black gram, replicating a traditional idli mix.

Preparation of idli batter

Finger millet, black gram, and rice were initially handpicked to remove foreign materials such as stones, broken grains, and plant debris. Subsequently, the grains were passed through mesh sieves 60 (250 μm) to eliminate fine particulate matter. Light impurities, including husks and dried leaf fragments, were removed using gentle air blowing. All cleaning procedures were conducted under hygienic laboratory conditions to prevent contamination. The cleaned grains were then soaked in potable water for 8 h at (25 ± 2°C) room temperature to ensure adequate hydration and to activate endogenous enzymatic reactions. The grains were wet pulverized (Model XYZ-WG20, ABC Instruments Pvt. Ltd., Mumbai, India) to produce a smooth and consistent batter. The batter was then mixed and allowed to ferment at room temperature for 10 h. The batter was tray-dried for 6 h at 60°C to stabilize it and reduce its moisture content. The dried mix was ground into a homogeneous, free-flowing powder using a 150 μm sieve (0.15 mm particle size; ASTM 100 mesh, Make: Labfine Test Sieves, Mumbai, India) and a laboratory grinder (Model XYZ-150, SreeValsa Engineering Co., Coimbatore, India). The finely ground mixture was chilled after processing and packed in 50-micron food-grade high-density polyethylene (HDPE) stand-up pouches.

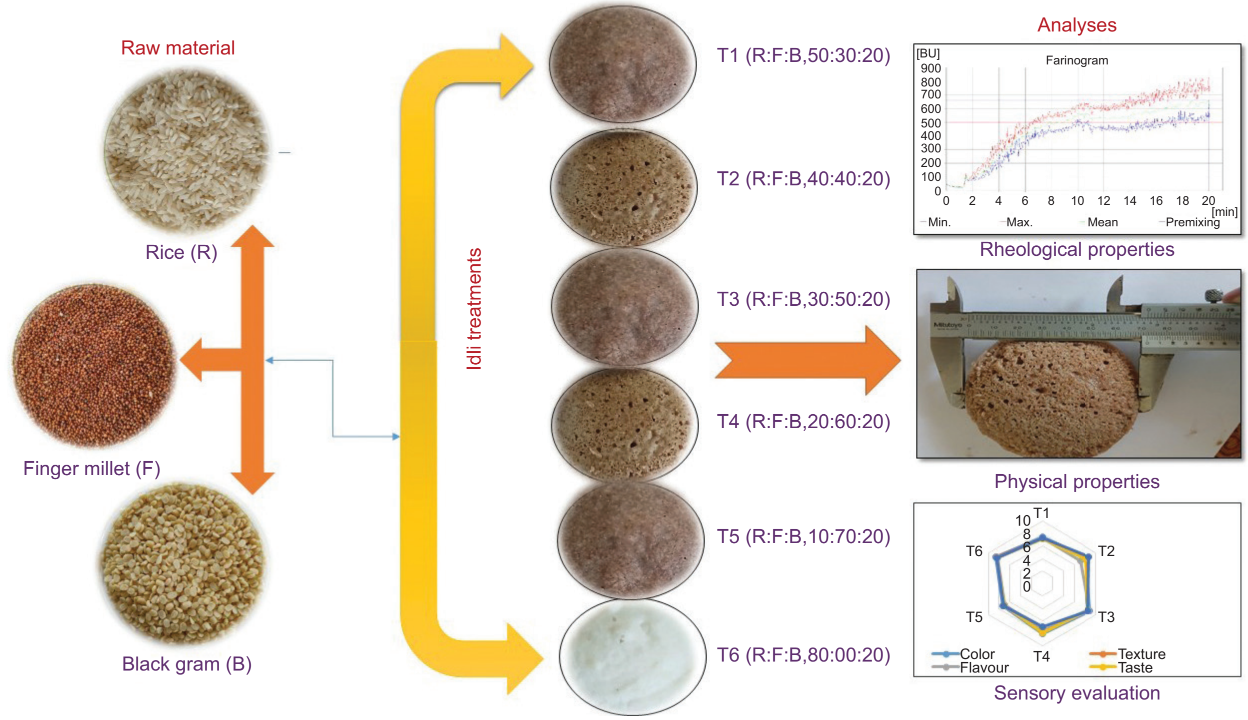

Figure 1. Experimental protocol of idlis.

Functional and rheological analysis

Amylograph

The gelatinization properties of the instant idli mix, including onset temperature (°C), peak gelatinization temperature (°C), and maximum viscosity (AU), were measured using an amylograph (Amylograph-E, Brabender GmbH and Co. KG, Germany) following the method described by Ronda *et al.* (2017). 80 g of the idli mix was combined with 450 mL of distilled water, and heated from 30 to 95°C at 1.5°C/min rate. Viscosity was recorded as a function of temperature. The pasting behavior provided insights into starch swelling and batter consistency.

Farinograph

The farinograph (Farinograph-E, Brabender GmbH and Co. KG, Germany) was used to assess water absorption (%), dough development time (min), dough stability (min), and mixing tolerance index (BU) of the idli mix. 300 g of idli mix (14% moisture basis) was mixed with water at 30°C to achieve 500 BU consistency, following the method described by Della Valle *et al.* (2022). The test provided information on hydration, dough tolerance, and mixing stability.

Extensograph

The extensograph (Extensograph-E, Brabender GmbH and Co. KG, Germany) was used to evaluate dough elasticity and gas retention properties, measuring energy (cm^2), resistance to extension (BU), extensibility (mm), and ratio number (R/E). 150 g of dough was proofed for 30, 60, and 90 min, and stretched until it ruptured. The force-extension curve provided insights into dough strength, extensibility, and fermentation behavior following the method described by Ronda *et al.* (2017).

Viscosity measurement

The apparent viscosity of idli batter was measured using a Brookfield DV2T Viscometer (Model: R/S Plus, Make: Brookfield Engineering Laboratories, USA) under controlled conditions. The premix was mixed with water in a 1:2 ratio to ensure uniform consistency. The viscosity was measured at 50 rpm using spindle RV3 at 25 ± 1°C. These parameters were selected based on previous studies analyzing batter flow properties (Della Valle *et al.*, 2022).

Measurement of idli expansion

The physical expansion of idlis was measured using a digital Vernier caliper (Mitutoyo Vernier Caliper, Model: 530-122, Japan) (Joshi *et al.*, 2014). Batter was filled into idli molds, and the initial height and diameter were recorded before steaming. After steaming for 15 min, the idlis were allowed to cool naturally at room temperature (28 ± 2°C) for 20 min. Final height and diameter were then measured using the following equation.

$$Expansion\ Ratio = \frac{Final\ Height}{Intial\ Height} \quad \text{(Eq. 1)}$$

Color measurement

The color characteristics of cooked idli samples were analyzed using a Premier Colorscan Colorimeter (Premier Colorscan; Premier Colorscan Instruments Pvt. Ltd., India) following the method by Susmitha *et al.* (2022). The CIE Lab parameters—L^* (lightness), a^* (red–green), and b^* (yellow–blue)—were recorded. Calibration was performed using a white tile and an open-air black reference. Samples were placed in the sample holder of the instrument for measurement. The total color difference (ΔE^*) between the samples and the control was determined using the following equation.

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad \text{(Eq. 2)}$$

Where:

ΔL^* = Difference in lightness between the idli sample and control.
Δa^* = Difference in redness between the idli sample and control.
Δb^* = Difference in yellowness between the idli sample and control.

Proximate and nutritional composition of idli premix

The proximate chemical composition of samples, such as moisture, ash, crude fat, crude protein, and fibre, was determined according to AOAC (2020). Carbohydrate content was calculated by difference.

Sensory evaluation

Sensory evaluation of the steamed idli samples was performed by 30 trained panelists (aged 22–45 years; 18 males and 12 females) using a 9-point hedonic scale, following standard procedures described by Karnat *et al.* (2024). Samples were coded and presented randomly, and organoleptic attributes, such as color, appearance, texture, flavor, taste, and overall acceptability, were assessed.

Statistical analysis

All experimental data were analyzed using SPSS 25 (IBM SPSS 25 Software, NY, USA), with results expressed as Mean ± Standard Deviation (SD). One- and two-way ANOVA (for extensiograph) were performed to assess the effects of formulation and other independent variables on the measured parameters. Significant differences between means were determined using Tukey's HSD test ($P < 0.05$) for multiple comparisons. All measurements were conducted in triplicate (n = 3) (McCormick and Salcedo, 2017).

Results and Discussion

Characterization of idlis

The physical properties of finger millet, rice, and black gram dal are presented in Table 1. Notable differences were observed among the three samples in terms of size, density, and flow-related characteristics. Finger millet showed the smallest grain dimensions, with a geometric mean diameter of 1.47 mm, while rice and black gram dal measured 3.07 and 3.10 mm, respectively. Bulk density ranged from 710.3 kg/m³ in rice to

Table 1. Physical properties of finger millet, rice, and black gram dal.

Physical property	Finger millet	Rice	Black gram dal
Length (mm)	1.59 ± 0.02[c]	5.90 ± 0.05[b]	5.94 ± 0.04[a]
Width (mm)	1.96 ± 0.03[c]	2.43 ± 0.04[b]	4.54 ± 0.06[a]
Thickness (mm)	0.95 ± 0.01[c]	2.01 ± 0.03[b]	4.23 ± 0.05[a]
Geometric mean diameter (mm)	1.47 ± 0.02[c]	3.07 ± 0.04[b]	3.10 ± 0.05[a]
Bulk density (kg/m³)	781.1 ± 5.2[b]	710.3 ± 4.8[c]	814.1 ± 6.0[a]
True density (kg/m³)	1277.1 ± 6.3[c]	1328.6 ± 7.1[b]	1346.1 ± 6.8[a]
Porosity (%)	38.9 ± 1.2[c]	46.53 ± 1.5[a]	39.48 ± 1.1[b]
Angle of repose (°)	29.26 ± 0.6[b]	34.1 ± 0.7[a]	27.51 ± 0.5[c]

Table 2. Effect of premix treatments on pH, titratable acidity, and TSS of idli batter (Mean ± SD).

Parameter	T1	T2	T3	T4	T5	T6 (Control)
pH	4.8 ± 0.01[b]	4.7 ± 0.01[c]	4.6 ± 0.01[d]	4.5 ± 0.01[e]	4.4 ± 0.01[f]	5.1 ± 0.01[a]
Titratable acidity	1.60 ± 0.02[a]	0.99 ± 0.01[b]	0.64 ± 0.01[c]	0.52 ± 0.01[cd]	0.25 ± 0.01[e]	0.76 ± 0.02[bc]
TSS	6.13 ± 0.05[b]	5.80 ± 0.04[c]	5.60 ± 0.03[d]	5.40 ± 0.02[e]	5.10 ± 0.03[f]	6.50 ± 0.06[a]

All values represent mean ± SD (n = 3). Superscripts within rows indicate statistically significant differences at P < 0.05.

814.1 kg/m^3 in black gram dal, while true density was highest in black gram dal (1346.1 kg/m^3) and lowest in finger millet (1277.1 kg/m^3). These density values are important for determining packaging volume and transport efficiency. Rice exhibited the highest porosity (46.53%), indicating more void space between particles compared to finger millet (38.9%) and black gram dal (39.48%). The angle of repose, which reflects the flowability of the grains, was lowest for black gram dal (27.51°), suggesting better flow behavior. In contrast, rice had the highest angle (34.1°), indicating relatively poor flow. These physical parameters are essential for equipment design, especially in mixing, conveying, and storage operations.

Idli, a fermented rice and lentil cake, is valued for its nutritional profile and soft texture. Batter rheology-elasticity, water absorption, starch gelatinization, and viscosity affects the quality of the cooked idli. Adding millet improves nutrition but impacts texture and structure (Upadhyay and Mehra, 2017). Based on (Tables 2 and 3), 50–60% millet substitution is optimal for balancing hydration, extensibility, and aeration, producing well-fermented, soft idlis. The formulation T3 (30% finger millet, 50% rice, 20% black gram) is referred to as optimized because it was selected based on sensory evaluation, texture analysis, and nutritional profiling, which collectively showed superior quality compared to other formulations. The batter pH of T3 was 4.6, ideal for fermentation; titratable acidity was 0.99%, indicating high lactic acid; TSS ranged from 5.20 to 6.10, with T3 at 5.80, reflecting moderate sugar and acid activity.

The nutritional composition of T3 idli exhibited higher moisture (59.66 g/100 g) and carbohydrate (30.03 g/100 g) contents, but slightly lower protein (10.14 g/100 g), compared to the control sample, which had 58.92 g/100 g moisture, 11.38 g/100 g protein, and 28.62 g/100 g carbohydrate, respectively, as shown in Table 4. These differences are attributed to the integration of finger millet (Longvah *et al.*, 2017). Functional properties such as water absorption capacity (14.5%), rehydration ratio (2.0), and reconstitution time (41 s) were superior in T3, making it more efficient for instant idli development (Kamble *et al.*, 2021). These findings are aligned with recent studies. Raja *et al.* (2023) demonstrated that pearl millet addition in 3D-printed idli formulations improved textural integrity.

Table 3. Functional properties of optimized (T3) and control (T6) Idli mix samples.

Functional property	T3	T6 (Control)
Water absorption capacity (%)	14.5 ± 0.2[a]	10.5 ± 0.2[b]
Wettability (s)	0.0 ± 0.0[a]	0.5 ± 0.1[b]
Rehydration ratio	2.0 ± 0.1[a]	1.9 ± 0.1[b]
Coefficient of rehydration	1.15 ± 0.05[a]	0.94 ± 0.05[b]
Reconstitution time (s)	41 ± 1[a]	52 ± 1[b]

All values represent mean ± SD (n = 3). Superscripts within rows indicate statistically significant differences at P < 0.05.

Table 4. Proximate composition of optimized (T3) and control (T6) formulations.

Parameters	T3 (Optimized)	T6 (Control)
Moisture (%)	52.32 ± 0.69[b]	58.58 ± 0.69[a]
Protein (%)	16.63 ± 0.69[a]	7.56 ± 0.69[b]
Fat (%)	0.47 ± 0.007[a]	0.35 ± 0.007[b]
Carbohydrate (%)	25.27 ± 98.61[b]	31.34 ± 98.61[a]
Crude Fibre (%)	4.05 ± 0.007[a]	1.88 ± 0.007[b]
Ash (%)	1.26 ± 0.007[a]	0.29 ± 0.007[b]

All values represent mean ± SD (n = 3). Superscripts within rows indicate statistically significant differences at P < 0.05.

Rheological properties of idli batters

Amylograph

The gelatinization onset temperature ranged from 71.0°C in T4 to 76.4°C in T6, exhibiting a decreasing trend with increasing millet. T4 (60% millet) had an onset temperature of 71.0°C, which was the lowest, indicating rapid water absorption and swelling of the granules due to hydration being facilitated by the high fiber content in millet. Similar gelatinization temperatures were reported by Mudau *et al.* (2022), who observed onset gelatinization temperatures in spontaneously fermented finger millet flours ranging from 69.4 to 82.5°C, with significant variation influenced by fermentation duration and cultivar type. These values are in close agreement with those observed in the present study (71.0°C in T4 to 76.4°C in T6), substantiating the significant role of finger millet in modulating the thermal transition behavior of starch during gelatinization.

Variable gelatinization temperatures ranging from 87.1 to 96.0°C indicated the difference in starch swelling behavior exhibited by the formulations. The highest gelatinization temperature of 96.0°C was seen in the control sample (T6), meaning starch granules required more heat before maximum swelling could occur due to low fiber content. In contrast, the lowest gelatinization temperature of 87.1°C was registered in T4 (60% millet), which may be attributed to the starch type and structure of millet, such as a comparatively lower amylose content or loosely bound granules, allowing for earlier gelatinization even with higher fiber and protein content (Kumar *et al.*, 2024). The findings indicate that the increasing millet in the formulation lowers the gelatinization temperature, which is consistent with earlier reports in composite batters, wherein proteins and fibers modified the starch structure to reduce those temperatures. This further cemented the role played by millet in altering the pace of the batter's pasting behavior, which make it amenable to quick cooking applications (Figure 2).

Extrusion processing significantly affects the gelatinization temperature of millet-based products, with variations depending on processing conditions and the amount of millet incorporated (Yadav *et al.*, 2022). The current findings ranged from 87.1 (T4) to 96.0°C (T6). These results demonstrate that millet inclusion has a considerable effect on starch gelatinization, likely by augmenting starch hydration and interaction with non-starch constituents such as dietary fiber and proteins, thereby altering thermal behavior during processing.

The gelatinization maximum or peak viscosity stood between 1882 and 2586 AU. Peak viscosity differed significantly across the treatments. T4 (60% millet) recorded the highest peak viscosity of 2586 AU, probably due to greater starch swelling and water holding capacity in millet-based formulations. On the other hand, T1 (30% millet) had the least peak viscosity of 1882 AU, implying inferior water uptake and poorer gelatinization when compared with higher millet formulations. The control sample (T6) showed a considerably moderate peak viscosity of 2158 AU, representative of starch with a stable network and balanced gelatinization. Thus, it was interpreted that more incorporation of millet enhanced water retention and starch swelling, thus producing a thicker and more viscous batter. However, excessive millet can diminish the peak viscosity through possible protein–lipid interactions that interfere with starch gelatinization. The results confirm that millet incorporation strongly affects the rheological and pasting properties of idli batter. Millet lowers the onset and peak temperature of gelatinization to allow for a fast cooking time due to its higher absorption of water. Peak viscosity increases with millet content up to 60% (T4), which means starch swelling and batter consistency are promoted by moderate millet inclusion. These, however, deteriorate when the excessive amount of millet (more than 60%) interferes with the starch structure, resulting in a reduction in viscosity and modification of textural properties. This provides evidence that, from a point of view of gelatinization, viscosity, and cooking properties, T4 (60% millet) is the best formulation, hence, the most appropriate formulation for instant idli premix. Previous studies have reported that roller-dried millet flour exhibits the highest degree of starch gelatinization, significantly influencing viscosity and water absorption in batter preparation. Millet-based batters require optimized hydration and fermentation conditions to achieve desirable texture and flow properties. T4 (60% millet) demonstrated the best gelatinization and pasting properties ($P < 0.05$), confirming its higher water absorption and improved batter viscosity.

Treatment T1 exhibited the lowest peak viscosity (1882 AU), suggesting weaker starch swelling, which may result in a denser idli texture. The control sample (T6) had the slowest gelatinization (96.0°C), further confirming that a millet-free formulation takes longer to absorb water and swell. Results indicate that moderate millet inclusion, more so in T4 and T5, improves the idli batter performance, whereas a higher quantity of millet might require an adjustment in the formulation to attain the desired texture and consistency.

Mudau *et al.* (2022) reported peak viscosity values for spontaneously fermented finger millet flours, with variations attributed to the degree of fermentation and flour composition. The present investigation found similar magnitudes, where peak viscosity ranged from 1882 AU (T1) to 2586 AU (T4). This trend clearly demonstrates the functional role of finger millet in enhancing pasting properties, possibly by increasing starch swelling and interaction with the matrix. This points to the ability of finger millet to regulate batter viscosity and improve its application for quick cooking.

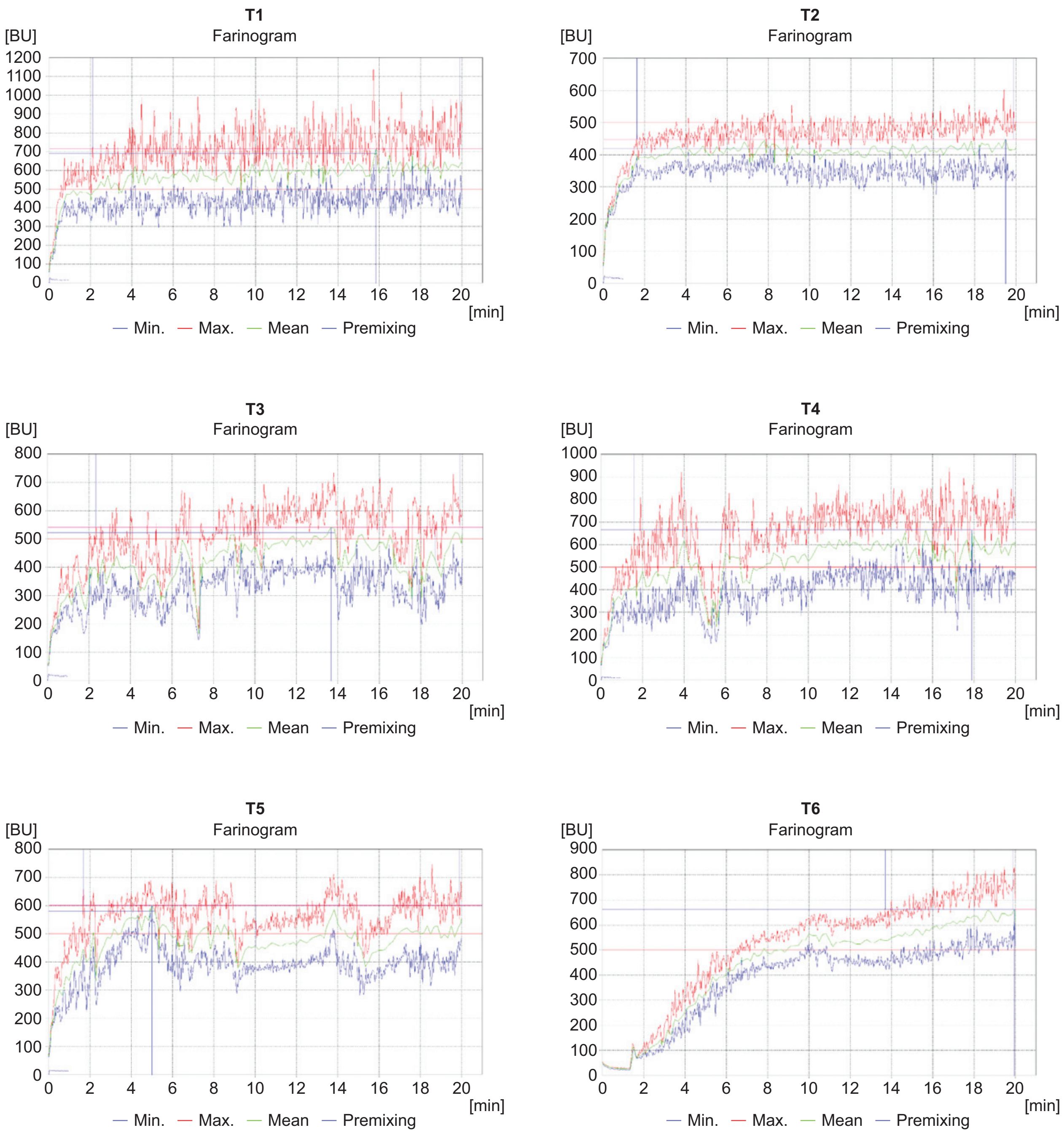

Figure 2. Farinogram profile of idli treatments (T1 to T6).

The gelatinization temperature ranged from 87.1 to 96.0°C, indicative of variations in starch swelling characteristics across the formulations. The control sample (T6) at 96.0°C had the highest gelatinization temperature, which implies that the starch granules required more heat to swell maximally because of their lower fiber content. On the other hand, T4 (60% millet) was shown to have a much lower gelatinization temperature. at 87.1°C, indicating faster swelling and hydration of starch as a result of higher fiber and protein content in millet. The results suggest that higher millet content reduces the gelatinization temperature, which is in conformity with prior studies on composite batters where proteins and fibers alter starch structure, resulting in lower gelatinization temperatures. This highlights the functional role of millet in influencing the pasting behavior of the batter, making it more suitable for quick cooking applications (Table 5).

Farinographic characteristics of idli batter

Water absorption varied significantly across formulations, ranging from 37.5% in T6 to 65.5% in T5. T5 (70% millet) exhibited the highest water absorption (65.5%, $P < 0.05$), confirming that higher millet content enhances hydration due to its fiber-rich nature. The control sample (T6) recorded the lowest absorption (37.5%, $P < 0.05$), indicating reduced water-binding capacity in the absence of millet (Table 6). Although numerical increases in water absorption were observed among intermediate formulations T1 (52.7%), T2 (54.1%), and T3 (56.5%), these differences were not statistically significant ($P > 0.05$), indicating that the inclusion of finger millet had no significant impact on the water absorption capacity. In contrast, Xiao *et al.* (2023) reported higher water absorption capacities, ranging from 36.2 to 66.8% in proso millet-based formulations, likely due to differences in millet variety, formulation ratio, or processing conditions.

Dough development time (DDT) was significantly influenced by millet content, ranging from 5.0 to 20 min, as shown in Figure 2. T6 (control) had the longest dough development time (DDT) of 20 min. However, T2, which also contains millet, exhibited a comparable DDT, indicating that factors other than water-binding capacity—such as starch–protein interactions or flour particle size—may have contributed to the delayed hydration behavior.

In contrast, T5 (70% millet) exhibited the shortest dough development time (DDT) of 5 min, indicating rapid hydration possibly facilitated by the combined effects of high dietary fiber, increased levels of damaged starch, and reduced gluten-forming proteins. Other formulations showed intermediate values: T1 (15.9 min), T2 (19.5 min), T3 (13.7 min), and T4 (17.9 min), demonstrating that higher millet inclusion may accelerate dough hydration. However, the drastic change in development time cannot be solely attributed to fiber content, as the physical and chemical properties of millet starch and protein matrix also influence water absorption and dough behavior (Kumar *et al.*, 2024).

Siroha and Bangar (2024) reported a reduction in DDT with increasing levels of proso millet substitution, with values ranging from 5.3 to 21.2 min across different flour blend ratios. These results are consistent with the current study, where DDT decreased from 20 min in the control

Table 5. Effect of finger millet proportion on amylographic characteristics of idli batter.

Treatment	Beginning of gelatinization (°C)	Gelatinization temperature (°C)	Gelatinization maximum (AU)
T1	71.9 ± 0.5^{bc}	87.3 ± 0.6^{bc}	1882 ± 30^{d}
T2	73.5 ± 0.4^{b}	90.1 ± 0.5^{b}	2165 ± 42^{c}
T3	73.4 ± 0.3^{b}	88.4 ± 0.4^{bc}	2421 ± 38^{b}
T4	71.0 ± 0.6^{c}	87.1 ± 0.3^{c}	2586 ± 35^{a}
T5	72.0 ± 0.5^{bc}	87.9 ± 0.4^{bc}	2576 ± 41^{a}
T6 (Control)	76.4 ± 0.2^{a}	96.0 ± 0.3^{a}	2158 ± 28^{c}

All values represent mean ± SD (n = 3). Superscripts within rows indicate statistically significant differences at P < 0.05.

Table 6. Effect of finger millet proportion on farinographic characteristics of idli batter.

Treatment	Water absorption (%)	Dough development time (min)	Dough stability time (min)	Mixing tolerance index (BU)
T1	56.5 ± 1.2^{bc}	15.9 ± 0.8^{b}	17.8 ± 0.6^{b}	0^{d}
T2	52.7 ± 1.1^{c}	19.5 ± 0.9^{a}	18.3 ± 0.5^{a}	0^{d}
T3	55.1 ± 1.3^{bc}	13.7 ± 0.7^{c}	17.6 ± 0.8^{b}	118^{b}
T4	60.1 ± 1.0^{b}	17.9 ± 0.6^{b}	18.3 ± 0.7^{a}	0^{d}
T5	65.5 ± 1.5^{a}	5.0 ± 0.5^{d}	18.2 ± 0.4^{a}	147^{a}
T6 (Control)	37.5 ± 0.9^{d}	20.0 ± 1.0^{a}	6.2 ± 0.6^{c}	0^{d}

(Mean ± SD; values followed by different letters (a, b, c, d) within a column indicate significant differences at P < 0.05 using Tukey's HSD test.)

(T6) to 5 min in T5 containing 70% millet. This inverse relationship highlights millet's influence on accelerating dough formation, likely attributed to its superior water absorption capacity and the functional role of dietary fiber in facilitating quicker gluten network development and starch–water interactions.

Dough stability time ranged from 6.2 to 18.3 min, with significant variations among the formulations, as presented in Figure 2 and Table 4. T2, T4, and T5 exhibited the highest stability times ($P < 0.05$), indicating better structural integrity and hydration balance. T3 and T1 showed comparable stability time. In contrast, the control sample (T6) had the lowest dough stability (6.2 min), reinforcing the positive role of millet incorporation in enhancing hydration and matrix strength. These findings are consistent with those reported by Dey *et al.* (2024), who documented dough stability values ranging from 6.0 to 18.5 min in millet-based composite flours, which were modulated by millet concentration and associated hydration dynamics. The current results reinforce the functional contribution of finger millet in improving dough stability through better water retention and fiber–starch–protein interactions. However, the marginally lower value in T3 suggests microstructural variation, while the reduced stability in T6 highlights the limited hydration performance in the absence of millet.

Mixing tolerance index (MTI) values varied significantly, indicating differences in structural resilience. 3. T5 (70% millet) had the highest MTI (147 BU, $P < 0.05$), making it more susceptible to softening and breakdown due to excessive fiber content. T3 exhibited an intermediate MTI (118 BU), showing moderate structural weakening. In contrast, T1, T2, T4, and T6 had an MTI of 0 BU, indicating strong dough integrity with minimal softening even after extended mixing. The farinographic analysis confirmed that millet incorporation significantly affects the hydration and structural properties of the Idli batter (Figure 2). Higher millet content increased water absorption, enhancing dough elasticity but potentially weakening structural stability. Dough development time was shortest in T5 (5.0 min) and longest in T6 (20.0 min), indicating that millet accelerates hydration but may compromise batter strength. Dough stability was highest in T2 and T4 (18.3 min, $P < 0.05$), making them ideal for maintaining structure during processing. Meanwhile, T5 had the highest MTI (147 BU, $P < 0.05$), confirming its tendency to soften and break down under mixing conditions. The results obtained from Farinograph after incorporating millet flour at various levels into idli premix is shown in Table 6.

Zhu (2014) reported that mixing tolerance index (MTI) values in millet starches varied substantially, ranging from 0 to 150 BU, depending on compositional attributes and processing conditions, and reflecting differences in dough softening behavior. These values are comparable to those observed in the current study, where MTI ranged from 0 BU in T1, T2, T4, and T6 to 147 BU in T5. The elevated MTI in T5 suggests that excessive millet incorporation may compromise dough resilience, likely due to interference from dietary fiber with the gluten–starch network. The intermediate MTI observed in T3 (118 BU) further supports a progressive weakening trend, consistent with earlier observations on starch structure disruption under mechanical shear. The results obtained from the Farinograph after incorporating millet flour at various levels into Idli premix is shown in Table 6.

Extensographic characteristics of idli premix

The extensographic characteristics of Instant Idli Premix were analyzed using the Brabender Extensograph E to assess the dough's elasticity, strength, and extensibility under different proving times (30, 60, and 90 min). The key parameters evaluated included energy (cm^2), resistance to extension (BU), extensibility (mm), and ratio number (R/E), all of which play a crucial role in determining the structural integrity, fermentation behavior, and textural properties of idli batter. The interaction between rice, black gram, and finger millet was examined to understand the effect of millet incorporation on the dough matrix (Table 7). As idli batter undergoes fermentation, changes in these extensographic parameters influence gas retention, aeration, and overall texture of the final steam product (Karnat *et al.*, 2024).

Energy denotes the total work exerted in stretching the dough, thereby affecting gas retention and the final idli texture. There was a significant interactive effect between treatment and proofing times ($P < 0.05$). T3 had the maximum energy values recorded for 30 and 60 min (36 ± 2.5 and 54 ± 3.1 cm^2), pointing toward the fact that a suitable level of millet incorporation helps increase elasticity and gas-holding capacity. Conversely, T6 (control) consistently had the least energy (24 ± 2.5 cm^2), whether during 30 or 60 min proofing, denoting a weak matrix formation. T5 (70% millet), on the other hand, showed variable values within a narrow range (32 and 30 cm^2) across time, indicating low flexibility due to excess millet**.** The higher dough resistance at increased millet levels is due to the gluten-free nature of finger millet, which weakens the dough's gluten network. The high dietary fiber content also absorbs more water and interferes with gluten formation, making the dough stiffer, less stretchable, and producing denser, less soft idlis. These energy values agree with the data of Tomić *et al.* (2020), who reported values ranging from 22 to 55 cm^2 depending on millet concentration and duration of fermentation.

Table 7. Effect of finger millet proportion on extensographic characteristics of idli batter at different proofing times.

Treatment	Proofing time	Energy n (cm^2)	Resistance (BU)	Extensibility (mm)	Ratio number (R/E)
T1	30 min	16 ± 2.5^{d}	19 ± 3.2^{c}	940 ± 3.0^{b}	50.6 ± 3.6^{b}
	60 min	64 ± 3.1^{a}	28 ± 3.8^{b}	773 ± 3.4^{b}	43.2 ± 4.2^{b}
	90 min	13 ± 2.7^{d}	18 ± 4.1^{d}	19 ± 2.8^{c}	1.2 ± 3.9^{d}
T2	30 min	32 ± 2.5^{b}	22 ± 3.2^{b}	1638 ± 3.0^{a}	1.1 ± 3.6^{d}
	60 min	22 ± 3.1^{c}	19 ± 3.8^{c}	1638 ± 3.4^{a}	0.9 ± 4.2^{d}
	90 min	19 ± 2.7^{c}	24 ± 4.1^{c}	1.1 ± 2.8^{d}	85.0 ± 3.9^{b}
T3	30 min	36 ± 2.5^{a}	62 ± 3.2^{a}	1638 ± 3.0^{a}	88.1 ± 3.6^{a}
	60 min	54 ± 3.1^{b}	19 ± 3.8^{c}	1638 ± 3.4^{a}	79.1 ± 4.2^{a}
	90 min	21 ± 2.7^{c}	19 ± 4.1^{c}	1638 ± 2.8^{a}	88.2 ± 3.9^{a}
T4	30 min	27 ± 2.5^{c}	34 ± 3.2^{b}	1638 ± 3.0^{a}	1.5 ± 3.6^{d}
	60 min	34 ± 3.1^{b}	27 ± 3.8^{b}	1638 ± 3.4^{a}	9.2 ± 4.2^{c}
	90 min	17 ± 2.7^{c}	18 ± 4.1^{d}	2.3 ± 2.8^{d}	100.0 ± 3.9^{a}
T5	30 min	32 ± 2.5^{b}	22 ± 3.2^{b}	20 ± 3.0^{c}	1.1 ± 3.6^{d}
	60 min	29 ± 3.1^{b}	100 ± 3.8^{a}	16 ± 3.4^{c}	6.1 ± 4.2^{c}
	90 min	30 ± 2.7^{b}	43 ± 4.1^{a}	19 ± 2.8^{c}	2.2 ± 3.9^{d}
T6	30 min	24 ± 2.5^{c}	33 ± 3.2^{b}	18 ± 3.0^{c}	1.8 ± 3.6^{d}
	60 min	24 ± 3.1^{c}	31 ± 3.8^{b}	18 ± 3.4^{c}	1.7 ± 4.2^{d}
	90 min	24 ± 2.7^{c}	49 ± 4.1^{b}	17 ± 2.8^{c}	2.9 ± 3.9^{d}

Values are Mean ± SD; different superscripts within columns denote significant differences at $P < 0.05$ across treatment × proofing time.

Dough strength is subjected to modulation due to interactions between millet level and proofing time.

Resistance to extension (BU) at different proofing times indicates the force needed to stretch the dough, reflecting its structural strength and rigidity. The treatment by proofing time interaction was significant at $P < 0.05$. Being in the T5 group, it reached the highest resistance of 100 ± 3.8 BU at 60 min, which insinuates that higher millet inclusion caused an increase in rigidity due to fiber–protein matrix formation. T6 exhibited a gradual increase with 38.2 ± 1.7 BU and ended up at 52.3 ± 2.2 BU, indicating the firmer dough when proofed for a longer period. T3 was somewhere in the middle with 62 ± 3.2 BU, absolute value at 30 min, which would clinch the retention of gas not to become overly stiff and confirmed that resistance increased with millet incorporation, ranging from 28 to 102 BU. Resistance is, therefore, validated to be linked both to millet content and proofing time progression.

Extensibility indicates the dough's ability to stretch before breaking, directly influencing idli softness. A two-way ANOVA revealed significant ($P < 0.05$) differences due to treatment, proofing time, and their interaction. T3 consistently showed the highest extensibility (1638 ± 3.0 mm across all time points), promoting better gas entrapment and lighter texture. T5 exhibited a sharp drop (16–20 mm), affirming that excess millet restricts dough stretchability, likely due to interference with the starch–protein network. T6 (control) remained low across all intervals (17–18 mm), resulting in a denser texture. The results confirm that both millet level and proofing time jointly affect extensibility behavior.

The R/E ratio reflects the balance between dough resistance and extensibility. T3 exhibited the most stable and favorable ratio values (88.1 ± 3.6 at 30 min, 79.1 ± 4.2 at 60 min, and 88.2 ± 3.9 at 90 min), suggesting optimal elasticity and structure. A significant interaction ($P < 0.05$) between millet content and proofing duration was observed. In contrast, T5 showed fluctuating and low values (e.g., 1.1 ± 3.6 at 30 min, 6.1 ± 4.2 at 60 min), indicating structural rigidity and poor flexibility. T6 displayed relatively low and consistent R/E values 403 (1.8–2.9), reflecting poor dough quality. Dubey *et al.* (2025) similarly documented R/E ratios 404 ranging from 1.0 to 90.5 in millet-based systems. Overall, moderate millet levels (T3) ensured better structural balance, while excessive incorporation led to rigidity and reduced quality.

Viscosity measurement

The viscosity of idli batter was analyzed using a Brookfield DV2T Viscometer to evaluate its flow behavior and consistency, which influence batter spreadability, steam penetration, and final texture. Apparent viscosity (cP) was measured at various shear rates (rpm), and statistical analysis via one-way ANOVA and Tukey's HSD test ($P < 0.05$) confirmed significant differences among treatments. T5 exhibited the highest viscosity across all shear rates ($P < 0.05$), indicating strong batter consistency but reduced flowability, while T4 achieved an optimal balance between viscosity and shear thinning behavior ($P < 0.05$), ensuring smooth spreading. T6 (control) had the lowest viscosity ($P < 0.05$), making it the most pourable but structurally weaker. T1 and T2 showed moderate viscosity, maintaining good pourability without compromising texture, whereas T3 had a viscosity range that promoted aeration and fermentation, enhancing idli texture ($P < 0.05$). These results suggest that moderate millet incorporation (T3, T4) optimizes batter viscosity for aeration and structure, while excessive millet (T5) may require additional water adjustments to maintain ideal flow properties. Viscosity at 50 rpm showed a significant increase with the increase in millet content. The optimized sample (T3) exhibited a mid-to-high viscosity (3900 ± 105^{bc} cP), reflecting a desirable balance between batter stability and flow. The increased viscosity in T4 and T5 may be attributed to higher fiber and protein contents, which enhance water binding and batter thickness. In contrast, the control showed the lowest viscosity, aligning with its lower compositional density and weaker structural network.

Expansion ratio of prepared idlis

The expansion ratio of idli batter formulated under various premix treatments ranged from 1.50 to 2.10 (data not shown). The control (T6) had the maximum expansion ratio of 2.10, indicating better fermentation efficiency and gas retention capacity. Among the treated formulations, T1 recorded the highest expansion ratio of 1.90, followed by T2 and T3 with 1.80 and 1.70, respectively. A steady decline in expansion ratio was observed from T1 to T5, with T5 recording the least value of 1.50. The given trend, therefore, possibly signifies the effects that the applied treatments had on the fermentability and aeration property of the batter. The least expansion observed in T5 might be due to either low leavening activity or the impaired gas-holding capacity of the batter, possibly arising from changes in the structural or biochemical properties of the mix.

Color parameters

The color parameters (L^*, a^*, b^*, and ΔE^*) exhibited statistically significant differences ($P < 0.05$) across all treatments (Table 8). The L^* values, representing lightness, ranged from 77.48 (T5) to 94.30 (T6), with the control (T6) showing the highest brightness. The optimized formulation T3 recorded a relatively high L^* value (79.89), indicating a visually appealing and sufficiently light-colored product. The reduced L^* values in T4 and T5 may be attributed to Maillard-type browning reactions or intensified fermentation-induced pigmentation (Chelliah *et al.*, 2017). The a^* values (redness–greenness axis) spanned from –0.46 (T6) to 2.99 (T5). The T3 treatment showed moderate redness (2.29), suggesting a visually natural and fermented tone. The negative a^* value in the control indicates a shift toward greenness, likely due to the absence of browning reactions typically enhanced by finger millet constituents (Chelliah *et al.*, 2017).

Conversely, T1 (3.54) and T6 (4.29) had significantly lower b^* values, possibly on account of pigment content being low or less polyphenol-related color change. These differences might have been due to polyphenols interacting with fermentation byproducts and the breakdown of carbohydrates during fermentation and steaming. The ΔE^* values for total color difference from control ranged from 14.94 (T3) to 17.54 (T5). Higher ΔE^* in T5 suggested that the color change was more perceptible relative to the control and thus may affect consumer acceptance. However, the optimized sample T3 maintained a moderate ΔE^*, indicating a balanced visual appeal without compromising nutritional enhancement.

Table 8. Colorimetric properties of idli samples.

Parameter	T1	T2	T3	T4	T5	T6 (Control)
L^*	80.22 ± 0.55^{b}	79.14 ± 0.63^{bc}	79.89 ± 0.48^{b}	78.67 ± 0.50^{c}	77.48 ± 0.52^{c}	94.30 ± 0.60^{a}
a^*	2.75 ± 0.12^{a}	2.81 ± 0.15^{a}	2.29 ± 0.10^{b}	2.37 ± 0.11^{b}	2.99 ± 0.14^{a}	-0.46 ± 0.08^{c}
b^*	3.54 ± 0.22^{d}	8.03 ± 0.35^{a}	7.12 ± 0.28^{b}	7.11 ± 0.30^{b}	7.90 ± 0.33^{a}	4.29 ± 0.25^{c}
ΔE^*	15.05 ± 0.50^{bc}	15.95 ± 0.52^{ab}	14.94 ± 0.48^{c}	16.13 ± 0.53^{a}	17.54 ± 0.55^{a}	0.50 ± 0.05^{d}

All values represent mean ± SD (n = 3). Superscripts within rows indicate statistically significant differences at $P < 0.05$.

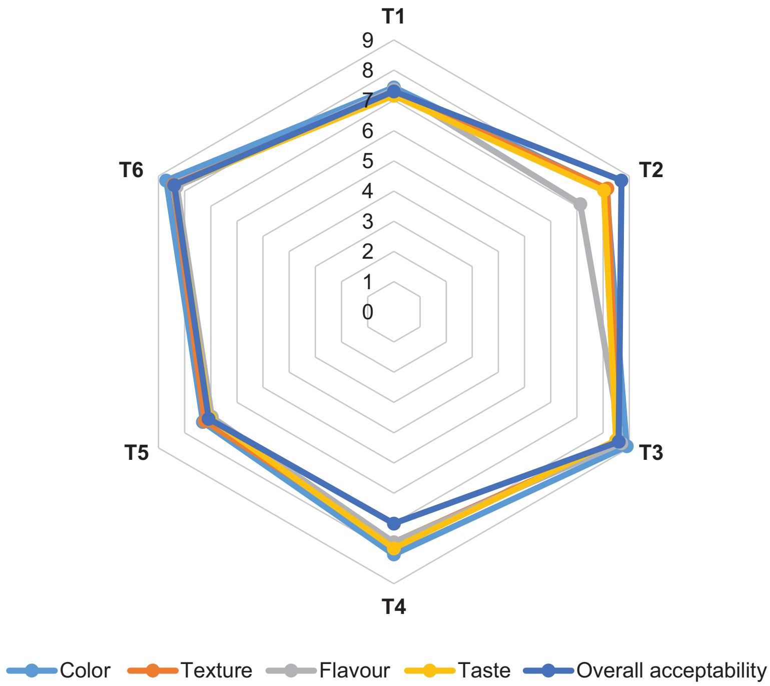

Figure 3. Sensory evaluation of Idli samples prepared from premix.

Sensory evaluation of idlis

Idli sensory evaluations in all premix treatment variations, T1 through T6, were undertaken based on color and appearance, texture, flavor, taste, and overall acceptability (Figure 3). Among all treatments, T2 ranked first with the highest overall acceptability of 8.70, followed by T3 (8.60), and the control (T6) at 8.40, indicating great consumer preference for these formulations. T3 scored the highest in color and appearance evaluation (8.83), texture (8.60), and taste (8.50). The scores were just about equal when comparing the treatments T2 and the control. T2 had moderate sensory properties, especially in texture (8.16) and taste (8.03), which led to its increased acceptability. Conversely, T5 received the lowest scores across most attributes, particularly flavor (6.96) and taste (7.03), which impacted its overall acceptability (7.08). T1 and T4 showed moderate acceptability levels, with T1 marginally outperforming T5. These findings indicate that both T2 and T3 yielded the most organoleptically favorable idli products, potentially due to optimized ingredient ratios or processing conditions.

Conclusion

The current study showed that adding finger millet to instant Idli batter significantly changed its rheological, thermal, and textural characteristics. By optimizing water absorption, dough stability, and batter viscosity, 50–60% millet was used to create softer, more aerated idlis with a desired sensory quality. While excessive inclusion (>60%) decreased extensibility and dough handling, showing an upper maximum for millet fortification, the gelatinization initiation at this range switched to lower temperatures with increased peak viscosity, suggesting enhanced starch–protein interactions. Finger millet can be used as a functional ingredient in instant idli premixes, enhancing protein, fiber, and minerals while preserving customer acceptance, according to the study. These developments can help expand the uses of millet, in line with the demand for nutrient-dense, sustainable staples worldwide. All things considered, this study identifies finger millet-based idli premix as a viable way to promote wholesome, easily prepared dishes with significant nutritional value and social significance.

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Mandatory Disclosure on Use of Artificial Intelligence

The authors declare that no AI-assisted tools were used in the preparation of this manuscript. All references have been manually verified for accuracy and relevance.

Author Contributions

All authors contributed equally to this article.

Conflicts of Interest

None.

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