Sustainable
Food Technology

Accepted Manuscript

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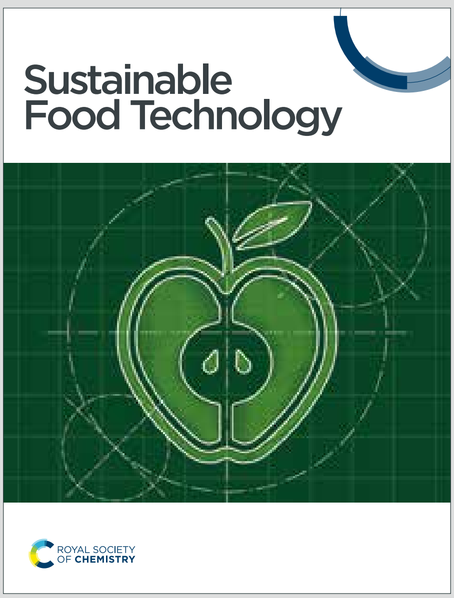

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Sustainability Spotlight statement

This study demonstrates how precision fractionation in roller milling can be leveraged to valorize all flour streams by linking stream-specific functionality to targeted end-use applications. By identifying optimal utilization pathways for break and reduction streams, the work minimizes reliance on over-refining and reduces waste generation, thereby improving resource efficiency within wheat processing systems. The ability to tailor flour blends for specific products, such as cookies, enhances processing efficiency, reduces energy and water inputs, and supports cleaner-label formulations. Overall, this approach advances a more efficient utilization of roller-milled flour streams by maximizing the functional potential of each stream while improving product quality and industrial sustainability.

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Stream-Specific Functional and Rheological Variability in Roller-Milled Wheat Flours: A Sustainable Approach to Cookie Quality Optimization and Flour Utilization

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DOI: 10.1039/D6FB00108D

Abstract

This study investigated the stream-specific functional, rheological, thermal, and end-product properties of roller-milled wheat flour streams, including break (B1-B4), reduction (C1-C5), and straight-run flour (SRF), to establish structure-function relationships for sustainable flour utilization and cookie quality optimization. Significant variability ($p < 0.05$) was observed among the streams, with damaged starch (SD) ranging from 3.48% (B1, C3) to 8.85% (SRF). Reduction streams exhibited higher swelling power (6.94 g/g at 98 °C) and solubility (11.64% at 55 °C), while DSC analysis revealed gelatinization temperatures ranging from 60.35 to 70.17 °C and enthalpy values from 4.13 to 8.91 J/g. Microvisco-amylograph analysis showed considerable variation in pasting behavior, with gelatinization temperatures ranging from 58.5 to 63.9 °C and peak viscosity ranging from 666 to 1032 BU, reflecting differences in starch damage and stream composition. Farinograph properties also varied significantly, with water absorption ranging from 52.0% to 63.9% and dough stability from 0.6 to 18.1 min. Cookie quality differed markedly among streams, where reduction fractions produced higher spread ratios (up to 7.3) and lower hardness (4925 g), while break streams yielded firmer cookie structures. Principal component analysis further confirmed strong relationships among starch functionality, rheology, and cookie-quality attributes. Overall, the findings demonstrate that selective utilization and recombination of milling streams can be strategically used to tailor flour functionality, improve product quality, and support resource-efficient production of application-specific flours for industrial baking applications.

Keywords: Flour-streams, Functional-Properties, Processing, Roller-Mill, Wheat, Cookie qualities

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1. Introduction

Roller milling is the predominant industrial process for fractionating wheat kernels into multiple flour streams with distinct physicochemical and functional properties. Sequential break-and-reduction operations separate endosperm, bran, and germ, generating streams that differ in particle size, protein content, ash content, and starch damage.[1] While this enhances process efficiency, it also creates substantial heterogeneity in flour functionality, necessitating stream-specific characterization for optimal utilization. [2,3] From a sustainability perspective, improving the utilization of these streams is critical to reduce resource losses and enhance value addition within wheat processing systems, where large quantities of by-products are generated annually (>150 million tons globally). [4]

Milling conditions, including roll gap, differential speed, and extraction rate, govern the variability among roller-milled streams. Reduction streams derived from inner endosperm are finer and richer in starch, whereas break streams contain more bran contamination and coarser particles.[5,6] Intensive grinding in later stages increases starch damage, which strongly influences hydration behavior, thermal transitions, and rheological properties.[7,8] These structural gradients lead to significant differences in pasting and functional characteristics, which are key determinants of processing performance.

Different grinding and flour fractionation methods strongly influence particle size, starch damage, hydration, and end-product quality.[9] Conventional roller milling enables gradual separation of endosperm, bran, and germ into stream-specific flours with distinct functional properties, whereas direct grinding methods followed by sieving often produce broader particle-size distributions and higher starch disruption. Fine fractions enriched in damaged starch (SD) generally exhibit greater water absorption and viscosity, while coarse bran-rich fractions contribute higher fiber and oil-binding capacity.[10–13] Therefore, understanding the effects of grinding intensity and stream fractionation is essential for developing application-specific flours and improving resource-efficient cereal processing strategies.

Functional properties such as water absorption, swelling power, and solubility are governed by starch granule integrity, particle size distribution, and protein-starch interactions. Increased starch damage enhances water binding and enzymatic susceptibility, whereas protein matrices restrict swelling and amylose leaching. [14,15] These interactions directly influence rheological and thermal behavior, including gelatinization, viscosity development, and retrogradation. [16,17]

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Understanding these relationships is essential for designing flours with targeted functionality while improving processing efficiency and product consistency.

From an application standpoint, such variability is particularly relevant for cookie production, where flour functionality governs dough spread, texture, and color development. Unlike bread systems, cookies require lower gluten strength, controlled hydration, and optimized starch functionality to achieve desirable spread and texture.[18] Improper utilization of milling streams can therefore result in suboptimal product quality and inefficient resource use.

Recent advances in sustainable food processing emphasize the need for efficient fractionation and valorization of cereal streams to improve resource efficiency and reduce waste.[19] However, most studies have focused on isolated compositional or functional attributes, with limited integration of multi-parameter functionality and end-product performance. Therefore, this study provides a comprehensive evaluation of roller-milled wheat flour streams by integrating functional, rheological, pasting, thermal, and flow behavior properties, along with cookie quality and multivariate (PCA and correlation) analysis.

By establishing clear structure-function-quality relationships and linking stream-specific variability to cookie performance, this work proposes a sustainable framework for precision flour blending and efficient stream utilization. Such an approach supports the development of application-specific flours, improves processing consistency, and contributes to sustainable wheat-based food systems.

2. Materials and Methods

2.1. Raw materials

Medium-hard wheat (Triticum aestivum), variety Lokwan, was procured from a local market in Mysore, Karnataka, India. They were cleaned using a Labofix laboratory cleaner (Brabender, Germany).

2.2. Wheat milling process

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Wheat milling was performed according to the procedure described by Hitlamani et al.[1] Briefly, cleaned wheat kernels were conditioned to 14-15% moisture and tempered at 24 ± 2 °C for 24 h before milling. The conditioned wheat was milled using an industrial-scale Bühler roller mill (Bühler AG, Switzerland) comprising break (B1-B4), reduction (C1-C5), purifier, and bran finishing systems, operating at 72% flour extraction (Supplementary Figure 1). Individual flour streams (break and reduction) and SRF were collected for analysis. Milling was carried out under standard conditions according to AACC Method 26-21.02, and samples were packed in airtight containers and stored refrigerated until further use.

2.3.Damaged Starch Determination

Damaged starch content was determined according to the method 76-30A [20] with slight modifications. Flour sample (1 g, 14% moisture basis) was weighed into a 125 mL conical flask, and 45 mL of enzyme reagent (at 30 °C) was added to obtain a uniform suspension. The mixture was incubated at 30 °C for 15 min with intermittent shaking. Subsequently, 3 mL of reagent 2 and 2 mL of reagent 3 were added, mixed thoroughly, and allowed to stand for 2 min. The mixture was filtered through Whatman No. 4 filter paper, discarding the initial filtrate.

An aliquot of 5 mL of filtrate was transferred into a boiling tube containing 10 mL of 0.1 N potassium ferricyanide, the tube was covered, heated in a boiling water bath for 20 min, and then rapidly cooled. The contents were transferred to a conical flask containing 25 mL of acetic acid salt solution, and the mixture was titrated with 0.1 N sodium thiosulfate. At the endpoint, 2 mL of 50% KI and 1 mL of 1% starch indicator were added, and titration was continued until the blue color disappeared. A blank was run simultaneously without a sample.
Damaged starch (%) was calculated based on the difference in titration values (B − A), corresponding to the amount of ferricyanide reduced, and expressed as maltose equivalent using standard conversion factors.

2.4.Alpha-amylase enzyme activity

Alpha-amylase enzyme activity using the falling number (FN) standard method (method 56-81B).[20] The FN apparatus water bath was preheated to boiling. Flour sample (7.0 g, corrected to 14% moisture basis) was weighed into an FN tube, and 25 mL of distilled water was added. The tube was sealed with a rubber stopper and shaken vigorously to obtain a uniform suspension. The tube was then placed in the boiling water bath, and the test was initiated. The slurry was automatically stirred for 60 s, after which the time required for the stirrer to fall through the liquefied paste was recorded as the FN (s). Results were expressed on a 14% moisture basis. An FN is inversely related to α-amylase activity of the flour.

2.5.Zeleny values

The sedimentation value of the wheat flour samples was determined according to the Method 56-61.02.[21] Briefly, 3.2 g of flour (14% moisture basis) was suspended in 50 mL of distilled water containing bromophenol blue (4 mg/L) in a 100 mL graduated cylinder and shaken for 5 min. Subsequently, 25 mL of a lactic acid-isopropyl alcohol reagent was added, followed by an additional 5 min of mechanical shaking. The mixture was allowed to settle for exactly 5 min, and the volume of the sediment was recorded in mL as the Zeleny value.

2.6.Water and Oil Holding Capacity

The water- and oil-holding capacities (WHC and OHC) of the flour samples were determined according to the method of Hitlamani et al.[22] with slight modifications. Briefly, 100 mg of flour was weighed into a 2 mL centrifuge tube, and 1 mL of distilled water or oil was added. The mixture was vortexed for 30 seconds, allowed to stand at room temperature for 30 minutes, and then centrifuged at 7000 rpm for 15 minutes. The supernatant was decanted, and the residue was weighed to calculate WHC and OHC using the following equation.

2.7.Swelling power and Solubility index

The swelling power (SP) and solubility index (SI) of the flour samples were determined according to the method of [22] with modifications. Briefly, 100 mg of the sample was weighed into a centrifuge tube, mixed with 1.0 mL of water, and heated at 45-90 °C for 30 minutes. The mixture was then centrifuged at 3000 *g* for 10 minutes. The supernatant was decanted, and the weight of the residue was recorded to calculate the SP using the standard equation. The remaining supernatant was poured into a petri plate (pre-weighed), evaporated to dryness over a water bath, and dried for five hours in an air oven set at 105 °C. The proportion of soluble was determined using the following equation and designated as the SI based on the dry weight and the weight of the residue. The experiment was repeated in triplicate.

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$$SwellingPower(SP)g/g = \frac{Weight\ of\ Residue}{Weight\ of\ the\ sample} \ldots\ldots\ldots\ldots (1)$$

$$Solubilty\ Index\ (SI)\% = \frac{Weight\ of\ dried\ supernatant}{Weight\ of\ the\ sample} \times 100 \ldots\ldots\ldots (2)$$

2.8.Dough mixing characteristics

Water absorption, dough development time, and stability were determined using a Brabender Farinograph (Duisburg, Germany) according to AACC Method 54-21.[20] Flour samples (50 g, 14% moisture basis) were mixed with water at 30 ± 2 °C to obtain a consistency of 500 BU, and farinograms were recorded for 10 min. Water absorption (%), development time (min), stability (min), and mechanical tolerance index (BU) were calculated from the curves. All measurements were performed in triplicate, and data were analyzed using one-way ANOVA followed by Tukey's test to determine significant differences at $p < 0.05$.

2.9.Pasting properties of flours

The gelatinization and pasting properties of stream flour were elevated using a 12 % (w/v) slurry, and changes over time and viscosity under different time and temperature conditions were recorded using a Brabender Micro-Visco-Amylograph (Brabender, Duisburg, Germany). The viscosity is expressed in Brabender Units (BU), which reflect the torque required to rotate the spindle in a given sample as per the method 22-10.[20]

2.10. Thermal properties

The thermal properties of stream flour samples were determined using Differential Scanning Calorimetry (DSC) (PerkinElmer, USA). A 5 mg sample was weighed into an aluminum pan, and 10 µl of deionized water was added using a micropipette. The sample pans were then hermetically sealed and left at room temperature for one hour to allow for equilibration. In the DSC, samples were heated from 30 °C to 120 °C at a rate of 10 °C/min, with a sealed, empty pan serving as the reference. The software was used to record the onset temperature (T_o), end set temperature (T_e), peak temperature (T_p), and enthalpy (ΔH).

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2.11. Flow behavior of flours

The flow behavior of flour suspensions was determined using a modular compact rheometer (MCR-52, Anton Paar, Graz, Austria) equipped with a parallel-plate geometry (75 mm diameter, P75 probe) and a plate gap of 1 mm. A 20% (w/v) aqueous suspension (5-7 mL) was loaded, and samples were equilibrated for 5 min at the test temperature (45, 65, and 85 °C).

2.12. FTIR analysis of flour

Fourier Transform Infrared (FTIR) spectrophotometer (Model/Make: IFS 25, Bruker, Germany) equipped with an Attenuated Total Reflectance (ATR) accessory was employed to analyze the functional properties of the flours. The flour streams were approximately 10 mg, which were directly spread over the ATR crystal without further preparation. The spectra of each sample were recorded over a wavenumber range of 4000–400 cm^{-1}, with a resolution of 4 cm^{-1} and an average of 20 scans, to achieve an optimal signal-to-noise ratio at room temperature (20 ± 2 ^{o}C). The acquired spectra were analyzed to identify the functional groups and molecular interactions of the flour. Key absorption bands were noted.

2.13. Preparation of cookie

Cookies were prepared according to AACC Method 10-52 [20] with slight modifications. The formulation consisted of 100 g of wheat flour, 60 g of powdered sugar, 30 g of fat, 3 g of skim milk powder, 0.75 g of ammonium bicarbonate, 1 g of sodium bicarbonate, 1 g of sodium chloride, and an appropriate amount of water. Ingredients were mixed using a Hobart mixer (Model N-50, Ontario, Canada) to obtain a uniform dough. The dough was sheeted to a thickness of 2 cm, cut into circular pieces (6.5 cm diameter), and baked at 200 °C for 12 min. [23] After baking, cookies were cooled to room temperature and stored in polypropylene pouches for further analysis.

2.14. Physical parameters of cookies

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Cookies were evaluated for physical characteristics, including diameter (mm), thickness (mm), and spread ratio. Diameter and thickness were measured using a digital caliper, and the mean of four cookies per batch was recorded. The spread ratio was calculated as the ratio of diameter to thickness. Textural properties were determined as breaking strength using a texture analyzer (TA-HDi, Stable Micro Systems, Surrey, UK) based on the three-point bending method [23]. Measurements were carried out at a crosshead speed of 50 mm/min using a 10 kg load cell, and the maximum force (g) required to fracture a cookie was recorded as the average of three replicates.

Surface color of the cookies was measured using a HunterLab colorimeter (LabScan XE, Hunter Associates Laboratory, Inc., Reston, VA, USA). Color values were expressed in terms of L^*, a^*, b^*, and ΔE, using a standard white calibration tile ($L^* = 92.76$, $a^* = -1.06$, $b^* = 2.81$) as reference.

2.15. Consumer pre-sensory evaluation of cookies

Cookies were evaluated for both physical and pre-sensory attributes. Samples prepared from different flour streams were assigned randomized codes before analysis. Pre-sensory evaluation was conducted by a panel of 20 semi-trained/untrained panelists, and informed oral consent was obtained from all participants regarding potential allergies (to gluten). The evaluation was conducted under controlled conditions (27 ± 2 °C and 53 ± 5% relative humidity). Panelists, familiar with free-choice profiling and Quality Descriptive Analysis (QDA), developed a scorecard based on relevant sensory descriptors. Each assessor evaluated the coded samples using a 10-point scale (0 = threshold, 10 = saturation) for attributes including surface color, cracking, crumb color, texture, mouthfeel, and flavor. Mean scores were calculated and used to generate sensory profiles.[24] Ethical approval was not required, as no personal or clinical data were collected.

2.16. Statistical analysis

Statistical analyses were performed using SPSS (version 16.0; SPSS Inc., USA) following the procedures described by Steel and Torrie. All experiments were conducted in triplicate, and results are expressed as mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was used to evaluate the effects of flour streams on the measured parameters, and

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significant differences among means were determined using Tukey's multiple range test at $p < 0.05$.

Principal component analysis (PCA) and Correlation (Pearson) were carried out using OriginPro 2026 (Student Version; OriginLab Corporation, USA) to explore relationships among functional, rheological, thermal, and quality attributes and to visualize sample discrimination based on multivariate data.

3. Results and discussions

Details on particle size distribution (PSD), color, and nutritional variability of roller-milled flour streams have been reported in our previous study. [1] A brief summary is provided here to support functional interpretation (data not shown). Significant heterogeneity was observed among B1-B4, C1-C5, and SRF streams due to milling progression. Early break streams (B1-B3) were dominated by finer endosperm particles (50-100 µm), whereas later streams (B4, C3-C5) contained a higher proportion of coarse fractions (>100 µm) due to increased bran contamination. Early reduction streams (C1-C2) exhibited finer and more uniform PSDs, while later streams became progressively coarser; SRF represented a composite distribution. Color and nutritional parameters also differed significantly ($p < 0.05$), with higher lightness and starch purity in early reduction streams and increased ash, protein, and darker color in later streams due to bran enrichment.[1]

To extend our previous study, [1] this work demonstrates how structural and compositional gradients strongly influence hydration, rheological, and pasting properties, thereby governing functional performance and cookie quality, while also providing opportunities for stream-specific utilization and valorization.

Such inherent variability can be strategically exploited to minimize material losses, reduce reliance on uniform blending, and enable the development of application-specific flours. Therefore, understanding these gradients is crucial for enhancing process efficiency, optimizing resource utilization, and supporting sustainable wheat processing systems while maintaining the desired product quality.

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3.1. Stream-specific starch damage gradients

3.1.1. Damaged starch

The SD content of roller-milled flour streams varied significantly due to differences in milling passage, particle size, and endosperm disruption (Table 1). Among break streams, B1 showed the lowest value (3.48%) due to minimal mechanical shear, while B2 exhibited a marked increase (7.10%), reflecting greater fragmentation during intermediate milling stages; values declined in B3 (4.30%) and B4 (4.10%) due to coarser fractions and may potentially reduce processing intensity during thermal applications. Reduction streams displayed wider variability, with moderate levels in C1 (5.65%) and C2F1 (5.25%), lower values in C2F2 (3.69%) and C3 (3.48%), and the highest in C4 (8.61%) due to intense grinding of finer particles. In contrast, C5 (5.86%) reflected increased bran contamination. [5] The SRF exhibited high SD (8.85%), attributed to its heterogeneous composition and greater friction induced by bran. These differences were statistically significant ($p < 0.05$), confirming the strong influence of the milling stage on starch damage.

This variability in SD presents an opportunity to optimize processes and use milling streams more efficiently. Streams with higher starch damage (B2, C4, and SRF) exhibit enhanced water absorption and enzymatic susceptibility, which can be advantageously directed toward bread-making applications, thereby improving functional efficiency and reducing the need for additional processing inputs. [18,25] Conversely, low-damage streams (B1, C2F2, C3) are better suited for products that require controlled hydration and softer dough systems, such as cookies, thereby minimizing formulation adjustments and improving product consistency.

Strategic segregation and recombination of these streams can therefore reduce over-processing, optimize energy use during milling, and enhance value addition across fractions. Recent studies have emphasized that stream-level valorization and targeted functionality-based utilization are key strategies for improving sustainability in cereal processing systems, enabling reduced waste generation and more efficient use of raw materials. [17,26] Thus, controlling starch damage not only influences functional performance but also contributes to sustainable milling practices by aligning stream properties with specific end-use applications. In addition, variations in starch damage may influence acrylamide formation in thermally processed end products.[9,27,28]

3.1.2. Falling number

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Falling number (FN) values varied significantly ($p < 0.05$) among roller-milled streams (Table 1), reflecting differences in starch damage and α-amylase activity. SRF showed a high FN (732.86 s), indicating low enzymatic activity and good grain quality. Among break streams, inner fractions (B3–B4: 730.79-838.02 s) exhibited higher FN than outer breaks (B1-B2: 631.52-652.28 s), due to lower bran/germ contamination and reduced enzyme presence. Similarly, early reduction streams (C1, C2B: 712-724 s) maintained higher FN, whereas later reductions (C4, C5: 533.07-583.36 s) showed significantly lower values, attributed to increased starch damage and finer particle size.

These results confirm the inverse relationship between starch damage and FN, as reported in recent studies. [29,30] Controlling FN through stream-specific milling and blending reduces the need for enzymatic corrections and processing aids, enabling more consistent flour performance with lower resource inputs. This aligns with sustainable cereal processing strategies that emphasize precision milling, reduced processing interventions, and improved utilization of intrinsic grain functionality. [5,31]

3.1.3. Zeleny sedimentation values

The Zeleny sedimentation values (ZSV) of roller-milled flour streams ranged from 13.19 mL (C5) to 29.55 mL (B3), indicating substantial variability in gluten quality and sedimentation behavior among the streams (Table 1). Among the break streams, B2 and B3 exhibited the highest ZSV (27.29 and 29.55 mL, respectively), reflecting superior gluten strength and better protein network formation associated with higher endosperm purity. In contrast, B1 and B4 showed comparatively lower values, suggesting weaker gluten aggregation. Reduction streams showed a progressive decline in ZSV, with early fractions (C1-C2F2) showing moderate values comparable to SRF (21.41 mL), whereas later fractions (C3-C5) recorded significantly lower sedimentation values. The lower ZSV observed in later reduction streams should not be attributed solely to starch damage or protein dilution, since ZS primarily reflects gluten quality and the ability of gluten proteins to form cohesive networks. The reduced sedimentation in C3-C5 is more likely associated with bran interference, disrupted gluten continuity, and altered protein aggregation caused by fiber-rich particles and non-gluten components,[1] which weaken gluten swelling behavior despite the presence of protein. SRF exhibited intermediate behavior, reflecting the composite contribution of both strong and weak flour fractions. Statistical analysis confirmed significant differences ($p < 0.05$) among the streams, with B2 and B3

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differing markedly from later reduction streams (C3-C5). These findings highlight the importance of stream-specific blending: high-ZSV fractions improve dough strength and bread-making quality, while low-ZSV streams may be better suited for products that require weaker gluten functionality, such as cookies and biscuits.

3.2.Hydration, thermal, and rheological relationships of roller-milled flour streams

The observed variations in WHC, OHC, SP, SI, thermal, and rheological behavior among roller-milled flour streams highlight the importance of stream-specific functionality in determining processing performance. Bran-rich and high-hydration streams exhibited enhanced water- and oil-binding capacities, whereas refined starch-rich fractions showed distinct swelling and flow characteristics. These functional differences demonstrate the potential of precision milling and selective stream utilization to improve resource-efficient flour applications by optimizing inherent flour functionality rather than relying on external additives. Such approaches support clean-label formulation, improved utilization of milling fractions, and reduced processing losses within sustainable cereal-processing systems. [32]

3.2.1. Water Holding Capacity (WHC)

WHC of roller-milled streams varied significantly ($p < 0.05$) from 1.87 mL/g (B2) to 2.14 g/g (C4). Break streams (B1- B3) exhibited lower WHC values (1.87-1.95 mL/g), reflecting their lower fiber content and predominance of endosperm fractions, whereas B4 and SRF showed slightly higher values due to increased bran incorporation (Figure 1). Early reduction streams (C1-C2F2) showed moderate WHC (1.95-2.00 mL/g), while late reduction streams (C3-C5) recorded the highest values (2.13-2.14 mL/g). Although SD generally contributes to water absorption, the relatively high WHC observed in C3 despite its low SD content (3.48%) suggests that additional factors, including particle-size distribution, bran-associated arabinoxylans, and ash content, also play important roles in water binding. Later reduction streams contain higher levels of non-starch polysaccharides and finer fibrous particles, which retain substantial amounts of water through hydrogen bonding and matrix entrapment mechanisms. Therefore, WHC in roller-milled streams is governed by the combined effects of starch damage, fiber composition, and particle structure rather than starch damage alone.
These observations are consistent with recent findings that milling-induced structural disruption enhances water-binding capacity by increasing surface area and the proportion of

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amorphous regions in starch granules. [9,32] Improved WHC in bran-rich streams enhances water-use efficiency during processing and supports the functional use of fiber-rich milling fractions, aligning with circular food system approaches and waste-minimization strategies. [32] These hydration differences subsequently influenced rheological and cookie-quality behavior discussed in later sections.

3.2.2. Oil Holding Capacity (OHC)

OHC varied significantly ($p < 0.05$) from 1.97 mL/g (C1) to 2.54 mL/g (C5) (Figure 1). Lower values in early break and reduction streams (B1–B3, C1–C2F2) reflect their starch-dominant composition, whereas higher OHC in SRF and C5 is associated with increased bran and germ fractions, which enhance lipid-binding capacity.

The higher OHC in bran-enriched streams is attributed to the presence of non-polar components and structural heterogeneity, which improve lipid retention and matrix interactions. Such behavior is consistent with recent studies showing that milling-induced compositional complexity enhances functional interactions among starch, proteins, and lipids. [33] From a sustainability standpoint, improved oil retention enhances flavor stability and reduces fat losses during processing, thereby improving ingredient efficiency and promoting the utilization of milling by-products.

3.2.3. Swelling Power and Solubility Index

Swelling power (SP) and solubility index (SI) varied significantly ($p < 0.05$) across streams and temperatures (Figure 2a). SP increased from 2.22-2.67 g/g at 55 °C to 6.36-6.94 g/g at 98 °C, reflecting progressive starch gelatinization. Reduction streams (C3, C4) exhibited significantly higher SP at 98 °C ($p < 0.05$), indicating greater starch purity and enhanced water-starch interactions, whereas break streams showed lower values due to protein-fiber constraints.

SI was highest at 55 °C (7.43-11.64%) and decreased at higher temperatures due to reduced amylose leaching post-gelatinization (Figure 2b). Reduction streams (particularly C4, C5) maintained significantly higher SI at moderate temperatures, while break streams (B1-B3) exhibited lower SI due to stronger protein–starch interactions.

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These trends are supported by recent studies demonstrating that milling intensity alters starch crystallinity and molecular order, thereby influencing hydration, SI, and pasting behavior.[34] Furthermore, physical modification approaches such as milling are increasingly recognized as green and sustainable techniques for tailoring starch functionality without chemical inputs, improving swelling and solubility characteristics while maintaining clean-label integrity. [35]

3.2.4. Dough mixing characteristics

Dough mixing parameters varied significantly ($p < 0.05$) across streams (Table 1). Water absorption ranged from 52.0% (B1) to 63.9% (C4), with higher values in reduction streams and SRF due to increased levels of SD, protein, and fiber, which enhanced hydration capacity.[7] Dough development time varied widely (0.9-20.0 min), with B2 and B3 showing prolonged development (19.5-20.0 min), indicating stronger gluten networks, whereas B1, C1, and C2F1 exhibited rapid development (<2 min), reflecting weaker gluten structure [22]. Dough stability (DS) followed a similar trend (0.6-18.1 min), with C3 and C4 showing higher stability (16.5-18.1 min), while B1 exhibited minimal stability.
Mixing tolerance index (MTI) ranged from 0 FU (B2, B3; strong dough) to 44 FU (B1; weak dough), with SRF showing moderate tolerance (24 FU). These variations highlight the strong influence of starch damage and compositional heterogeneity on dough behavior. [8,18] Streams with moderate starch damage (B2, C3, C4) exhibited optimal gluten development and stability, whereas very low (B1) or high (SRF) damage resulted in weaker dough performance.[36,37]

These results demonstrate that stream-specific selection can reduce reliance on external dough improvers and optimize processing efficiency. Strong gluten streams (B2, B3, C3, C4) are suitable for bread applications, while weaker streams (B1, C2F2) are ideal for cookies and flatbreads. Such targeted utilization and blending strategies support clean-label product development, reduced processing inputs, and efficient use of cereal resources, aligning with recent resource-efficient processing approaches. [38,39]

3.2.5. Pasting properties

The pasting properties of roller-milled flour streams differed significantly ($p < 0.05$) among break (B1- B4), reduction (C1- C5), and SRF streams, reflecting variations in starch damage, particle size, and bran contamination (Table 2). Beginning of gelatinization (BG) temperature ranged from 58.5 °C in C2F2 to 63.9 °C in SRF and 62.8 °C in C3. Lower BG values observed in refined reduction streams (C2F2, B1-B3, and C1) indicate easier starch hydration and a lower thermal energy requirement, likely due to greater starch disruption and reduced structural barriers. In contrast, SRF and C3 exhibited significantly higher BG values ($p < 0.05$), suggesting restricted water penetration due to bran-rich components and stronger starch-fiber interactions. Similar trends have been reported for bran-enriched and damaged-starch systems in wheat flour pasting behavior. [22,29,40]

Peak viscosity varied significantly ($p < 0.05$) from 666 ± 11 BU in SRF to 1032 ± 24 BU in B2. Break streams B1-B3 exhibited comparatively higher viscosities (890-1032 BU), indicating greater swelling capacity and better granule integrity at moderate starch damage levels. Conversely, SRF and C3 showed significantly lower viscosities (666 and 712 BU, respectively), likely due to the dilution effect of bran particles and restricted granule swelling. Excessive starch disruption reduces paste viscosity because fragmented granules lose their ability to retain water and maintain structural integrity during heating. [9,41,42]

Hot paste viscosity (HPV) also differed significantly ($p < 0.05$), ranging from 423 BU in SRF to 699 BU in B2. Higher HPV values in B1- B3 and C1- C2F2 indicate improved paste stability under heating and shear, whereas bran-rich streams (SRF and C3) exhibited lower HPV due to weakened starch continuity and interference from non-starch components. Cold paste viscosity (CPV), which reflects retrogradation tendency and gel formation during cooling, ranged from 838 BU in SRF to 1114 BU in C2F2. Reduction streams C1, C2F1, and C2F2 exhibited significantly higher CPV values (1090 -1114 BU), indicating stronger amylose reassociation and firmer gel formation during cooling.

Breakdown viscosity, representing the susceptibility of swollen granules to shear disintegration, ranged from 242 BU in B3 to 333 BU in B2. The significantly higher breakdown in B2 suggests greater swelling and weaker granule resistance during heating, while lower values in SRF, B3, and C2F2 indicate restricted swelling and comparatively stable paste structures.[9] Setback viscosity, associated with amylose retrogradation and gel firmness, varied significantly ($p < 0.05$) from 369 BU in B2 to 482 BU in C4. Later reduction streams,

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particularly C4 and C3, exhibited higher setback values, indicating greater retrogradation tendency and firmer gel formation, whereas B1 and B2 showed lower setback, suggesting softer texture and better freshness retention.

These results demonstrate that controlled starch modification through milling offers a green, chemical-free approach to tailor functional properties, reducing reliance on additives and energy-intensive processing. Break streams with moderate starch damage are suitable for low-moisture products (cookies, chapati), while reduction streams with higher setback are better suited for firm-texture applications (pasta, noodles). Efficient utilization and blending of these streams support clean-label product design, reduced processing inputs, and promote functional utilization of bran-rich fractions, aligning with sustainable cereal processing strategies. [38,43]

3.2.6. Melting Properties

DSC thermograms of roller-milled flour streams revealed significant differences ($p < 0.05$) in starch gelatinization behavior among break, reduction, and SRF streams (Table 2). The onset temperature (T_o) ranged from 60.35 °C (B3) to 65.37 °C (SRF), peak temperature (T□) from 66.83 °C (C5) to 72.51 °C (SRF), and end temperature (T_e) from 73.63 °C (C4) to 79.12 °C (SRF). Higher T_o and T□ values observed in SRF, B1, and C1 indicate greater crystalline order and restricted water penetration within starch granules. In contrast, lower values in B3, C4, and C5 suggest easier hydration and partial disruption of granule structure caused by milling-induced starch damage and bran interference. Similar thermal behavior has been associated with differences in starch crystallinity and granule integrity in wheat flour systems.[22,44]

Gelatinization enthalpy (ΔH) also varied significantly ($p < 0.05$), ranging from 4.13 J/g (B4) to 8.93 J/g (C5). Higher ΔH values in reduction streams such as C5 (8.93 J/g), C2F2 (7.15 J/g), and B3 (7.31 J/g) indicate the presence of more ordered crystalline regions and relatively intact starch structures requiring greater energy for gelatinization. In contrast, lower ΔH values in B1, B4, and C1 suggest partial crystalline disruption due to mechanical shear during milling and increased interference from bran-associated components.[36,37]

The close relationship between DSC thermal transitions and MVA pasting properties confirms that starch crystallinity, granule integrity, and milling-induced damage are key determinants of flour functionality and end-product performance.[16,22,23] These results demonstrate that controlled physical modification during roller milling can strategically tailor starch functionality without chemical treatments, supporting clean-label processing and reducing the

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need for energy-intensive functional additives. Streams with lower gelatinization temperatures and moderate ΔH are better suited for cookies and flatbreads that require controlled spreading and a softer texture. In contrast, streams with higher ΔH and stronger paste stability are more appropriate for viscosity-dependent products such as noodles and pasta.

3.2.7. Flow rheological behavior

The apparent viscosity (η) and shear stress (τ) of roller-milled flour stream suspensions varied significantly ($p < 0.05$) with temperature, shear rate, and flour stream composition (Figure 3). All samples exhibited non-Newtonian pseudoplastic (shear-thinning) behavior, where viscosity decreased progressively with increasing shear rate due to disruption and alignment of hydrated starch and protein structures under shear.

At 45 °C, viscosity values were relatively low, ranging approximately from 250-3200 mPa·s at low shear rates, and decreased sharply to below 100 mPa·s at higher shear rates (>250 s^{-1}). Reduction streams and SRF generally exhibited significantly higher viscosities ($p < 0.05$) than break streams, indicating greater hydration and earlier swelling behavior. Correspondingly, shear stress increased steadily with shear rate, reaching approximately 12-31 Pa at 300 s^{-1}. SRF and later reduction streams (C3-C5) showed significantly higher shear stress values, reflecting increased resistance to flow due to enhanced water binding and suspended particulate interactions. [37]

At 65 °C, a substantial increase in viscosity was observed across all streams, with maximum values reaching approximately 45,000-70,000 mPa·s at low shear rates, confirming the onset of starch gelatinization and network formation. Reduction streams, particularly C3-C5 and SRF, retained significantly higher viscosities during shear compared to early break streams (B1-B3), likely due to higher water absorption, SD, and stronger starch-water interactions. Viscosity decreased continuously with increasing shear rate, reaching approximately 2,000-6,000 mPa·s at high shear rates (>300 s^{-1}), indicating shear-induced breakdown of swollen starch granules. Shear stress increased markedly at this temperature, ranging from approximately 150 to 1,300 Pa, with C3 and SRF showing the highest values, indicating significantly stronger paste consistency and internal structural resistance ($p < 0.05$).

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At 85 °C, all flour streams exhibited the greatest viscosity development, indicating extensive starch gelatinization. Initial viscosities exceeded 70,000 mPa·s in several streams before declining progressively under shear to approximately 3,000-6,000 mPa·s at high shear rates. Reduction streams maintained comparatively greater viscosity stability, whereas break streams showed more pronounced viscosity reduction, suggesting weaker thermal stability and reduced paste integrity. Shear stress values at 85 °C ranged from approximately 500 to 2,500 Pa, significantly higher ($p < 0.05$) than those observed at 45 and 65 °C. However, fluctuations observed in some streams at higher shear rates indicate partial granule rupture and instability of the gelatinized matrix under intense shear conditions. These findings are consistent with established starch gelatinization and flow behavior reported in wheat systems. [16,44]

Correlation analysis demonstrated strong positive relationships between rheological parameters and starch functionality. Apparent viscosity and shear stress were positively correlated with water absorption, SP, and SD content (r = 0.62-0.89), indicating that highly hydrated and swollen starch systems generated greater flow resistance. Similarly, viscosity showed positive correlations with peak and final viscosities obtained from MVA analysis (r = 0.71-0.93), confirming consistency between dynamic flow behavior and pasting performance. In contrast, negative correlations were observed between viscosity and ZSV (r = -0.48 to -0.76), suggesting that streams with stronger gluten structure exhibited lower starch swelling and flow resistance.

These rheological findings strongly support the DSC and pasting results, in which streams exhibiting higher SP, water absorption, and gelatinization enthalpy also showed greater viscosity development and shear resistance. Overall, the results confirm that milling-induced variations in starch damage, particle size, and bran incorporation significantly govern flow behavior and thermal rheology of flour systems. From an application perspective, break streams with lower viscosity and weaker shear resistance are more suitable for cookies and flatbreads that require softer dough systems. In contrast, reduction streams with higher viscosity stability and stronger paste structure are advantageous for products that demand greater water retention and structural integrity.

3.3.FTIR of roller-milled flour streams

DOI: 10.1039/D6FB00108D

The FTIR spectra of the processed flour streams (B1-B4, C1-C5) and SRF revealed distinct absorption bands corresponding to the major flour constituents (Figure 4). Characteristic peaks were observed at 3600-3000 cm^{-1}, 3000-2800 cm^{-1}, 1700-1500 cm^{-1}, and 1200-800 cm^{-1}, corresponding to protein, lipid, and carbohydrate functional groups, consistent with earlier reports on cereal flours. [45]

The broad band at 3280-3270 cm^{-1} (Figure 4b) corresponds to O-H stretching vibrations of hydroxyl groups in starch and non-starch polysaccharides, with slight intensity variation across streams, reflecting differences in moisture content and hydrogen bonding. [23] The 2925 and 2850 cm^{-1} peaks were attributed to C-H stretching of aliphatic groups in lipids and proteins (Figure 4c). Break streams (B1, B2) showed stronger lipid-associated peaks, consistent with their higher bran and germ contamination compared to later reduction streams (C3-C5).

The amide I (1650 cm^{-1}) and amide II (1540 cm^{-1}) peaks, arising from C=O stretching and N-H bending vibrations of proteins, were prominent across all streams (Figure 4d). However, SRF and reduction streams (C3-C5) exhibited higher peak intensities, indicating greater protein concentrations, consistent with the compositional distribution of endosperm-rich fractions. [46] In the fingerprint region (1200-800 cm^{-1}), strong bands at 1150, 1075, 1012, 995, and 930 cm^{-1} were observed, corresponding to C-O, C-C stretching, and glycosidic linkages in starch polysaccharides (Figure 4e). [23,47] Variations in band intensity between break (B1-B4) and reduction (C1-C5) streams indicated differences in starch structure and the extent of SD. Notably, SRF and C4 showed relatively more intense peaks at 1022 cm^{-1}, confirming their higher starch damage, as also supported by farinograph and amylograph results. These results confirm that roller milling segregates functional components, with bran-associated fractions (B1-B2) being richer in lipids and fiber, while signals from starch and protein dominate the reduction streams (C3-C5) and the SRF. These molecular-level differences corroborate the functional and rheological behavior observed in farinograph and pasting studies, underlining the role of particle size distribution and SD content in defining flour functionality.

3.4.Cookie's physical and sensory quality

DOI: 10.1039/D6FB00108D

The quality attributes of cookies prepared from different RMFS exhibited significant variation in color, spread ratio, and textural properties (Table 3), reflecting the compositional and functional heterogeneity of the break and reduction streams.

3.4.1. Color of cookies

Color analysis showed that lightness (L*) values ranged from 49.89 to 65.05, with the lowest value observed for C3 (49.89) and the highest for SRF (65.05), indicating darker cookies in certain reduction streams (Table 3). The relatively lower L* values in streams such as C3 and B4 may be attributed to higher levels of reducing sugars and ash, which promote Maillard browning reactions during baking[23]. The redness (a) and yellowness (b) values also varied significantly, with C3 exhibiting the highest a (13.08), suggesting intensified browning, while C5 showed the highest b (22.87), indicating enhanced yellow pigmentation, possibly due to carotenoid content in endosperm-rich fractions. The total color difference (ΔE) ranged from 35.42 to 48.04, with higher values in C3 and B4, confirming pronounced visual differences compared to the reference (SRF).

3.4.2. Spread ratio of cookies

The spread ratio, a key indicator of cookie quality, varied from 5.8 to 7.3, with the highest value observed in C5 (7.3), followed by C1, C2F1, C2F2, and C4 (7.0). In contrast, break streams such as B3 (5.8) and B2 (6.1) exhibited lower spread ratios (Table 3). This behavior can be attributed to differences in protein content, particle size, and SD levels, where lower gluten strength and finer particles in reduction streams promote greater dough flow and spreading during baking. [18,23,48] Conversely, higher fiber and bran content in break streams likely restricted spread due to increased water absorption and dough viscosity.

3.4.3. Texture of cookies

Texture analysis revealed significant differences in hardness and fracturability among the samples. Cookie hardness ranged from 4925.28 to 9632.65 g, with the highest hardness observed in B4 (9632.65 g) and the lowest in C5 (4925.28 g) (Table 3). The higher hardness in break streams may be due to bran interference and stronger structural rigidity, whereas reduction streams, particularly C5, produced softer cookies due to better starch gelatinization

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and reduced gluten network formation. Fracturability values ranged from 7.93 to 9.82 mm, with B3 (9.82 mm) and SRF (9.36 mm) showing higher values, indicating more brittle structures. The relatively lower fracturability in C5 (7.93 mm) suggests a more cohesive and less brittle texture, which is desirable in cookie products.

These results are consistent with earlier rheological and DSC findings, where reduction streams exhibited higher starch functionality and controlled gelatinization behavior, leading to improved spread and softer textures. In contrast, break streams with lower gelatinization enthalpy and greater structural heterogeneity produced firmer, less spreadable cookies. Such relationships between flour functionality and cookie quality have been widely reported in wheat-based systems. [6,18,49]

Statistically, one-way ANOVA revealed that flour stream type had a significant effect ($p < 0.05$) on all measured parameters (color attributes, spread ratio, hardness, and fracturability). Post hoc analysis (Tukey's HSD) indicated that reduction streams, particularly C5, differed significantly from break streams in terms of higher spread ratio and lower hardness, confirming their superior suitability for cookie applications. However, C2F1 and C2F2 showed no significant differences ($p > 0.05$), suggesting similar functional performance.

Overall, the study demonstrates that stream-specific selection of roller-milled flours plays a crucial role in determining cookie quality, with reduction streams, especially C5, offering optimal characteristics in terms of spread, texture, and color, making them more suitable for cookie production.

3.4.4. Consumer pre-sensory qualities of cookies

Sensory evaluation revealed significant variation among cookies prepared from different flour streams (Figure 5). Overall acceptability (OA) ranged from 6.81 to 8.20, with SRF (8.20) exhibiting the highest score, followed by C2F2 (7.49) and C1/C2F1 (7.35), indicating superior sensory quality of these samples. Cookies from early-reduction streams showed balanced attributes in surface color, cracking, and mouthfeel, contributing to higher acceptability. Break stream cookies (B1-B3) generally showed moderate scores (OA: 6.81-7.11), with lower surface cracking and aroma, indicating less desirable texture and flavor development. In contrast, B4 and C1 exhibited improved surface characteristics (surface color and cracking >8.0), although

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texture scores were comparatively lower. Higher texture scores were observed in C3-C5 (8.21-8.34), suggesting firmer and more rigid structures; however, these samples showed reduced mouthfeel and aftertaste, likely due to increased bran content. Aroma was highest in C4 (8.04) and C5 (8.17), whereas aftertaste scores declined in these streams, indicating a possible flavor imbalance due to higher lipid levels.[23] Overall, cookies from refined and balanced streams (SRF, C2F2, C1) demonstrated superior sensory performance, with optimal texture, appearance, and flavor, while coarse or bran-rich streams (C3-C5) exhibited limitations in palatability despite higher textural firmness. These findings highlight the importance of stream selection in achieving desirable sensory quality in cookies.

3.5. Multivariate relationships

3.5.1. Principal component analysis

Principal component analysis (PCA) clearly differentiated the roller-milled flour streams based on their functional, rheological, thermal, and hydration properties (Figure 6a). PC1 and PC2 explained 34.8% and 21.08% of the total variability, respectively. PC1 was primarily driven by hydration- and starch-related variables, including water absorption (WA), SP (at 55, 75, and 98 °C), SI (at 55, 75, and 98 °C), SD, and particle-size parameters, indicating strong starch-dominated hydration behavior. In contrast, PC2 was mainly associated with protein and thermal functionality, including ZSV, DS, DDT, gelatinization temperatures (To, Tp, Te), and pasting viscosities (PV, HPV, CPV), reflecting gluten strength and thermal stability.

Break streams (B1-B3) clustered closely with viscosity, DS, ZSV, and thermal-transition parameters, indicating stronger gluten functionality and improved structural properties. Among these, B2 and B3 showed strong association with peak viscosity, hot paste viscosity, and dough-strength parameters, suggesting that moderate starch damage and higher protein quality contributed to enhanced gluten development and paste stability. In contrast, reduction streams (C3-C5) were positioned along the positive side of PC1 and were strongly associated with water absorption, SP, SI, and particle-size attributes, reflecting greater hydration capacity and starch-dominated behavior. The close alignment of C3 and C4 with hydration-related variables indicates that these streams exhibit greater water-binding capacity, driven by finer particles, increased SD, and stronger non-starch polysaccharide interactions. SRF occupied an intermediate position, reflecting the combined contribution of break and reduction fractions.

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A supplementary Table 1 containing the factor loadings for PC1 and PC2 has been added to better illustrate the contribution of individual variables to the observed clustering patterns.

For cookies, PC1 (37.30%) captured sensory-textural quality (overall acceptability, mouthfeel, taste, hardness), while PC2 (26.66%) was driven by color attributes (L*, a*, b*, ΔE) and fracturability. Samples such as C1, C2F1, C2F2, and B2 exhibited superior quality, while higher spread was inversely related to hardness. These multivariate relationships highlight the trade-off between hydration and structural strength, confirming that stream-specific functionality governs the optimization of cookie quality.

3.5.2. Correlation analysis

Pearson correlation analysis revealed strong interrelationships among the functional, rheological, thermal, and particle-size properties of roller-milled flour streams (Figure 7). Hydration-related parameters, including WA, SP, SI, WHC, and OHC, showed strong positive correlations (r = 0.62-0.91), indicating that flour streams with greater starch accessibility and finer particle size exhibited enhanced water-binding and swelling behavior. Similarly, peak viscosity, HPV, and CPV were highly positively correlated (r = 0.74-0.96), reflecting coordinated starch swelling and paste stability during heating and cooling.

Gluten-strength parameters, including ZSV, DS, and FN, showed negative correlations with hydration and swelling properties (r = -0.45 to -0.82), indicating a trade-off between starch-dominated functionality and protein-driven dough strength. Thermal parameters (To, Tp, Te, and ΔH) were positively associated with final viscosity and setback viscosity (r = 0.51-0.79), suggesting that greater starch crystallinity contributed to stronger gel formation and retrogradation behavior.

Particle-size parameters (diameter and width) positively correlated with WHC, OHC, and color coordinates (a* and b*), indicating that coarser, bran-rich fractions exhibited greater hydration capacity and darker color development, while L* showed negative correlations with bran-associated properties. Overall, the correlation analysis demonstrated that starch damage, particle size, hydration behavior, and protein quality collectively govern the functional and rheological performance of roller-milled flour streams.

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3.6. Practical implications for selective stream utilization

The observed stream-specific variability demonstrates that roller-milled flour fractions can be selectively utilized to meet targeted product requirements rather than being uniformly recombined into straight-run flour. Break streams with stronger gluten functionality and lower swelling behavior are more suitable for structurally stable products. In contrast, reduction streams with higher hydration and starch functionality are better suited for cookies and other low-moisture baked products that require greater spread and a softer texture. Such selective utilization enables more efficient use of inherent flour functionality while reducing dependence on external additives and excessive processing modifications.

The findings further highlight the potential of precision milling and stream recombination strategies for developing application-specific flours with improved consistency and performance. Selective utilization of bran-rich and starch-rich fractions may also support improved valorization of milling streams and more resource-efficient cereal processing systems.

3.7. Limitations of this study

This study used a single wheat variety; therefore, the observed stream-specific functional and rheological behavior may vary with genotype, grain hardness, and growing conditions. In addition, cookie preparation and quality evaluation were conducted at laboratory scale, which may not fully reflect industrial processing conditions. Furthermore, the findings were validated only for cookie applications, and the suitability of these flour streams for other wheat-based products, such as bread, noodles, and extruded foods, requires further investigation. Future studies should evaluate multiple wheat varieties, industrial-scale processing conditions, and broader end-product applications to strengthen the applicability of stream-specific flour utilization strategies.

4. Conclusion

This study demonstrated pronounced stream-specific variability in the functional, rheological, thermal, and hydration properties of roller-milled wheat flours. Reduction streams exhibited finer particle size, greater starch damage, and higher SP (6.94 g/g), resulting in

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enhanced hydration and starch-dominated functionality. In contrast, break streams exhibited lower swelling and solubility but superior DS and gluten-related characteristics. Straight-run flour showed intermediate behavior due to the combined contribution of all milling fractions. The relationships among starch damage, hydration behavior, rheology, and pasting properties highlighted an important milling trade-off: highly hydrated streams produced softer, higher-spread cookies with lower hardness. In contrast, protein-rich streams contributed to a firmer texture and improved dough handling. These functional differences were further reflected in the cookies' physical and sensory quality attributes.

Overall, the study establishes clear structure-function-quality relationships across roller-milled flour streams and demonstrates that precision milling and selective stream blending can be strategically used to tailor flour functionality for optimized cookie applications. The findings provide a practical framework for developing application-specific flours with improved processing performance, product consistency, and targeted end-use quality. Future studies should validate these findings across different wheat varieties and industrial-scale processing conditions, while also exploring optimized blending strategies, acrylamide mitigation, and interactions between starch and non-starch components to further enhance product functionality and quality.

Acknowledgments

Author Mr. Veeranna H. greatly acknowledges the Indian Council of Medical Research (ICMR), Government of India, for awarding a Senior Research Fellowship [Award No. 3/1/2/240/2021-Nut].

Funding

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations

Conflict of interest: The authors declare no competing interests.

Consent for publication: All authors agreed to the publication of the manuscript.

Consent to participate and human/animal ethics: Not applicable

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DOI: 10.1039/D6FB00108D

Data availability

Data will be made available on reasonable request.

Author Contributions

V.H- Writing original manuscript, methodology, formal analysis, data curation, validation, visualization, Conceptualization; **A.A.I** - Conceptualization, Writing & editing, Supervision, validation, resources, project administration.

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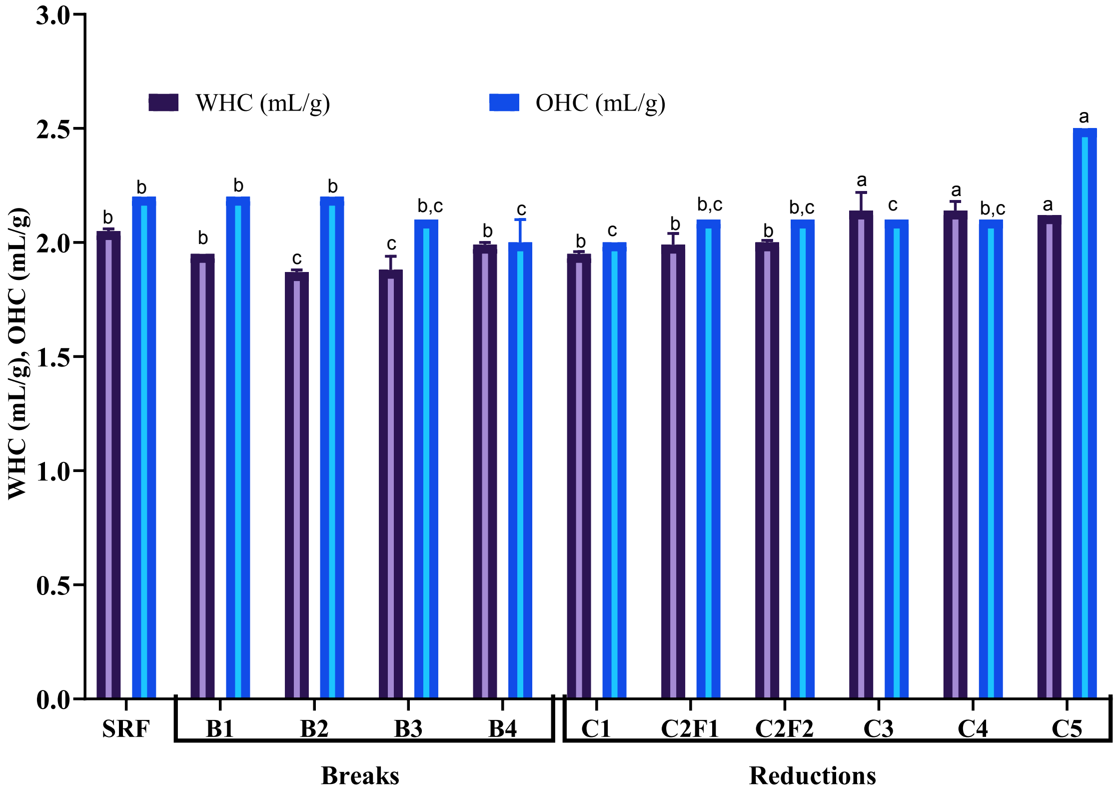

Figure 1: Water and oil holding capacity of roller-milled flour breaks (B1-B4), reductions (C1-C5), and straight run flour (SRF).

Values are expressed as mean ± standard deviation (n = 3). Mean values followed by different superscript letters differ significantly ($p < 0.05$), whereas values sharing the same letter are not significantly different ($p > 0.05$) according to Tukey's HSD test.

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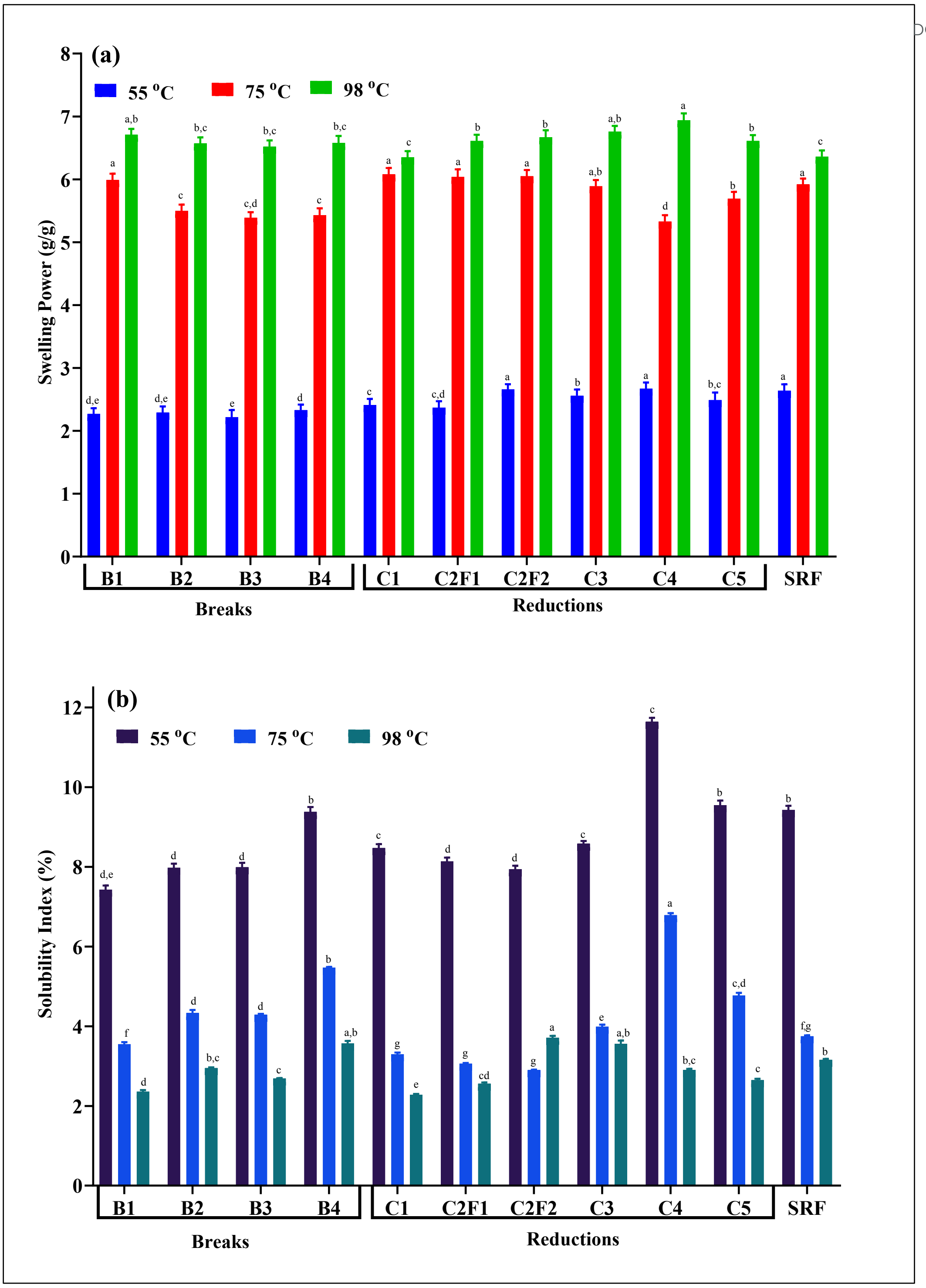

Figure 2: (a)-Swelling power (g/g) and (b)-Solubility index (%) of roller-milled flour breaks (B1-B4), reductions (C1-C5), and straight run flour (SRF).

Values are expressed as mean ± standard deviation (n = 3). Mean values followed by different superscript letters differ significantly ($p < 0.05$), whereas values sharing the same letter are not significantly different ($p > 0.05$) according to Tukey's HSD test.

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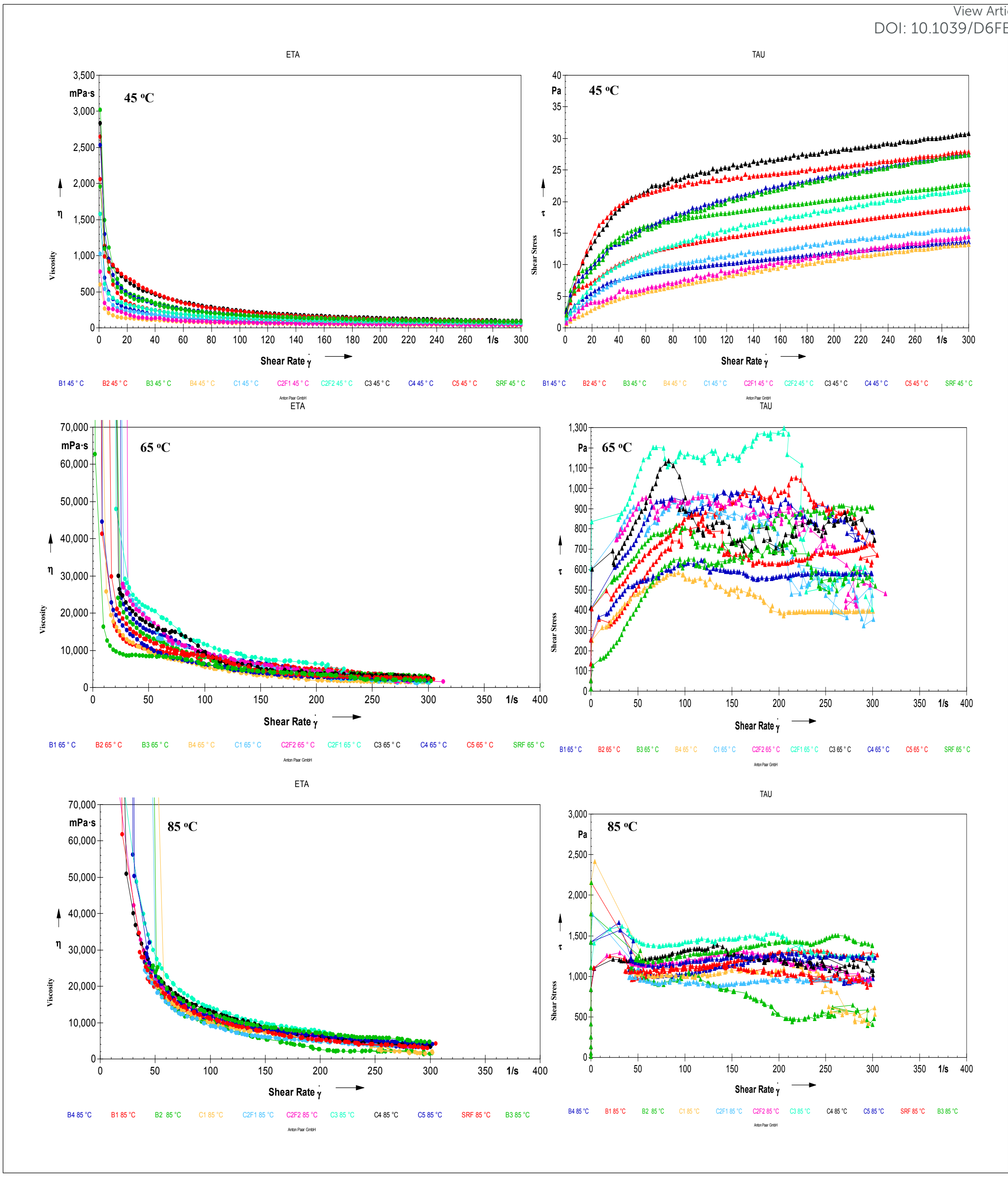

Figure 3: Flow behavior of the stream flour at different temperatures. Breaks (B1-B4), reductions (C1-C5), and straight run flour (SRF)

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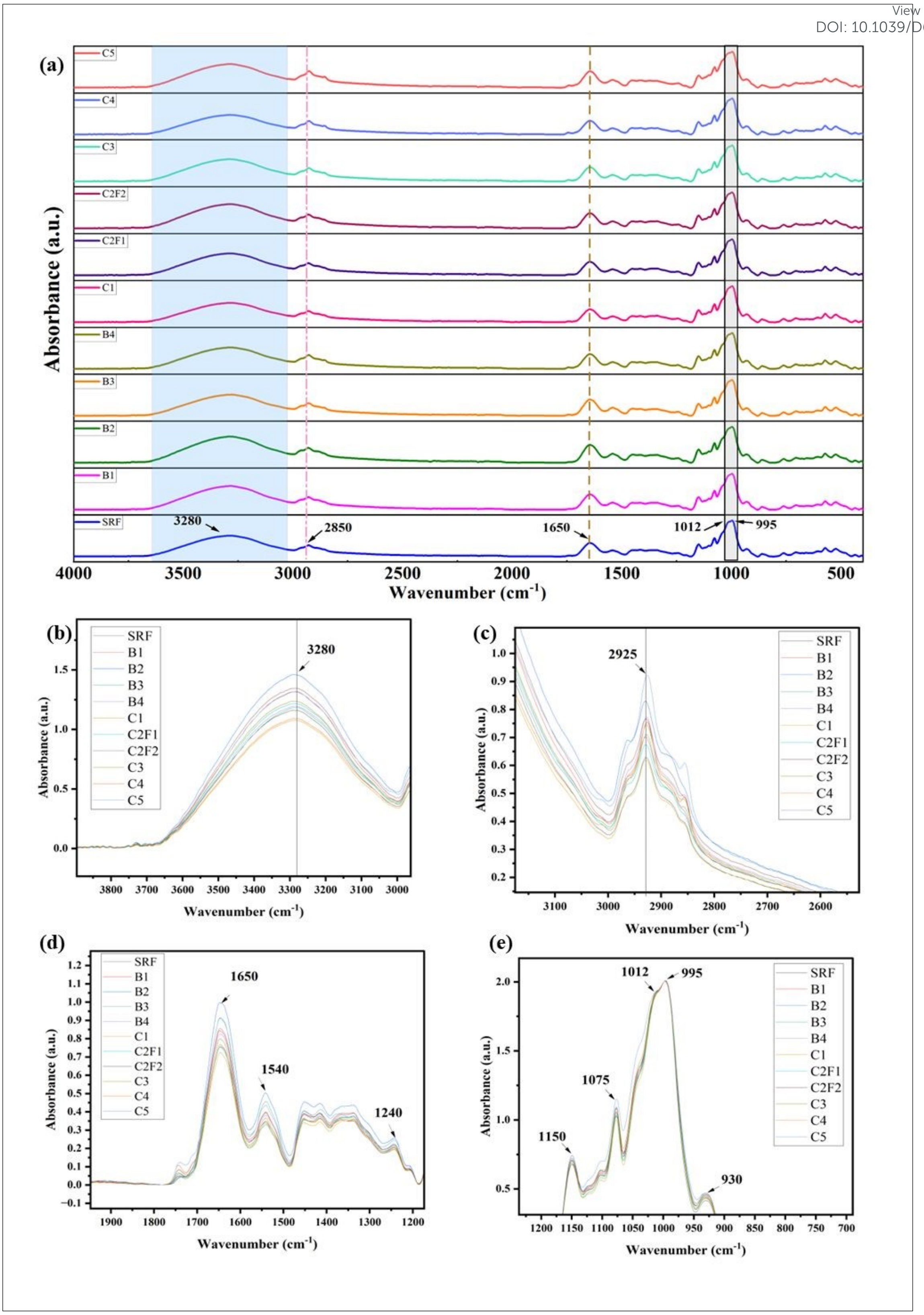

Figure 4. FTIR spectra of stream flour: (b): O-H/C-H-O region; (c): C-H/Ester region; (d): Amid/protein region; (e): Starch region. Breaks (B1-B4), reductions (C1-C5), and straight run flour (SRF)

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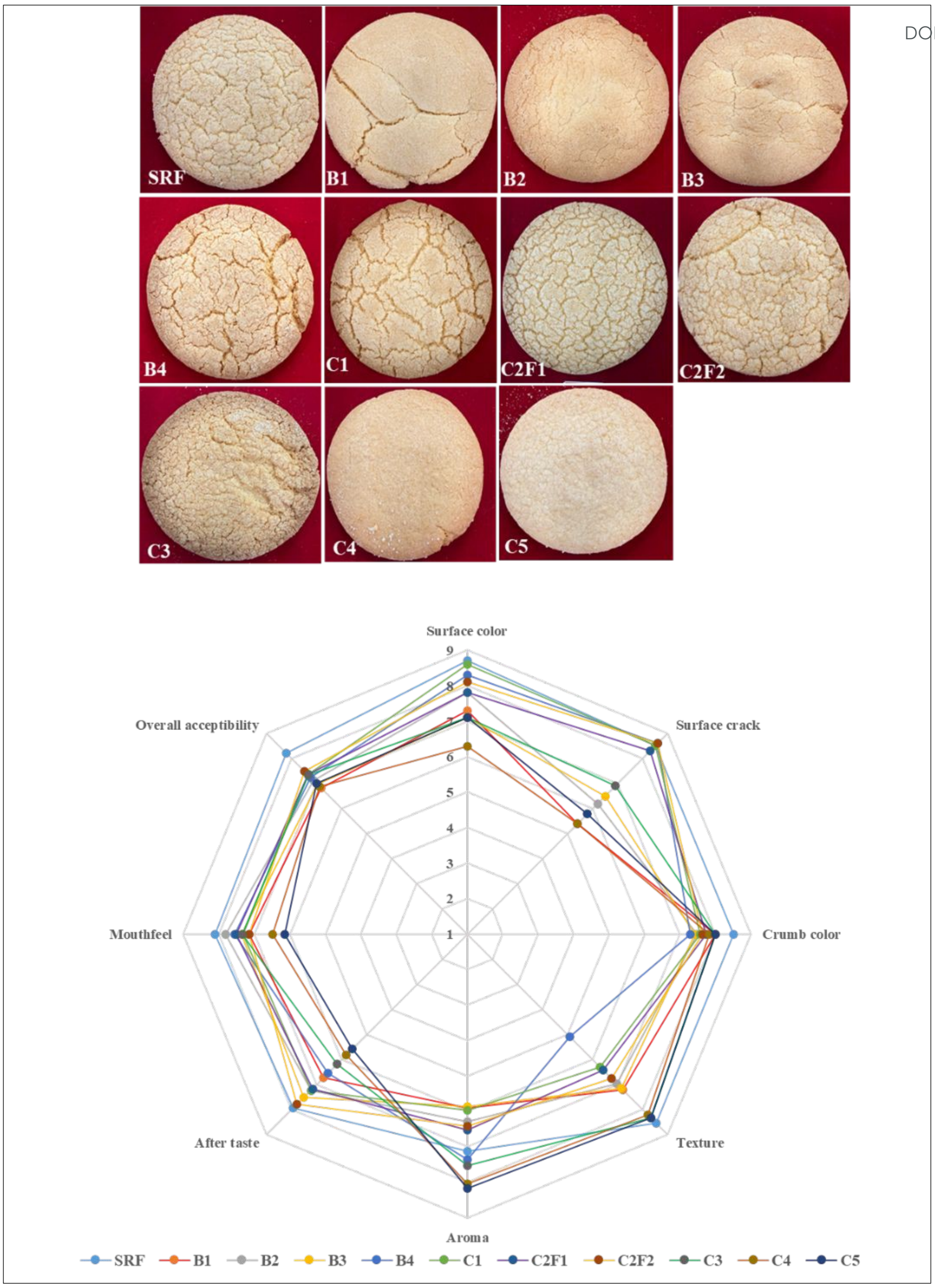

Figure 5: Cookies visualization and sensory qualities: Roller-milled flour breaks (B1-B4), reductions (C1-C5), and straight run flour (SRF)

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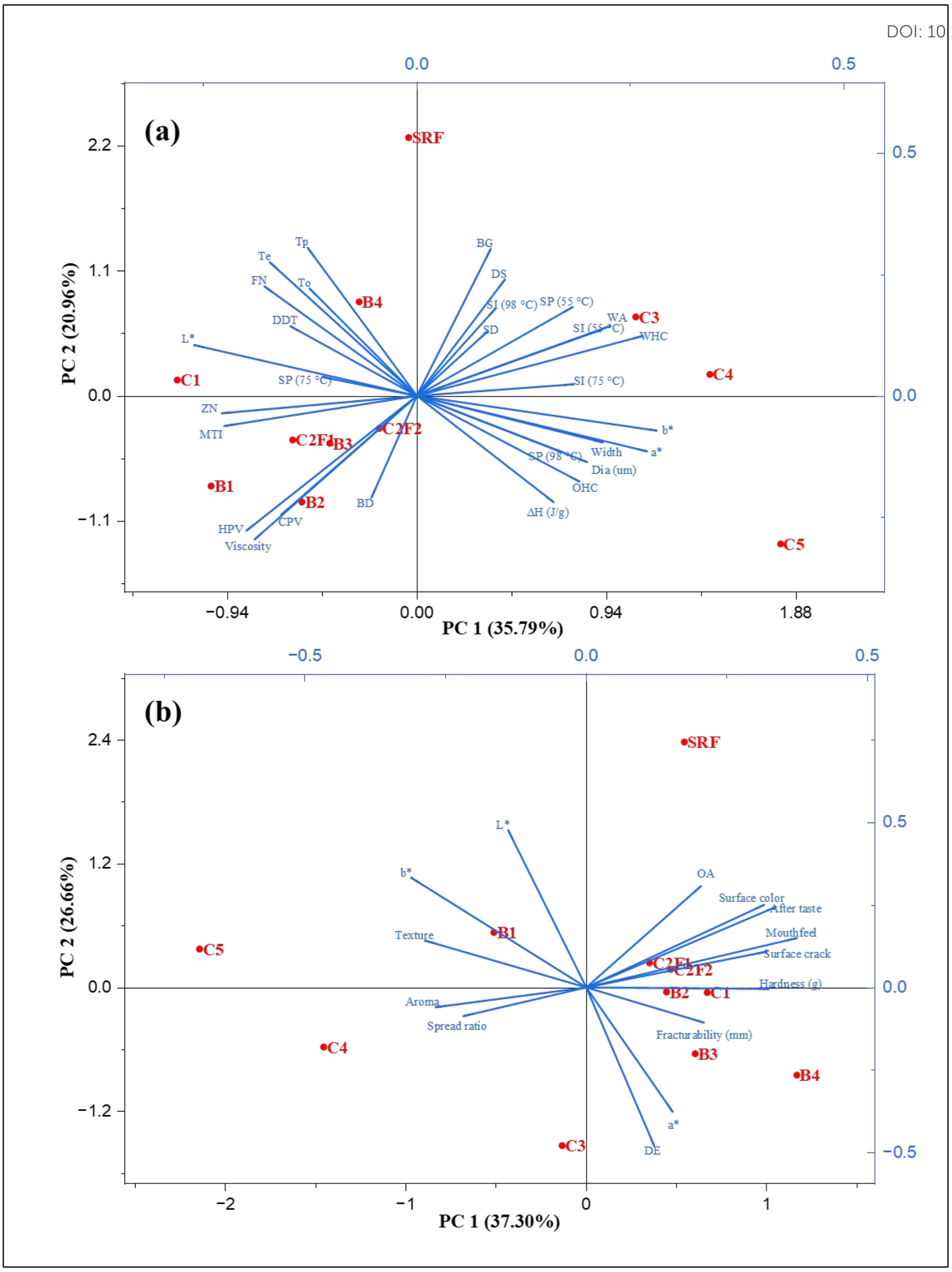

Figure 6: Principal component analysis (PCA) of (a) flour stream properties and (b) cookie quality attributes. (a) Biplots showing the distribution of roller-milled wheat flour streams (B1–B4, C1–C5, SRF) based on integrated functional, rheological, pasting, and thermal properties. (b) PCA of cookie physical, color, and sensory attributes, illustrating sample discrimination based on textural, sensory acceptability, and color parameters. The percentage of variance explained by PC1 and PC2 is indicated on the axes.

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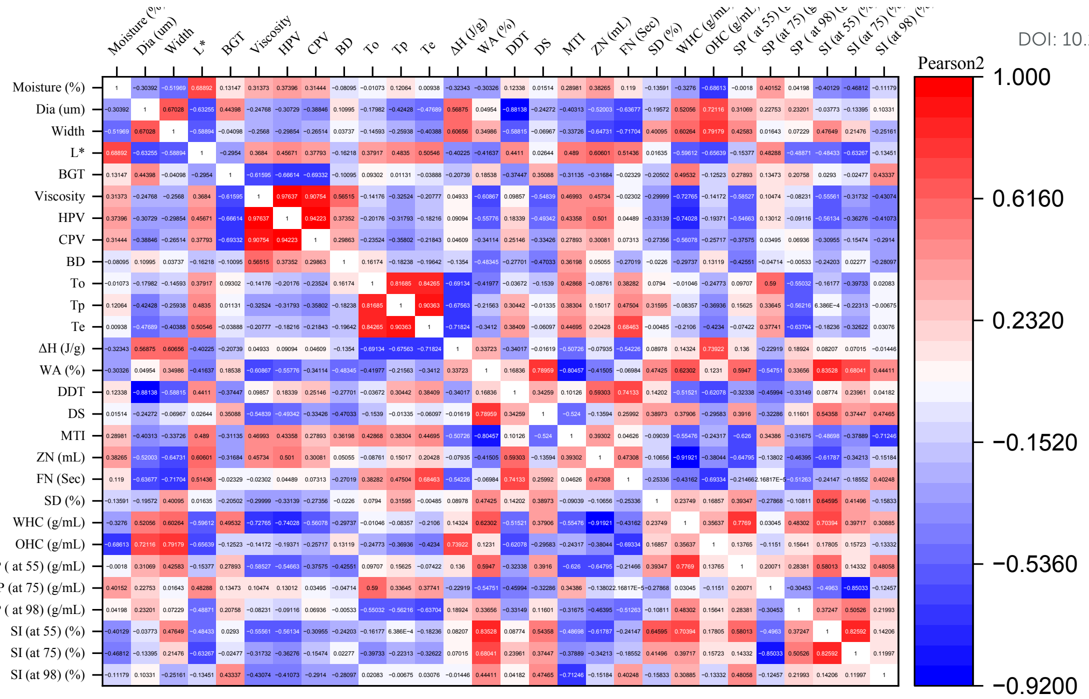

Figure 7. Pearson correlation heatmap showing the relationships among functional, rheological, thermal, pasting, particle-size, and color properties of roller-milled wheat flour streams. Positive correlations are represented in red, and negative correlations in blue, with color intensity corresponding to the correlation strength (r).

Table 1: Damaged starch , Falling number, Zeleny, and Dough mixing of flour streams

	SRF	**B1**	**B2**	**B3**	**B4**	**C1**	**C2F1**	**C2F2**	**C3**	**C4**	**C5**
Damaged starch (%)	8.85 ± 0.03^{a}	3.48 ± 0.05^{j}	7.1 ± 0.1^{c}	4.3 ± 0.06^{g}	4.1 ± 0.01^{h}	5.65 ± 0.08^{e}	5.25 ± 0.05^{f}	3.69 ± 0.04^{i}	3.48 ± 0.05^{j}	8.61 ± 0.1^{b}	5.86 ± 0.03^{d}
Falling number (sec)	732.86 ± 14^{b}	631.52 ± 21^{f}	652.28 ± 11^{e}	730.79 ± 32^{b}	838.02 ± 18^{a}	$723.56\pm13.5^{b,c}$	656.55 ± 16^{e}	712.59 ± 13^{d}	659.64 ± 16^{e}	583.36 ± 231^{g}	533.07 ± 7^{h}
Zeleny (mL)	21.41 ± 0.5^{c}	21.62 ± 0.2^{c}	27.29 ± 0.3^{b}	29.55 ± 0.7^{a}	20.01 ± 0.1^{d}	20.65 ± 0.1^{d}	21.14 ± 0.1^{c}	20.59 ± 0.15^{d}	$15.99\pm0.10.1^{e}$	14.76 ± 0.2^{f}	13.19 ± 0.1^{g}
<u>Dough mixing Characteristics</u>											
Water absorption (%)	59.6 ± 0.3^{b}	52.00 ± 0.12^{e}	56.70 ± 0.23^{d}	$58.90\pm0.31^{b,c}$	59.70 ± 0.25^{b}	56.00 ± 0.3^{d}	57.70 ± 0.2^{c}	$58.30\pm0.18^{b,c}$	59.40 ± 0.3^{b}	63.90 ± 0.5^{a}	59.60 ± 0.45^{b}
Development time (min)	1.5 ± 0.07^{f}	0.9 ± 0.03^{g}	20 ± 0.9^{a}	$19.5\pm1.2^{a,b}$	9.5 ± 0.56^{c}	1.7 ± 0.1^{f}	1.5 ± 0.1^{f}	2.2 ± 0.11^{e}	1.5 ± 0.05	7.5 ± 1.2^{d}	1.7 ± 0.1^{f}
Stability (min)	16.4 ± 0.5^{b}	0.6 ± 0.1^{h}	11.2 ± 1.5^{d}	12.4 ± 1.3^{c}	16.2 ± 2.1^{b}	9.1 ± 1.0^{f}	16.9 ± 2.1^{b}	10.1 ± 1.5^{e}	16.5 ± 2.5^{b}	18.1 ± 0.5^{a}	7.8 ± 0.55^{g}
Tolerance Index (MTI) (FU)	24 ± 3.5^{e}	44 ± 5.2^{a}	26 ± 1.5^{d}	22 ± 2.1^{f}	20 ± 1.02^{g}	32 ± 2.5^{b}	31 ± 1.5^{c}	11 ± 1.1^{i}	14 ± 1.5^{h}	15 ± 1.5^{h}	15 ± 1.9^{h}
Time to breakdown:	3.1 ± 0.1^{d}	1.2 ± 0.1^{h}	20 ± 4.2^{a}	20 ± 1.5^{a}	19 ± 0.5^{b}	2 ± 0.1^{g}	2.1 ± 0.3^{f}	2.8 ± 0.1^{e}	$2.4\pm0.1^{e,f}$	20 ± 0.57^{a}	9.6 ± 0.56^{c}

Values are expressed as mean ± standard deviation (n = 3). Mean values within a row followed by different superscript letters differ significantly ($p < 0.05$), whereas values sharing the same letter are not significantly different ($p > 0.05$) according to Tukey's HSD test.

Breaks- B1, B2, B3, & B4; Reductions- C1F1, C2F1, C2F2, C3, C4, C5; SRF- Stright run flour

Table 2: Pasting and Melting properties of stream flours

	SRF	B1	B2	B3	B4	C1	C2F1	C2F2	C3	C4	C5
Pasting properties											
BG (^oC)	$63.9±0.2^a$	$59.2±0.5^c$	$59.8±0.23^c$	$59.8±0.17^c$	$60.7±0.52^b$	$59.7±0.14^c$	$59.7±1.1^c$	$58.5±0.5^d$	$62.8±0.55^a$	$60.2±0.15^b$	$60.1±0.51^b$
Viscosity (BU)	$666±11^i$	$974±19^c$	$1032±24^a$	$890±14^e$	$856±9^f$	$980±10^b$	$953±07^d$	$951±4.5^d$	$712±121^h$	$805±2^g$	$842±16^f$
HPV (BU)	$423±4^i$	$677±2^{b,c}$	$699±7^a$	$648±4^d$	$578±3^e$	$688±9.5^b$	$690±11^a$	$697±07^a$	$440±4.5^h$	$544±5.5^{f,g}$	$552±12^f$
CPV (BU)	$838±13^j$	$1053±9^{c,d}$	$1068±27^c$	$1021±31^f$	$1038±36^e$	$1093±21^b$	$1090±27^b$	$1114±34^a$	$864±12^i$	$1026±11^g$	$965±17^h$
Breakdown (BU)	$243±7^e$	$297±3^b$	$333±3^a$	$242±5.2^e$	$278±2.5^c$	$292±4^b$	$263±2^d$	$254±6^e$	$272±4^c$	$261±5^c$	$290±2.5^b$
Set back (BU)	$415±11^d$	$376±5^g$	$369±3^i$	$373±2^h$	$460±7^b$	$405±42^e$	$400±3^{e,f}$	$417±9^d$	$424±5.5^c$	$482±3.3^a$	$413±6^d$
Melting characteristics											
T_o (^oC)	$65.37±0.26^a$	$63.99±0.17^c$	$62.53±0.08^{d,e}$	$60.35±0.06^h$	$63.85±0.11^c$	$64.56±0.12^b$	$62.59±0.05^{d,e}$	$62.53±0.13^{d,e}$	$62.87±0.21^d$	$61.07±0.27^g$	$62.13±0.31^f$
T_p (^oC)	$72.51±0.31^a$	$69.74±0.14^c$	67.98±0.11	$67.85±0.13^h$	$69.12±0.09^{c,d}$	$70.17±0.23^b$	$67.55±0.08^h$	$68.16±0.10^f$	$68.1±0.31^f$	$68.01±0.08^{f,g}$	$66.83±0.22^e$
T_e (^oC)	$79.12±0.09^a$	$77.1±0.10^c$	$74.21±0.12^e$	$75.11±0.08^{d,e}$	$77.71±0.15^b$	$77.28±0.11^{b,c}$	$75.21±0.07^d$	$75.22±0.22^d$	$74.91±0.06^e$	$73.63±0.05^f$	$73.75±0.76^f$
ΔH (J/g)	$5.08±0.06^{e,f}$	$4.27±0.09^g$	$6.32±0.05^{c,d}$	$7.31±0.12^b$	$4.13±0.08^i$	$4.27±0.09^h$	$6.45±0.10^c$	$7.15±0.08^b$	$5.16±0.11^e$	$6.19±0.13^d$	$8.93±0.07^a$

Values are expressed as mean ± standard deviation (n = 3). Mean values within a row followed by different superscript letters differ significantly ($p < 0.05$), whereas values sharing the same letter are not significantly different ($p > 0.05$) according to Tukey's HSD test.

Breaks- B1, B2, B3, & B4; Reductions- C1F1, C2F1, C2F2, C3, C4, C5; SRF- Stright run flour
BG-Beginning of gelatinization; HPV- Hot paste viscosity; CPV-Cold paste viscosity; Onset Temperature -To; Peak temperature -Tp; End point -Te

Table 3: Physical qualities of cookies

Fractions	L*	a*	b*	DE	Spread ratio	Hardness (g)	Fracturability (mm)
SRF	65.05±0.46[a]	9.74±0.0[g]	22.29±0.12[a,b]	35.42±0.33[i]	6.2±0.11[e]	7418.193±166[d,e]	9.36±0.33[b]
B1	59.99±o.67[b]	9.11±0.20[h,i]	21.43±0.12[d]	38.89±0.61[h]	6.6±0.10[c,d]	8376.173±192[b]	7.95±0.21[h]
B2	54.94±1.28[f,g]	10.69±0.31[e]	20.94±0.46[e]	43.41±0.86[c]	6.1±0.06[e]	8414.308±572[b]	8.23±0.63[f,g]
B3	54.20±1.11[g]	11.61±0.08[b]	20.44±0.19[f,g]	44.10±0.89[b,c]	5.8±0.10[f]	7432.903±340[d]	9.82±0.22[a]
B4	52.89±0.72[h]	11.20±0.12[d,e]	19.41±0.18[h]	44.74±0.61[b]	6.7±0.15[c]	9632.65±568[a]	9.4±0.12[b]
C1	55.60±0.59[f]	11.47±0.20[d]	20.68±0.19[e,f]	42.94±0.58[d,e]	7.0±0.15[b]	7048.02±570[g]	8.81±0.49[e]
C2F1	57.42±0.24[d]	11.06±0.08[f]	21.48±0.12[d]	41.62±0.17[e]	7.0±0.10[b]	7929.43±579[c]	8.63±0.19[e,f]
C2F2	56.30±0.72[e]	11.64±0.14[b]	21.45±0.39[d]	42.68±0.49[d]	7.0±0.10[b]	7284.548±419[f]	8.76±0.28[e]
C3	49.89±0.47[i]	13.08±0.27[a]	20.31±0.03[f,g]	48.04±0.35[a]	6.9±0.12[b]	6355.95±537[i]	9.05±0.26[d]
C4	58.34±1.59[c]	11.52±0.62[b,c]	22.07±0.23[b,c]	41.26±1.40[e,f]	7.0±0.05[b]	6558.488±271[h]	9.23±0.22[b,c]
C5	59.91±0.23[b]	9.23±0.10[h]	22.87±0.34[a]	39.69±0.36[g]	7.3±0.02[a]	4925.275±643[j]	7.93±0.21[h]

Values are expressed as mean ± standard deviation (n = 3). Mean values within a column followed by different superscript letters differ significantly ($p < 0.05$), whereas values sharing the same letter are not significantly different ($p > 0.05$) according to Tukey's HSD test.

Breaks- B1, B2, B3, & B4; Reductions- C1F1, C2F1, C2F2, C3, C4, C5; SRF- Stright run flour

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Data availability

Data will be made available on reasonable request.