Applied Food Research xxx (xxxx) 102778

Contents lists available at ScienceDirect

Applied Food Research

journal homepage: www.elsevier.com/locate/afres

Production-related variation in wheat flour affects mixing and starch-pasting behaviour

Narges Samanian [a], Feruza B. Abdullayeva [a], Gulnoza Djakhangirova [a], Rakhmonov Kakhramon [b], Khodjiev Shukhrat [b], Mansur Akbarov [c], Bakhtiyar Rzayev [d], Bekzod Khakimov [e,*], Suvankul S. Ravshanov [a,*]

[a] Tashkent Institute of Chemical Technology, Navoiy Street 32, 100011, Tashkent, Uzbekistan
[b] Bukhara State Technical University, Q. Murtazayev Street 15, 200117, Bukhara, Uzbekistan
[c] Karshi State Technical University, Mustakillik Avenue 225, 180700, Karshi, Uzbekistan
[d] Kazakh Agrotechnical Research University, Zhenis Avenue 62, 010011, Astana, Kazakhstan
[e] Department of Food Science, University of Copenhagen, Rolighedsvej 26, 1958, Frederiksberg C, Denmark

UNCORRECTED PROOF

ARTICLE INFO

Keywords:
Wheat flour
Commercial flour
Mixolab
Starch damage
Falling number
Dough rheology
Thermo-mechanical behaviour

ABSTRACT

Commercial wheat flours produced from the same grain type and with similar quality characteristics can differ in processing performance, but how production-related variation is expressed across individual stages of dough development remains unclear. We hypothesized that these differences translate into distinct phase-specific changes in dough thermo-mechanical behaviour. We compared commercial flours produced from common wheat (Triticum aestivum L.) harvested in Uzbekistan and obtained from six industrial milling companies. Each flour was characterised using conventional physicochemical and technological measurements together with complete Mixolab thermo-mechanical profiling. Univariate and multivariate analyses identified production-related differences and explored relationships between conventional flour characteristics and Mixolab responses. The largest differences were observed for the gluten deformation index, falling number, mechanical starch damage and gas-production capacity. Water absorption ranged from 54.9 to 60.0%, while cooling setback varied from 1.114 to 2.092 N·m. Mechanical starch damage was associated with dough development time, the gluten deformation index with the protein-weakening slope, and falling number with hot-paste torque retention. Principal component analysis showed distinct producer profiles and coordinated trade-offs among mixing performance, starch gelatinisation, paste stability and cooling behaviour rather than a single overall quality gradient. Together, these findings show that production-related variation is expressed across specific processing phases and that combining conventional measurements with phase-resolved Mixolab profiling improves the functional characterisation of commercial flours, although validation against end-use performance remains necessary.

1. Introduction

Wheat flour functionality is determined by the combined effects of genotype, growing environment, storage, milling and flour standardisation. In this study, conventional flour-quality measurements comprised moisture, ash, wet gluten, gluten quality, flour fineness and whiteness, falling number, mechanical starch damage, gas-forming capacity and titratable acidity. These tests are essential for routine quality control, but each describes only one component of a system in which gluten proteins, starch, arabinoxylans, lipids, endogenous enzymes and water interact (Hu et al., 2023; Yazar, 2023). Consequently, flours with similar conventional specifications can differ in water requirements, dough development, thermal stability and starch-pasting behaviour (Singh et al., 2019; Selga et al., 2024; Rezette et al., 2025a).

Milling conditions can contribute to variation in flour particle characteristics and mechanical starch damage (Li et al., 2014; Tian et al., 2022; Chen et al., 2025; Han et al., 2025). However, milling conditions were not directly evaluated in the present study, and the observed differences therefore cannot be attributed to specific milling practices. Damaged starch absorbs more water and is more susceptible to amylolysis than intact starch, although flour hydration is also influenced by protein, soluble starch and water-extractable arabinoxylans (Gibson et al., 1992;

* Corresponding authors.
E-mail addresses: bzo@food.ku.dk (B. Khakimov), suvankulravshanov@gmail.com (S.S. Ravshanov).

https://doi.org/10.1016/j.afres.2026.102778
Received 1 August 2026; Received in revised form 12 October 2026; Accepted 27 October 2026
2772-5022/© 20XX

Dexter et al., 1994; Hatcher et al., 2002; Islam et al., 2024; Rezette et al., 2025b). Wet gluten content reflects recoverable gluten quantity but does not describe glutenin polymerization, the gliadin-to-glutenin balance or network connectivity, which contribute to dough development and resistance to mechanical and thermal deformation (Moldestad et al., 2011; Ortolan & Steel, 2017; Schuster et al., 2023). In this study, production-related variation refers to production-related differences arising from commercial flour production, including wheat-lot selection and blending, milling and flour standardisation; the design does not permit attribution to individual production factors. Such differences may influence separate stages of processing rather than create a single overall gradient of flour quality.

Falling number is widely used as an indirect indicator of α-amylase-related liquefaction, yet it does not fully describe starch gelatinization, paste breakdown or torque retention during continued heating and shear (Moot & Every, 1990; Mangan et al., 2022; Fairlie et al., 2023; Kaur et al., 2024). The Mixolab complements routine flour tests by recording dough torque during controlled mixing, heating and cooling. Its characteristic phases describe initial hydration and dough development, thermo-mechanical protein weakening at C2, starch gelatinization at C3, hot-paste behaviour at C4 and cooling-induced torque development at C5. Previous studies have related these responses to cultivar, grain hardness, flour composition, enzymatic activity, isolated starch properties and end-product performance (Dvořáček et al., 2019; Singh et al., 2019; Harati et al., 2020; Kim et al., 2023).

Conventional quality measurements and empirical rheological tests have also been combined with multivariate analysis to differentiate commercial flours and evaluate their processing suitability (Selga et al., 2024; Rezette et al., 2025a). However, less is known about how production-related differences in routinely measured flour characteristics are expressed across individual Mixolab phases. This question is particularly relevant for commercial flours because they integrate variation arising from wheat-lot selection, blending, milling and standardisation, even when they are marketed as the same flour type.

We hypothesized that production-related differences in conventional flour characteristics would be expressed as distinct phase-specific changes in dough thermo-mechanical behaviour. The objectives were to characterise production-related differences, identify the Mixolab processing phases most affected, explore associations between conventional flour characteristics and phase-specific Mixolab responses, and assess whether integrating these measurements provides a more informative functional profile of commercial flour performance.

2. Materials and methods

2.1. Commercial flour sampling and experimental design

The study included 18 commercial soft-wheat flour samples obtained from six industrial milling companies in Uzbekistan, with three independent commercial production lots collected from each company (Producer 1–Producer 6). The identities of the participating milling companies were anonymized because they constitute commercially sensitive information and were not necessary for the scientific interpretation of the results. All samples represented the same commercial flour type supplied by the participating milling companies. The flours were produced from commercial lots of common wheat (Triticum aestivum L.) harvested in Uzbekistan in 2024. No flour improvers, exogenous enzymes or other technological additives were used during flour production. Samples were collected within 24 h after production, sealed in moisture-impermeable polyethylene bags and stored at 5 ± 1 °C in the dark for no longer than 14 days. Before analysis, sealed samples were equilibrated at 22 ± 2 °C for 2 h. Conventional flour-quality measurements and Mixolab analyses were performed in technical triplicate. Technical replicates were averaged for each flour sample before statistical analysis, and the independent commercial production lot was treated as the experimental unit.

2.2. Conventional indicators of flour composition and milling quality

Moisture content was determined by drying a 5.0 g flour sample at 130 ± 3 °C for 8 h and expressed as g/100 g flour (as-is basis). Ash content was determined by incinerating a 5.0 g flour sample at 600 ± 15 °C to constant mass and expressed as g/100 g dry matter. Wet-gluten content was determined according to ISO 21415-2:2015 using a Glutomatic 2200 gluten washer and Gluten Index Centrifuge 2015 (Perten Instruments, Hägersten, Sweden). A 10.0 g flour sample was mixed with 4.8 mL of 2% (w/v) sodium chloride solution, mechanically washed for 5 min, centrifuged for 1 min at 6000 rpm and weighed. Wet-gluten content was expressed as g/100 g flour. Gluten quality was evaluated using an IDK-3 M gluten deformation meter (VNIIZ, Moscow, Russia). A 4.0 g wet-gluten specimen was conditioned in distilled water at 18 ± 2 °C for 15 min and measured under the instrument's calibrated load for 30 s. Results were expressed in conventional IDK units; higher values indicate greater gluten deformability and generally weaker gluten characteristics. Flour fineness was determined by sieving 50.0 g of flour for 10 min through standardized 330 and 160 μm sieves. Results were expressed as the percentage retained on the 330 μm sieve (coarse fraction) and the percentage passing through the 160 μm sieve (fine fraction). Flour whiteness was measured using a CropLAB Whiteness Meter (PIS Ukraine, Dnipro, Ukraine). Samples were levelled in the sample holder and measured in triplicate after automatic calibration. Results were expressed in instrument-specific whiteness units. Mechanical starch damage was determined using an SDmatic analyzer (CHOPIN Technologies, Villeneuve-la-Garenne, France) according to ISO 17715:2013. Flour was dispersed in an iodine-containing solution, and iodine absorption by mechanically damaged starch was measured amperometrically. Results were expressed in Chopin–Dubois units (UCD).

The Hagberg–Perten falling number was measured according to ISO 3093:2009 using an automatic FN 1500 system (Perten Instruments AB, Huddinge, Sweden). Following moisture determination, a test portion equivalent to 7.0 g of flour at 15% moisture was suspended in 25.0 mL of distilled water at 22 ± 2 °C and shaken to obtain a uniform suspension. The viscometer tube and stirrer were immediately placed in a boiling-water bath for the programmed heating and stirring cycle. The total time from immersion until the stirrer fell the specified distance through the gelatinized paste was recorded as the falling number and expressed in seconds. Gas-forming capacity was determined using a Yago–Ostrovsky volumetric apparatus. Dough prepared from 100 g flour (14% moisture basis), 10 g compressed baker's yeast and 60 mL water was fermented at 30 ± 1 °C for 5 h. Carbon dioxide production was measured volumetrically by displacement of saturated sodium chloride solution and expressed as cm^3 CO_2 per 100 g flour. Titratable acidity was determined by titration of a suspension prepared from 5.0 g flour and 50 mL distilled water with 0.1 mol/L sodium hydroxide using phenolphthalein as indicator. The endpoint was defined as a faint pink colour persisting for at least 30 s. Results were expressed as mL of 0.1 mol/L NaOH per 100 g flour.

2.3. Phase-resolved Mixolab thermomechanical analysis

Thermomechanical dough behaviour was evaluated using a Mixolab 2 analyser (CHOPIN Technologies, Villeneuve-la-Garenne, France) operated with the standard Chopin+ protocol. The instrument software automatically calculated the required flour mass and water addition according to flour moisture content to produce 75 g dough with a target consistency of 1.10 ± 0.05 N·m at C1. Water absorption was expressed on a 14% flour-moisture basis. Dough was mixed at 80 rpm and maintained at 30 °C for 8 min, heated from 30 to 90 °C at 4 °C/min, held at 90 °C for 7 min, cooled to 50 °C at 4 °C/min and held at 50 °C for 5 min, giving a total analysis time of 45 min. Twenty primary Mixolab descriptors were recorded (Supplementary Table S1): water absorption, dough development time, stability, amplitude, C1 torque, C1 temperature, C2 torque, C2 temperature, C2 time, protein-weakening slope α, C3 torque,

UNCORRECTED PROOF

C3 temperature, C3 time, starch-gelatinization slope β, C4 torque, C4 temperature, C4 time, hot-paste stability slope γ, C5 torque and C5 temperature. Torque, temperature, time and slope were expressed in N·m, °C, min and N·m/min, respectively, and the original α, β and γ signs generated by the instrument software were retained. C1 represented maximum dough consistency during mixing, C2 protein weakening, C3 starch gelatinization, C4 hot-paste consistency and C5 final consistency after cooling. Six additional descriptors were calculated: C1−C2 (protein weakening), C3−C2 (gelatinization increase), C3−C4 (hot-paste breakdown), C5−C4 (cooling setback), C4/C3 (hot-paste torque retention) and C5/C4 (final-to-hot-paste torque ratio). Mixolab descriptors were interpreted as phase-associated functional indices because both proteins and starch contribute to dough torque throughout mixing, heating and cooling.

2.4. Statistical analysis and multivariate exploration

Producer means and standard deviations (SD) were calculated from the three independent flour samples per producer. Producer effects were evaluated by one-way analysis of variance (ANOVA), with classical omega-squared (ω^2) reported as the effect-size estimate. Homogeneity of variance was assessed using Levene's test. For variables with a significant omnibus test, pairwise producer differences were evaluated using Tukey's honestly significant difference test. The Benjamini–Hochberg procedure was applied separately to the conventional flour characteristics and the Mixolab variables presented in Tables 1 and 2 using a false discovery rate (FDR) of 5%. Pairwise comparisons were interpreted only for variables with adjusted q-values < 0.05. Nine domain-guided relationships between conventional flour characteristics and selected Mixolab-derived properties were evaluated using Spearman's rank correlation. Bias-corrected and accelerated 95% bootstrap confidence intervals were calculated from 10,000 resamples, and correlation p-values were adjusted across these nine relationships using the Benjamini–Hochberg procedure. A broader exploratory correlation analysis was also performed across the conventional flour characteristics and selected Mixolab-derived descriptors, with false-discovery-rate correction applied across the complete set of relationships included in that analysis. Principal component analysis (PCA) was performed using all conventional flour characteristics together with the selected primary and derived Mixolab variables included in the multivariate dataset (Supplementary Table S1). Variables were mean-centred and scaled to unit variance before analysis. Scores and correlation loadings for the first two principal components were examined, and producer groups were visualized using 80% descriptive covariance ellipses. Statistical analyses were performed in Python 3.13 using pandas, SciPy, statsmodels and scikit-learn.

3. Results and discussion

3.1. Production-associated differences in physicochemical and technological flour characteristics

The flour samples differed significantly in most conventional characteristics (Table 1). Nine of the 11 variables remained significant after false-discovery-rate correction, whereas Fineness 1 did not differ and ash was borderline. Wet gluten varied only from 27.0 to 28.0%, indicating broadly similar recoverable gluten quantity across producers. In contrast, the gluten deformation index was substantially higher for Producer 3 (103 units) than for the other producers (87.0–88.0 units). Thus, the main gluten-related distinction involved deformability rather than quantity. This distinction is consistent with the established view that gluten content alone cannot describe dough strength. Gluten functionality also depends on the size and organisation of glutenin polymers, the gliadin-glutenin balance and network connectivity (Ortolan & Steel, 2017; Schuster et al., 2023). The present data do not identify which molecular feature caused the IDK difference, but they show that commercial flours with nearly identical wet-gluten contents can differ markedly in an empirical measure of gluten quality. The narrow wet-gluten range should be considered when interpreting the gluten-related associations, which may not extend to flours with substantially lower or higher gluten contents.

Falling number varied from 359 s for Producer 6 to 775 s for Producer 2, mechanical starch damage was highest for Producers 1 and 3, and gas-production capacity was greatest for Producer 6. Thus, a specific finding of this study is that independent production lots marketed as the same flour type had nearly identical wet-gluten contents but pronounced differences in gluten deformability, falling number, mechanical starch damage and gas-production capacity, with different producer rankings across these properties. This property-specific pattern provided the basis for testing which conventional measurements were linked to particular Mixolab phases (Selga et al., 2024; Rezette et al., 2025a).

Table 1
Physicochemical and technological characteristics of commercial soft-wheat flours obtained from six industrial milling companies in Uzbekistan. The study comprised 18 flour samples representing three independent commercial production lots from each company (n = 3 per producer). The participating companies are identified as Producer 1–Producer 6; their identities were anonymised because they constitute commercially sensitive information and were not required for scientific interpretation of the results. Data are presented as mean (standard deviation). Differences among producers were evaluated by one-way analysis of variance (ANOVA). To account for multiple testing, ANOVA p-values for the 11 characteristics were adjusted using the Benjamini–Hochberg procedure at a 5% false discovery rate; adjusted values are reported as q-values. For characteristics with q < 0.05, producer means not sharing a lowercase superscript letter differ significantly according to Tukey's honestly significant difference test (p < 0.05). Fineness 1 and Fineness 2 represent the percentages of flour retained on a 330-µm sieve and passing through a 160-µm sieve, respectively. * Acidity unit - mL 0.1 mol/L NaOH/100 g flour; Mechanical starch damage unit - Chopin–Dubois units (UCD); Gas-production capacity unit - cm^3 CO_2/100 g flour. Abbreviations: IDK, gluten deformation index; UCD, Chopin–Dubois units; ANOVA, analysis of variance; FDR, false discovery rate; HSD, honestly significant difference.

Characteristic	Producer 1	Producer 2	Producer 3	Producer 4	Producer 5	Producer 6	p-value	q-value
Moisture (%)	16.2 (0.2) bc	16.1 (0.3) c	15.6 (0.2) c	16.8 (0.3) ab	17.0 (0.3) a	16.2 (0.2) bc	1.72 × 10−4	2.36 × 10−4
Wet gluten (%)	28.0 (0.4) a	27.0 (0.2) b	27.0 (0.3) b	28.0 (0.4) a	27.0 (0.2) b	27.0 (0.3) b	0.001	0.002
Gluten IDK (units)	88.0 (1.0) b	87.0 (1.0) b	103.0 (1.0) a	87.0 (1.0) b	87.9 (0.9) b	87.5 (0.5) b	2.87 × 10−10	1.58 × 10−9
Fineness 1 (%)	0.33 (0.01)	0.33 (0.01)	0.33 (0.02)	0.34 (0.01)	0.34 (0.02)	0.35 (0.01)	0.458	0.458
Fineness 2 (%)	99.13 (0.01) a	99.10 (0.01) ab	99.10 (0.02) ab	99.08 (0.01) bc	99.06 (0.01) cd	99.04 (0.01) d	1.64 × 10−5	3.02 × 10−5
Falling number (s)	650 (10) c	775 (13) a	700 (9) b	465 (15) e	520 (20) d	359 (20) f	2.41 × 10−12	2.66 × 10−11
Ash (%)	0.70 (0.00)	0.70 (0.00)	0.70 (0.00)	0.70 (0.00)	0.77 (0.06)	0.77 (0.06)	0.046	0.05
Flour whiteness (units)	46.5 (0.5) a	44.9 (0.4) b	45.0 (0.5) b	43.2 (0.4) c	41.2 (0.4) d	40.4 (0.6) d	8.51 × 10−9	2.34 × 10−8
Mechanical starch damage (UCD)*	26.0 (0.5) a	25.5 (0.5) ab	26.0 (0.5) a	25.1 (0.3) ab	24.4 (0.4) b	22.0 (0.5) c	1.30 × 10−6	2.87 × 10−6
Gas production capacity (cm^3)*	920 (20) cd	840 (20) d	860 (20) cd	1070 (30) b	940 (40) c	1300 (50) a	5.41 × 10−9	1.99 × 10−8
Acidity*	3.0 (0.2) a	2.6 (0.1) ab	2.2 (0.1) b	2.4 (0.1) b	3.0 (0.2) a	2.4 (0.2) b	1.02 × 10−4	1.60 × 10−4

UNCORRECTED PROOF

3.2. Thermal transitions reveal producer-specific functional differences

The complete Mixolab profiles followed the expected progression from dough development through protein weakening and starch gelatinisation to hot-paste behaviour and cooling setback (Fig. 1). Producer curves were relatively close near the initial target consistency but became more widely separated during heating and cooling. This pattern was also evident in the phase-specific results: water absorption varied by 5.1 percentage points and stability by 4.42 min, whereas C3 torque ranged from 1.814 to 2.053 N·m and cooling setback from 1.114 to 2.092 N·m (Table 2; Fig. 2). The principal producer differences therefore emerged when the flour matrix was exposed to thermal transitions in addition to mechanical mixing.

The flour from Producer 3 developed the highest gelatinisation-related torque (2.053 N·m), whereas the flour from Producer 6 showed the lowest hot-paste and final torques. After cooling, the flour from Producer 5 reached the highest final torque (3.953 N·m), while Producer 6 remained lowest (2.769 N·m). These contrasts confirm that producer differentiation became more pronounced in the starch-dominated heating and cooling phases than around the initial target-consistency region. Similar studies have shown that Mixolab heating and cooling phases can reveal variation that is less apparent during initial mixing, as starch swelling, paste stability and water redistribution become increasingly influential with rising temperature (Dvořáček et al., 2019; Singh et al., 2019; Azie et al., 2026).

3.3. Hydration and mixing properties differ among producers

Water absorption, development time, stability and amplitude all differed among producers (Table 2; Fig. 2A,B). Water absorption ranged from 54.9% for Producer 3 to 60.0% for Producer 2. Development time ranged from 1.86 min for Producer 6 to 6.31 min for Producer 3, whereas stability was highest for Producer 6 (9.43 min) and lowest for Producer 4 (5.01 min). The different rankings show that the amount of water needed to reach target consistency, the time required to develop the dough and the ability to resist continued mixing describe related but non-equivalent functions. Mechanical starch damage was positively associated with development time ($\rho = 0.59$, 95% CI 0.12–0.88, $q = 0.0209$; Fig. 3A). This association is compatible with altered competition and redistribution of water among damaged granules, proteins and other hydrophilic components, although the present data cannot establish a specific mechanism. Importantly, starch damage was not significantly associated with water absorption after correction across the broader correlation screen (Supplementary Fig. S1D). Large-scale modelling has similarly shown that water absorption depends jointly on protein, damaged and soluble starch and water-extractable arabinoxylans (Rezette et al., 2025b). The results

Table 2
Selected Mixolab-derived thermo-mechanical properties of commercial soft-wheat flours from six industrial milling companies in Uzbekistan. Data are presented as mean (standard deviation) for three independent commercial production lots per company (18 samples; n = 3 per producer). Companies are coded as Producer 1–Producer 6 because their identities are commercially sensitive and not required for scientific interpretation. Variables are grouped by the principal thermo-mechanical phase they describe. Producer differences were evaluated by one-way analysis of variance (ANOVA). The resulting p-values for all variables were adjusted using the Benjamini–Hochberg procedure at a 5% false discovery rate and reported as q-values. For variables with $q < 0.05$, means not sharing a lowercase superscript letter differ according to Tukey's honestly significant difference test ($p < 0.05$). Water absorption is expressed on the instrument's 14% moisture basis. C2 represents minimum torque during protein weakening; C3, maximum torque associated with starch gelatinisation; C4, torque during high-temperature holding, reflecting hot-paste stability; and C5, final torque after cooling. The instrument-calculated slopes α, β and γ describe protein weakening, starch gelatinisation and hot-paste stability, respectively. Torque differences (C1−C2, C3−C2, C3−C4 and C5−C4) were calculated from the corresponding primary values. Abbreviations: ANOVA, analysis of variance; FDR, false discovery rate; HSD, honestly significant difference; C1–C5, characteristic Mixolab torques; α, protein-weakening slope; β, starch-gelatinisation slope; γ, hot-paste stability slope.

Mixolab variable	Producer 1	Producer 2	Producer 3	Producer 4	Producer 5	Producer 6	p-value	q-value
1. Hydration and initial mixing								
Water absorption (%)	55.9 (0.4) c	60.0 (0.5) a	54.9 (0.1) d	57.6 (0.1) b	59.3 (0.2) a	57.4 (0.1) b	2.27 × 10−10	8.18 × 10−10
Development time (C1 time) (min)	4.43 (0.23) c	5.87 (0.35) a	6.31 (0.12) a	3.96 (0.03) c	5.09 (0.18) b	1.86 (0.01) d	3.04 × 10−11	1.47 × 10−10
Stability (min)	6.41 (0.41) d	8.02 (0.59) b	7.50 (0.19) bc	5.01 (0.05) e	6.92 (0.31) cd	9.43 (0.08) a	4.17 × 10−8	1.07 × 10−7
Amplitude (N·m)	0.067 (0.006) bc	0.077 (0.006) b	0.057 (0.006) c	0.070 (0.000) b	0.070 (0.000) b	0.090 (0.000) a	1.11 × 10−5	1.43 × 10−5
2. Protein weakening during heating								
C2 torque (N·m)	0.542 (0.016) b	0.587 (0.003) ab	0.571 (0.020) ab	0.480 (0.011) c	0.563 (0.027) ab	0.612 (0.033) a	1.11 × 10−4	1.34 × 10−4
C2 dough temperature (°C)	52.8 (0.5) c	58.2 (0.4) a	53.1 (0.4) c	54.5 (0.2) b	55.6 (0.5) b	55.3 (0.8) b	7.91 × 10−8	1.78 × 10−7
Alpha slope (α) (N·m/min)	−0.050 (0.004) b	−0.079 (0.005) d	−0.030 (0.002) a	−0.072 (0.002) cd	−0.079 (0.007) d	−0.061 (0.007) bc	1.63 × 10−7	3.27 × 10−7
C1 − C2 (N·m)	0.638 (0.029) a	0.506 (0.018) b	0.560 (0.020) b	0.651 (0.007) a	0.531 (0.024) b	0.503 (0.032) b	7.30 × 10−6	1.01 × 10−5
3. Starch gelatinization								
C3 torque (N·m)	1.869 (0.045) b	1.898 (0.049) b	2.053 (0.017) a	1.814 (0.032) b	1.915 (0.054) b	1.873 (0.021) b	1.72 × 10−4	1.94 × 10−4
C3 dough temperature (°C)	81.0 (0.5) c	83.6 (0.6) b	81.7 (0.2) c	84.9 (0.4) a	80.9 (0.6) c	83.2 (0.2) b	3.18 × 10−7	5.21 × 10−7
Beta slope (β) (N·m/min)	0.350 (0.027) bc	0.292 (0.024) cd	0.488 (0.012) a	0.270 (0.015) d	0.507 (0.047) a	0.364 (0.013) b	2.75 × 10−7	4.95 × 10−7
C3 − C2 (N·m)	1.327 (0.048) b	1.311 (0.048) b	1.482 (0.035) a	1.334 (0.027) b	1.352 (0.078) ab	1.261 (0.039) b	0.003	0.003
4. Hot-paste stability and breakdown								
C4 torque (N·m)	1.809 (0.041) bc	1.835 (0.053) bc	1.995 (0.017) a	1.741 (0.029) cd	1.860 (0.055) b	1.655 (0.022) d	4.51 × 10−6	6.76 × 10−6
Gamma slope (γ) (N·m/min)	−0.006 (0.006) b	−0.049 (0.004) c	0.019 (0.007) a	0.025 (0.003) a	−0.011 (0.001) b	−0.058 (0.002) c	3.27 × 10−11	1.47 × 10−10
C3 − C4 (N·m)	0.060 (0.005) c	0.063 (0.004) bc	0.058 (0.003) c	0.073 (0.004) b	0.055 (0.001) c	0.218 (0.008) a	4.46 × 10−14	8.03 × 10−13
5. Cooling and starch reassociation								
C5 torque (N·m)	3.778 (0.054) ab	3.297 (0.096) c	3.810 (0.043) a	3.623 (0.022) b	3.953 (0.083) a	2.769 (0.062) d	3.57 × 10−10	1.07 × 10−9
C5 dough temperature (°C)	53.5 (0.1) c	54.0 (0.2) ab	54.3 (0.1) a	53.7 (0.1) bc	53.8 (0.1) bc	53.8 (0.2) abc	0.001	0.001
C5 − C4 (N·m)	1.969 (0.036) b	1.462 (0.048) d	1.815 (0.040) c	1.882 (0.025) bc	2.092 (0.039) a	1.114 (0.042) e	8.09 × 10−12	7.28 × 10−11

UNCORRECTED PROOF

therefore suggest that starch damage was more closely related to development kinetics than to the final Mixolab absorption value in this sample set. Similar multidimensional relationships among particle characteristics, damaged starch, protein composition, pasting behaviour and dough rheology have been reported across wheat flours differing in growing environment (Singh et al., 2023).

3.4. Gluten quantity does not predict protein stability

The C2 torque ranged from 0.480 N·m for Producer 4 to 0.612 N·m for Producer 6 (Fig. 2C). Producer 6 combined moderate wet gluten with the highest C2 torque and mixing stability, whereas Producer 4 combined high wet gluten with low C2 torque and stability. The protein-phase rankings therefore did not follow wet-gluten content, indicating that recoverable gluten quantity alone was insufficient to describe resistance to combined mechanical and thermal stress. Wet gluten was negatively associated with stability in the targeted analysis ($\rho = -0.61$, 95% CI −0.86 to −0.13, $q = 0.0209$; Fig. 3B). Because wet gluten varied over a narrow range and observations clustered by producer, this relationship should be treated as a sample-specific association rather than a causal effect. The lack of a significant wet gluten–C1−C2 relationship in the broader screen (Supplementary Fig. S1A) reinforces this caution. In contrast, IDK was positively associated with the protein-weakening slope α ($\rho = 0.54$, 95% CI 0.04–0.84, $q = 0.032$; Fig. 3C). This links an empirical measure of gluten deformability to the rate of torque loss during heating and mixing. Structural studies show that dough resistance changes with hydration and temperature-dependent reorganisation of the gluten network (Harati et al., 2020; Jia et al., 2022). The current results are consistent with that broader framework, but they do not identify the underlying protein composition responsible for the observed producer differences. Previous work likewise shows that protein composition and structure, rather than protein quantity alone, contribute to dough rheology and can modify starch-pasting behaviour (Shevkani et al., 2024; Katyal et al., 2024).

3.5. Falling number is associated with hot-paste torque retention

The C3 torque was highest for Producer 3 (2.053 N·m), and C4 remained highest for the same producer but was lowest for Producer 6 (Fig. 2D). Hot-paste breakdown (C3−C4) was small for Producers 1–5 but approximately three to four times greater for Producer 6 (Fig. 2E). These differences show that the magnitude of gelatinisation and the ability of the resulting paste to retain torque during continued heating varied independently among the flours. Falling number was positively associated with C4/C3 ($\rho = 0.59$, 95% CI 0.05–0.89, $q = 0.0209$; Fig. 3D), indicating greater proportional torque retention in flours with higher falling number. This direction agrees with the expected effect of lower α-amylase-related liquefaction on paste viscosity and with controlled germination studies linking increasing α-amylase activity to lower falling number and pasting viscosity (Kaur et al., 2024). Nevertheless, the negative association between falling number and C3−C4 did not remain significant in the broader exploratory correlation analysis (Supplementary Fig. S1B), and Producer 3 had the highest C3 and C4 without the highest falling number. Falling number therefore captured an enzyme-related component of paste behaviour but not the full starch-phase response. Mechanical starch damage was also examined in the broader correlation analysis, but its associations with C4 torque and water absorption did not remain significant after FDR correction (Supplementary Fig. S1C,D). Thus, the present data do not support assigning the observed hot-paste differences to starch damage alone (Mangan et al., 2022; Fairlie et al., 2023; Rakita et al., 2023). Falling number should therefore be interpreted as complementary to direct Mixolab starch-phase measurements.

3.6. Paste breakdown and setback drive functional separation

The largest producer differences occurred after the C3 maximum. The final cooling torque (C5) ranged from 2.769 N·m for Producer 6 to 3.953 N·m for Producer 5, and C5−C4 ranged from 1.114 to 2.092 N·m

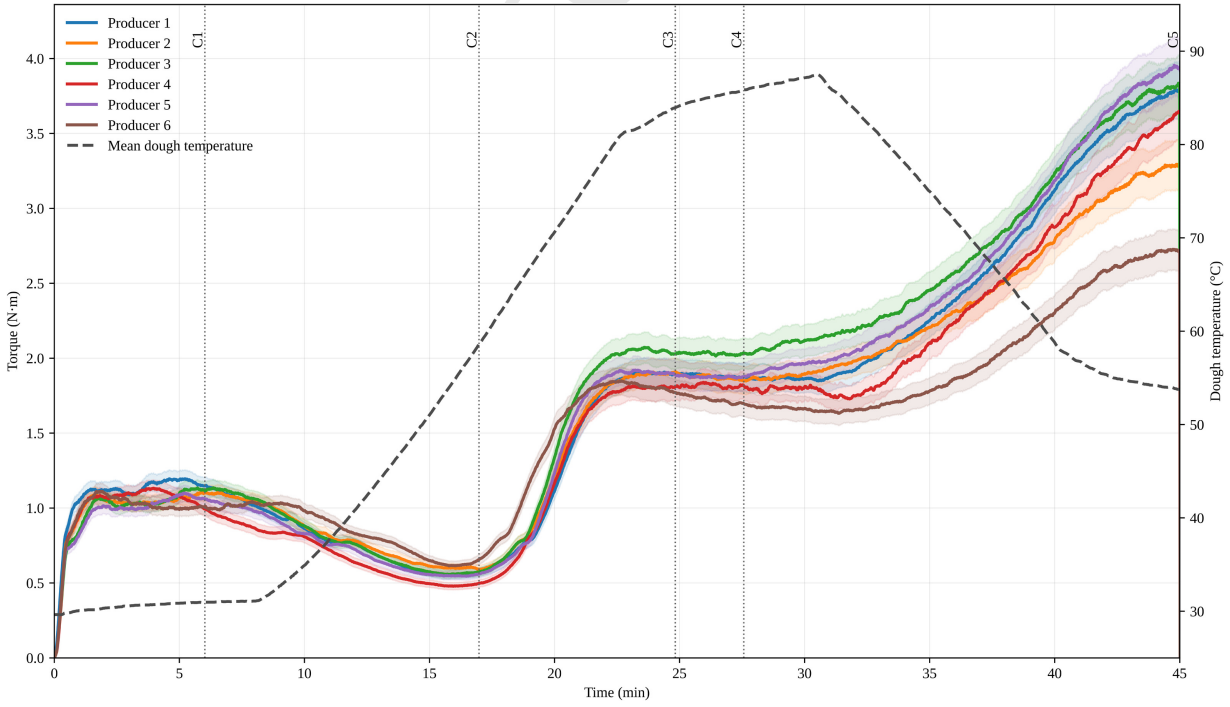


Fig. 1. Complete Mixolab thermo-mechanical profiles of wheat flour samples obtained from six producers. Solid coloured curves show the producer mean torque response during the standard Chopin+ protocol, and the semi-transparent shaded regions indicate ± standard deviation across three independent flour samples. The grey dashed curve shows the mean dough-temperature profile. Vertical dotted lines identify C1, initial dough development and target consistency; C2, the minimum torque during thermo-mechanical protein weakening; C3, the maximum torque associated mainly with starch gelatinisation; C4, the hot-paste stage; and C5, the final torque after cooling and short-term starch reassociation. The shaded regions are descriptive and were not subjected to pointwise inferential testing.

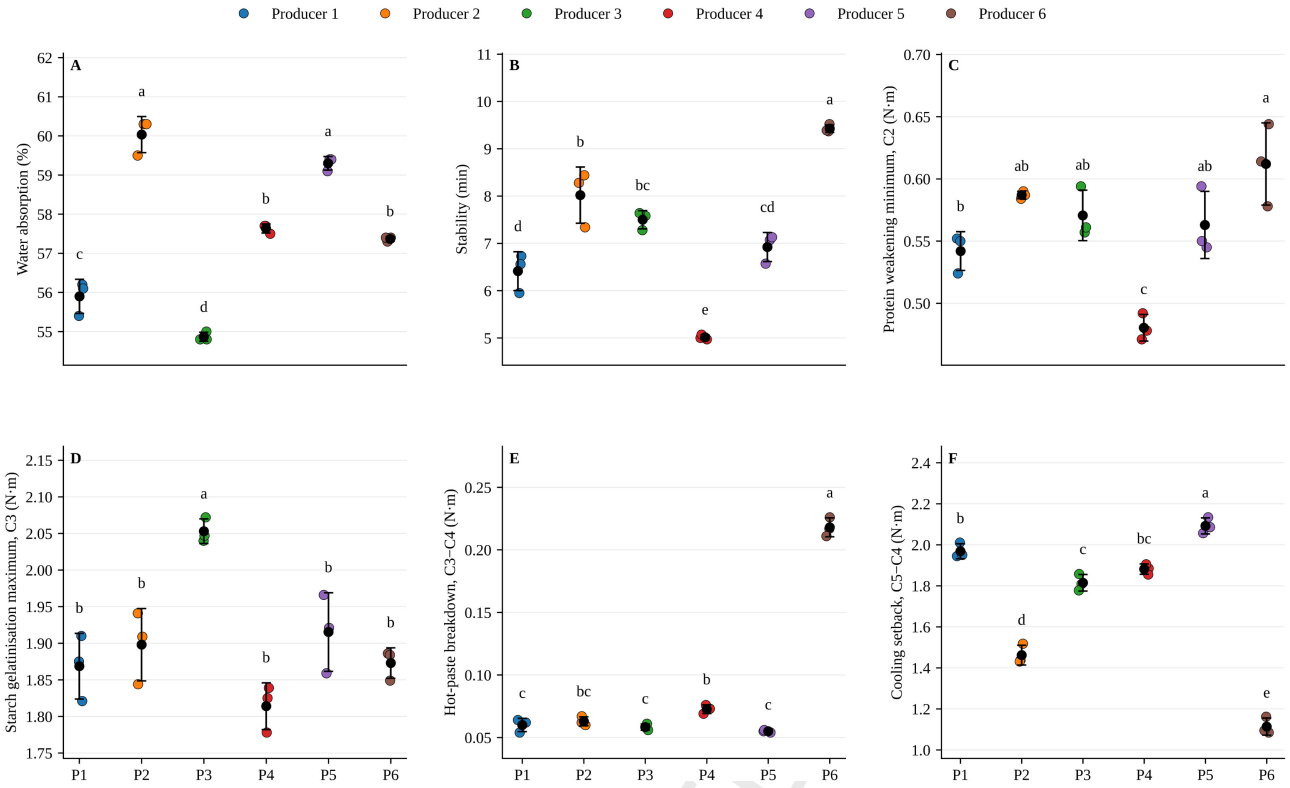


Fig. 2. Phase-specific comparison of selected Mixolab-derived thermo-mechanical dough properties. Panels show: (A) water absorption; (B) dough stability; (C) C2 torque; (D) C3 torque; (E) C3−C4, used as an index of hot-paste breakdown; and (F) C5−C4, used as an index of cooling setback. The three coloured points represent independent flour samples, and the black point with vertical error bars is the producer mean ± SD. Lowercase letters indicate Tukey HSD groupings at $p < 0.05$ for variables that remained significant after 5% FDR correction.

(Fig. 2F). Producer 6 combined the greatest hot-paste breakdown with the lowest cooling setback, whereas Producer 5 showed the highest setback. Resistance to breakdown during heating and torque development during cooling were therefore distinct properties rather than consecutive expressions of one general starch-quality trait. The C3−C4 difference is commonly interpreted as loss of paste consistency during continued heating and shear, whereas the C5−C4 difference reflects short-term reassociation during cooling. Both responses can be influenced by starch molecular architecture and by interactions with proteins, lipids and non-starch polysaccharides (van Rooyen et al., 2023). The present data support functional differentiation among producers but do not permit assignment of the differences to a specific molecular cause. Their practical relevance will depend on the intended product: high paste retention and low setback are not universally advantageous. Accordingly, these variables should be considered process-functionality descriptors rather than direct rankings of baking quality.

3.7. *Integrated profiles reveal functional trade-offs*

The standardised heatmap showed that no producer was consistently high or low across the selected conventional and Mixolab variables (Fig. 4). The flour from Producer 1 combined high wet gluten, flour whiteness and mechanical starch damage with below-average water absorption and mixing stability. The flour from Producer 2 was characterised by high falling number and water absorption but relatively low cooling setback. The profile of Producer 3 combined high gluten deformation index and starch-gelatinisation torque, whereas Producer 4 combined high wet gluten with low stability and protein-phase torque. Producer 5 showed high water absorption and cooling setback. In contrast, Producer 6 combined high gas-production capacity, mixing amplitude and stability with low falling number, mechanical starch damage and cooling setback. The heatmap therefore identified producer-specific combinations of properties rather than a common progression from low- to high-quality flour. In practice, the relative importance of these characteristics depends on the intended application; hydration and mixing descriptors are particularly relevant to dough handling, whereas hot-paste and cooling descriptors characterise starch-phase behaviour during thermal processing.

The resulting PCA model provided a sample-level view of the same multivariate structure (Supplementary Fig. S2). The first two principal components accounted for 56.4% of the total autoscaled variance. The first principal component explained 36.2% and mainly described a contrast between high mixing amplitude, gas-production capacity and hot-paste breakdown on its positive side and high hot-paste torque retention, final cooling torque, mechanical starch damage and cooling setback on its negative side. Accordingly, samples from Producer 6 were positioned at the positive extreme of this component, consistent with their high amplitude and breakdown but low setback, whereas samples from Producer 3 clustered toward the negative side and were associated with greater torque retention and starch-phase torque.

The second principal component explained a further 20.1% of the variance and separated variables related to starch gelatinisation and thermo-mechanical resistance from those related mainly to wet-gluten quantity and protein-phase torque loss. Positive loadings were observed for C3 torque, mixing stability, C2 torque, gluten deformation index and the gelatinisation slope, while wet gluten and C1−C2 torque loss loaded in the opposite direction. Samples from Producer 3 were therefore clearly positioned on the positive side of this component, whereas those from Producer 4, and to a lesser extent Producer 1, occupied the negative side. Producers 2 and 5 were closer to the centre of the scores plot, indicating less extreme combinations of the variables represented by the first two components. Joint interpretation of scores and loadings thus supported the univariate results: wet-gluten quantity, resistance during mixing and heating, and starch-pasting behaviour varied partly

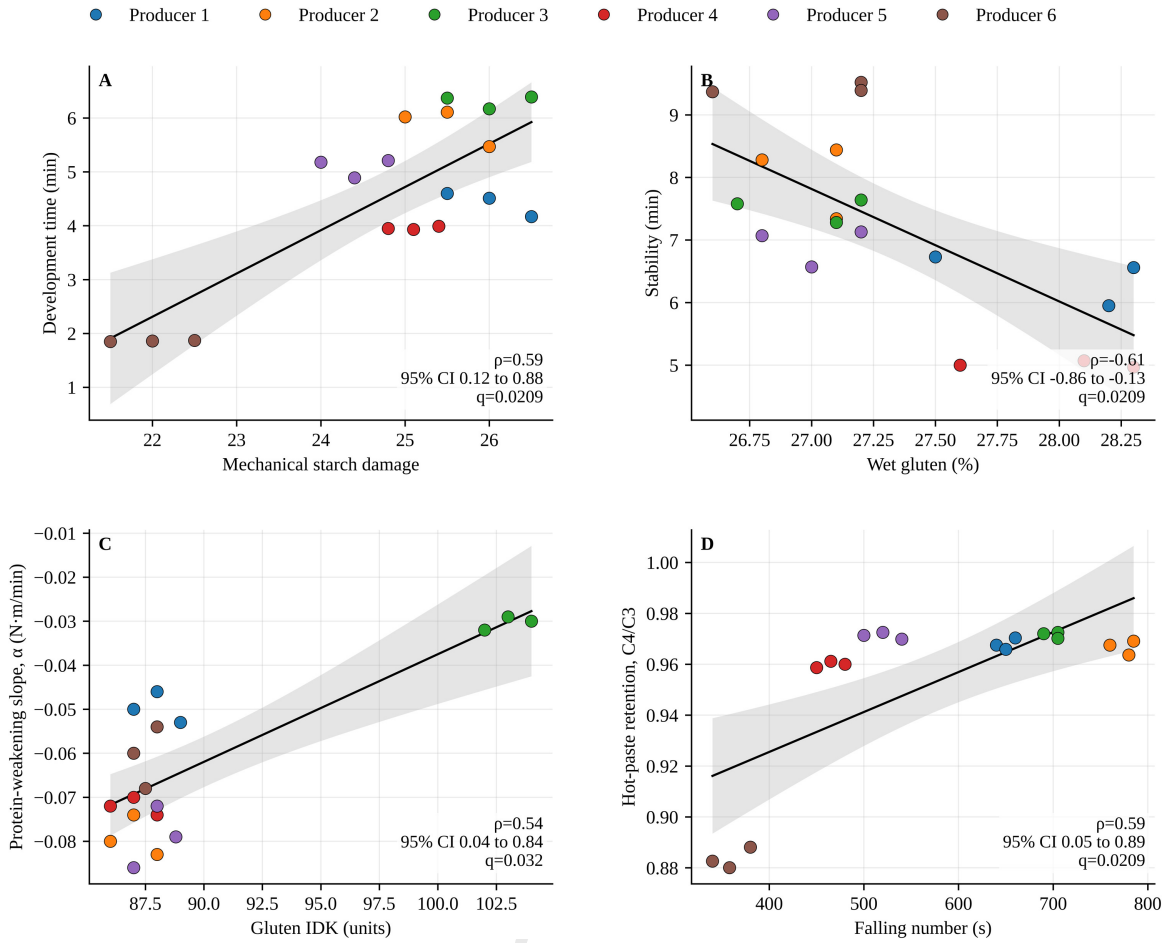


Fig. 3. Correlation analysis between conventional wheat flour characteristics and selected Mixolab-derived properties. Panels show: (A) mechanical starch damage versus development time; (B) wet gluten versus stability; (C) gluten deformation index versus the protein-weakening slope α; and (D) falling number versus C4/C3. Each point represents one independent flour sample. Black lines show simple linear trends, and shaded regions show 95% confidence bands. Spearman correlation coefficients, bootstrap 95% confidence intervals and Benjamini–Hochberg-adjusted q-values across nine domain-guided exploratory relationships are shown.

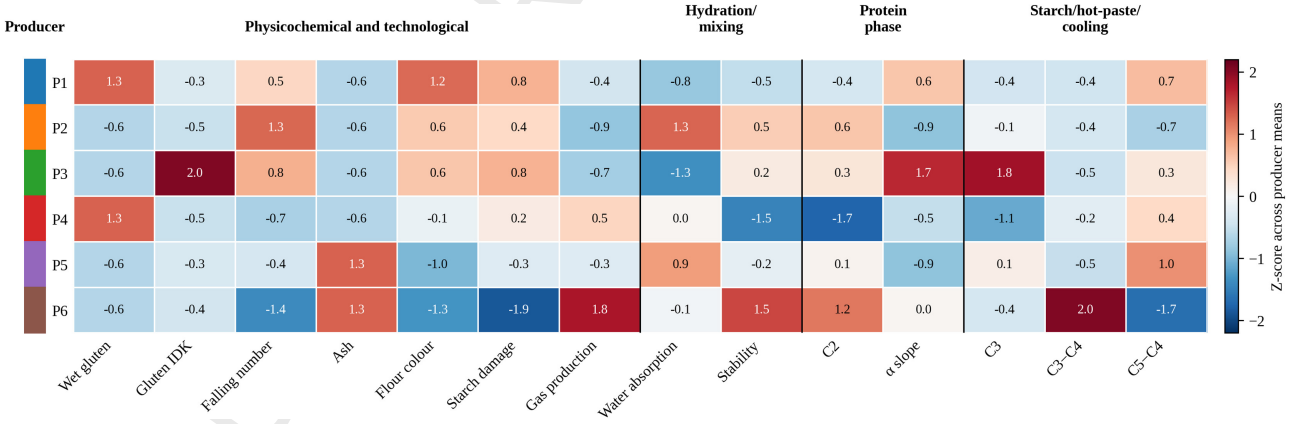


Fig. 4. Standardised producer profiles across conventional flour-quality and Mixolab variables. Producer means were calculated from three independent flour samples and z-standardised across the six producers for each variable. Positive z-scores indicate values above the six-producer mean and negative z-scores indicate values below it. The heatmap is descriptive and was not used for clustering, classification or universal quality ranking.

independently and generated distinct producer profiles. Similar benefits of integrating physicochemical, pasting and rheological measurements have been reported for differentiating wheat materials and their processing suitability (Selga et al., 2024; Rezette et al., 2025a; Singh et al., 2025). Nevertheless, the analysis comprised 36 variables for 18 samples, and several Mixolab descriptors were mathematically related. The principal component model, including the producer ellipses, should therefore be regarded as a descriptive representation of covariation rather than as a validated classification model.

3.8. Study limitations

The study was designed to characterise production-related differences in flour functionality rather than identify the specific wheat-lot, milling or blending factors responsible for these differences, as detailed information on commercial production practices was unavailable. In addition, the findings were not validated against end-product performance. Future studies incorporating larger multi-batch datasets, complementary Farinograph or Rapid Visco Analyzer measurements where relevant, and standardised product tests are needed to determine the applicability of the identified functional profiles across different processing applications.

4. Conclusions

Production-related differences among the commercial wheat flours were expressed across distinct processing phases rather than through a single conventional quality indicator. Although wet-gluten content differed only slightly among producers, substantial differences were observed in mixing stability, thermo-mechanical protein weakening, starch gelatinization, hot-paste breakdown and cooling setback. Conventional flour-quality measurements therefore captured only part of the functional variation revealed by phase-resolved Mixolab analysis. The observed associations between mechanical starch damage and dough development time, gluten deformation index (IDK) and the protein-weakening slope, and falling number and hot-paste torque retention provide functional links between routine flour-quality measurements and specific stages of dough development. Together with the integrated heatmap and principal component analysis, these results show that production-related differences reflect distinct functional profiles and trade-offs rather than a universal quality ranking. Integrating conventional flour-quality measurements with phase-resolved Mixolab analysis therefore provides a more comprehensive basis for characterising commercial wheat flours according to processing requirements: hydration and mixing descriptors inform dough-handling behaviour, whereas hot-paste and cooling descriptors characterise starch-phase responses during thermal processing. Future validation against end-product performance will determine the applicability of these functional profiles for product-specific quality assessment.

Declaration of AI use

AI was used for correction of grammar and typographical errors. The authors reviewed and edited the resulting text and take full responsibility for the content of the publication.

Funding

This work was supported by the ERASMUS + International Credit Mobility programme of the European Union and the European World Talent Camp for Uzbekistan Scientists in Food Science & Technology within the ECAMPUZ project (ERASMUS-EDU-2022-CBHE), co-funded by the European Union.

CRediT authorship contribution statement

Narges Samanian: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Feruza B. Abdullayeva:** Writing – review & editing, Methodology, Investigation. **Gulnoza Djakhangirova:** Writing – review & editing, Methodology, Investigation. **Rakhmonov Kakhramon:** Writing – review & editing, Methodology, Investigation. **Khodjiev Shukhrat:** Writing – review & editing, Methodology, Investigation. **Mansur Akbarov:** Writing – review & editing, Methodology, Investigation. **Bakhtiyar Rzayev:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Data curation. **Bekzod Khakimov:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis. **Suvankul S. Ravshanov:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the participating milling enterprises and laboratory personnel who supported flour sampling and analytical measurements.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2026.102778.

Data availability

The sample-level data supporting the findings of this study are available from the corresponding author upon reasonable request. Producer identities are not publicly disclosed because they constitute commercially sensitive information.

References

Azie, C. O., Solomou, K., Alyassin, M., & Campbell, G. M. (2026). Investigating effects of bran particle size on dough rheology using a modelling approach based on the Chopin Mixolab. *Journal of Cereal Science*, *127*, Article 104345. https://doi.org/10.1016/j.jcs.2025.104345.

Chen, J., Zhang, P., Li, L., Yang, T., Cao, W., Liu, W., Duan, X., & Ren, G. (2025). Comparative analysis of roller milling strategies on wheat flour physicochemical properties and their implications for microwave freeze-dried instant noodles. *Foods*, *14*, 2885. https://doi.org/10.3390/foods14162885.

Dexter, J. E., Preston, K. R., Martin, D. G., & Gander, E. J. (1994). The effects of protein content and starch damage on the physical dough properties and bread-making quality of Canadian durum wheat. *Journal of Cereal Science*, *20*, 139–151. https://doi.org/10.1006/jcrs.1994.1054.

Dvořáček, V., Bradová, J., Sedláček, T., & Šárka, E. (2019). Relationships among Mixolab rheological properties of isolated starch and white flour and quality of baking products using different wheat cultivars. *Journal of Cereal Science*, *89*, Article 102801. https://doi.org/10.1016/j.jcs.2019.102801.

Fairlie, W., Edwards, J., Mather, D., & Kuchel, H. (2023). End-use quality of wheat affected by late maturity α-amylase. *Journal of Cereal Science*, *109*, Article 103610. https://doi.org/10.1016/j.jcs.2022.103610.

Gibson, T. S., Al Qalla, H., & McCleary, B. V. (1992). An improved enzymic method for the measurement of starch damage in wheat flour. *Journal of Cereal Science*, *15*, 15–27. https://doi.org/10.1016/S0733-5210(09)80053-2.

Han, H., Lee, E., & Kweon, M. (2025). Predominant factors in milling and wheat variety influencing particle size and quality of whole wheat flour. *Journal of Food Science*, *90*, Article e70191. https://doi.org/10.1111/1750-3841.70191.

Harati, H., Bekes, F., Howell, K., Noonan, S., Florides, C., Beasley, J., Diepeveen, D., & Appels, R. (2020). Signatures for torque variation in wheat dough structure are affected by enzymatic treatments and heating. *Food Chemistry*, *316*, Article 126357. https://doi.org/10.1016/j.foodchem.2020.126357.

Hatcher, D. W., Anderson, M. J., Desjardins, R. G., Edwards, N. M., & Dexter, J. E. (2002). Effects of flour particle size and starch damage on processing and quality of white salted noodles. *Cereal Chemistry*, *79*, 64–71. https://doi.org/10.1094/CCHEM.2002.79.1.64.

Hu, X., Cheng, L., Hong, Y., Li, Z., Li, C., & Gu, Z. (2023). How starch and gluten impact dough machinability and resultant bread qualities: An extensive review. *Critical Reviews in Food Science and Nutrition*, *63*, 1930–1941. https://doi.org/10.1080/10408398.2021.1969535.

Islam, M. A., Kulathunga, J., Ray, A., Ohm, J.-B., & Islam, S. (2024). Particle size reduction influences starch and protein functionality, and nutritional quality of stone milled whole wheat flour from hard red spring wheat. *Food Bioscience*, *61*, Article 104612. https://doi.org/10.1016/j.fbio.2024.104612.

Jia, R., Zhang, M., Yang, T., Ma, M., Sun, Q., & Li, M. (2022). Evolution of the morphological, structural, and molecular properties of gluten protein in dough with different hydration levels during mixing. *Food Chemistry X*, *15*, Article 100448. https://doi.org/10.1016/j.fochx.2022.100448.

UNCORRECTED PROOF

Katyal, M., Singh, N., & Kathuria, D. (2025). Protein characterization and amino acid profiles of various wheat varieties and their effect on pasting properties of starch. *Starch/Stärke*, *77*, Article 2300105. https://doi.org/10.1002/star.202300105.

Kaur, N., Gasparre, N., & Rosell, C. M. (2024). Expanding the application of germinated wheat by examining the impact of varying alpha-amylase levels from grain to bread. *Journal of Cereal Science*, *120*, Article 104059. https://doi.org/10.1016/j.jcs.2024.104059.

Kim, H. R., Kim, M.-R., Ryu, A. R., Bae, J.-E., Choi, Y.-S., Lee, G. B., Choi, H.-D., & Hong, J. S. (2023). Comparison of rheological properties between Mixolab-driven dough and bread-making dough under various salt levels. *Food Science and Biotechnology*, *32*, 193–202. https://doi.org/10.1007/s10068-022-01186-w.

Li, E., Dhital, S., & Hasjim, J. (2014). Effects of grain milling on starch structures and flour/starch properties. *Starch/Stärke*, *66*, 15–27. https://doi.org/10.1002/star.201200224.

Mangan, D., Draga, A., Ivory, R., Cornaggia, C., Blundell, M., Howitt, C., McCleary, B., & Ral, J. P. (2022). A novel enzymatic method discriminating wheat pre-harvest sprouting from late maturity α-amylase. *Journal of Cereal Science*, *105*, Article 103480. https://doi.org/10.1016/j.jcs.2022.103480.

Moldestad, A., Mosleth, E., Hoel, B., Skjelvåg, A., & Uhlen, A. (2011). Effect of temperature variation during grain filling on wheat gluten resistance. *Journal of Cereal Science*, *53*, 347–354. https://doi.org/10.1016/j.jcs.2011.02.005.

Moot, D. J., & Every, D. (1990). A comparison of bread baking, falling number, α-amylase assay and visual method for the assessment of pre-harvest sprouting in wheat. *Journal of Cereal Science*, *11*, 225–234. https://doi.org/10.1016/S0733-5210(09)80166-5.

Navarro, J., Moiraghi, M., Quiroga, F., León, A., & Steffolani, M. (2020). Effect of wholewheat flour particle shape obtained by different milling processes on physicochemical characteristics and quality of bread. *Food Technology and Biotechnology*, *58*, 325–336. https://doi.org/10.17113/ftb.58.03.20.6766.

Ortolan, F., & Steel, C. J. (2017). Protein characteristics that affect the quality of vital wheat gluten to be used in baking: A review. *Critical Reviews in Food Science and Nutrition*, *16*, 369–381. https://doi.org/10.1111/1541-4337.12259.

Pagani, M. A., Giordano, D., Cardone, G., Pasqualone, A., Casiraghi, M., Erba, D., Blandino, M., & Marti, A. (2020). Nutritional features and bread-making performance of wholewheat: Does the milling system matter? *Foods*, *9*, 1035. https://doi.org/10.3390/foods9081035.

Rakita, S., Torbica, A., Pezo, L., & Nikolić, I. (2023). Effect of climatic conditions on wheat starch granule size distribution, gelatinization and flour pasting properties. *Agronomy*, *13*, 1551. https://doi.org/10.3390/agronomy13061551.

Rezette, L., Kansou, K., Della Valle, G., Le Gall, S., & Saulnier, L. (2025). The role of wheat flour minor components in predicting water absorption. *Food Chemistry*, *463*, Article 141232. https://doi.org/10.1016/j.foodchem.2024.141232.

Rezette, L., Saulnier, L., Morel, M.-H., Méléard, B., Le Gall, S., & Kansou, K. (2025). Impact of wheat flour composition on dough properties: Focus on the minor components. *Journal of Cereal Science*, *124*, Article 104233. https://doi.org/10.1016/j.jcs.2025.104233.

Schuster, C., Huen, J., & Scherf, K. A. (2023). Comprehensive study on gluten composition and baking quality of winter wheat. *Cereal Chemistry*, *100*, 142–155. https://doi.org/10.1002/cche.10606.

Selga, L., Johansson, E., & Andersson, R. (2024). Prediction models to evaluate baking quality instruments for commercial wheat flour. *Cereal Chemistry*, *101*, 681–691. https://doi.org/10.1002/cche.10772.

Shevkani, K., Katyal, M., & Singh, N. (2024). A comparative review of protein and starch characteristics and end-use quality of soft and hard wheat. *Food Chemistry Advances*, *4*, Article 100613. https://doi.org/10.1016/j.focha.2024.100613.

Singh, N., Dubey, A., Katyal, M., Singh, A. M., Ahlawat, A. K., & Kathuria, D. (2025). Diversity in physicochemical, pasting, and rheological properties of various old and new wheat lines for the preparation of chapati and deep fried puffs. *International Journal of Food Science and Technology*, *60*. https://doi.org/10.1093/ijfood/vvae041.vvae041.

Singh, N., Gujral, H. S., Katyal, M., & Sharma, B. (2019). Relationship of Mixolab characteristics with protein, pasting, dynamic and empirical rheological characteristics of flours from Indian wheat varieties with diverse grain hardness. *Journal of Food Science and Technology*, *56*, 2679–2686. https://doi.org/10.1007/s13197-019-03756-z.

Singh, N., Katyal, M., Virdi, A. S., Saini, J. S., Singh, A. M., & Ahlawat, A. K. (2023). Insights into the particle size, protein form, pasting and dough rheological properties of flour obtained from wheat grown at high and low altitude. *International Journal of Food Science and Technology*, *58*, 3850–3864. https://doi.org/10.1111/ijfs.16487.

Tian, X., Wang, X., Wang, Z., Sun, B., Wang, F., Ma, S., Gu, Y., & Qian, X. (2022). Particle size distribution control during wheat milling: Nutritional quality and functional basis of flour products—A comprehensive review. *International Journal of Food Science and Technology*, *57*, 7556–7572. https://doi.org/10.1111/ijfs.16120.

van Rooyen, J., Simsek, S., Oyeyinka, S. A., & Manley, M. (2023). Wheat starch structure–function relationship in breadmaking: A review. *Comprehensive Reviews in Food Science and Food Safety*, *22*, 2292–2309. https://doi.org/10.1111/1541-4337.13147.

Yazar, G. (2023). Wheat flour quality assessment by fundamental non-linear rheological methods: A critical review. *Foods*, *12*, 3353. https://doi.org/10.3390/foods12183353.

UNCORRECTED PROOF