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Understanding the influence of *in situ* produced dextran on wheat dough baking performance: Maturograph, biaxial extension, and dynamic mechanical thermal analysis

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ABSTRACT

Rheological tests performed under conditions relevant to those experienced during proof and oven rise are necessary for understanding the mechanisms of dextran addition on wheat dough baking performance. This study evaluated the effect of a high molecular weight (*Mw*) dextran, produced *in situ* by *Weissella confusa* A16 or externally added, on wheat dough rheological properties including, (i) proofing behavior using a maturograph; (ii) bi-axial extensional profile using a dough inflation system; and (iii) viscoelastic characters (proof) and thermo-mechanical properties (simulated baking) by dynamic mechanical thermal analysis (DMA). The externally-added dextran increased dough elasticity, tenacity, and viscoelastic characters, but reduced dough extensibility at bubble rupture. DMA tests of doughs under dynamic heating conditions showed a sharp increase of elastic and loss moduli until maximum between 75 and 95 °C, accompanied by a drastic decrease of Tan δ (dough stiffening). Dextran addition exhibited a weakening effect on the dough thermal properties i.e., decreased peak moduli during heating. On the other hand, the mild acidic conditions during sourdough fermentation favored the activity of *in situ* produced dextran, conferring significantly improved thermal-mechanical properties and dough extensibility. This may explain the superior ability of *in situ* produced dextran to improve bread volume and crumb softness compared to the external-added dextran. By analyzing rheological parameters, we showed that the maximum proofing moduli in DMA, fermentation stability, dough level, and elasticity in maturogram were predictors of good baking quality. Overall, our study provides the mechanistic underpinning and optimum of dextran as a natural improver of bread quality.

1. Introduction

Wheat bread making is a multistage dynamic process (Cauvain, 2015). During mixing, a three-dimensional gluten matrix is formed, which creates the viscoelastic properties of dough. These properties determine the ability of the dough to retain gas bubbles and expand when CO_2 is generated during yeast alcoholic fermentation. During baking, starch gelatinization and protein denaturation/coagulation take place at temperatures above 60 °C, which transform the dough into crumb (Wang & Sun, 1999). The rheological properties of dough during baking are important in maintaining the gas cell stability during thermal expansion. When the dough temperature increases, the gas cell walls (starch-protein matrix) undergo extensional thinning due to the increased pressure generated by expanding gases. Starch gelatinization and gluten denaturation cause a stiffening of the membranes enclosing the gas cells and eventually gas cell opening. The timing of cell rupture during baking is crucial for optimal volume rise and final texture of the bread (Grenier, Rondeau-Mouro, Dedey, Morel, & Lucas, 2021).

Dextrans are hydrocolloids employed to improve dough rheological and bread textural properties. Dextrans are extracellular polysaccharides consisting of predominately α-(1 → 6) D-glucopyranosyl units and varying degrees of α-(1 → 2), α-(1 → 3) or α-(1 → 4) branches (Monsan et al., 2001). They are synthesized by dextransucrase (EC

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Abbreviations

BU	Brabender units
CFU	colony forming unit
CSD	control sourdough
CSDB	control sourdough bread
CWB	control wheat bread
DSD	dextran-enriched sourdough
DSDB	Dextran-enriched sourdough bread
DMA	dynamic thermomechanical analysis
FESEM	field emission scanning electron microscopy
G′	storage modulus
G"	loss modulus
GEM	general edible medium
LAB	lactic acid bacteria
MU	maturogram units
TPA	texture profile analysis
TTA	total titratable acidity
HPAEC-PAD	high performance anion exchange chromatography with pulsed amperometric detection

2.4.1.5), which is released from lactic acid bacteria (LAB), using sucrose as the substrate (Leemhuis et al., 2013). In breadmaking, the positive effects of dextrans on dough rheological properties and bread volume and texture parameters are considered as a function of their structure and concentration (Wang, Maina, Coda, & Katina, 2021). In general, dextrans with high *M*w and linear chain structure display superior moisture retention, loaf volume increment, anti-staling effect, and amylopectin recrystallization inhibitory effect (Lacaze, Wick, & Cappelle, 2007; Rühmkorf et al., 2012; Zhang, Guo, et al., 2018). Furthermore, dextrans can be utilized in sourdough baking via *in-situ* production during LAB fermentation (Wang, Maina, et al., 2021), which represents a clean label alternative to commercial hydrocolloids (e.g., HPMC and xanthan gum). Dextrans can be produced in wheat sourdoughs at significant levels, such as 5.8–18 g/kg (Galle et al., 2012; Katina et al., 2009; Tang et al., 2018), and the inclusion of 10–40% (dough weight) of the dextran-enriched sourdough has shown to be effective in improving dough and bread quality. Nevertheless, the functions of *in-situ* produced dextrans can be affected by acidification during sourdough production, which consequently determines the acidity of the bread dough. Mild acidity favors the functionality of dextrans in modulating dough rheology and baking quality (Zhang et al., 2020; Zhang, Guo, Li, Jin, & Xu, 2019), whereas intensive acidification counteracts the positive effects of dextrans (Kaditzky, Seitter, Hertel, & Vogel, 2008).

Existing rheological studies on doughs enriched with dextran have been largely performed in small deformation dynamic shear oscillation (Galle et al., 2012; Wang et al., 2018; Zhang et al., 2019, 2018a, b). The dynamic oscillation tests allow the simultaneous measurement of elastic (G′) and viscous (G″) moduli, but the deformation conditions applied (small strains $\leq$1% within the linear region, high strain rates e.g., 0.1/s, shear deformation, and ambient temperature) do not appropriately mimic the conditions encountered during breadmaking. These conditions involve large strains, low strain rates 10^{-2}–10^{-4}/s, biaxial extension, and elevated temperatures that eventually reduce dough extensibility due to protein denaturation (Dobraszczyk & Morgenstern, 2003). Therefore, conflicting results have been reported and no convincing relationships have been established between dynamic rheological parameters and bread quality characteristics (Galle et al., 2012; Wang et al., 2018; Zhang et al., 2019). A combination of empirical methods (e.g., maturograph fermentation) and fundamental methods (e.g., bubble inflation) that simulate the baking process may offer the most appropriate approaches for measuring rheological properties of doughs. Maturograph records gas production and loss by measuring the changes in height of a yeasted dough during proofing. Dobrasczcyk/Roberts dough inflation system (DIS) measures the biaxial extensional rheological properties of doughs at large strains up to failure, which mimics the gas cell growth during proofing and early stage of baking (Dobraszczyk, Smewing, Albertini, Maesmans, & Schofield, 2003). DIS may also provide indicative information on molecular mechanisms i.e., physical structural interactions between high *Mw* polymers, like gluten proteins and dextran, by measuring strain hardening properties (Dobraszczyk & Morgenstern, 2003). Furthermore, dynamic mechanical thermal analysis (DMA) can be a useful tool for studying the time- and temperature-dependent changes in rheological and mechanical properties of doughs during heating/simulated baking (Bollaín, Angioloni, & Collar, 2006; Rouillé, Chiron, Colonna, Valle, & Lourdin, 2010). DMA has been widely utilized in evaluating the viscoelastic behavior of polymers, which facilitates the simultaneous determination of mechanical and thermal properties of polymeric materials over a broad range of temperatures (−150−600 °C) and frequencies (0.01–200 Hz) (Kevin, 2008, p. 240). The DMA tests solve the limitations of a shear rheometer by operating in an oscillatory compressive mode (Bollaín et al., 2006).

The aim of this study was to determine the effects of a high *Mw* dextran, produced *in situ* by sourdough fermentation or added as an ingredient, on the rheological and thermo-mechanical behavior of wheat dough under simulated baking conditions using a maturograph, dough inflation system, and DMA. The measured rheological properties were correlated to the final bread quality. A commercial low *Mw* dextran and a dextran-free sourdough with high levels of acidity were used as the control to evaluate the potential influence of *Mw* and sourdough acidification on dextran functionality.

2. Materials and methods

2.1. Materials

Commercial wheat flour (RAISIO, Finland; protein 12%, fat 2.1%, fiber 4.0%, moisture 13.1%), fresh baker's yeast (Suomen Hiiva Oy, Finland), sucrose (Dan Sukker, Finland), salt (Meira Oy, Finland), and rapeseed oil (Sunnuntai, Bunge Oy, RAISIO, Finland) were used in bread making. The moisture content of the wheat flour was determined using AACCI method 44-15A (AACC International, 2000). Dextran T250 (*Mw*: 250000 g/mol, purity 95–100%) was purchased from Pharmacosmos A/S (Holbaek, Denmark). *W. confusa* A16 dextran (*Mw*: 3300000 g/mol, purity 82.09%, moisture 9.76%, ash 6.09%, protein 1.91%) was isolated and purified according to Wang et al. (2020).

2.2. Sourdough preparation and metabolite determination

The strains used in this study were *W. confusa* A16 (isolated in Burkina Faso and was available at the Department of Food and Nutrition, University of Helsinki, Finland) and florapan (LA4K, Lallemand, Montreal, Canada), a commercial starter culture including lactic acid bacteria *Lactobacillus brevis* and *Lactobacillus plantarum* and yeast *S. cerevisiae*. *W. confusa* A16 was routinely cultivated in MRS broth (Neogen, UK) at 30 °C for 24 h. For sourdough preparation, the strain was subcultured in general edible medium (GEM, 20 g dextrose, 20 g sucrose, 30 g soy peptone, 7 g yeast extract, 1 g $MgSO_4 \bullet 7H_2O$ in 1 L 0.01 mol/L potassium phosphate buffer, pH 6.3) for 24 h at 30 °C and inoculated to doughs at a starting cell density of 10^6 CFU/g. The florapan starter was added at a ratio of 1:1000 to wheat flour. Three types of sourdough were prepared: (1) dextran-enriched sourdough fermented by *W. confusa* A16 (A16 DSD, mild acidity), (2) control sourdough fermented by *W. confusa* A16 (A16 CSD, mild acidity), and (3) control sourdough fermented by florapan (florapan CSD, high acidity) (see Supplementary Material Table S1 for formulations). In A16 DSD, 10% (w/w) wheat flour was replaced by sucrose to support *in situ* dextran

production, whereas in CSD no sucrose was added. Wheat flour, distilled water, and cell culture were mixed to a dough yield of 250 as described in Wang et al. (2018). The fermentations were carried out at 30 °C for 48 h for florapan CSD, and at 25 °C for 24 h for A16 CSD and DSD.

Cell counts of presumptive LAB were examined by serial dilutions of 10 g samples in sterile 0.9% (w/v) NaCl solution and then plated on MRS agar (Lab M Limited, UK) supplemented with 0.001% cycloheximide (Oxoid Ltd., UK) at 30 °C for 48 h. Yeasts were counted on YM agar with 0.01% chloramphenicol (Oxoid, Basingstoke, UK) at 30 °C for 48 h. The pH at 0 and 24 h was measured using a MP225 pH meter (Mettler Toledo, Leicester, UK). TTA (total titratable acidity) of the sourdoughs was determined using an EasyPlus Automated Titrator (Mettler Toledo) and expressed as the amount (mL) of 0.1 mol/L sodium hydroxide solution needed to adjust the pH of 10 g samples in 100 ml Milli-Q water to 8.5. Dextran and free mono-, di- and oligosaccharides were determined on 100 mg of freeze-dried sourdough samples using a high performance anion exchange chromatography with pulse amperometric detection (HPAEC-PAD) as described by Katina et al. (2009) and Xu et al. (2017). Organic acids were extracted from 1 g of freeze-dried samples and determined using a high performance liquid chromatography (HPLC) as previously described by Wang et al. (2020).

2.3. Dough rheological measurements

Six types of bread dough were prepared: (1) control wheat bread (CWB) dough, (2) florapan control sourdough bread (florapan CSDB) dough, (3) *W. confusa* A16 control sourdough bread (A16 CSDB) dough, (4) *W. confusa* A16 dextran-enriched sourdough bread (A16 DSDB) dough, (5) wheat bread dough containing purified *W. confusa* A16 dextran at three different concentrations i.e. 0.2, 0.4, and 0.87% flour weight, and (6) wheat bread dough with T250 dextran at 0.2, 0.4, and 0.87% fw. For types 2, 3, and 4 formulations, sourdoughs were employed at 43.2% dough weight. The utilization level of sourdough was determined to ensure a sufficient amount of dextran in the final bread (i.e., 0.87% fw in A16 DSDB) and meanwhile a low level of acidity (Katina et al., 2009). For types 5 and 6 formulations, dextrans were added as aqueous solutions prepared by the following steps: (1) appropriate amount of dextran powder was weighed into a screw cap bottle; (2) preheated Milli-Q water (60 °C) was added and the suspension was heated at 60 °C with magnetic stirring at a speed of 200 rpm for 16 h; (3) the solution was allowed to cool down, with continuous stirring, at 25 °C to enable adequate hydration of the polymers. The dextran aqueous solutions were stored at 4 °C and used within one week.

2.3.1. Farinograph water absorption

Water absorption (i.e., percentage of water required to yield a standard dough consistency of 500 BU (Brabender Units)) was determined using a Farinograph (Brabender GmbH & Co.KG, Germany) equipped with a 300 g mixing bowl at 30 °C, according to the AACC method 54-21 (AACC International, 2000). The optimum water absorption (60.1%) of wheat flour was used in the follow-up rheological measurements for all formulations to keep a same flour to water ratio (Supplementary Material Table S1).

2.3.2. Dynamic mechanical analysis of dough: temperature sweep

Dough viscoelastic properties were measured using a Dynamic Mechanical Analyzer (DMA) (TA instruments, New Castle, USA) connected to a Gas Cooling Accessory (GCA) and equipped with 15 mm steel parallel plates. The bread dough samples for DMA temperature runs were prepared using the Brabender Farinograph with a 50 g mixing bowl according to Table S1 without the addition of yeast. Dough samples were mixed to optimal dough development for 7 min and rested for 15 min at 4 °C prior to DMA measurement to allow relaxation. Following the method by Rouillé et al. (2010) with slight modifications, a cylindrical sample of dough (≈0.3 g) with fixed geometry (thickness 5 mm, diameter 7 mm) was applied with the compression clamp. Dough samples were carefully coated with paraffin oil to avoid moisture loss. Samples were oscillated at a frequency of 1 and 5 Hz in the compression mode. Before the measurement, oscillation amplitude test was performed to determine the linear viscoelastic region and thus the strain amplitude was set in the linear range for all samples at 0.1%. To maintain contact between sample and plates during the temperature sweep, a constant static force, which was supposed to be negligible compared to modulus values, was fixed at 0.01 N. Temperature was increased from 25 °C to 140 °C with a heating rate of 5 °C/min (corresponded to the estimated heating rate of the dough in the oven). Parameters related to physical transitions in the dough were collected using the TA Instruments' Universal Analysis 2000 Program: T_{onset}, onset temperature of starch gelatinization, from evolution of G' during heating (calculated as the intersection of the tangents of the baseline before the sudden increase in G' and the tangent of the steep G' profile after T_{onset}); $Tan(\delta)_{onset}$, tan δ value at onset G'; G'_{peak}, storage modulus at peak; T_{peak}, the temperature corresponding to G'_{peak}; G''_{peak}, loss modulus at peak; G^*_{peak}, complex modulus at peak. The measurements were carried out with at least three replicates on independent dough compositions.

2.3.3. Dynamic mechanical analysis of dough: proofing sweep

The bread dough samples for DMA proofing runs were prepared using the Brabender Farinograph with a 300 g mixing bowl according to Table S1 with yeast. Dough samples were mixed to optimal dough development for 7 min and kept at room temperature (20 °C) for 15 min for rest. Dough pieces (100 g) were subsequently rounded in the ball homogenizer for 15 s. DMA humidity accessory was used with parallel compression plates of 15 mm diameter at a frequency of 1 Hz and strain amplitude of 0.1%. Approximately 0.4 g of cylindrical dough (thickness 5 mm, diameter 9 mm) was placed between plates and paraffin oil was applied to prevent sample drying. Measurements ($n = 3$) were performed at a relative humidity of 75% and isothermal running temperature of 35 °C for 45 min. At the peak point, the following parameters were obtained: maximum storage modulus G'_{max}, the corresponded time T_{max}, maximum loss modulus G''_{max}, maximum complex modulus G^*_{max}, and $Tan(\delta)_{max}$.

2.3.4. Maturogram evaluation

The proving properties of the bread doughs were determined using a Brabender Maturograph (Duisburg, Germany). Dough samples were prepared as described above in the DMA proofing sweep. The rounded dough (100 g) was placed in the plastic measuring container and pressed by a pressing device before starting proving in the temperature- and humidity-controlled cabinet (35 °C & 75%, respectively) of maturograph. The sensing probe contacted the dough with a weight of 5 g every 2 min. The increasing volume of the fermenting dough lifted the sensing probe and the movement was transmitted and recorded on the Maturogram. The curve raised until maximum dough maturity was reached and dropped thereafter. Four parameters were derived from the analysis of the Maturogram curves: (1) a final proving time, calculated as time in minutes from the start of the final proof to the first drop of the curve after the maximum, namely the time needed to obtain optimum fermenting maturity; (2) proving stability, evaluated with a gauge in the range of the curve's maximum, provides the time tolerance during which the loaf has to be put into the oven for only then an optimum baking volume can be obtained; (3) Elasticity, calculated as the band width in the range of the maximum peaks and expressed in Maturograph units (MU); and (4) Dough level, evaluated as the value in MU from the zero line to the maximum peak of the curve, which is the maximum fermentation volume of the dough in the Maturograph. Four replicate measurements were made for each dough formulation.

2.3.5. Dough inflation test

The biaxial extensional rheological properties of doughs were measured using a Stable Micro Systems Dough Inflation System (Model DR/DIS2) at 22 °C (Dobraszczyk, 1997). Dough samples were prepared

in a farinograph (7 min mixing time) according to Table S1 without yeast, sugar, and fat. The dough sample (ca. 500 g) was rolled into an approximately 8 mm sheet thickness. Five test dough pieces were taken from the dough sample with a circular sample cutter (brushed with paraffin oil) and gently placed in the center of the sample retainer (oiled) to avoid deformation. The dough pieces were compressed to a fixed thickness of 2.67 mm in 30 s using a standard dough press. The prepared dough discs were allowed to rest for 5 min at ambient temperature (22 °C) with a cover to avoid moisture loss and surface drying. During testing, the dough sheet was inflated by volume displacement of air using a piston driven by a TA-XT2i texture analyzer (Stable Micro Systems Ltd., Godalming, UK). The test flow rate was set at 26.7 cm^3/s, volume (to cause the dough bubble to burst) was 2000,000 mm^3 and trigger volume (volume of air required to lift the dough sheet from the sample retainer) was 40,000 mm^3, and break sensitivity was 2.03 cm of water. Parameters obtained from the Stress–Hencky strain curves included: P (mm), tenacity (the maximum pressure required during inflation of the bubble corresponded to the maximum height of the curve); L (mm), drum distance (the length of the curve from start of inflation till the point of rupture); P/L, configuration ratio of the curve; W (J), baking strength or deformation energy (the energy necessary to inflate the dough bubble until rupture); bubble burst strain (maximum Hencky strain to failure); bubble burst stress (maximum bubble wall stress at failure); and strain hardening index b (exponent value obtained by fitting the empirical exponential equation to the stress–strain curve: $\sigma = k\varepsilon xp^{b\varepsilon}$, where σ is the stress, K is the constant, ε is the Hencky strain, and b is the strain hardening index) (Dobraszczyk et al., 2003; Dobraszczyk & Salmanowicz, 2008).

2.4. Bread making and quality characterization

The six types of bread dough described in section 2.3 were baked using a straight-dough baking process according to Wang et al. (2020). For types 5 and 6 formulations, only one dextran addition level, i.e., 0.87%, was used. Baking was performed on two different days (i.e., two independent trials) and ten breads were prepared for each bread type on each baking day. Breads were stored in plastic bags at ambient temperature. The volume of breads was determined after 1 day of storage using a 3D laser-based scanner (Volscan Profiler 300, Stable Micro Systems, Surrey, UK) and triplicate measurements were performed for each bread type. Texture Profile Analysis (TPA) of bread crumbs on days 1 and 4 of storage was made using a TA-XT2i texture analyzer with a 36-mm diameter probe and a force load cell of 5 kg (Wang et al., 2019). Acidity (pH and TTA) of the bread crumbs was determined as described earlier (Wang et al., 2019).

2.5. Statistical analysis

Statistical analysis was performed on all data using the SPSS Statistics 24.0 program (IBM SPSS Inc., Chicago, US) with one-way univariate analysis of variance (ANOVA) followed by Turkey's post hoc multiple comparison test at significance level $p < 0.05$. The principal component analysis (PCA) was conducted to study the relationship between dough rheological parameters and bread textural properties by using R packages "FactoMineR" (Lê, Josse, & Husson, 2008) and "factoextra" (Kassambara & Mundt, 2019).

3. Results and discussion

3.1. Microbial growth, acidity, dextran, and metabolite formation of sourdoughs

The cell density of presumptive lactic acid bacteria at 0 h (initial inoculum) was 5.9–6.4 log cfu g^{-1} (Table 1). At the end of fermentation, the LAB cell density increased ca. 3.2 log cycles, ranging from 9.1 to 9.6 log cfu g^{-1}. The initial cell density of yeasts was 5.3 log cfu g^{-1} in sourdoughs fermented by florapan starters (florapan CSD) and less than 2 log cfu g^{-1} in sourdoughs fermented by *W. confusa* A16 (A16 CSD and A16 DSD), and remained approximately at these levels until the end of fermentation. The pH and TTA values of sourdoughs before fermentation were 6.0 and 1.5–1.7 mL, respectively (Table 1). After fermentation, the acidity level (TTA) in florapan CSD was 2.5 times higher than that in A16 CSD and A16 DSD. Correspondingly, the lactic acid concentration was significantly higher in florapan CSD compared to A16 CSD and A16 DSD (Table 1). The acetic acid was only detected in florapan CSD.

The added 10% sucrose in A16 DSD was completely hydrolyzed by the bacterial dextransucrase activity into glucose and fructose (Supplementary Material Table S2). The glucose was partially utilized for dextran production (2.9% dry matter, Table 1) and partially for synthesizing glucooligosaccharides (Supplementary Material Fig. S1) via the acceptor reaction with flour endogenous maltose (Katina et al., 2009; Shukla et al., 2014), whereas the fructose was accumulated (Table S2). In A16 CSD, a small amount of dextran (0.4% dm) was formed due to the endogenous sucrose (0.9% dm) present in wheat flour.

3.2. Rheological characterization of bread doughs

3.2.1. Water absorption

The water absorption of flour was significantly decreased by adding florapan CSD or A16 CSD compared to control wheat dough (Table 2). Acidification negatively affects the gluten hydration due to gluten protein hydrolysis (Thiele, Grassl, & Gänzle, 2004). When A16 DSD (dextran content 0.87% fw) was applied, the water absorption was increased to the levels higher than control wheat dough ($p < 0.05$). The relationship between water absorption and A16 dextran (Mw: 3300000 g/mol), externally added at 0.2, 0.4, and 0.87% fw, was concentration dependent. This is in agreement with the study by Zannini, Waters, and Arendt (2014). The supplementation of T250 dextran (*Mw*: 250000 g/mol) at 0.2–0.87% also increased water absorption but to a significantly lesser degree than that of A16 dextran at 0.2%. Funami et al. (2005) correlated the higher water binding ability of hydrocolloids with a higher molecular weight and a higher radius of gyration, and therefore

Table 1
Cell counts, pH and TTA, organic acids, and dextran (% dry matter) of sourdoughs.

	Lactic acid bacteria (log cfu/g)		Yeast log cfu/g)		pH		TTA (mL)		Lactic acid (% dm)	Acetic acid (% dm)	Dextran (% dm)
	0 h	24–48 h	0 h	24–48 h	0 h	24–48 h	0 h	24–48 h			
Florapan CSD[a]	6.4 ± 0.4 [b]	9.6 ± 0.2 [b]	5.3 ± 0.0	4.9 ± 0.1	6.0 ± 0.0 [a]	3.5 ± 0.1 [a]	1.7 ± 0.1 [b]	15.4 ± 0.1[b]	0.97 ± 0.06 [c]	0.21 ± 0.01	nd
A16 CSD	5.9 ± 0.0 [a]	9.1 ± 0.0 [a]	<2	<2	6.0 ± 0.1 [a]	4.0 ± 0.0 [b]	1.7 ± 0.0 [b]	6.2 ± 0.1 [a]	0.75 ± 0.00 [b]	nd	0.4 ± 0.0 [a]
A16 DSD	5.9 ± 0.0 [a]	9.3 ± 0.1 [a]	<2	<2	6.0 ± 0.0 [a]	4.0 ± 0.0 [b]	1.5 ± 0.0 [a]	6.0 ± 0.2 [a]	0.66 ± 0.00 [a]	nd	2.9 ± 0.1 [b]

Different superscript letters in the same column indicate statistical significance ($p < 0.05$).

[a] Florapan (LA4K, Lallemand, Montreal, Canada): a commercial starter culture including lactic acid bacteria (*Lb. brevis* and *Lb. plantarum*) and yeast *S. cerevisiae*; CSD: control sourdough; DSD: dextran-enriched sourdough; A16: *W. confusa* A16.

Table 2
Maturogram evaluation (35 °C, RH 60%, n = 4) and farinograph water absorption (500 BU) of bread doughs.

Bread doughs	Water absorption (%)	Final fermentation time (min)	Dough level (MU[a])	Elasticity (MU)	Fermentation stability (min)
CWB[b]	60.1 ± 0.1 ^{c}	30.0 ± 2.0 ^{ab}	240.0 ± 0.0 ^{ab}	180.0 ± 0.0 ^{cd}	6.0 ± 0.0 ^{ab}
Florapan CSDB	56.9 ± 0.1 ^{a}	32.8 ± 1.0 ^{b}	215.0 ± 5.8 ^{a}	132.5 ± 5.0 ^{a}	6.0 ± 0.0 ^{ab}
A16 CSDB	58.4 ± 0.1 ^{b}	30.0 ± 1.6 ^{ab}	235.0 ± 10.0 ^{ab}	142.5 ± 5.0 ^{ab}	6.5 ± 0.6 ^{abc}
A16 DSDB	61.9 ± 0.1 ^{d}	29.5 ± 1.0 ^{ab}	312.5 ± 9.6 ^{c}	202.5 ± 5.0 ^{de}	7.3 ± 0.5 ^{c}
A16 dextran 0.2%	63.1 ± 0.2 ^{e}	30.7 ± 1.2 ^{ab}	325.0 ± 13.2 ^{cd}	216.7 ± 20.8 ^{e}	6.0 ± 0.0 ^{ab}
A16 dextran 0.4%	63.9 ± 0.1 ^{f}	30.7 ± 1.2 ^{ab}	346.7 ± 5.8 ^{d}	226.7 ± 11.5 ^{e}	6.3 ± 0.6 ^{abc}
A16 dextran 0.87%	66.5 ± 0.2 ^{g}	29.3 ± 1.2 ^{ab}	400.0 ± 0.0 ^{e}	230.0 ± 10.0 ^{e}	7.0 ± 0.0 ^{bc}
T250 dextran 0.2%	61.6 ± 0.1 ^{d}	29.7 ± 1.5 ^{ab}	236.7 ± 15.3 ^{ab}	156.7 ± 5.8 ^{abc}	5.3 ± 0.6 ^{a}
T250 dextran 0.4%	61.7 ± 0.3 ^{d}	29.3 ± 1.2 ^{ab}	250.0 ± 10.0 ^{b}	170.0 ± 10.0 ^{bc}	5.3 ± 0.6 ^{a}
T250 dextran 0.87%	61.7 ± 0.1 ^{d}	28.3 ± 1.0 ^{a}	255.0 ± 19.1 ^{b}	172.5 ± 22.2 ^{bcd}	6.5 ± 0.6 ^{abc}

Different superscript letters in the same column indicate statistical significance ($p < 0.05$).

[a] MU: Maturogram units.

[b] CWB: control wheat bread; CSDB: control sourdough bread; DSDB: dextran-enriched sourdough bread; A16 dextran: purified high Mw dextran produced by *W. confusa* A16; T250 dextran: commercial low Mw dextran purchased from Pharmacosmos.

more intermolecular hydrogen bonds with water.

3.2.2. Maturogram

The maturogram records the proofing behavior of yeast-containing bread doughs and the evaluation is summarized in Table 2. The final fermentation time (describes the optimal time to reach the peak volume of the product) lay in the range of 28–33 min. The dough level (represents the resistance of the dough against mechanical stress/strain during proofing) and elasticity were significantly reduced by incorporating florapan CSD compared to control wheat dough. Utilizing A16 CSD did not change the dough level, but induced a dramatic decrease in dough elasticity ($p < 0.05$) compared to control wheat dough. During yeast fermentation, the gluten network is the principal structural element enabling the dough gas-holding capacity (Cauvain, 2015). Gluten proteins consist of polymeric high *Mw* glutenins (intermolecular disulfide (SS) bonds) that impart dough elasticity, and gliadins and low *Mw* glutenins (intramolecular SS bonds) that confer a viscous character (Abedi & Pourmohammadi, 2021). The negative influence of acidification on dough elasticity might be related to the weakening effect of organic acids on gluten network i.e., the reduced degree of glutenin polymerization (Su et al., 2019). The depolymerization of glutenin macropolymers is attributed to the increased intermolecular electrostatic repulsion under acidic pH, which induces unfolding and disentanglement of gluten proteins and prevents the formation of new disulfide bonds (Wehrle, Grau, & Arendt, 1997). Furthermore, proteolytic activity of flour endogenous or bacterial proteases (optimal pH ca. 4.0) may degrade glutenin subunits (Kawamura & Yonezawa, 1982; Thiele et al., 2004).

Adding A16 DSD significantly increased the dough level and elasticity compared to control wheat dough, suggesting that dextran could reduce the adverse effect of acidification on dough elasticity. This was confirmed by adding purified A16 dextran to wheat control dough, which generated a significant increase in dough level and elasticity and a positive correlation was observed between dextran concentration (0.2–0.87%) and dough level. However, applying T250 dextran in the same concentration range did not affect the dough level and led to reduced dough elasticity compared to control wheat dough, indicating that the effect of dextrans on dough rheological properties depended on their structure and *Mw*. Dextran with high *Mw* and few branches, has been suggested to interact with gluten proteins, e.g., via hydrogen bonds and steric interactions, that strengthens the gluten network and thus leads to higher elasticity and resistance to mechanical deformation (Lacaze et al., 2007; Ross, McMaster, David Tomlinson, & Cheetham, 1992). The fermentation stability (reflects the tolerance of final proofing time that ensures the highest volume of the product) of the dough samples varied from 5.3 to 7.3 min (Table 2). The incorporation of florapan CSD or A16 CSD had no impact on the fermentation stability, whereas the inclusion of A16 DSD (dextran 0.87%) significantly enhanced the fermentation stability compared to control wheat. The supplementation of purified A16 or T250 dextran did not improve the fermentation stability with an exception for A16 dextran at the highest utilization dosage (0.87%) where the value increased significantly. These results imply that the ability of dextran to enhance fermentation stability is both *Mw*- and concentration-dependent.

3.2.3. Dough inflation

The bi-axial extensional parameters of bread doughs are presented in Table 3. Adding florapan CSD significantly decreased the peak pressure (P, also called tensile strength, related to the stiffness of the dough), drum distance (L, extensibility), deformation energy (W, baking/gluten strength), bubble burst stress and strain, and strain hardening index compared to control wheat dough, indicating a softer dough with less strength or resistance against bubble failure. This might be explained by the high level of acidification in florapan CSD, possibly causing intensive degradation of the structure of the gluten network (Schwab, Mastrangelo, Corsetti, & Gänzle, 2008). Strain hardening stabilizes the dough membrane during extension and is thought to arise mainly from the entanglement of the glutenin polymers (Dobraszczyk et al., 2003). In general, the higher the strain hardening index, the greater the deformation allowed before gas cell failure (Dobraszczyk & Roberts, 1994). Using A16 CSD or A16 DSD also reduced ($p < 0.05$) the peak pressure, deformation energy, and bubble burst stress, but significantly improved the drum distance compared to control wheat dough. The drum distance is a measure of how much the dough can be extended before rupture and has a strong, positive correlation with baking quality, e.g., bread volume (Dobraszczyk et al., 2003). Furthermore, incorporating A16 CSD or A16 DSD dramatically decreased the configuration ratio (P/L, the balance between dough resistance and extensibility) compared to control wheat, whereas including florapan CSD significantly increased the P/L values. These results suggested that mild acidification resulted in a softer but more extensible dough than control, while intensive acidification generated a more inextensible dough. Additionally, the dough prepared with A16 DSD exhibited significantly higher peak pressure and deformation energy than its control counterpart A16 CSD, suggesting enhanced dough strength or stiffness with dextran presence.

When adding purified A16 dextran at increasing concentrations, the peak pressure, deformation energy, and P/L values gradually increased ($p < 0.05$), whereas the drum distance, bubble burst strain, and strain hardening index decreased ($p < 0.05$). Irrespective of the utilization dosage, T250 dextran did not affect significantly any of the biaxial rheological parameters. Similar results were obtained in previous studies where the addition of HPMC increased peak pressure and deformation energy of wheat dough (Bollaín & Collar, 2004); the use of xanthan gum increased the P/L values and deformation energy of composite cassava-wheat dough (Shittu, Aminu, & Abulude, 2009). The peak pressure and P/L values of composite barley-wheat dough

Table 3
Dough inflation parameters (22 °C, n = 15).

Bread doughs	P Pressure (mm)	L Drum Distance (mm)	W Deformation energy	P/L Configuration ratio	Bubble Burst Stress (KPa)	Bubble Burst Strain	Strain Hardening Index b
CWB[a]	150.9 ± 33.6 ^{d}	60.4 ± 4.9 ^{cd}	401.4 ± 41.4 ^{c}	2.68 ± 0.47 ^{b}	332.3 ± 42.2 ^{c}	2.15 ± 0.14 ^{cd}	1.61 ± 0.04 ^{d}
Florapan CSDB	97.6 ± 10.5 ^{c}	25.7 ± 2.9 ^{a}	124.4 ± 15.9 ^{ab}	3.86 ± 0.57 ^{cd}	51.8 ± 7.7 ^{a}	1.45 ± 0.08 ^{a}	1.39 ± 0.06 ^{b}
A16 CSDB	40.1 ± 3.6 ^{a}	83.8 ± 14.9 ^{e}	102.2 ± 20.9 ^{a}	0.48 ± 0.21 ^{a}	96.7 ± 39.4 ^{ab}	2.33 ± 0.44 ^{d}	1.58 ± 0.11 ^{cd}
A16 DSDB	69.9 ± 10.4 ^{b}	70.8 ± 10.2 ^{d}	178.4 ± 43.5 ^{b}	1.02 ± 0.12 ^{a}	131.7 ± 39.3 ^{b}	2.21 ± 0.20 ^{cd}	1.56 ± 0.05 ^{cd}
A16 dextran 0.2%	179.0 ± 20.8 ^{ef}	60.2 ± 7.2 ^{cd}	425.8 ± 41.4 ^{c}	2.83 ± 0.67 ^{b}	349.5 ± 72.1 ^{c}	2.12 ± 0.11 ^{cd}	1.54 ± 0.06 ^{cd}
A16 dextran 0.4%	205.6 ± 26.4 ^{f}	52.9 ± 12.4 ^{c}	458.6 ± 90.2 ^{c}	4.15 ± 1.41 ^{d}	335.5 ± 85.8 ^{c}	1.97 ± 0.20 ^{bc}	1.47 ± 0.12 ^{bc}
A16 dextran 0.87%	286.1 ± 32.7 ^{g}	40.4 ± 5.2 ^{b}	531.9 ± 57.1 ^{d}	7.14 ± 0.92 ^{e}	289.8 ± 42.5 ^{c}	1.80 ± 0.12 ^{b}	1.18 ± 0.14 ^{a}
T250 dextran 0.2%	154.7 ± 14.9 ^{de}	62.9 ± 7.7 ^{cd}	419.6 ± 37.9 ^{c}	2.41 ± 0.40 ^{b}	345.1 ± 61.9 ^{c}	2.15 ± 0.16 ^{cd}	1.62 ± 0.06 ^{d}
T250 dextran 0.4%	161.1 ± 9.4 ^{de}	54.5 ± 12.1 ^{c}	401.2 ± 82.7 ^{c}	3.12 ± 0.34 ^{bc}	331.5 ± 57.5 ^{c}	2.00 ± 0.17 ^{bc}	1.61 ± 0.08 ^{d}
T250 dextran 0.87%	160.9 ± 14.5 ^{de}	60.4 ± 10.1 ^{cd}	415.8 ± 46.3 ^{c}	2.86 ± 0.49 ^{b}	331.2 ± 66.9 ^{c}	2.07 ± 0.16 ^{bcd}	1.59 ± 0.07 ^{cd}

[a] See Table 2 for samples codes. Different superscript letters in the same column indicate statistical significance ($p < 0.05$).

increased and drum distance decreased with the supplementation of guar gum or xanthan gum (Li, Hou, & Chen, 2016). The peak pressure gradually increased, whereas Henky strain, strain hardening index, and extensibility (drum distance) decreased with increased β-glucan addition to wheat dough (Ahmed & Thomas, 2015). The presence of hydrocolloids has been suggested to favor entanglements of gluten proteins, leading to higher dough strength (Bollaín & Collar, 2004). However, interactions between hydrocolloids and gluten proteins may limit the extensibility of wheat dough due to increased dough rigidity (Zannini et al., 2014). Furthermore, peak pressure and deformation energy were found to be linked to the water absorption capacity of the flour, and the addition of ingredients that increase the water absorption would increase these two parameters (Jødal & Larsen, 2021). Water content has been shown to have a great influence on biaxial extensional rheology parameters of wheat dough (Ahmed & Thomas, 2015). Increasing water content generally reduces the peak pressure and deformation energy due to the softening effect on gluten network, i.e., decreased entanglements in the gluten polymers (Cappelli et al., 2018). On the other hand, the use of hydrocolloids exhibiting high water-binding capacity may compete with gluten proteins for water and thus affect their hydration. In this study, all dough formulations initially contained the same amount of water i.e., the optimum water level (60.1%) for control wheat dough, even though the addition of A16 dextran was observed with significantly higher farinograph water absorption (63.1–66.5%) (Table 2). Future experiments should consider following the bi-axial extensional properties of optimally developed dextran-containing doughs (i.e., at optimum farinograph water absorptions).

3.2.4. DMA-proofing sweep

Bread dough displays an intermediate rheological behavior between a viscous liquid and elastic solid. Adequate elasticity is required to retain the carbon dioxide gas, while sufficient viscosity is needed for the gas cell expansion (Dobraszczyk & Morgenstern, 2003). The viscoelastic properties of the yeasted bread doughs under simulated yeast fermentation conditions (45 min proofing at 35 °C and 75% RH) were analyzed by a dynamic oscillatory test. In all doughs, the rheological properties exhibited a time-dependent change during yeast fermentation. The elastic modulus (G′) predominate over loss modulus (G"), indicating an elastic-like behavior (data not shown). The maximum values of moduli (G'_{max}, G''_{max}, G^*_{max}) and tangent of the phase angle ($Tan(\delta)_{max}$, the ratio of G"/G′), as well as the time at which G'_{max} occurred (T_{max}) are summarized in Table 4. The T_{max} (23.5–27.9 min) and $Tan(\delta)_{max}$ were comparable in all bread doughs. Adding florapan CSD significantly decreased the G'_{max}, G''_{max}, and G^*_{max} compared to control wheat dough, implying that intensive acidification had an adverse effect on the viscoelasticity of wheat dough. Utilizing A16 CSD did not affect those maximum moduli values, whereas including A16 DSD significantly increased the maximum moduli values compared to control wheat. The enhancing effect of dextran on elastic and loss moduli was likely attributed to the interactions between dextran and gluten-starch associations (Zhang, Li, Yang, Jin, & Xu, 2018) and inadequate gluten hydration (Navickis, Anderson, Bagley, & Jasberg, 2010). In addition, the increased content of β-sheet secondary protein structure (the way of gluten proteins to store elastic energy) with dextran presence in mild acidic conditions may contribute to the elastic behavior of wheat dough (Wellner et al., 2005; Zhang et al., 2020). The use of purified A16 dextrans (0.2–0.87% fw) also significantly enhanced the maximum moduli values and a positive dose–response relationship was observed. By contrast, the incorporation of T250 dextran yielded no significant changes in maximum moduli values except for a slight increase in G'_{max} ($p < 0.05$) at dextran concentrations above 0.4%. This implies that high

Table 4
Dynamic thermomechanical analysis (DMA) parameters of bread doughs under proofing condition (35 °C, RH 75%, 1 *HZ*, n = 3).

Bread doughs	T_{max} (min)[a]	$Tan(\delta)_{max}$	G'_{max} (Mpa)	G''_{max} (MPa)	G^*_{max} (Mpa)
CWB[b]	23.8 ± 1.4 ^{a}	0.58 ± 0.03 ^{a}	0.43 ± 0.01 ^{bc}	0.16 ± 0.00 ^{ab}	0.45 ± 0.01 ^{ab}
Florapan CSDB	27.9 ± 1.9 ^{a}	0.59 ± 0.01 ^{a}	0.24 ± 0.03 ^{a}	0.10 ± 0.01 ^{a}	0.25 ± 0.03 ^{a}
A16 CSDB	26.5 ± 1.8 ^{a}	0.55 ± 0.04 ^{a}	0.42 ± 0.01 ^{b}	0.14 ± 0.02 ^{ab}	0.45 ± 0.01 ^{ab}
A16 DSDB	24.9 ± 1.0 ^{a}	0.57 ± 0.04 ^{a}	0.63 ± 0.02 ^{e}	0.33 ± 0.05 ^{bc}	0.74 ± 0.11 ^{b}
A16 dextran 0.2%	23.6 ± 1.6 ^{a}	0.51 ± 0.05 ^{a}	0.50 ± 0.01 ^{cd}	0.21 ± 0.07 ^{ab}	0.54 ± 0.03 ^{ab}
A16 dextran 0.4%	27.6 ± 5.6 ^{a}	0.60 ± 0.02 ^{a}	0.69 ± 0.02 ^{e}	0.29 ± 0.13 ^{abc}	0.74 ± 0.07 ^{b}
A16 dextran 0.87%	23.5 ± 3.4 ^{a}	0.53 ± 0.02 ^{a}	1.07 ± 0.06 ^{f}	0.45 ± 0.11 ^{c}	1.31 ± 0.26 ^{c}
T250 dextran 0.2%	24.1 ± 1.2 ^{a}	0.59 ± 0.04 ^{a}	0.44 ± 0.02 ^{bc}	0.14 ± 0.02 ^{ab}	0.46 ± 0.01 ^{ab}
T250 dextran 0.4%	25.1 ± 0.7 ^{a}	0.54 ± 0.05 ^{a}	0.52 ± 0.01 ^{d}	0.25 ± 0.03 ^{abc}	0.56 ± 0.01 ^{ab}
T250 dextran 0.87%	24.0 ± 2.4 ^{a}	0.54 ± 0.02 ^{a}	0.53 ± 0.01 ^{d}	0.24 ± 0.02 ^{abc}	0.55 ± 0.00 ^{ab}

[a] G'_{max}: storage modulus at peak; T_{max}: the time corresponding to G'_{max}; G''_{max}: loss modulus at peak; G^*_{max}: complex modulus at peak; $Tan(\delta)_{max}$: tan δ value at peak. The results present are averaged values from 3 to 5 replicate measurements.

[b] See Table 2 for samples codes. Different superscript letters in the same column indicate statistical significance ($p < 0.05$).

Mw dextran contributes to the viscoelastic behavior of doughs during yeast fermentation.

3.2.5. DMA-temperature sweep

During baking, dough undergoes physical, chemical, and biochemical changes leading to altered rheological properties and structural transformation into a light, porous product (Grenier et al., 2021). The evolution of moduli (G′, G", G*) and tan δ with temperatures ranging from 25 °C to 140 °C (simulating the conditions of baking process), obtained by DMA (at 1 *HZ*) from the unyeasted dough samples, are shown in Figs. 1–2 and Supplementary Material Fig. S2. For all samples, over the entire temperature range, G′ exceeded G'' (tan δ < 1) with the elastic properties predominate over viscous properties. The responses of dough samples during heating followed a similar trend where three principal stages could be distinguished from the modulus-temperature curves. In the first stage, the moduli values (G′, G", and G*) increased slowly with increasing temperatures from 25 °C to 75 °C. In previous studies, however, a slight decrease in moduli values in the temperature interval of 40–60 °C was observed with flour-water or gluten-starch model doughs, attributing to gluten protein destabilization (reduced physical interactions e.g., hydrogen and ionic bonds) and increased gluten mobility (Singh & Bhattacharya, 2005; Struck, Straube, Zahn, & Rohm, 2018).

In the second stage, a sharp increase in moduli was observed in the interval 75–95 °C due to dough structural changes (or dough/crumb transition) induced by starch gelatinization, protein denaturation (crosslinking), and water redistribution or evaporation. The beginning of this stage was labelled as T_{onset} (76–80 °C), which corresponds to the inflexion point of G′ and represents the beginning of the physical phenomena taking place during starch gelatinization. The T_{onset} values were higher than those reported for flour-water and gluten-starch doughs (54–68 °C) (Jekle, Mühlberger, & Becker, 2016; Wang & Sun, 1999; Zanoletti et al., 2017). Sugar, salt, and the presence of polymers are known to elevate the starch gelatinization temperature (Angioloni & Rosa, 2005; Jekle et al., 2016; Wang, Chen, et al., 2021). Using sourdoughs (florapan CSD, A16 CSD, and A16 DSD) significantly increased T_{onset} and $Tan(\delta)_{onset}$ compared to control wheat dough (Table 5), indicating a delaying effect on the onset of gelatinization. Adding purified A16 or T250 dextran (0.2–0.87%) also caused a progressive increase in T_{onset} compared to control wheat dough. Dextran has been suggested to compete with starch for available water, and thus affects gelatinization (Zhang et al., 2019).

After T_{onset}, the elastic modulus increased rapidly and reached a peak (G'_{peak}) at temperature (T_{peak}) ranging from 89.2 to 94.6 °C (Table 5). A drastic decrease in tan δ (the ratio of the moduli G"/G') was observed between 80 and 100 °C (Fig. 2), indicating a more pronounced contribution of elastic/solid behavior or structural alteration toward higher elastic properties. The increase in moduli until maximum at 70–100 °C (peak temperature depending on flour quality and the presence of other ingredients) and the dramatic decline in tan δ (dough/crumb transition) have been well documented (Agyare, Xiong, Addo, & Akoh, 2004; Moreira, Chenlo, & Arufe, 2015; Singh & Bhattacharya, 2005; Sommier, Chiron, Colonna, Valle, & Rouillé, 2005; Struck et al., 2018; Wang & Sun, 1999). The quantitative contribution of starch gelatinization, protein denaturation, and water redistribution, which occur concurrently in the same temperature range, to rheological properties is still under debate (Dreese, Faubion, & Hoseney, 1988; Grenier et al., 2021; Nakonecznyj, Ingman, & Schofield, 1995; Rosell, Collar, & Haros, 2007; Rouillé et al., 2010). Starch gelatinization during heating involves multiple phenomena, including water uptake and swelling of the starch granules, crystal melting (water entering the crystalline region and the double helix structure destroyed), amylose leaching that generates a continuous matrix promoting viscosity and G′ increase, and disintegration of the starch granules that leads to viscosity decrease (Jekle et al., 2016; Moreira et al., 2015; Wang, Chen, et al., 2021). Gluten proteins are unfolded at elevated temperatures, facilitating hydrophobic interactions as well as disulfide bond formation (or crosslinking) via SH-SS interchange reactions and oxidation of SH groups (Abedi & Pourmohammadi, 2021). These interactions are accompanied by decreased protein solubility and formation of large protein aggregates, resulting in the increased elastic character of the dough matrix. At above 90 °C, gliadins are incorporated/polymerized into the glutenin structure (gliadins-glutenin crosslinking), leading to large protein aggregates exhibiting a rapid change from viscous to elastic behavior (Abedi & Pourmohammadi, 2021; Delcour et al., 2011; Stathopoulos, Tsiami, Dobraszczyk, & Schofield, 2006; Stathopoulos, Tsiami, Schofield, & Dobraszczyk, 2008; Weegels, de Groot, Verhoek, & Hamer, 1992). Moreover, water evaporation and redistribution (i.e., withdrawal of water from the gluten proteins during starch gelatinization) also contributes to the increased elastic behavior of the dough matrix (Chong,

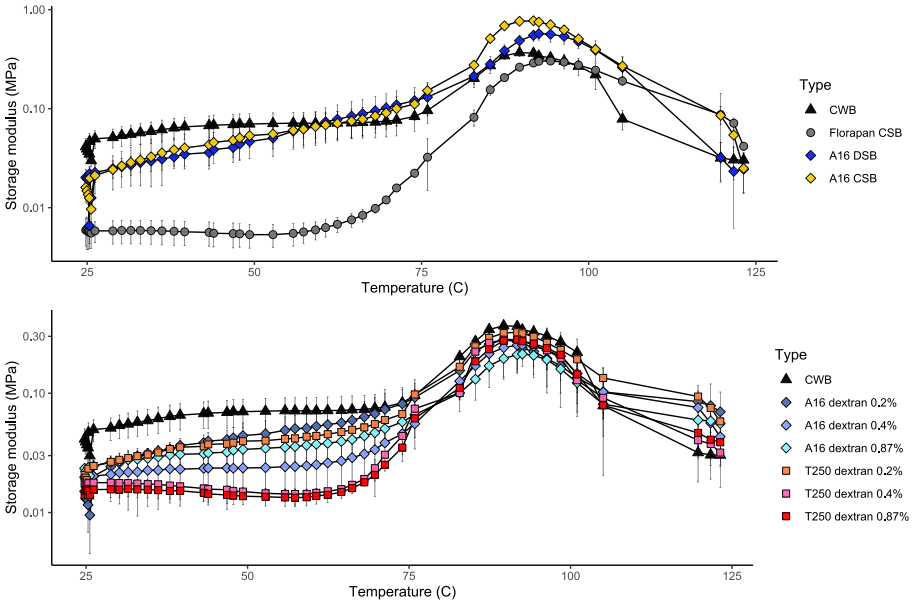

Fig. 1. Storage modulus (G′) of bread doughs under baking conditions in dynamic thermomechanical analysis (DMA). The lines present are averaged results (n = 3–5).

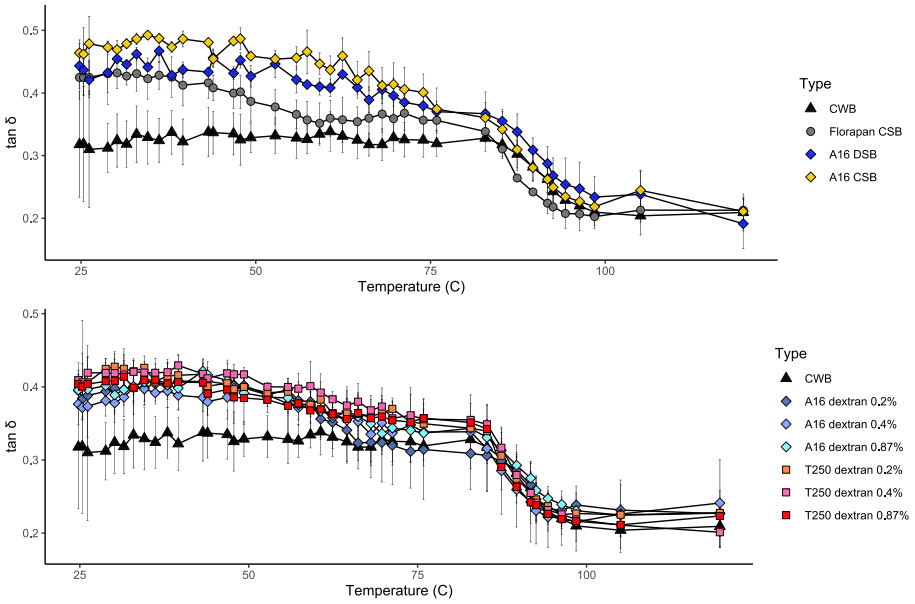

Fig. 2. Loss tangent (tan δ) of bread doughs under baking conditions in DMA. The lines present are averaged results (n = 3–5).

Table 5
Dynamic thermomechanical analysis (DMA) parameters of bread doughs under increasing temperature (simulate baking) condition (25–140 °C, 1 *HZ*, n = 3–5).

Bread doughs	T_{onset} (°C)[a]	$Tan(\delta)_{onset}$	T_{peak} (°C)	G'_{peak} (Mpa)	$G"_{peak}$ (Mpa)	G^*_{peak} (Mpa)	$Tan(\delta)_{peak}$
CWB[b]	75.7 ± 0.2 ^{a}	0.32 ± 0.02 ^{ab}	89.5 ± 1.4 ^{a}	0.35 ± 0.02 ^{c}	0.09 ± 0.00 ^{b}	0.36 ± 0.02 ^{c}	0.37 ± 0.03 ^{a}
Florapan CSDB	80.1 ± 1.0 ^{de}	0.39 ± 0.02 ^{e}	94.6 ± 1.9 ^{c}	0.30 ± 0.01 ^{ab}	0.08 ± 0.00 ^{ab}	0.32 ± 0.01 ^{ab}	0.43 ± 0.01 ^{b}
A16 CSDB	79.2 ± 0.7 ^{cde}	0.36 ± 0.01 ^{cde}	91.7 ± 0.6 ^{abc}	0.77 ± 0.05 ^{e}	0.21 ± 0.02 ^{d}	0.79 ± 0.05 ^{e}	0.50 ± 0.01 ^{c}
A16 DSDB	80.5 ± 1.3 ^{e}	0.37 ± 0.01 ^{de}	93.5 ± 0.2 ^{bc}	0.55 ± 0.08 ^{d}	0.16 ± 0.03 ^{c}	0.57 ± 0.09 ^{d}	0.48 ± 0.01 ^{c}
A16 dextran 0.2%	76.3 ± 0.5 ^{ab}	0.30 ± 0.02 ^{a}	89.2 ± 0.6 ^{a}	0.29 ± 0.01 ^{ab}	0.07 ± 0.00 ^{ab}	0.30 ± 0.01 ^{ab}	0.42 ± 0.02 ^{b}
A16 dextran 0.4%	77.0 ± 0,7 ^{abc}	0.32 ± 0.02 ^{abc}	90.0 ± 1.9 ^{ab}	0.25 ± 0.01 ^{ab}	0.07 ± 0.01 ^{ab}	0.26 ± 0.01 ^{ab}	0.40 ± 0.01 ^{ab}
A16 dextran 0.87%	78.1 ± 0.6 ^{bcd}	0.34 ± 0.01 ^{abcd}	91.9 ± 0.1 ^{abc}	0.20 ± 0.04 ^{a}	0.06 ± 0.01 ^{a}	0.21 ± 0.04 ^{a}	0.40 ± 0.02 ^{ab}
T250 dextran 0.2%	76.3 ± 0,6 ^{ab}	0.35 ± 0.02 ^{bcd}	90.6 ± 1.1 ^{ab}	0.33 ± 0.02 ^{bc}	0.09 ± 0.00 ^{b}	0.34 ± 0.03 ^{bc}	0.43 ± 0.00 ^{b}
T250 dextran 0.4%	76.5 ± 1.2 ^{ab}	0.37 ± 0.00 ^{de}	90.4 ± 2.4 ^{ab}	0.29 ± 0.01 ^{ab}	0.07 ± 0.01 ^{ab}	0.30 ± 0.02 ^{ab}	0.43 ± 0.00 ^{b}
T250 dextran 0.87%	77.9 ± 0.6 ^{abcd}	0.36 ± 0.00 ^{de}	91.2 ± 1.8 ^{abc}	0.28 ± 0.01 ^{ab}	0.07 ± 0.01 ^{ab}	0.29 ± 0.01 ^{ab}	0.41 ± 0.02 ^{b}

[a] T_{onset}: onset temperature of starch gelatinization, from evolution of G′ during heating (calculated as the intersection of the tangents of the baseline before the sudden increase in G′ and the tangent of the steep G′ profile after T_{onset}); $Tan(\delta)_{onset}$: tan δ value at onset G′; G'_{peak}: storage modulus at peak; T_{peak}: the temperature corresponding to G'_{peak}; $G"_{peak}$: loss modulus at peak; G^*_{peak}: complex modulus at peak; $Tan(\delta)_{peak}$: tan δ value at peak. The results present are averaged values from 3 to 5 replicate measurements.

[b] See Table 2 for samples codes. Different superscript letters in the same column indicate statistical significance ($p < 0.05$).

Mohammed, Linter, Allen, & Charalambides, 2017; Delcour et al., 2011).

Utilizing florapan CSD significantly decreased the G'_{peak} values compared to control wheat dough. Intensive acidification induces a high degree of collapse of starch granules and hydrolysis of amylose and amylopectin chains, leading to less chain entanglements and thus reduced elastic and loss moduli (Hirashima, Takahashi, & Nishinari, 2005). Acid hydrolysis also leads to reduced thermal stability of the gluten network, with higher acidity inducing stronger weakening effects (Huang, Zhang, Zhang, & Wang, 2018). In contrast, including A16 CSD doubled the G'_{peak} values ($p < 0.05$) compared to control wheat dough, implying increased structural strength or stiffness of the dough or a higher degree of molecular interactions. Mild acidification has been suggested to promote rupture of starch granules with a minor extent of amylose hydrolysis, resulting in a higher number of leached amyloses contributing to enhanced network formation (increased chain entanglements) and elastic characters (Hirashima et al., 2005). Adding A16 DSD also significantly increased the G'_{peak} values, but to a lesser extent compared to its control counterpart A16 CSD. Including purified A16 dextrans to wheat dough promoted a gradual decrease in G'_{peak} ($p < 0.05$) with increasing dextran levels. Supplementing T250 dextran at concentrations higher than 0.4% also generated a small but significant decline in G'_{peak}. The changes in peak loss modulus ($G"_{peak}$) and complex modulus (G^*_{peak}) followed the same trend as G'_{peak}. These results suggest the addition of dextran leads to weaker thermal properties of wheat dough.

The use of hydrocolloids has been reported to affect the rheological properties of doughs during heating, particularly thermal weakening and a reduction of peak torque (Rosell et al., 2007). Hydrocolloids are known to retard starch gelatinization via interactions (or forming complex) with the leached amylose and/or amylopectin that negatively affect the continuous matrix formation of leached amylose, exerting force to starch granules that restricts the endogenous components leaching out to the surrounding phase, and competing with starch to bind free water and prevent swelling (Buksa & Krystyjan, 2019; Rosell et al., 2007). The higher the *Mw* of the hydrocolloids, the stronger their interactions with starch molecules (Funami et al., 2005). High *Mw* dextran exhibiting high water binding capacity reduces the peak viscosity of wheat starch during heating (Zhang, Guo, et al., 2018, 2019). Dextran may form a film around the starch granules (refer to FESEM images in Supplementary Material Fig. S3) that acts as a physical barrier toward amylose leaching and the diffusion of water into starch granules, leading to suppressed swelling and starch gelatinization. Furthermore, high *Mw* dextran has a weakening effect on thermal properties of hydrated gluten (Nawrocka, Szymańska-Chargot, Miś, Wilczewska, & Markiewicz, 2017; Zhang et al., 2020). This is likely related to the

intervention in glutenin cross-linking (increased free SH groups) and reduced gluten aggregation with the presence of dextran (Zhang et al., 2020).

The peak tan δ value ($Tan(\delta)_{peak}$) was significantly increased upon the inclusion of sourdoughs or purified dextrans compared to control wheat dough. In the third stage, after the peak temperature T_{peak}, the moduli decreased dramatically with further increasing temperatures (Fig. 1 and Fig. S2) due to starch granule disintegration. Furthermore, the moduli were frequency dependent, increasing with frequency from 1 to 5 *HZ* (data not shown), which is typical of a cross-linked polymer network.

3.3. Bread volume and texture properties

Characteristics of sourdough or dextran enriched wheat breads and the control wheat bread (CWB) are summarized in Table 6. The use of florapan CSD led to a significant decrease (21%) in loaf-specific volume and increase (38%) in crumb hardness (on day 1) compared to CWB, indicating that intensive acidification adversely affected gas holding capacity and promoted crumb firming. This correlated with the observation in dough rheological measurements. The inclusion of A16 CSD increased the specific volume by 5% and decreased the crumb hardness by 6% compared to CWB. The positive effects were generated by the improved dough extensibility and thermal rheological properties due to mild acidification. Remarkably, the incorporation of A16 DSD to wheat bread improved the specific volume by 15% and reduced the crumb hardness by 29% ($p < 0.05$). Adding purified A16 dextran (0.87% fw) to bread formulations resulted in a 9% increment of specific volume and 17% reduction of crumb hardness ($p < 0.05$). No significant effects on loaf volume and crumb hardness were observed when T250 dextran (0.87%) was added to wheat bread. The difference in crumb hardness persisted during the 4 d of storage. The *in situ* produced high *Mw* dextran and *ex situ* added dextran (synthesized by the same strain and used at the same concentration) both demonstrated great potential for improving wheat bread qualities. However, the *in situ* produced dextran outperformed the *ex situ* addition, suggesting synergetic effects of dextran and mild acidification (Kaditzky & Vogel, 2008; Zhang et al., 2019). High *Mw* dextran increased elasticity, tensile strength, and viscoelastic characters of wheat dough but negatively influenced the extensibility and thermal properties (i.e., thermal weakening effect). When applied *in situ*, the dough extensibility and thermal-mechanical properties were increased, likely due to the mildly acidic conditions. Of note, in the context of *in situ* application, the influence of the accumulated fructose and the synthesized glucooligosaccharides on dough rheological and bread textural properties warrants further investigation.

Table 6
Specific (Sp.) volume, crumb hardness (after 1 and 4 days of storage), and acidity of bread.

Bread	Sp. volume (mL/g)	Day 1 Hardness (g)	Day 4 Hardness (g)	pH	TTA (mL)
CWB[a]	4.49 ± 0.11 ^{b}	115.9 ± 9.3 ^{c}	221.8 ± 17.9 ^{bc}	5.7 ± 0.0 ^{c}	3.3 ± 0.0 ^{a}
Florapan CSDB	3.56 ± 0.05 ^{a}	160.3 ± 24.5 ^{d}	332.4 ± 47.6 ^{d}	4.0 ± 0.0 ^{a}	8.4 ± 0.1 ^{c}
A16 CSDB	4.72 ± 0.07 ^{c}	108.8 ± 10.9 ^{bc}	211.8 ± 20.7 ^{bc}	4.8 ± 0.0 ^{b}	5.2 ± 0.0 ^{b}
A16 DSDB	5.16 ± 0.03 ^{e}	82.1 ± 9.9 ^{a}	186.6 ± 13.5 ^{a}	4.8 ± 0.0 ^{b}	5.2 ± 0.1 ^{b}
A16 dextran	4.91 ± 0.08 ^{d}	96.6 ± 11.7 ^{b}	200.6 ± 21.6 ^{ab}	5.7 ± 0.0 ^{c}	3.3 ± 0.1 ^{a}
T250 dextran	4.43 ± 0.05 ^{b}	108.2 ± 17.2 ^{bc}	229.5 ± 22.8 ^{c}	5.7 ± 0.0 ^{c}	3.2 ± 0.0 ^{a}

Different superscript letters in the same column indicate statistical significance ($p < 0.05$).

[a] See Table 2 for samples codes. A16 dextran: bread with added purified dextran (0.87% fw) from W. confusa A16; T250 dextran: bread with added commercial T250 dextran (0.87% fw).

3.4. Correlations between rheological parameters and bread quality

Principal component analysis (PCA) with 26 parameters of dough rheology and bread quality was performed to assess how the parameters differ between the breads and how the dough rheological parameters were associated with the bread properties (Fig. 3). Both principal components together accounted for 64.9% of data variability. Inspections of the biplot (Fig. 3) showed that principal component 1 (PC1) described a dimension mainly correlated with baking volume and crumb hardness. PC2 described a dimension mainly correlated with deformation energy and strain hardening index. The maximum moduli (G'_{max}, G''_{max}, G^*_{max}) in DMA proofing sweep, fermentation stability, dough level, and elasticity in maturogram all had strong positive correlations with baking volume, indicating predictors of good bread quality. On the other hand, crumb hardness was positively associated with final fermentation time in maturogram, T_{max} and $Tan(\delta)_{max}$ in DMA proofing sweep, and T_{peak} and $Tan(\delta)_{onset}$ in DMA temperature sweep, which also strongly and negatively correlated with baking volume. Taken together, the PCA essentially confirmed our findings described previously, with the florapan CSDB having higher crumb hardness and lower loaf volume, and A16 DSDB having enhanced fermentation stability and higher baking volume. The A16 CSDB had higher values in peak moduli (G'_{peak}, G''_{peak}, G^*_{peak}) from DMA temperature sweep and extensibility from dough inflation. The addition of T250 dextran had negligible effects on bread volume or crumb hardness, while the addition of A16 dextran was slightly positively associated with baking volume.

4. Conclusion

The results from this work suggest that maturograph, dough inflation system, and DMA may be used effectively to predict baking performance of dextran-enriched matrices, providing complementary information on the rheological behavior of doughs during proof and oven rise. The use of low *Mw* dextran had negligible effects on dough rheological parameters and bread quality. In contrast, dextran with high *Mw* demonstrated great potential in modifying dough rheology. The *in situ* produced high *Mw* dextran was more effective in improving bread volume and texture attributes compared to the *ex situ* addition. *Ex situ* added dextran provided a stronger dough (higher elasticity and gluten strength) but with less extensibility and weakened thermal properties during heating. Taken together, tailored sourdough with mild acidification and optimal dextran production provides a dual advantage that enhances both gluten strength and dough extensibility, as well as thermal stability.

Author statement

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Declaration of interests

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.

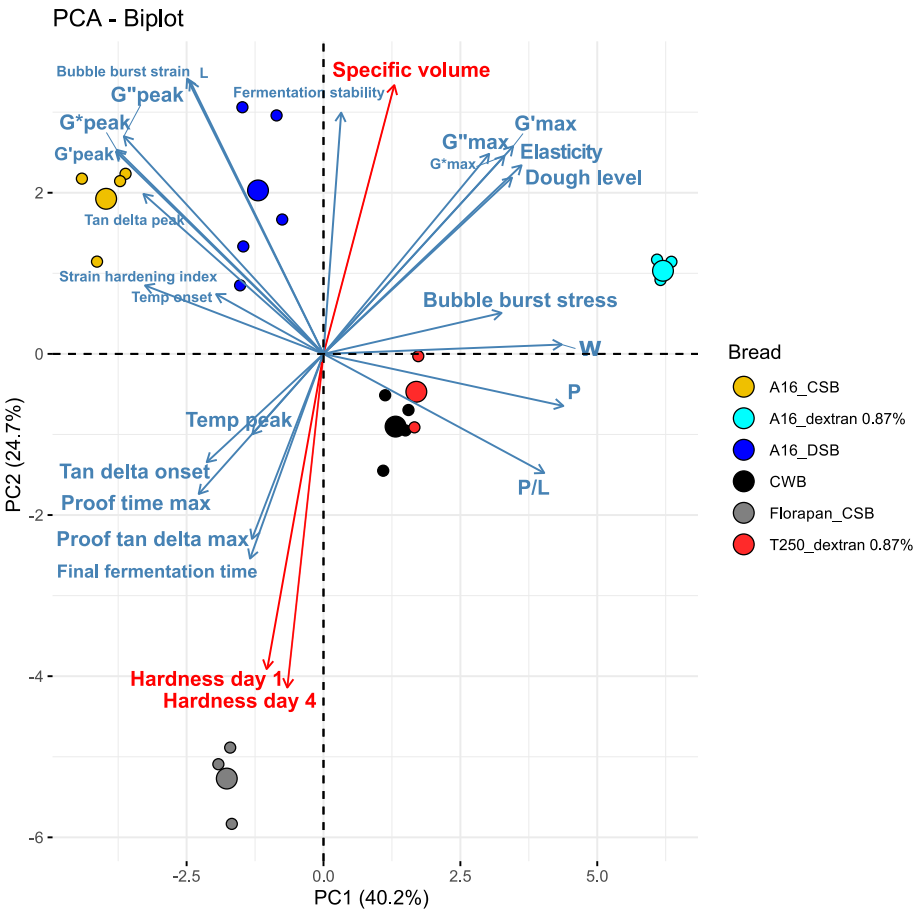

Fig. 3. Principal Component Analysis Bi-plot for rheological parameters and bread properties (see Table 2 for sample codes).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodhyd.2022.107844.

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