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Exploring the relationship between physical properties and sensory characteristics of newly developed white breads with improved nutritional composition – initial insights

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Exploring the relationship between physical properties and sensory characteristics of newly developed white breads with improved nutritional composition – initial insights

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ABSTRACT

Staple foods such as bread are key contributors to the diet. Accordingly, there is growing emphasis on improving the nutritional composition of wheat (e.g., increasing the dietary fibre content); however, the impacts of such improvements on bread characteristics remains unclear. A series of experiments were conducted to determine the relationship between physical properties (slice dimensions, cell crumb, water activity, moisture content, colour and texture analysis) and sensory profile (via a trained sensory panel; n = 12) of five newly developed white breads compared with a commercial standard. Overall, sensory profiling identified twenty-seven attributes to describe the breads; key differences between breads related to the appearance (i) colour: crust (top/side) and crumb (centre) and (ii) density which could be explained by physical properties to varying extents. For example, breads higher in dietary fibre tended to have smaller slice height, larger cell area, higher water activity and moisture content as well as instrumental texture (springiness) and colour (darker) differences. In summary, findings are promising in terms of tested white bread prototypes and provide key insights for further product development. Going forwards, developing nutritionally enhanced white bread without modulating cost and quality could have noteworthy public health benefits.

1. Introduction

Bakery goods are widely consumed and considered ideal products to deliver enhanced nutritional properties; accordingly, biofortification and/or reformulation can be strategies to make such products healthier (Fischer, 2018; Lin, 2022). Approximately 40 % of average daily dietary fibre intake in the UK comes from cereal based products; therefore, they have a key role in the diet (Public Health England, 2020). More specifically, bread can be described as a fundamental staple food in the UK where nearly all households buy bread, with sliced white bread being the most commonly purchased bread type (Lockyer & Spiro, 2020; Statista, 2023; UK Flour Millers, 2023). However, white bread is produced from refined flour resulting in lower contents (due to bran and germ of the grain removal during the milling process) of important nutrients (e.g., dietary fibre, vitamins, minerals, phytoestrogens, phenolic compounds, etc.); thereby, adversely negatively contributing to disease risk (Lal et al., 2021; Lin, 2022; Slavin et al., 1999). Hence, improving the quality of staple food sources (such as wheat-based products) could have widespread public health benefits (Mattei et al., 2015). For example, dietary fibre is essential for human health and improving intake can reduce risk of cardiovascular disease, coronary events, stroke, type 2 diabetes and cancer (colorectal); however,

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consumption is often below recommendations (Kebbe et al., 2021; Koc et al., 2020; Public Health England, 2020; Reynolds et al., 2019; SACN, 2015; Scheelbeek et al., 2020; Stephen et al., 2017). UK adults (aged 19 years and over) are recommended to consume 30 g/d of dietary fibre yet mean intake typically below the 20 g/d threshold (Public Health England, 2020; SACN, 2015). Therefore, there is increasing demand from the food industry to develop strategies to promote dietary fibre without impacting products cost and quality, at a population level.

Thus, growing wheat with naturally higher dietary fibre could be a viable strategy to help shift consumption patterns. Arabinoxylan is the predominant cell wall polysaccharide of wheat grain and constitutes around 50 % of the total dietary fibre fraction of white (refined) flour (Barron et al., 2020; Gebruers et al., 2008). Moreover, the arabinoxylan content varies between wheat cultivars and is also affected by environmental factors (Lovegrove et al., 2020). Genetic differences have been exploited to develop lines with naturally higher dietary fibre (Lovegrove et al., 2020; Tremmel-Bede et al., 2017, 2020). However, dietary fibre (arabinoxylan) and other factors can modulate bread parameters (e.g., dough, bread, sensorial properties, oral processing) and the subsequent impact depends on the specific source, amount, fractional composition, ingredients and baking procedures (Pietiainen et al., 2022; Prieto-Vazquez del Mercado et al., 2022; Pu et al., 2021; Tremmel-Bede et al., 2017; Zannini et al., 2022). More broadly, dietary fibre and protein can influence loaf volume, crumb structure, water absorption, colour, texture and sensory aspects of bread to differing extents; therefore, modulating consumer acceptance and potential uptake (Bagdi et al., 2016; Curti et al., 2013; Gomez et al., 2003; Grigor et al., 2016; Hemdane et al., 2017; Ktenioudaki & Gallagher, 2012; Lin, 2022; Martin et al., 2013; Prieto-Vazquez del Mercado et al., 2022; Rosell & Santos, 2010; Schonhofen et al., 2017; Zhang et al., 2019). The relationships between instrumental and sensorial aspects have not been widely explored. Accordingly, the aim of this paper is to investigate the physical and sensorial characteristics of new nutritionally enhanced white bread in the context of lower or higher dietary fibre (arabinoxylan) and protein content to gain initial insights for future development.

2. Materials and methods

2.1. Breadmaking

Initial pilot baking was conducted to screen new "Minax" flours for suitability in white bread based on different analyses (such as wheat analysis, flour quality and test baking performance) using Allied Technical Centre (ATC) in-house procedures. The "Minax" flours are novel UK grown (Rothamsted, UK) with naturally higher dietary fibre (arabinoxylan) compared with conventional white flour and varied in protein content (13.6–17.5 %) (Lovegrove et al., 2020; Tremmel-Bede et al., 2017, 2020). Accordingly, five "Minax" flours were selected and described as lower (Minax-61, 128 and 168 – total (TOT): 22.6–25.9 mg g^{-1}; water extractable (WE): 12.7–16.0 mg g^{-1}) or higher (minax-100 and 159 – TOT: 30.8–31.3 mg g^{-1}; WE: 19.9–20.6 mg g^{-1}) in dietary fibre coupled with a standard commercial white flour resulting in six breads for breadmaking and additional analyses.

Breads were baked (in duplicate) utilising the Chorleywood breadmaking process (CBP) adhering to the standard in-house procedure (hence benefiting from industry expertise) (800 g into a four-piece lidded loaf using a four-strap tin; ingredients (all supplied by ATC) are outlined in Table 1). The doughs were mixed using a Laboratory Z-blade, Morton, Scotland, UK) with the following settings: mixer (K5), energy (11.0 W h/kg) and baked at 250 °C for 24-min. The proportion of water added varied depending on the individual flour water absorption level (58.1–67.8 %) based on the Farinograph analysis (Gouseti et al., 2019). All breads were cooled at ambient temperature prior to slicing (20 slices per loaf at 13.2 mm thickness) and subsequently packaged (in sealed polythene bread bags) before freezing at −18 °C on day one post baking, for future analyses. The breads were stored at −18 °C until further analysis (e.g., removed from the freezer the day before and defrosted at room temperature) and microbiological clearance testing was completed prior to consumption at an accredited laboratory (SGS analytics, Northumberland, UK).

Table 1
Summary of baking ingredients as % of flour weight.

Ingredients	% of flour weight
White flour	100
Yeast	4.50
Dough conditioner	0.65
Vegetable fat	0.30
Salt	1.40
Soya	0.50
Enzyme softener	0.25
Vinegar (20 %)	0.30
Calcium propionate	0.22

2.2. Physical properties

All analyses were conducted utilising four slices from two different loaves using a pre-allocated design to ensure consistency between breads (Fig. 1).

2.2.1. Slice dimensions

The bread slice dimensions (mm) were recorded by taking into account the height (vertically; top to bottom) and width (horizontally; side to side) from a central perspective using a digital calliper (Fisherbrand™ Traceable™, Fisherbrand™, Texas, USA).

2.2.2. Cell crumb analysis

The bread slices were analysed (via scanned images) for cell crumb structure using a method adapted from Lau et al. (2022). In brief, the bread slice was scanned (HP Scanjet G2710 Photo Scanner, Hewlett-Packard, USA) adhering to tag image file format (TIFF), colour and 300 dots per inch (DPI) settings. The cropped images (slice crumb centre; 8.0 × 10.0 cm) were subsequently analysed by (i) selecting the blue colour from split channels (enhanced contrast 0.40 %; normalised); and (ii) binarizing the image post applying an optimal threshold, using image processing software (Image J, National Institutes of Health, USA). The parameters namely cell size (average) (mm^2) and cell crumb area (%) were calculated.

2.2.3. Water activity and moisture content

Two bread slices (crumb + crust) were blended (Magimix 5200XL, Surrey, UK) into fine crumbs for 15-s to enable subsequent analysis: (1) water activity (aw) was recorded using a tabletop meter (HydroLab C1, Rotronic, UK); and (2) moisture content (%) was measured utilising a moisture analyser (Sartarious MA37, Goettingen, Germany) at 105 °C.

2.2.4. Colour

The bread slice crumb and crust colour were analysed using a colorimeter (Chroma meter CR-400, Tokyo, Japan) utilising three measurements (top crust, side crust and centre crumb; to align with the sensory attributes) reflecting the CIELAB system (illuminant C and 10° viewing angle). Three colour-coordinates were recorded: (1) L^* (dark-light); (2) a^* (green-red) and (3) b^* (blue-yellow) as well as the total colour difference (ΔE^*) (comparing the standard with the Minax-based breads) which was subsequently recorded to understand human perceivable differences (e.g., less than one: non-perceivable differences, one to three: minor perceivable differences and more than three: perceivable differences) (Bodart et al., 2008).

$$\Delta E^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2}$$

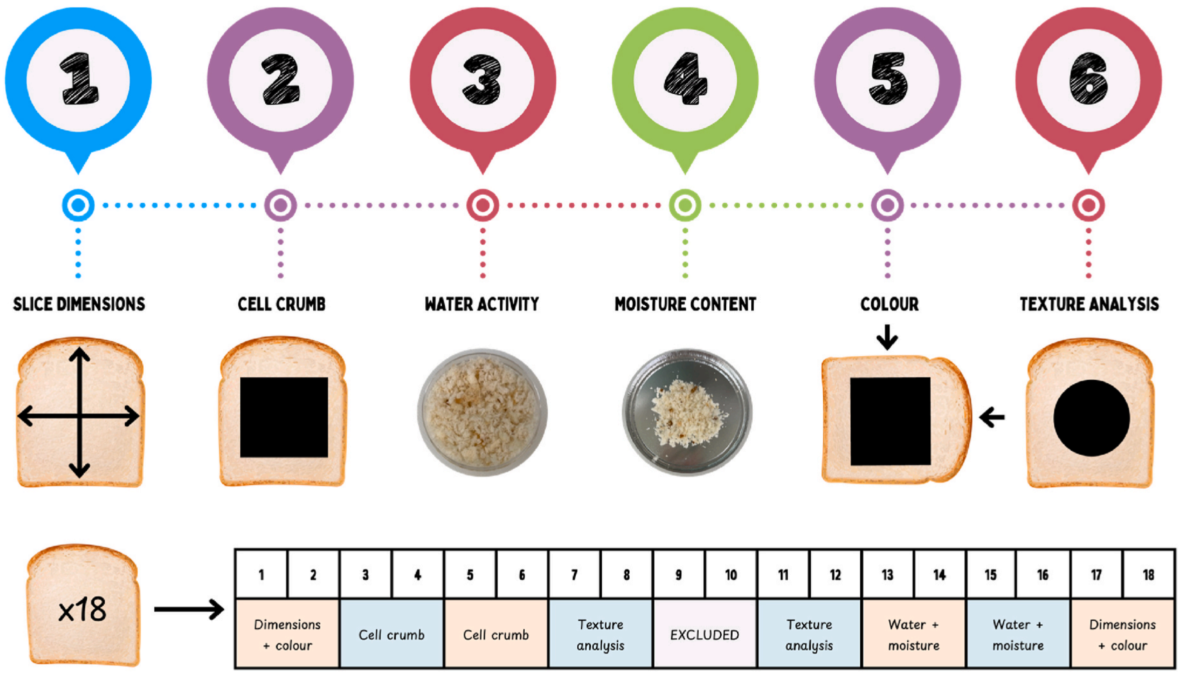


Fig. 1. Summary of physical properties measurements sites and pre-allocated design for each slice.

2.2.5. Texture profile analysis (TPA)

The textural properties of the bread slices were measured using a texture analyser (TAX-Plus, Stable Micro Systems, Surrey, UK). The analysis was performed on two stacked slices (2 × 40 g) in the centre using a double compression test adapted from the American Association of Cereal Chemists (AACC) 74–09 utilising: (i) 5 kg load cell; (ii) 40 mm flat-ended glass cylinder probe; (iii) 1.70 mm/s test speed; (iv) 40 % strain; and (v) 5-s waiting time (AACC, 1997). The resulting parameters: hardness (maximum force at first compression), chewiness (similar trend to hardness: hardness x gumminess x springiness), cohesiveness (relative resistance between compressions: area two divided by area one), springiness (ability to spring back: distance two divided by distance one) and resilience (product's fight to regain its original height: area four divided by area three) were recorded from the Exponent software (version 6.1.16.0, Stable Micro Systems, UK) (Texture Technologies, 2023).

2.3. Sensory evaluation

The trained sensory panel (n = 12; 10 female and 2 male) utilised descriptive sensory profiling (an adapted quantitative descriptive analysis (QDA) method) to determine the sensory profile adhering to ISO 8586:2012 and 1132:2012 (Stone & Sidel, 2004; Heymann et al., 2012; International Organisation for Standardization, 2012a; International Organisation for Standardization, 2012b). In brief, the panellists (screened for sensory acuity and have extensive profiling experience) developed a consensus vocabulary identifying 27 attributes from different modalities: appearance (visual + touch), aroma, taste/flavour, mouthfeel and aftereffects (post 30-s delay). The panellists were presented with a 40 g bread slice; all evaluation was conducted in temperature-controlled isolated booths (22 °C) under artificial daylight with palate cleansers (carrot sticks and filtered water) during the 2-min rest period between breads. In addition, the panellists agreed on an eating protocol namely: (1) panellists were asked to assess the bread for visual appearance followed by physically touching the bread (using approximately half a slice); and (2) the remaining slice was used for aroma, taste/flavour, mouthfeel and aftereffects consuming both the crust and crumb from the top corner of each slice. Panellists undertook scoring via Compusense Software (Compusense Cloud, Ontario, Canada) in separate sessions using visual analogue scales (VAS; 0–100) with relevant anchors on iPads (Apple, London, UK) adhering to a sequential randomly balanced allocated order. It should be noted that all panellists had consented to evaluate different food-based products as part of the company's employment contract; therefore, this work was not subject to additional ethical review nor consent.

2.4. Statistical analysis

The physical properties data were analysed using a one-way analysis of variance (ANOVA) with multiple pairwise comparisons (on significant results) conducted with Tukey Honestly Significant Difference (HSD) in XLSTAT (version 2022.3.2.1348, Addinsoft, USA). SenPAQ (version 6.3, Qi Statistics, UK) was utilised to analyse the descriptive sensory profiling data via ANOVA as outlined in previous work (Norton et al., 2021). In brief, the main effects (product and panellists) were tested against the product by panellists' interaction (fixed effect: product and random effect: panellists). If the ANOVA denoted a significant value subsequent multiple pairwise comparisons were performed by Tukey-Kramer HSD. In addition, multiple factor analysis (MFA) was carried out to explore the relationships between breads, composition (dietary fibre and protein), physical properties and sensory data using mean scores in XLSTAT. For all analyses significance was defined as $p < 0.05$.

3. Results and discussion

3.1. Physical properties

3.1.1. Slice dimensions

The scanned images of the bread slices are summarised in Table 2. Breads significantly differed ($p < 0.0001$) in slice height where the standard and Minax-61 were the tallest in height and Minax-100 was the shortest (Table 2). There was also a noteworthy overall trend for slice width ($p = 0.052$); however, this resulted in no significant differences between individual breads (Table 3). This suggests that dietary fibre (arabinoxylan) and/or protein may modulate dough expansion subsequently reducing slice height. This is in agreement with previous findings that high protein can lead to overstrong dough which restricts

Table 2
Scanned images of white bread slices (scans reduced to 45 %).

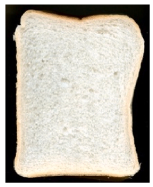
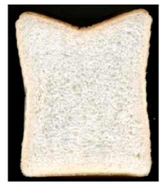
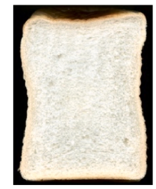
Standard	Minax-61	Minax-100	Minax-128	Minax-159	Minax-168
					

Table 3
Physical properties (mean ± standard deviation) of white breads by dimensions, cell crumb, water activity, moisture content and colour.

Parameters	Standard	Minax-61	Minax-100	Minax-128	Minax-159	Minax-168	p-value
Height (mm)	148.2 ± 2.3[a]	147.3 ± 3.7[a]	130.3 ± 5.5[c]	142.5 ± 1.2[ab]	136.9 ± 3.5[bc]	144.2 ± 7.3[ab]	**< 0.0001**
Width (mm)	108.8 ± 2.8	107.2 ± 2.6	104.6 ± 3.9	105.0 ± 4.8	101.7 ± 1.0	108.2 ± 2.9	0.052
Cell size (mm^2)	0.05 ± 0.009[a]	0.05 ± 0.008[a]	0.08 ± 0.03[a]	0.06 ± 0.02[a]	0.08 ± 0.03[a]	0.05 ± 0.007[a]	**0.04**
Cell crumb area (%)	53.2 ± 2.5[b]	54.8 ± 3.8[b]	60.6 ± 6.2[ab]	58.6 ± 5.4[ab]	66.6 ± 4.9[a]	55.3 ± 2.5[b]	**0.005**
Water activity (aw)	0.982 ± 0.003[a]	0.978 ± 0.003[ab]	0.984 ± 0.004[a]	0.973 ± 0.002[b]	0.982 ± 0.003[a]	0.979 ± 0.004[ab]	**0.003**
Moisture content (%)	39.8 ± 0.2[b]	39.6 ± 0.3[b]	41.8 ± 0.7[a]	40.3 ± 0.4[b]	40.5 ± 0.7[b]	40.6 ± 0.3[b]	**< 0.0001**
Crust (top) - L*(dark-light)	42.7 ± 10.2	40.9 ± 4.5	38.4 ± 2.3	44.3 ± 7.7	47.4 ± 8.4	42.0 ± 5.7	0.58
Crust (top) - a* (green-red)	13.6 ± 1.1	14.7 ± 0.5	15.5 ± 1.5	13.9 ± 0.9	14.6 ± 0.5	15.2 ± 0.6	0.07
Crust (top) - b* (blue-yellow)	26.5 ± 4.9	25.3 ± 3.5	22.5 ± 4.1	26.8 ± 8.0	28.2 ± 6.8	26.1 ± 5.2	0.80
Crust (top) – ΔE*	–	10.6 ± 9.3	9.5 ± 3.9	11.4 ± 7.6	7.8 ± 3.1	9.7 ± 7.6	0.97
Crust (side) - L* (dark-light)	73.9 ± 1.7[ab]	75.9 ± 2.8[ab]	69.6 ± 3.3[b]	73.7 ± 2.2[ab]	71.4 ± 4.9[ab]	77.7 ± 2.1[a]	**0.02**
Crust (side) - a* (green-red)	5.1 ± 1.2	3.0 ± 1.2	4.8 ± 0.3	4.0 ± 1.1	5.3 ± 2.0	3.0 ± 1.5	0.07
Crust (side) - b* (blue-yellow)	31.5 ± 2.0	27.2 ± 3.2	31.4 ± 1.5	29.0 ± 1.9	31.7 ± 2.1	29.3 ± 2.7	0.07
Crust (side) - ΔE*	–	5.9 ± 3.9	5.6 ± 2.1	4.8 ± 1.2	7.8 ± 1.4	5.3 ± 3.4	0.55
Crumb (centre) - L* (dark-light)	79.2 ± 3.3[ab]	80.6 ± 2.9[ab]	76.2 ± 1.4[b]	83.9 ± 1.2[a]	77.7 ± 3.7[ab]	76.7 ± 5.4[ab]	**0.04**
Crumb (centre) - a* (green-red)	−0.8 ± 0.05[a]	−1.2 ± 0.1[bc]	−1.3 ± 0.07[c]	−1.1 ± 0.07[b]	−1.3 ± 0.08[c]	−1.7 ± 0.04[d]	**< 0.0001**
Crumb (centre) - b* (blue-yellow)	12.1 ± 0.7[a]	11.3 ± 0.3[ab]	10.3 ± 0.9[ab]	10.1 ± 0.8[b]	10.7 ± 1.3[ab]	10.5 ± 0.7[ab]	**0.04**
Crumb (centre) - ΔE*	–	4.2 ± 1.8	4.0 ± 2.4	7.1 ± 3.4	3.3 ± 1.3	7.0 ± 3.7	0.20

Data reflects four slices from two different batches (n = 4) and differing letters express significance from pairwise comparisons. L* denotes lightness ranging from 0 (black) to 100 (white); a* evaluates greenness (negative values) and redness (positive values); b* measures blueness (negative values) and yellowness (positive values); and the total colour differences ΔE*compared the standard with Minax-based breads.

expansion and arabinoxylan can negatively impact the gluten network structure (Gomez et al., 2003; Hemdane et al., 2017; Rosell & Santos, 2010; Schofield, 1983).

3.1.2. *Cell crumb structure*

There was an overall significant difference ($p = 0.04$) relating to average cell size; however, there were no pairwise differences between individual breads (Table 3). In addition, breads significantly varied ($p = 0.005$) in terms of the cell area within the crumb; the standard, Minax 61 and 168 had the smallest cell areas whereas Minax-159 had the largest cell area (Table 3). Therefore, it is likely that dietary fibre and/or protein increased the cell area due to the reduced gas cell stability leading to coalescence (Han et al., 2019; Ni et al., 2020).

3.1.3. *Water activity and moisture content*

There were significant differences between breads for water activity ($p = 0.003$) and moisture content ($p < 0.0001$) (Table 3). For example, Minax-128 had the lowest water activity whereas the standard, Minax-100 and 159 had the highest water activity. Breads (standard, Minax-61, 128, 159 and 168) had similar moisture content; yet, Minax-100 had a higher moisture content. This implies that dietary fibre and/or protein increased both water activity and moisture content; such a finding could be expected due to the higher water absorbing capacity of arabinoxylan (e.g., x10 and x11 its dry weight for the water-insoluble and water-soluble fraction respectively) (Guzmán et al., 2015; Finnie & Atwell, 2016). In addition, arabinoxylan content can modulate various processing and quality traits (e.g., dough viscosity, flour water-absorption and bread quality); however, the extent varies with the solubility and molecular weight of the soluble fraction (Courtin & Delcour, 2002).

3.1.4. *Colour*

Colour measurements were recorded in three areas resulting in varying results. There were no significant differences between breads relating to colour differences in terms of crust top (Table 3). However, there were significant differences ($p = 0.02$) relating to lightness values (L^*) from the side crust where Minax-168 and Minax-100 were lighter and darker respectively (Table 3). The crumb colour significantly differed ($p < 0.05$) between breads for all colour coordinates (L^*, a^* and b^*). For example, Minax-128 was the lightest in colour whereas Minax-100 was the darkest in colour. There were also significant differences ($p < 0.0001$) in degree of greenness where the standard and Minax-168 had lower and higher green values respectively. The breads also significantly differed ($p = 0.04$) in the extent of yellowness where Minax-128 was less yellow and the standard was more yellow (Table 3). Dietary fibre and/or protein can result in darker colour but the magnitude of this may depend on the dietary fibre type, source and amount (Almeida et al., 2013; Amoriello et al., 2020). However, it should be noted that the Minax breads were higher in protein than commercial breads and Maillard reactions or other protein-related effects may have resulted in increased crumb colour development. In addition, all colour differences (between the standard and Minax-based breads) were greater than 3.0 which, are considered to be human-perceivable differences (Bodart et al., 2008).

3.1.5. *Texture profile analysis*

The breads varied significantly ($p < 0.05$) in all measured instrumental textural properties (Fig. 2). For example, Minax-168 was the hardest whereas the standard and Minax-128 was the softest. Similar trends were observed for chewiness where Minax-168 was the chewiest and the standard, Minax-61 and Minx-128 were least chewy. Minax-159 and 168 were most springy whereas Minax-100 was least springy.

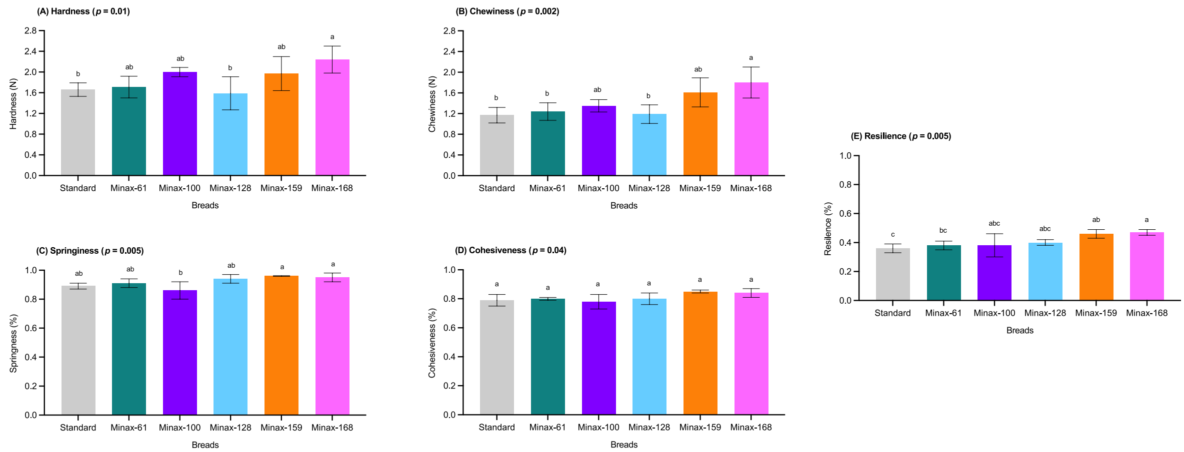


Fig. 2. Instrumental textural attributes (means ± standard deviation) of white breads by (**A**) hardness; (**B**) chewiness; (**C**) springiness; (**D**) cohesiveness; and (**E**) resilience. Data reflects four slices (analysis performed on two stacked slices) from two different loaves (n = 4) and differing letters express significance from multiple pairwise comparisons.

Overall, there was a significant effect ($p = 0.04$) for cohesiveness; however, no significant differences were observed between individual breads. There were also differences in resilience; the standard and Minax-168 being the least and most resilient respectively. This suggests dietary fibre (arabinoxylan) content and/or protein had minimal impact on instrumental texture and the key effect related to springiness (e.g., the bread's spring back ability post first compression cycle). However, dietary fibre-rich breads were polarised in terms of the result (e.g., enhanced dietary fibre lines represented both the least and most springy); therefore, additional investigation to establish the causation of this structural attribute is needed. Springiness is related to elasticity and freshness; accordingly, higher values are considered more desirable whereas lower springiness can contribute to crumbling post slicing (Matos & Rosell, 2012; McCarthy et al., 2005). In addition, it is likely that the causes of the reduction in slice height could also have implications on the textural properties to varying extents depending on the specific dietary fibre source (Dhen et al., 2018).

3.2. Sensory profile

The descriptive sensory profiling demonstrated four significant differences ($p < 0.05$) from twenty-seven attributes between breads as summarised in Table 4. In summary, panellists perceived colour differences relating to the top crust (lighter: Minax-61 and 168 and darker: Minax-128), side crust (lighter: Minax-128 and darker: standard) and crumb colour (lighter: Minax-168 and darker: Minax-159) as well as differences in density (size of bubbles; no differences between individual breads from pairwise comparisons). It should be noted that there were no significant differences for other modalities (such as appearance touch, aroma, taste + flavour, mouthfeel and aftereffects). It was important to understand whether subtle physical properties differences are perceivable by human senses using analytical methodology (e.g., descriptive analysis) to subsequently determine bread sensory quality (Stone & Sidel, 2004; Callejo, 2011). Overall, it was apparent that arabinoxylan content and/or protein had minimal impact on the sensory profile and key effects related to the visual appearance. Such findings can be explained by the physical properties (e.g., larger cell area, smaller slice height and darker colour) to varying extents. It is likely that the lack of effects may relate to relatively small differences in dietary fibre content and how it was incorporated into the food matrix (using a more natural process compared with fortification) and subsequent breadmaking recipes. Going forwards, next steps should focus on capturing consumers' insights to understand the extent of perceivable differences by naïve consumers as well as utilising more sensitive sensory methodology (such as discrimination testing) to better identify commercially relevant differences (especially if breads only have small incremental increases in dietary fibre content) (Lignou & Norton, 2024). In addition, future work should focus on the most common applications of white sliced bread such as toast or sandwiches (Caines, 2022).

3.3. Multiple factor analysis (MFA)

MFA was used to further analyse the relationships between observations (breads) and the multiple tables of variables (composition, physical properties and sensory data). This process involved performing principal component analysis (PCA) for each table of data individually (composition, physical properties and sensory data) before a weighted PCA on the combined columns of all tables was conducted. Fig. 3 shows the correlation maps of observations and variables respectively where the total variation (71.69 %) can be explained in components one (F1) and two (F2).

The standard, Minax-61 and 128 (lower in dietary fibre and protein) breads were positively correlated with the first factor and with attributes such as sweet and salty taste as well as exhibiting a more uniform crust colour and elasticity. In contrast, breads higher in dietary fibre and protein (Minax-100 and 159) were negatively correlated with first factor (located in quadrants two and three on the opposite side) and correlated with taste and aftereffect attributes such as sour, bitter and degree of baked. These two breads were also negatively correlated with size dimensions (height and width) resulting in smaller slices overall. There were also various negative correlations such as cell crumb with density, lighter crust/crumb with less degree of baked and mouthdrying with salivating. It is also worth noting that the springiness instrumentally measured was positively correlated with the springiness as perceived by the panel which means that this parameter can be used as a good predictor for assessing whether breads can return to their initial shape after pressing. Minax-168 (lower in dietary fibre and protein) was positively correlated with these variables alongside hardness resulting in a bread with desirable characteristics. This suggests MFA provides an appropriate method to describe relevant relationships between composition (dietary fibre and protein) and bread characteristics (physical properties and sensory).

In addition, it should be noted that protein can interact with other ingredients subsequently impacting processing and bread quality (e.g., water absorption, dough network structure, appearance and textural attributes, etc.) (Prieto-Vazquez del Mercado et al., 2022). Moreover, hard wheats used for breadmaking typically have higher protein contents than soft wheats due to various factors such as environmental effects, agronomic treatments and genetic differences (Malik et al., 2013; Shevkani et al., 2024). Accordingly, to overcome such a challenge, the

Table 4
Sensory profile (mean ± standard error) of white breads by different modalities and corresponding reference and/or description.

Modality	Attribute	Reference and/or Description	Standard	Minax-61	Minax-100	Minax-128	Minax-159	Minax-168	p-value
Appearance visual	Crust colour uniformity	Overall uniformity of crust colour	45.7 ± 3.7	51.8 ± 3.1	50.1 ± 2.8	47.8 ± 3.4	42.2 ± 3.5	50.6 ± 3.5	0.23
	Crust colour (top)	Intensity of crust colour (top-down perspective)	61.7 ± 3.2[ab]	54.7 ± 3.4[b]	63.8 ± 3.0[ab]	64.7 ± 2.7[a]	57.1 ± 3.5[ab]	55.1 ± 1.9[b]	**0.005**
	Crust colour (side)	Intensity of crust colour (side perspective)	41.3 ± 2.6[a]	31.5 ± 2.3[bc]	36.9 ± 2.6[abc]	39.2 ± 2.7[ab]	27.4 ± 3.0[c]	33.4 ± 2.3[abc]	**0.001**
	Crumb colour (centre)	Intensity of crumb colour (imagine a square in the middle)	28.7 ± 3.0[abc]	23.4 ± 2.5[bc]	30.4 ± 3.3[ab]	26.1 ± 3.4[abc]	31.5 ± 3.2[a]	21.1 ± 2.8[c]	**0.002**
	Density	Size of bubbles	51.5 ± 3.3[a]	55.7 ± 3.8[a]	43.4 ± 2.8[a]	50.4 ± 3.4[a]	44.1 ± 3.1[a]	55.0 ± 3.6[a]	**0.02**
Appearance touch	Elasticity	Resistance to stretching (top-down)	43.5 ± 3.7	52.0 ± 4.0	44.9 ± 4.5	48.5 ± 3.8	37.9 ± 4.2	50.3 ± 3.4	0.06
	Springiness	Return to initial shape after pressing (press with thumb)	44.7 ± 3.6	40.5 ± 3.2	40.2 ± 3.1	43.5 ± 3.4	46.4 ± 4.0	49.0 ± 3.3	0.30
	Surface Softness	Degree of softness by touching (stroke it)	55.4 ± 4.2	51.3 ± 4.0	53.8 ± 3.6	52.6 ± 3.5	59.9 ± 3.9	56.0 ± 3.2	0.24
Aroma	Sour	Citric acid (0.76 g/L)	13.2 ± 2.3	13.2 ± 2.3	16.5 ± 2.9	12.3 ± 2.4	16.1 ± 3.1	14.8 ± 1.9	0.75
	Yeasty	Bread yeast & water	34.2 ± 3.0	37.0 ± 3.3	34.5 ± 3.5	36.3 ± 3.1	29.1 ± 2.8	36.6 ± 3.5	0.12
	Doughy	Flour & water mixture	39.3 ± 3.7	41.2 ± 4.0	35.6 ± 4.2	41.7 ± 3.6	33.1 ± 3.3	38.8 ± 4.1	0.39
	Degree of baked (crust)	Intensity of baked note associated with the crust	54.4 ± 4.1	48.3 ± 3.9	57.7 ± 4.2	56.5 ± 4.3	54.8 ± 4.2	53.3 ± 3.6	0.36
Taste + flavour	Salty	Sodium chloride (1.19 g/L)	15.7 ± 1.7	15.1 ± 2.2	12.9 ± 1.4	13.6 ± 1.1	13.0 ± 1.6	14.6 ± 1.3	0.33
	Sour	Citric acid (0.76 g/L)	13.6 ± 2.6	11.0 ± 2.2	17.0 ± 3.1	12.1 ± 2.3	14.0 ± 2.9	12.5 ± 2.1	0.41
	Sweet	Sucrose (5.76 g/L)	18.7 ± 2.7	15.4 ± 2.4	15.1 ± 2.8	18.0 ± 2.7	16.0 ± 2.4	16.5 ± 2.3	0.34
	Bitter	Quinine (0.04 g/L)	13.6 ± 2.8	10.9 ± 2.7	16.2 ± 3.5	15.0 ± 3.0	16.7 ± 2.2	12.0 ± 2.0	0.22
	Doughy	Flour & water mixture	39.2 ± 3.4	36.5 ± 3.4	33.3 ± 2.5	36.6 ± 3.4	33.6 ± 3.2	32.3 ± 3.1	0.57
	Degree of baked (crust)	Intensity of baked note associated with the crust	49.9 ± 3.7	45.1 ± 3.4	52.5 ± 4.0	53.6 ± 3.6	48.6 ± 3.5	43.6 ± 3.0	0.06
Mouthfeel	Hardness	Degree of force with first bite	37.8 ± 3.0	39.5 ± 3.2	37.1 ± 2.4	40.3 ± 3.6	40.4 ± 3.0	41.6 ± 3.5	0.56
	Chewy	Ease of ability to chew	49.1 ± 3.0	50.0 ± 3.1	48.4 ± 2.8	47.9 ± 3.4	46.0 ± 3.4	45.2 ± 3.2	0.72
	Mouthdrying	Drying sensation within the mouth	36.8 ± 3.6	36.5 ± 3.2	37.6 ± 3.7	36.3 ± 3.8	36.0 ± 2.8	34.8 ± 3.5	0.94
	Tooth packing	Bread crumb sticking to the teeth surface	37.3 ± 4.0	35.1 ± 3.5	33.3 ± 3.7	37.4 ± 3.5	34.7 ± 3.5	36.1 ± 3.3	0.72
	Mouthcoating (film)	Film like coating within the mouth	26.1 ± 4.2	18.4 ± 3.6	24.7 ± 3.5	21.8 ± 3.7	24.6 ± 3.9	20.5 ± 3.5	0.12
Aftereffects	Sour	Citric acid (0.76 g/L)	12.3 ± 2.0	9.3 ± 2.0	13.7 ± 2.6	10.3 ± 2.3	12.8 ± 2.8	9.8 ± 1.8	0.39
	Bitter	Quinine (0.04 g/L)	10.4 ± 2.7	10.5 ± 3.1	12.2 ± 2.7	11.1 ± 3.1	11.1 ± 2.2	9.7 ± 2.2	0.94
	Salivating	Increased saliva within the mouth	30.1 ± 2.1	31.6 ± 1.9	29.6 ± 2.2	31.8 ± 2.9	31.3 ± 2.1	31.1 ± 2.2	0.95
	Mouthdrying	Drying sensation within the mouth	31.1 ± 3.2	34.1 ± 3.1	33.3 ± 3.7	32.5 ± 3.1	32.8 ± 2.8	32.4 ± 2.7	0.93

Data collected on visual analogue scales (VAS; 0–100) reflects two replicates (scored in separate sessions) from the trained sensory panel (n = 12) and differing letters express significance from pairwise comparisons.

recipe (informed from pilot baking) had sufficient dough conditioner and proportion of water added to help deal with potential challenges resulting from the higher protein content (range: 13.6–17.5 %) than expected in the flour. The breadmaking was also conducted by a commercial bakery which may have minimised measured differences resulting from the variation in protein and dietary fibre contents. Therefore, future work is required to explore the relationship between dietary fibre and protein in the context of white bread to fully quantify the extent of consumer-relevant differences. In addition, developing models that can predict the impact of dietary fibre variation on processing properties will enable bakers to adjust their processes in order to maximise benefits of high fibre white bread to consumers.

4. Conclusion

This paper conducted a series of experiments to determine the relationship between physical properties and sensory characteristics of white bread prototypes varying in dietary fibre and protein content. It was evident that the key sensorial effects between breads related to the appearance (colour and density). This could be explained by the physical properties to varying extents such as breads higher in dietary fibre tended to have smaller slice height, larger cell area, higher water activity and moisture content as well as instrumental texture (springiness) and colour (darker) differences. Accordingly, future work should focus on additional product development to minimise cited reductions in quality resulting from enhancing dietary fibre/protein and explore the

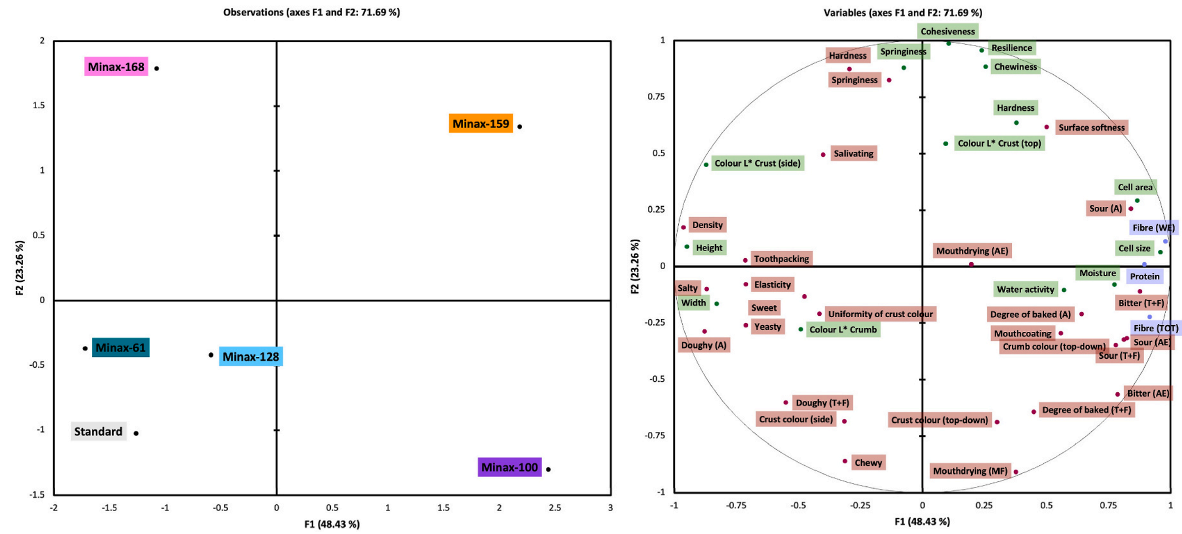


Fig. 3. Overview of multiple factor analysis by observations (bread representation) and variables distribution (**composition**, **physical properties** and **sensory: A – aroma; T + F – taste + flavour; MF – mouthfeel; and AE – aftereffects**).

application of naturally higher-than-average wheat in other baked food matrices as well as capturing relevant consumer insights. Overall, developing white bread with enhanced nutritional composition without modulating cost, taste and current processes could have widespread and transformative benefits for the food industry and consumers.

CRediT authorship contribution statement

Victoria Norton: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julia Rodriguez-Garcia:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Carol Wagstaff:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Alison Lovegrove:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Peter Shewry:** Writing – review & editing, Methodology, Funding acquisition. **Mark Charlton:** Writing – review & editing, Methodology, Funding acquisition. **Nicola Gillett:** Writing – review & editing, Methodology, Funding acquisition. **Marcus Tindall:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Anneke Prins:** Writing – review & editing, Investigation. **Stella Lignou:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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.

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Data availability

Data will be made available on request.

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