EFFECTS OF BLACKCURRANT FIBRE ON DOUGH PHYSICAL PROPERTIES AND BREAD QUALITY CHARACTERISTICS

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Abstract

Wheat flour was partially replaced with blackcurrant pomace, soluble, and insoluble dietary fibre in dough and bread formulations. The impact of blackcurrant fibre on physical properties of doughs and breads was probed using a set of complementary physicochemical techniques. The effect of fibre on aromatic profile of substituted breads was performed using analysis of volatile compounds. Analysis of fibre-substituted doughs and breads revealed that supplementation with pomace or insoluble fibre at concentrations >5 % w/w or with pectin at concentrations >0.5 % w/w alters their overall physicochemical responses. Pomace and pectin primarily acted as water-binders and decreased the extent of gluten hydration but insoluble fibre did not bind water to the same extent suggesting higher interaction capacity between its cellulosic components and gluten proteins resulting in formation of stiffer doughs. More than one hundred volatiles were determined with alcohols, furan derivatives and aldehydes being the major aromatic compounds.

Keywords: *blackcurrant; fibre; dough; bread; aroma*

1. Introduction

The interest for incorporation of dietary fibre (DF) in bakery formulations has risen in recent years due to their physiological benefits or technological functionality [1]. DFs obtained from cereals have been explored and applied in bakery formulations, while utilisation of those derived from fruit and vegetable co-products is also a topic of ongoing research [2, 3]. Incorporation of DFs into bread dough leads to changes in the rheology and bread quality, as a result of the numerous macromolecular interactions. Investigations of the impact of DF on dough and bread quality have indicated that changes in dough viscoelastic behaviour affect loaf volume, crumb hardness and sensory properties of bread [2, 4]. However, the negative technological impacts of DF may be alleviated by selecting fibres that have a beneficial ratio of insoluble-to-soluble DFs [5].

Fruit DFs derived from co-products of juice and wine industries have higher ratios of insoluble-to-soluble DF (1:0.22-0.40) as a result of higher proportion of soluble DF when compared to cereal DFs (1:0.07) [1, 3]. Moreover, fruit soluble DFs are often bound to phenolic compounds and their addition in bread may result in delivery of additional health benefits [6]. Fruit DFs have been previously added in bread to replace wheat flour leading to variable end-product quality [7, 8]. These studies focused on the impact of soluble and insoluble DFs on either dough rheology or bread quality. However, the impact of fruit pomace and its DF fractions on both dough rheology and final bread quality has not been studied yet.

In our previous work, we have identified blackcurrant pomace as a source of soluble and insoluble DF and have performed comprehensive analysis of these fibre fractions [9]. It was therefore hypothesised that blackcurrant DF could be utilised as flour substitute in white bread formulations. Although a major motivation was to increase DF content of bread, the highly aromatic nature of blackcurrant pomace could be an additional benefit, potentially allowing creation of breads with distinctive aromas. Therefore, a further component of the current study was to evaluate the aromatic profile of breads containing blackcurrant pomace and its fractions. The aim of this study was to formulate fibre-enriched bread using DFs from blackcurrant pomace. The objectives, therefore, were to study the technological influence of blackcurrant pomace and its soluble and insoluble fractions on the physical properties of dough and bread.

2. Materials and methods

2.1 Materials

Dried blackcurrant pomace (*Ribes nigrum* L.) consisting of stems, seeds and exocarp was obtained from Lucozade Ribena Suntory (LRS, UK). The pomace was milled using Retsch ZM 1000 ultra-centrifugal mill (Retsch GmbH, Haan, Germany) equipped with 0.5 mm sieve at 10000 rpm. Blackcurrant soluble DF (SDF, pectin) and insoluble DF (IDF) were obtained following the isolation procedures described elsewhere [9]. Major physicochemical characteristics of samples are shown in Table S1. Bread flour (13.4 % w/w protein, 66.8 % w/w starch, <0.01 % w/w salt, Sainsbury’s, UK), vegetable shortening (TREX, mixture of rapeseed and palm oils, Princes Limited, UK) and dried yeast (94 %, Sainsbury’s, UK) were obtained from a local supermarket.

2.2 Sample preparation

Dough ingredients were mixed using a Minorpin mixer for 7 min at room temperature using two formulations (Table 1). Formulation 1 was used for creep-recovery, differential scanning calorimetry (DSC) and scanning electron microscopy (SEM) experiments. Doughs for dynamic dough density measurements (DDD) and breadmaking were prepared using formulation 2. DFs were incorporated in the dough by partially replacing flour at the following levels: 5, 10, 15 or 20 % w/w for blackcurrant pomace and IDF or 0.5, 1.0, 1.5 and 2.0 % w/w for pectin, plus a control with no DF. The preliminary work has shown that doughs formulated with substitution levels above 20 % w/w of blackcurrant pomace and IDF, and 2.0 % w/w of pectin had non-homogeneous structure indicating the absence of gluten network development.

The dough for breadmaking was prepared by mixing ingredients in a spiral mixer (Kenwood 1200W, Italy) for 7 min. After mixing, the dough (800 g) was proved at 38°C for 30 min in electric oven (Whirlpool Appliances LTD, UK). Following the first fermentation stage, the dough was divided into eight pieces of ~100 g, moulded, and proved for another 30 min and finally the loaves were baked at 175°C for 27 min (Whirlpool Appliances LTD, UK). After cooling, samples were packed in zip-lock bags, sealed and stored at room temperature overnight.

2.3 Rheological measurements

Fresh dough was loaded onto the rheometer (Kinexus, Malvern, UK) equipped with serrated parallel-plate geometry (diameter 40 mm) with 1 mm gap at 25°C. Samples were trimmed and the edges were covered with light silicone oil to prevent evaporation. Creep was performed at constant shear stress of 7 Pa for 30 min within the LVR of the sample that was determined using amplitude sweep experiments (0.01–100 % strain, 1 Hz, 25°C). Creep was followed by 30 min recovery and finally by frequency sweeps performed in the range of 0.1-100 Hz at a shear strain of 0.05 % within the LVR. The compliance curves of dough samples for the creep and recovery phase were fitted to a Burgers model and fitting was performed using Prism 6 software (Graphpad Software, Inc.).

2.4 Dynamic dough density measurements and thermal properties of dough

DDD measurements were performed as described previously [10]. Starch gelatinisation temperatures were determined using DSC. Dough samples (50–60 mg) were sealed in aluminium pans (Alod-Al) and heated at a rate of 10°C min^{-1} from 20-140°C using a Star

System DSC1 (Mettler Toledo, Switzerland) with an empty pan as a reference to determine peak (T_p) gelatinisation temperatures.

2.5 Analysis of bread loaves

Breadcrumbs were examined using a TA-XT2 texture analyser (Stable Microsystems, Surrey, UK). Each loaf was cut into 25 mm thick slices and compression tests were performed using a 20 mm diameter cylindrical probe. Compression was performed at 40% strain with a test speed of 1.7 mm s^{-1} and with a trigger force of 5 g. Hardness (N) and Young's modulus (kPa) were obtained from averaging values of forty-eight replicates. Loaf specific volume (LSV) was measured with the poppy seed displacement method (AACC method 10-05.01).

2.6 Dough and bread morphology

The morphology of dough was studied using FEI Quanta FEG 250 scanning electron microscope. Fresh dough samples were fixed to 30 mm diameter aluminium SEM stub using double-sided conductive carbon tape (Agar Scientific, UK). Samples were dehydrated and coated with a layer of gold/palladium using a sputter coater (Quorum Technology SC7920) for 60 s. Images were obtained at 20 kV accelerating voltage.

Bread samples were dissected and at least fifteen images were captured from each sample using a flatbed scanner followed by image analysis on ImageJ (v. 1.51m9, NIH, USA). The images were saved with a resolution of 1240×1753 pixels, converted to 8-bit greyscale, and thresholding was accomplished using the Otsu algorithm. The length-scale of the image was converted into cm using an image of known length. Following this, a square selection of constant size was drawn in each image and particles were analysed after excluding the edges to obtain the morphological characteristics of breadcrumbs.

2.7 Volatile analysis

Freshly baked breads were cooled for 15 min at room temperature and two slices from the loaves centre were cut into small pieces, frozen in liquid nitrogen, ground and stored at

−20°C until analysis. Volatile compounds were isolated and analysed by HS-SPME-GC-MS following the procedure described in detail elsewhere with some modifications [11]. Chromatographic separation was achieved using a DB-WAX capillary column (60m×0.32 mm i.d.×0.25 μm film thickness, Agilent Technologies) with helium as a carrier gas at flow rate of 2 mL min^{-1}.

2.8 Statistical analysis

Statistical analysis of the data was performed by means of two-factor analysis of variance. Significant differences among the respective means were determined using Tukey's least significant difference test. The Shapiro–Wilk test was applied to test normality of data. *t*-Test and post hoc Duncan's test were applied to study the differences between means of concentrations of volatile compounds.

3. Results and discussion

3.1 Dough rheological behaviour

Storage modulus was the predominant viscoelastic function highlighting the solid-like viscoelastic behaviour of all samples (Figures 1a and inset, and S1). Elastic modulus (G') of samples formulated with 0.5 and 1.0 % w/w of pectin, or 5 % w/w of pomace or IDF, was comparable to that of control dough, indicating that DF does not affect dough viscoelasticity at these levels of substitution (Figures 1a and S1). Further addition of DFs resulted in increase of G' with concomitant reduction of tanδ indicating stiffening of the dough (Figure 1a, inset). Addition of IDF increased dough elasticity to a greater extent than pomace or pectin at all substitution levels. This was attributed to the higher cellulose content present in IDF as opposed to pomace.

Changes in viscoelastic behaviour of dough substituted with IDF and pomace may be caused by the "dilution" of the gluten network and the water-binding properties of these fractions. Recent studies have attributed the strengthening of fibre-substituted doughs to the conformational alterations of gluten proteins upon addition of DF leading to the formation of stiffer dough network [8, 12]. Changes in viscoelasticity can be also attributed to the microstructural reordering induced by the presence of fibre particles. In control dough, the continuous gluten network surrounds starch granules uniformly (Figure 1b), whereas in fibre-enriched samples the presence of particles resulted in partial separation of starch granules from the gluten network (Figure 1c). These qualitative microstructural changes have repercussions that are reflected in the mechanical spectra of the samples. Incorporation of all fibres at maximum substitution levels leads to a drop of tanδ, particularly for samples with IDF (10-20% w/w) (Figure 1a, inset) suggesting that water-binding properties of some fibre components may also contribute to the G'. This is also evidenced by the minimum microstructural changes induced in samples with pectin, as mechanical changes were not associated with substantial modifications in the gluten network (Figure S2a).

The impact of soluble DF on dough viscoelastic behaviour varies. Previous studies that focused on incorporation of pectin (0.5-2% w/w) in dough or pectin-gluten mixtures have reported a disruptive effect of pectin on the gluten network leading to losses in elasticity [13, 14]. Contrasting results were observed at higher concentrations (3-6 % w/w) that were attributed to the increase in dough viscosity caused by the strong pectin-water interactions [15]. The disruptive effect of pectin on the gluten network could be attributed not only to its water-binding ability, but also to the polyelectrolyte nature of pectin that interacts with gluten proteins *via* carboxyl groups resulting in formation of complexes that interfere with the formation of gluten network. It has been previously suggested that the extent of interaction between pectin and gluten depends on the degree of methyl-esterification of pectin [13, 14]. Low methoxylated pectin (LM) has higher negative charge density than high methyl-esterified (HM) pectin and, therefore, it has greater interaction capacity with gluten proteins. Blackcurrant pectin used in the present work was LM pectin (Table S1) suggesting strong interactions with gluten proteins leading to stiffening of the dough and increase in G' (Figure S1).

Creep-recovery tests were used to further investigate the influence of DFs on doughs (Figure 2a). During creep, sample-compliance increased with partial structure recovery after stress removal. The instantaneous (J_0) and retarded (J_1) elastic compliances decreased with DF concentration indicating stiffer structure formation (Figure 2a, Table 2). J_0 values of dough substituted with 0.5-1.5% w/w of pectin and 5% w/w of pomace or IDF were comparable to those for control-dough and were higher than J_0 values of samples formulated with higher levels of DF (Table 2). High J_0 values imply softer doughs with lower ability to recover after stress removal. The low compliances (J_0 and J_1) and high steady-state viscosity (η_0) confirmed that dough forms a highly elastic network upon increase of fibre concentration (10-20% w/w for pomace or IDF and 1.5-2.0% w/w for pectin) that may lead to reduced loaf volumes. Similar trends in rheological behaviour were reported for doughs enriched with highly polymerised inulin [4]. High retardation times (λ) indicate-slower dough elastic response, whereas low λ indicates elastic behaviour closer to ideal. Addition of pomace, IDF (5-15% w/w) and pectin (0.5-1.5% w/w) did not affect λ of samples in the creep phase; comparable trends have been reported for doughs formulated with blackcurrant pomace at substitution level of 10-30% w/w [8]. Generally, addition of soluble DF increases λ in white flour formulations and the magnitude of increment depends on the structural features of the fibre [16].

Compliances (J_0, J_1) in the recovery phase demonstrated trends comparable to those during creep (Table 2). The instantaneous elastic recovery is related to baking performance with higher instantaneous elastic recoveries yielding higher bread volumes. Consequently, inspection of J_0 values shows that dough substituted with 5-10% w/w of pomace or IDF and 0.5% w/w of pectin may result in loaves with volumes comparable to the control. The degree of structure recovery after load removal impacts breadmaking quality of dough. Dough recovery depends on the elastic portion of the material, whereas permanent deformation is determined by the viscous component of the maximum compliance ($J_{\max}$). The elastic recovery of doughs was expressed as $J_1^0/J_{\max}$ and the low values are associated with more viscous material (Table 2). The highest elastic recovery was observed for doughs formulated with 15, 20% w/w of pomace and 2% w/w of pectin. Substitution of dough with lower levels of pomace (5-10% w/w) and pectin (0.5-1.5% w/w) resulted in lower recovery of the material that was comparable to the control. IDF-enriched doughs demonstrated recovery ability comparable to control at all substitution levels. High permanent deformation of IDF-doughs indicates that elastic bonds are not dominant, particularly at high substitution levels, as opposed to pomace- and pectin-enriched doughs. Interplay between IDF components (e.g., cellulose) and gluten proteins interrupt elastic interactions between gluten proteins. In contrast, high elasticity and recovery ability of dough formulated with pomace (>10% w/w) and pectin (>1.5% w/w) could be attributed to the presence of components that enhance elasticity of gluten network.

3.2 Dynamic dough density (DDD) measurements and thermal properties of dough

Incorporation of pomace and IDF at 5-10% w/w or pectin at 0.5-1.0% w/w had negligible impact on the mechanical properties of dough and these formulations were further tested in DDD measurements to link rheology with breadmaking ability. Dough-density changes as a function of time were monitored, as maximum expansion of dough corresponds to the minimum density (Figure 2b, Table 3). Substitution of flour with 0.5% w/w of pectin and 5% w/w of pomace or IDF did not alter expansion ability of gluten network, as indicated by the minimum density values (Table 3). Dough expansion and gas retention ability gradually decreased with increasing DF concentration, as indicated by higher minimum-density values and shorter fermentation times for pomace-, IDF- and pectin-substituted doughs (Table 3, Figure 2b). The impact of IDF on dough expansion ability was comparable to that of pomace at all levels of substitution. Rheological analysis of samples formulated with high concentrations of pomace, IDF (>10% w/w) or pectin (>1.0% w/w) exhibited strong elasticity (Figures 1, S1, and 2) suggesting that greater gas pressure is required to achieve expansion comparable to the less elastic control dough.

Addition of inulin in dough results in decrease of dough volume [4] similarly to blackcurrant pectin, however, fermentation times of doughs formulated with blackcurrant LM-pectin were shorter. In contrast, prolonged fermentation times have been reported in doughs formulated with HM-pectins [5]. Similarly, shorter fermentation times have been reported for dough formulated with alginates [17]. A downward trend in fermentation times was observed upon increase of pomace and IDF levels and was comparable to results obtained for dough substituted with carob fibres [18]. Generally, DDD results are in agreement with rheology, particularly for doughs enriched with 5% w/w of blackcurrant pomace or IDF, or 0.5% w/w pectin, whereas deviations were observed at higher concentrations.

DFs interact strongly with water, thus restricting access of starch granules to water leading to limited granule swelling and higher gelatinisation temperatures (T_{peak}). Substitution of model doughs with pectin resulted in a considerable shift of starch T_{peak} towards higher values (Table 3). Generally, addition of pectin had the highest impact on T_{peak} compared to pomace and IDF. Previous studies on incorporation of soluble DF in dough demonstrated variable trends in the effect of fibre on thermal transitions of starch. Addition of arabinoxylan or β-glucan in fibre-starch mixtures (1% w/w) did not modify T_{peak} [19]. In contrast, delayed endothermic transitions of starch have been reported in pectin-wheat flour mixtures (1% w/w).[20] Dough formulated with IDF exhibited T_{peak} values comparable to the control suggesting negligible impact on starch swelling dynamics (Table 3). Comparable results have been reported for doughs formulated with pea and carob fibre [18]. In contrast, addition of predominantly insoluble DFs in gluten-free dough formulations resulted in elevation of T_{peak} values [21]. Changes in water-starch interactions are frequently attributed to the high water-binding capacity of IDF [22]. Calorimetric findings show that IDF did not measurably interact with water, thus highlighting its impact on the continuity of gluten network (Figure 1c). Variations in the water-binding capacity of IDF from different sources may be attributed to the compositional characteristics of each fibre, particle size, and water-affinity of the individual fibrous components. Particle size of blackcurrant IDF used in our work was larger (<0.5 mm) than in the aforementioned studies, suggesting a decrease in water-binding capacity due to the reduction of the total surface area available to interact with water. Additionally, the presence of substantial amount of lignin may form water-impermeable fibre complexes. Finally, addition of pomace modified T_{peak} by restricting water access to the amorphous parts of the granules because of their higher content of soluble fibre (Table S1).

3.5 Characterisation of fibre enriched bread

High rigidity and low expansion ability of doughs formulated with 10% w/w pomace and IDF or 1.0% w/w of pectin during the fermentation stage resulted in lower loaf specific volumes (LSV) compared to control in congruence with rheology (Table 4, Figure 3a, b). Moreover, at the highest substitution levels pomace and IDF had greater impact on LSV than pectin. Similarly, low LSV values were reported for breads formulated with IDF isolated from peas, lentils, and chickpeas whereas LSV values for breads substituted with soluble fibre from the same sources were comparable to the control [22]. Reduction of LSV is the result of formation of a tightly packed crumb structure. Breads at the highest levels of fibre substitution had low LSV with elastic (Young's modulus, E) and hard (hardness) crumb structures. Generally, a good relationship between instantaneous elastic compliance (J_0) of dough, DDD expansion of yeasted dough, and LSV has been demonstrated. This shows that all DFs studied exert their effects predominantly during proving, rather than baking, as is reflected in the final volume of the loaves. Contrasting results have been reported for breads formulated with wheat bran where fibre acts during baking thus lowering the final bread volume [10].

Cellular structure and mechanical properties of breadcrumb are closely related and have direct impact on the final bread acceptance. Loaves with 5% w/w of pomace or IDF had similar total number of gas cells compared to control. Incorporation of pomace and IDF at 10% w/w resulted in reduction of total cell number and average cell area (Table 4, Figure 3a). The presence of fewer small gas cells highlights the formation of dense crumb in loaves formulated with 10% w/w of pomace and IDF and is further supported by the high *E* and low LSV. Similar observations were made for grape and blackcurrant pomaces [8, 23]. Contrasting results were observed for samples formulated with pectin at all levels of substitution. Addition of 0.5% w/w of pectin increased the total number of cells whereas formulations with 1.0% w/w were comparable to the control (Table 4, Figure 3b). The presence of pectin at either 0.5 or 1.0% w/w did not affect average cell area, as was observed in loaves prepared with 10% w/w of pomace or IDF. No clear relationship was established between cell structure, Young's modulus and hardness for pectin-substituted breads.

Mechanical properties of crumb are commonly attributed to the geometrical characteristics of the gas cells. Generally, the crumb of all samples had more elongated shape of gas cells than the control, as indicated by the circularity values (< 1) and the asymmetry of gas cells, which increased when the substitution levels were raised (pomace and IDF – 10% w/w, pectin - 1.0% w/w). Moreover, solidity, a measure of shape disorder of gas cells, was also higher in DF-enriched breads than in control, indicating the formation of gas cells of ruffled and non-uniform shape. In contrast, improvement of gas cell symmetry (i.e., circularity) has been reported upon addition of LM or HM pectins in bread formulations [14] showing that under certain circumstances pectin may contribute to stabilisation of gas cells and prevent formation of irregular and coarse crumb structures.

3.7 Analysis of bread aroma

The addition of blackcurrant pomace and its fractions had both a qualitative and quantitative effect on aroma profile of breads (>100 compounds were determined) (Table S2). Alcohols and carbonyl compounds, stemming either from the Ehrlich pathway during fermentation, lipid oxidation or Strecker degradation, were the major aroma compounds and higher amounts were identified in breads formulated with pomace and IDF compared to the control. The 3-methyl-1-butanol and 2-phenylethanol, being positively correlated with the aroma of wheat breadcrumb, were principal alcohols identified in all samples. The 1-hexanol and 1-octen-3-ol, products of linoleic acid degradation, were primarily identified in IDF volatile fraction, while terpinen-4-ol was identified exclusively in breads substituted with pomace originating from the raw material [24]. The twofold increase of carbonyl compounds in the case of pomace and IDF-containing breads could be attributed to the presence of lipids derived not only from wheat flour but also from the blackcurrant raw material [9]. Blackcurrant pomace contains a high percentage of polyunsaturated fatty acids, mainly linoleic, oleic, and hexadecanoic acid [25], which are the precursors of a number of active odorous components. Similarly, high ester and carbonic acids concentrations were measured in breads formulated with pomace and IDF with acetic, hexanoic and octanoic acids associated with "cheesy/fatty" odours be notably increased upon their addition. On the other hand, the amount of heterocyclic aroma compounds, mainly produced during baking process, was significantly decreased in substituted breads. The pyrazine content varied across the bread samples, exhibiting a ~63% decrease in the pomace sample, while only a very small amount was present in the IDF. The same pattern was also followed by other Maillard volatiles (e.g. pyrrole, pyridine, pyran derivatives) possibly due to the ability of lignin to bind amino acids, thus decreasing their availability to participate in reactions taking place during baking [26]. Finally, concentration of terpene hydrocarbons, being previously detected in the volatile fraction of blackcurrant aroma extracts isolated from berries, leaves and buds [24, 27] was significantly higher in breads baked with DFs compared to wheat bread.

4. Conclusions

Addition of blackcurrant pectin and pomace resulted in formation of elastic doughs, as a result of their water-binding properties and interactions with its components. High interaction potential of blackcurrant pectin and gluten proteins was attributed to the low degree of esterification of this pectin. In contrast, blackcurrant IDF did not measurably interact with water and demonstrated disruptive impact on the continuity of the gluten network. This behaviour was attributed to the high contents of lignin and cellulose in IDF. It was shown that substitution of dough with 5% w/w of pomace and IDF or 0.5% w/w of pectin results in production of breads with textural and aroma characteristics comparable to control. However, image analysis of breadcrumbs demonstrated that addition of pomace, pectin and IDF at all levels modified morphology of gas cells. Overall, it has been shown that blackcurrant DFs may be used as novel, sustainable ingredients in bread formulations.

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Conflict of interest

The authors declare that they have no conflict of interest.

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TABLES

Table 1. Formulations of model dough in g/100 g of dough (% w/w). In parenthesis, dough formulations are expressed as percentage on flour weight.

Ingredient	Formulation 1	Formulation 2
Flour and fibre	62.5 (100%)	58.6 (100%)
Water	37.5 (60%)	35.1 (60%)
Salt	-	1.0 (1.7%)
Yeast	-	2.4 (4%)
Fat	-	2.9 (5%)

Table 2. Effect of blackcurrant pomace, pectin, and IDF on creep-recovery compliance parameters of model non-yeasted doughs. $J_1^0/J_{\max}$ is the elastic portion of maximum creep compliance, $J_{\max}$ the maximum creep compliance (i.e., compliance at the end of creep phase), and J_1^0 the steady-state compliance (i.e., the elastic component, calculated by subtracting the terminal point of recovery curve from $J_{\max}$ value). Mean values in the same column with different letter are significantly different than the control ($p \leq 0.05$).

		Creep phase		
Sample	**J_0 ($\times10^{-4}$ Pa^{-1})**	**J_1 ($\times10^{-4}$ Pa^{-1})**	**λ (s)**	**η_0 ($\times10^{6}$ Pa s)**
Control	2.08±0.82^{a}	8.00±0.96^{a}	227.00±12.80^{a}	1.19±0.37^{a}
Pomace (% w/w)				
5	2.76±0.22^{a}	11.16±3.85^{a}	129.2±35.64^{b}	0.81±0.02^{a}
10	0.82±0.11^{b}	8.16±2.20^{a}	243.00±1.70^{a}	2.50±0.09^{b}
15	0.45±0.03^{b}	1.52±0.26^{b}	117.1±31.14^{b}	9.05±0.10^{b}
20	0.25±0.04^{b}	1.41±0.37^{b}	129.3±6.01^{b}	11.12±0.94^{b}
IDF (% w/w)				
5	1.34±0.15^{a}	7.85±1.68^{a}	155.3±15.27^{a}	1.95±0.19^{a}
10	0.52±0.08^{b}	3.71±0.43^{a}	221.70±4.60^{a}	4.04±0.58^{b}
15	0.32±0.08^{b}	2.79±0.34^{b}	262.80±14.50^{a}	7.29±0.33^{b}
20	0.10±0.04^{b}	0.94±0.12^{b}	333.90±2.76^{b}	25.41±1.38^{b}
Pectin (% w/w)				
0.5	1.48±0.22^{a}	4.19±0.32^{a}	151.40±25.10^{a}	1.51±0.27^{a}
1.0	1.40±0.52^{a}	4.35±1.35^{a}	193.90±35.00^{a}	2.31±0.11^{a}
1.5	1.17±0.15^{a}	2.72±0.47^{b}	213.30±4.10^{a}	2.98±0.0.21^{b}
2.0	0.63±0.06^{b}	3.55±0.29^{a}	139.50±7.00^{b}	4.88±0.03^{b}
		Recovery phase		
Sample	**J_0 ($\times10^{-4}$ Pa^{-1})**	**J_1 ($\times10^{-4}$ Pa^{-1})**	**λ (s)**	**$J_1^0/J_{\max}$ (%)**
Control	15.90±3.23^{a}	7.65±0.55^{a}	209.00±22.30^{a}	33.56±1.78^{a}
Pomace (% w/w)				
5	22.84±2.18^{a}	9.52±1.03^{a}	268.90±36.20^{a}	34.29±0.56^{a}
10	8.98±2.41^{a}	3.14±0.15^{b}	209.10±35.99^{a}	54.01±7.76^{a}
15	1.74±0.70^{b}	2.42±0.37^{b}	313.40±17.96^{a}	61.51±3.54^{b}
20	1.67±0.07^{b}	0.91±0.06^{b}	273.10±19.01^{a}	66.03±9.45^{b}
IDF (% w/w)				
5	11.71±0.98^{a}	5.30±0.06^{b}	220.80±10.32^{a}	37.28±2.05^{a}

10	6.17±0.91^b	2.16±0.26^b	206.30±30.76^a	31.18±0.29^a
15	4.57±1.33^b	1.16±0.28^b	323.80±8.06^a	29.14±8.13^a
20	1.45±0.21^b	0.23±0.15^b	195.40±4.70^a	16.28±0.82^a
Pectin (% w/w)				
0.5	12.73±5.66^a	6.00±0.26^a	263.60±64.42^a	40.26±12.37^a
1.0	7.81±0.55^b	4.44±0.68^b	231.50±5.30^a	42.89±3.62^a
1.5	5.54±0.58^b	3.18±0.68^b	296.80±39.03^a	44.12±3.78^a
2.0	3.15±0.51^b	3.22±1.00^b	264.20±14.35^a	63.16±4.64^b

Table 3. Dynamic dough density (DDD) parameters of yeasted doughs, and starch gelatinisation temperatures (T_{peak}) of non-yeasted doughs substituted with different levels of blackcurrant dietary fibres. Mean values in the same column with different letter are significantly different than the control ($p \leq 0.05$).

Sample	Minimum density (g cm^{-3})	Fermentation time to minimum density (s)	T_{peak} (°C)
Control	0.33±0.02^a	2496 ±223^a	63.9±0.3^a
Pomace (% w/w)			
5	0.33±0.01^a	2220±113^a	64.4±0.3^b
10	0.48±0.02^b	1487±42^b	64.8±0.3^b
15	0.72±0.02^b	907±21^b	64.5±0.2^b
20	0.88±0.00^b	700±14^b	64.5±0.2^b
IDF (% w/w)			
5	0.37±0.02^a	2347±106^a	63.9±0.1^a
10	0.51±0.04^b	1417±100^b	64.1±0.2^a
15	0.77±0.06^b	907±49^b	64.2±0.3^a
20	0.94±0.02^b	650±71^b	64.2±0.2^a
Pectin (% w/w)			
0.5	0.34±0.01^a	2730±101^a	64.5±0.3^b
1.0	0.44±0.01^b	2067±112^b	65.3±0.2^b
1.5	0.55±0.03^b	1547±45^b	66.3±0.2^b
2.0	0.61±0.02^b	1230±57^b	67.0±0.3^b

Table 4. Characterisation of breads formulated with blackcurrant dietary fibre. Mean values in the same column with different letter are significantly different than the control ($p \leq 0.05$).

Sample	**LSV[*] (cm^3 g^{-1})**	**Young's modulus (kPa)**	**Hardness (N)**	**Total number of cells**	**Average cell area (cm^2)**	**Circularity**	**Solidity**
Control	3.7±0.2^{a}	57.2±20.4^{a}	5.6±1.7^{a}	201±34^{a}	0.24±0.08^{a}	0.49±0.04^{a}	0.75 ±0.02^{a}
Pomace (% w/w)							
5	3.4±0.2^{b}	80.1±24.7^{b}	7.7±1.7^{b}	175±43^{a}	0.25±0.05^{a}	0.44±0.03^{b}	0.71 ±0.02^{b}
10	2.8±0.3^{b}	95.6±26.7^{b}	11.4±2.4^{b}	91±28^{b}	0.11±0.06^{b}	0.40±0.03^{b}	0.67 ±0.02^{b}
IDF (% w/w)							
5	3.5±0.3^{a}	70.2±28.4^{a}	6.3±1.8^{a}	229±44^{a}	0.24±0.06^{a}	0.41±0.03^{b}	0.69 ±0.02^{b}
10	2.5±0.4^{b}	100.4±25.6^{b}	10.9±2.9^{b}	61±24^{b}	0.08±0.03^{b}	0.40±0.04^{b}	0.67 ±0.02^{b}
Pectin (% w/w)							
0.5	3.6±0.3^{a}	58.2±19.4^{a}	5.0±1.2^{a}	239±32^{b}	0.27±0.07^{a}	0.42±0.03^{b}	0.70 ±0.02^{b}
1.0	3.1±0.3^{b}	93.8±28.3^{b}	8.5±1.7^{b}	225±69^{a}	0.24±0.07^{a}	0.39±0.03^{b}	0.67 ±0.02^{b}

[*] LSV stands for loaf specific volume and equals to loaf volume (cm^3) over loaf weight (g).

FIGURE CAPTIONS

Figure 1. a) Representative mechanical spectra of model doughs formulated with blackcurrant dietary fibres with inset showing loss tangent of samples, b) scanning electron micrograph of control dough, and c) scanning electron micrograph of samples enriched with insoluble dietary fibres (20 % w/w). **GF** stands for gluten film, **SG** for starch granules, and **FP** for fibre particles.

Figure 2. a) Effect of blackcurrant pomace (POM), pectin (PECT) and insoluble dietary fibre (IDF) on creep and recovery curves of model dough. Inset shows creep-recovery data of model doughs substituted with the maximum levels of dietary fibre (20 % w/w of blackcurrant pomace and IDF, 2 % w/w of blackcurrant pectin). b) Representative curves showing changes in dough density as a function of fermentation time at different levels of substitution of model dough with blackcurrant pomace (POM), pectin (PECT) and insoluble dietary fibre (IDF). Dotted grey lines indicate maximum expansion of control dough that corresponds to the lowest density value of the curve. Increase of density after the plateau region indicates collapse of dough network.

Figure 3. Middle sections of breads formulated with a) 5-10 % w/w of blackcurrant pomace (POM), b) 0.5-1.0 % w/w of pectin (PECT) and c, d, e) image analysis of the air-cell structure of samples. c) An image is captured from approximately the middle area of the crumb, d) image conversion to 8-bit followed by thresholding. Size analysis has been carried out in the yellow square after excluding cells at the edges, and e) islets are air-cells and spatial dimensions were measured for each one and red dots are air-cell counts.