



Wholegrain oat quality indicators for production of extruded snacks

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ABSTRACT

Extrudates made of 30 different wholegrain oat flour samples with diverse chemical composition were prepared using a twin-screw extruder (screw speed 400 rotations per minute, temperature profile 140-130-90-85 °C (die to feed), flour feed rate was 60 g/min and total moisture content 15%). Each wholegrain oat flour was mixed with 30% rice flour (dry basis) and extruded under constant temperature, screw speed, water and feed rates. Generic descriptive sensory analysis was performed for 10 selected samples. Principal component analysis (PCA) and partial least squares regression (PLS) models were used to assess interactions between the sensory and instrumental data. Degree of extrudate expansion varied between 143 and 305%, while density varied between 198 and 785 kg/m³. Hardness of samples were between 44 and 150 N. As expected, starch content was positively, and fat content negatively correlated with degree of expansion. Musty aroma and the perceived hardness correlated with fat content in the PLS model, while the perceived crispiness correlated with expansion. Quality indicators such as thousand seed weight (TSW), and peak viscosity showed significant correlation with expansion in both instrumental and sensory tests; therefore, they can be utilized as quick predictive measurements to assess the quality of wholegrain oat based extrudates.

1. Introduction

Wholegrain oats have several properties that make them healthy, as they are a good source of dietary fibre (DF), which includes beta-glucan, as well as providing vitamins, proteins and unsaturated fat (Martínez-Villaluenga & Peñas, 2017). Dietary fibres in general lower risk of heart disease, type 2 diabetes, as well as certain types of cancer, while beta-glucan has been clinically proven to lower cholesterol levels (Daou & Zhang, 2012; Murphy et al., 2012; Weickert & Pfeiffer, 2008). Oats are also a source of unique phytochemicals, avenanthramides, that have shown bioavailability and anti-inflammatory effect in humans (Meydani, 2009). In addition, oats that have not been contaminated by cereals containing gluten are also suitable for consumption by coeliacs (Martínez-Villaluenga & Peñas, 2017).

Extrusion processing is a widely used method for producing puffed snacks and breakfast cereal products. Extruded oats are mainly used as breakfast cereals. From an extrusion perspective, oats are a challenging raw material, especially due to their high fat and dietary fibre content, compared to other commonly used extrusion raw materials such as maize or rice. Fat acts as a lubricant during extrusion, reducing shear

and thus limiting starch gelatinization (Moraru & Kokini, 2003; Singh & Smith, 1997). DF, especially insoluble DF (IDF), also reduces expansion during extrusion by affecting water binding and melt rheology, as well as by physical disruption of bubble formation (Robin et al., 2011; Santala et al., 2014; Yanniotis et al., 2007). Finally, as starch is generally the main structure former during extrusion of expanded snacks, the relatively low starch content of oat compared to corn or rice may hinder the formation of desirable and crispy expanded structure (Guy, 2001). In order to improve performance during extrusion, oats are frequently mixed with other refined high in starch ingredients. However, as the health effects of oats are mainly associated with the unique DF composition (Martínez-Villaluenga & Peñas, 2017) and extrusion cooking can increase the extractability of beta-glucan (Brahma et al., 2016; Roye et al., 2021), there is consumer and industry demand for maximizing oat content in extruded products, while retaining acceptable sensory properties. This makes it even more important to define the quality indicators behind these technological challenges. Previous studies on extrusion of oats have mostly focused on one type of oat flour, and optimising the conditions for that particular oat flour (Brahma et al., 2016; Liu et al., 2000; Sandrin et al., 2018; Singh & Smith, 1997; Wang

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et al., 2019). Many of these have found that relatively high temperatures (155–175 °C) and screw speeds resulted in the highest expansion (Liu et al., 2000; Sandrin et al., 2018; Wang et al., 2019). Sensory analysis of oat extrudates has indicated that a higher oat content in an oat-corn puff had negative effect on visual attributes and lead to a harder extrudates, while oat related flavours were increased (Liu et al., 2000). Similarly, oat based snacks were found to be inferior to barley-based ones, e.g. from appearance and texture perspective (Mäkilä et al., 2014). Higher product temperature has been related with more expanded and open cell structure and crispier products (Liu et al., 2000). However, harsh processing conditions may increase the lipid oxidation rate of oats (Moisio et al., 2015), potentially leading to flavour problems. Sensory trials of extruded oats have included attributes such as stale and musty, which could be indicators of lipid oxidation (Liu et al., 2011; Salmenkallio-Marttila et al., 2004). One way to counteract the fat oxidation, while improving extrudate structure, is defatting of the oat flour (Sibakov et al., 2014). Although high lipid and dietary fibre content of oat flour have been associated with poor extrudate quality, there is a large variation in the chemical composition and techno-functional properties of oat flours, depending on e.g. variety and growth conditions (Jokinen et al., 2021, 2023). Therefore, there is a need to develop systematic understanding for oat quality factors to enable production of appealing wholegrain extruded oats.

In the last five years the use of oats in food production increased dramatically and expanded from traditional cereal foods (e.g. bakery products, porridge, extruded breakfast cereals and snacks) towards novel dairy and meat alternatives. Despite the increased use of oats, the quality parameters and technological properties needed from oat groats and flours are not adequately understood. There are no quality indicators for oats as analogue to wheat and malting barley where certain quality parameters are well defined for predicting performance during processing or end-product quality. In comparison to wheat and malting barley, there is a lack of scientific literature from a food technology perspective, as well as standardized analysis methods for quality indicators. The aim of this research was to define quality indicators for oats in extrusion when it comes to chemical composition and techno-functional properties, as well as to identify rapid tests to determine the suitability of oat raw materials for extrusion processing. This was accomplished by examining sensory characteristics, macrostructure and instrumental textural properties and correlating them with chemical composition and grain and flour characteristics.

2. Materials and methods

2.1. Raw materials

Finnish wholegrain oat flour samples ($n = 30$, F1-F30) representing 23 different cultivars, with composition described previously by our team (Jokinen et al., 2021) were extruded. Starch content in the flours varied between 57.8% and 71.9%, fat between 5.4% and 9.4%, protein between 10.6% and 19.2%, and DF between 8.5% and 13.2%.

All oat flours were ground at the same commercial oat miller (Vääksyn mylly, Vääksy, Finland), as described by Jokinen et al. (2021). As noted in a subsequent study, the mill stones were changed between the first 10 samples (F1-F10) and the rest (F11-F30) (Jokinen et al., 2022). This resulted in large variation in the particle sizes between the materials. To achieve similar particle sizes flours F11-F30 were milled again with a hammer mill. After the second milling, particle sizes were similar between the two batches, i.e. D50 of 361 μm on average for the F1-10 samples and 387 μm for F11-30 (Jokinen et al., 2022) 30% (dry matter basis) white rice flour (Leipurin Oyj, Vantaa, Finland, Lot 4419, country of origin Spain), was added to each oat flour before extrusion, in order to achieve some expansion with all oat flours, as pre-trials showed that certain flours did not expand as such. The reported composition of the rice flour was 75.8% carbohydrates, of which 0.1% was sugars and 0.6% dietary fibre, 7.4% protein and 1% fat.

2.2. Extrusion processing

A co-rotating twin screw extruder (APV Baker Perkins MPV 19/25, Peterborough, UK) was used for the extrusion trials. Constant extrusion conditions were used for all 30 samples, based on preliminary trials with F3. The screw speed was 400 rotations per minute (RPM), temperature profile 140-130-90-85 °C (die to feed), flour feed rate was 60 g/min and total moisture content 15%. Ribbons were cut at the die exit, which were dried for 30 min at 105 °C in an oven. Extrusions were run in duplicates for each raw material. The screw configuration is shown in Santala et al. (2014).

2.3. Instrumental analyses

Expansion ratio, specific length and density were measured as described previously by Alam et al. (2016) for all samples. Briefly, 10 cm ribbons were cut with an electric saw. The thickness of these was measured in 3 spots with Vernier calipers, and the samples were weighed. Instrumental texture analysis was performed by a uniaxial compression test as described by Alam et al. (2016) using TA XT2i Texture Analyzer (Stable Micro Systems Ltd., Godalming, UK). 1 cm pieces were cut with an electric saw, which were then compressed at 1 mm/s with a 25 mm probe. Hardness, i.e. the peak force, crispiness work (CW) and crispiness index (CI) were calculated from the force-deformation curve.

2.4. Sensory evaluation

The panel of 14 assessors, students and staff of University of Turku and Turku University of Applied Sciences, participated in the sensory evaluation. Prior to the tests, participants were informed about protocols and test settings, and written consents were obtained. During four training sessions the panel agreed on 22 attributes to be evaluated by generic descriptive analysis (GDA) and six colours by check all that apply method (CATA) (Supplementary Table 1). The 10 most extreme samples were selected by the research team for evaluation based on the results of aforementioned instrumental analyses and preliminary sensory tests with oat flours (data not shown). Of the duplicate extrusion samples, only one was used in evaluation. Samples were cut into 2 cm long pieces and stored at $-20\text{ }^{\circ}\text{C}$ in plastic bags until evaluation (in total 4 months). In the evaluation, three pieces of a sample were served from a transparent disposable 4 cl plastic container covered with a glass lid. Samples were coded with a random three-digit code and evaluated in duplicate during four sessions. The order of the samples was randomized for both the assessors and between the evaluation sessions. The samples were served monadically and there was a mandatory 30-s break between each sample. The intensities of the attributes were rated on a line scale from 0 ("no attribute observed") to 10 ("strong attribute"). For palate cleansing active-carbon filtered water and a piece of unsalted water biscuit (Carr's Table Water, UK) was provided. Sensory evaluation was conducted in a sensory laboratory in controlled conditions (ISO 8589). Data were collected electronically with Compusense Cloud version 21.0 (Compusense Inc., Guelph, Ontario, Canada).

2.5. Statistical analysis

The performance of assessors in Generic Descriptive Analysis (GDA) was analysed with PanelCheck 1.4.2 (Nofima, Tromsø, Norway) following the workflow by Tomic et al. (2010). Overall performance of the panel was examined with three-way ANOVA, assessor, sample and replicate effects and their two-way interactions. Univariate methods (p-MSE plot, F & p plot, MSE plot and Eggshell plot) and principal component analysis (PCA) based multivariate methods (Manhattan and Tucker-1 plots) were used.

Statistical significance of attributes evaluated by GDA was analysed by applying a two-way mixed analysis of variance (ANOVA) model in

which the samples as fixed factors, and assessors and replicates as random factors with their main effects and sample*assessor and sample*replica interactions. Tukey's HSD post hoc test was used to determine between-group differences. Cochran's Q test was run to determine if there is a significant difference in colour between samples and pairwise comparisons were performed using Dunn's post hoc test with a Bonferroni correction for multiple comparisons to identify differing samples (Laerd Statistics, 2017). The results were considered statistically significant when $p < 0.05$. All significance calculations were performed with IBM SPSS Statistics 27.0 (IBM Corporation, Armonk, NY).

The raw data from the GDA were averaged over assessors and replicates before the principal component analysis (PCA). PCA was also used to examine correlations between extrudate instrumental analysis results, grain- and flour data. For the latter PCA data was autoscaled (mean-centered and divided by the standard deviation of each variable), whereas only mean-centering was used for the sensory PCA. PLS-regression was used to study interactions between instrumental measurements (X-data) and the sensory variables (Y-data). The data were autoscaled with full cross-validation and multivariate analyses were performed with the Unscrambler software version 11.0 (Camo Analytics AS., Oslo, Norway). Chemical composition and thousand seed weight (TSW) (Jokinen et al., 2021), Rapid Visco Analyzer results, DF properties (Jokinen et al., 2023), as well as particle size and dry fractionation data (Jokinen et al., 2022) for the 30 oat flour samples were included in the data analysis.

3. Results and discussion

3.1. Macrostructure and texture

Expansion, density and textural characteristics varied greatly depending on the oat flour sample. Expansion ratio of samples varied between 143% (F17) and 305% (F30) and density between 198 (F30) and 785 kg/m³ (F17) (Fig. 1). Direct comparison between values obtained from other studies is difficult, due to differences between extruders, screw configurations and extrusion conditions. Expansion ratios of extruded 100% wholegrain oat flour reported in the literature are generally very low (113%–164%) (Brahma et al., 2016; Espinosa-Ramírez et al., 2021; Sibakov et al., 2014). However, higher expansions have been achieved with addition of e.g. corn, wheat starch or rice: e.g. Expansions of 360% were achieved with 30% corn flour (Liu et al., 2000), 270% with 30% addition of wheat starch (Yao et al., 2006), while Sandrin et al. (2018) extruded oat-rice extrudates in a 60:40 proportion, obtaining expansion values between 148 and 246% and densities of 290–541 kg/m³ depending on extrusion conditions. The results of the current study are in a similar range to Sandrin et al. (2018), indicating that different compositions of the oat flour can affect the characteristics of the extrudate as much or more than the conditions.

Hardness of extrudates varied between 44 N (F27) and 150 N (F18), while CI varied between 3×10^{-5} and CW between 2 and 32 Nmm (Fig. 2). Samples with poor expansion and high density were also the ones that were the hardest and least crispy (e.g. F15, F17 and F18). CI showed relatively large standard deviations, due to some samples being very brittle. The calculation of CI uses variables such as the number of peaks, area under the force-deformation curve and curve length. When part of the samples ruptured almost instantly during compression, the value of these variables was very low in some replicates. Thus, in this case, the hardness measurement likely was a better indicator of overall texture than CI. Similarly as with macrostructure, extrusion of 100% wholegrain has previously resulted in very hard extrudates (ca 400 N) (Sibakov et al., 2014). Again, in studies where other starch sources were included, hardness was clearly lower e.g. ca 75 N with 30% added corn or 30% wheat starch (Liu et al., 2000; Yao et al., 2006), which are in a similar range to this study.

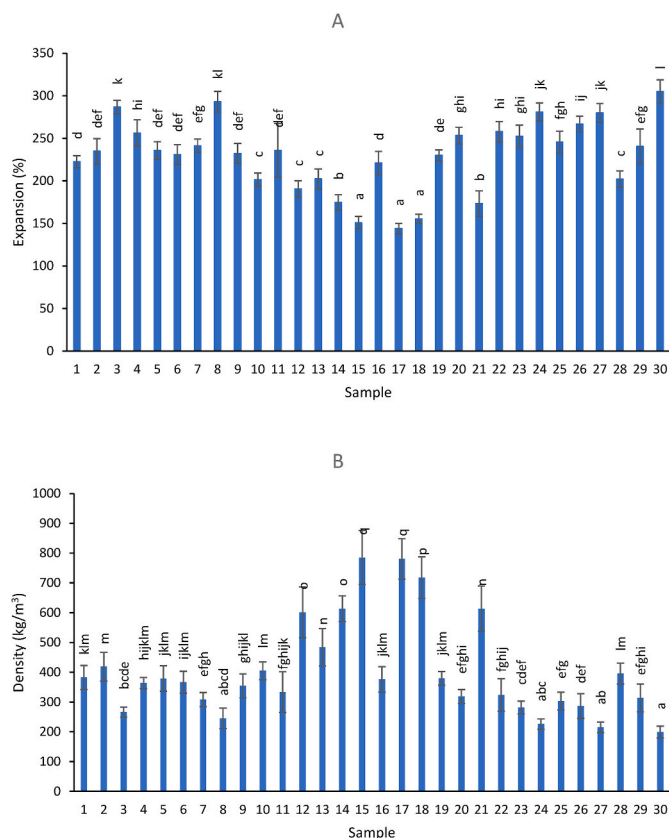


Fig. 1. Expansion ratio (A) and density (B) of extruded samples. Numbers 1–30 represent the oat flour samples F1–F30. Data are the mean of 20 replicate measurements \pm standard deviation. Significant differences $p < 0.05$ were found for both density and expansion.

3.2. Interactions between extrudate and raw material characteristics

The PCA included a variety of compositional factors (such as starch, protein, fat and DF content), grain properties (TSW), technofunctional properties (RVA, Air Classification results, particle size, as well as extrudate properties (macrostructure, instrumental texture). The first two principal components explained 49% of the variation in the data. Of the extrudate characteristics, density, CW and hardness correlated positively with each other, while expansion correlated negatively with these (Fig. 3). Of the compositional factors, fat content, protein content, total DF (TDF) and water-soluble dietary fibre that precipitates (SDFP) correlated positively with density and hardness, while starch correlated most strongly with expansion. Increased fat content causes reduction in specific mechanical energy, and reduction in starch gelatinization (Lin et al., 1997), while also promoting formation of amylose-lipid complexes (Thachil et al., 2014) which may interfere with expansion. DF content, especially water insoluble DF (IDF) reduces expansion by increasing melt viscosity and reducing elasticity (Robin et al., 2012). Interestingly, in this study water soluble DF (SDF) correlated more strongly with density and hardness than IDF, whereas in previous studies IDF had a more negative effect in extrusion (Pai et al., 2009; Yanniotis et al., 2007). However, addition of beta-glucan to extruded snacks has shown reduction in expansion (Kour et al., 2019). On the other hand, increased content of non-starch components will reduce the content of the main structure former in expanded snacks, i.e. starch.

From the other analyses performed for the oat flours, RVA peak viscosity, thousand seed weight (TSW) and yield of fine fraction in air-classification correlated with expansion, while the yield of coarse-fraction correlated with extrudate density and hardness (Fig. 3). RVA results are dependent on both starch content and quality, but are also

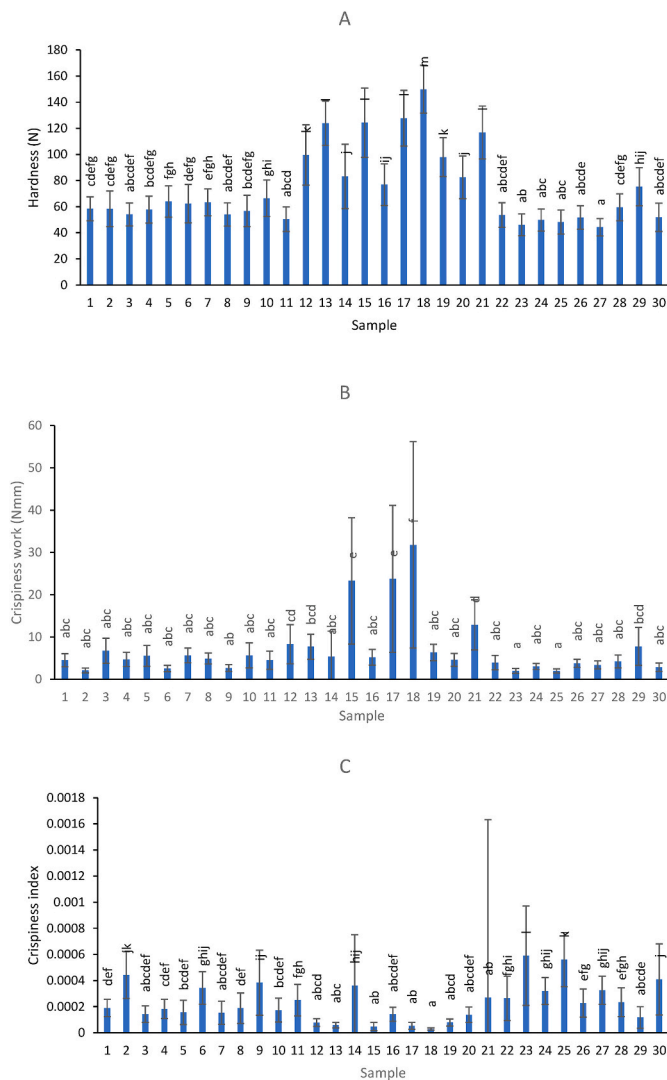


Fig. 2. Extrudate hardness (A), crispiness work (B) and crispiness index (C). Numbers 1–30 represent the oat flour samples F1–F30. Data are the mean of 20 replicate measurements ± standard deviation. Significant differences $p < 0.05$ were found for all three attributes.

affected by other components, such as proteins and beta-glucan (Gamel et al., 2012). Peak viscosity indicates the swelling power of the starch granules and has been found to correlate with a variety of quality characteristics of flours. Lipids may also limit the swelling capacity of starches, reducing peak viscosity (Batey, 2007), which may also explain why RVA Peak viscosity correlated negatively with lipid content. TSW describes the average size of the whole grains, therefore a higher TSW would also have a higher proportion of endosperm, where the main part of the starch is located. TSW of oats has previously been shown to correlate positively with starch content, and negatively with fat, protein and dietary fibre (Asp et al., 1992). The strong correlation between air-classification yields and extrusion behaviour is probably related to the effect of lipids on behaviour in air-classification, where high lipid content strongly affects the yields e.g through adhesion to processing equipment as well as through agglomeration (Sibakov et al., 2011). In addition to this, dietary fibre is often present in the coarse fraction, i.e. higher coarse fraction yield could give an indication of dietary fibre content. Rapid NIR-based methods for analyzing composition, could help with predicting the performance of oat flours during extrusion, by giving information on compositional characteristics (Flak, 2020) – this is also the likely explanation why TSW could work as a quality indicator

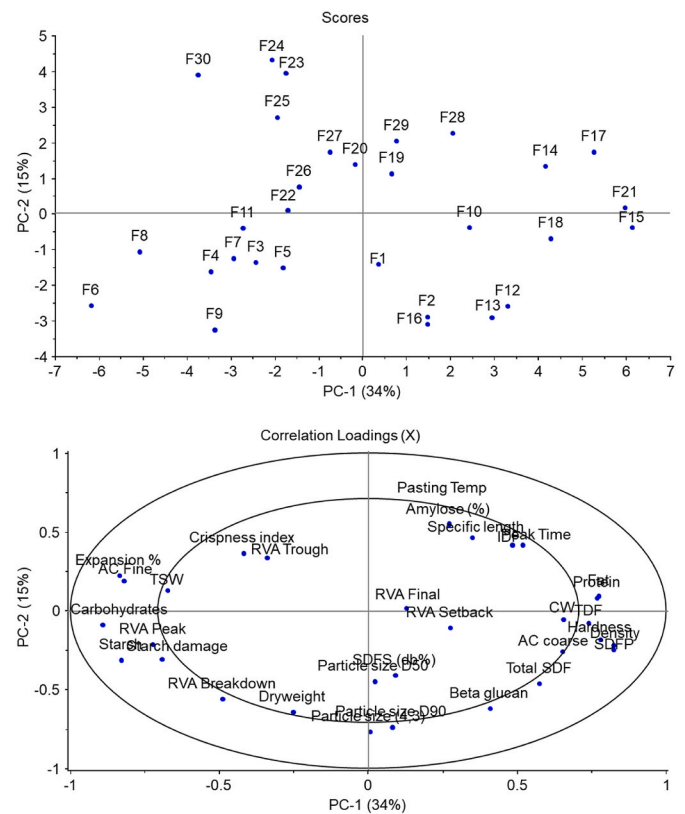


Fig. 3. Scores and loadings for all 30 oat flour samples (F1–F30) including data on the flours, as well as extrudates (structure and texture).

for extrusion. RVA, on the other hand, provides information of all the components on the viscous properties of the flour during heating, therefore it is not only affected by the amounts of individual components but also on the state of the starch and other components. However, more work would be needed to confirm these as being valid quality indicators.

3.3. Sensory profiling

3.3.1. Panel performance

The sample effect was significant for all appearance and textural attributes as well as for musty aroma, roasted and musty flavours, and aftertaste. The assessor effect was significant for all attributes except for aroma intensity and cereal aroma. There was also a significant replicate effect for thickness and hardness. There was an agreement on the appearance and the texture attributes, especially thickness, pore size, uneven surface, crispiness, and hardness. The assessors also had the highest discriminability and the best repeatability on these attributes. Odours and flavours were harder for the panel to agree and discrimination was challenging probably due to mild odours and flavour of extrudates. None of the assessors had a systematically weak performance for all properties, so everyone was included in the following data analyses.

3.3.2. Sensory profile of oat extrudates

The panel used mostly appearance and textural attributes to differentiate the extrudates, especially thickness, pore size, uneven surface, and hardness with F-values 117.9, 129.7, 97.3, and 80.8 respectively. Of a total of 22 attributes studied, statistically significant differences ($p < 0.05$) were observed in five appearance attributes (thickness, pore size, uneven surface, uneven colour and dark particles), two odour attributes (odour intensity and musty aroma), three flavour attributes (popcorn, roasted, and musty) and all five textural attributes according to the analysis of variance.

The properties commonly appreciated by consumers in extrudates are high expansion, low hardness, and small density (Mäkilä et al., 2014). Liu and others (2000) proved a high content of oat flour in extrudates associated with undesirable appearance and textural properties. However, despite the high percent of oat flour used in this study, the oat extrudates varied in crispness (on the scale between 4.1 and 7.6), hardness (3.5–7.9), chewiness (2.7–6.2), and grittiness (1.6–5.9). The choice of oat flour used for extrusion has therefore great importance in terms of the textural properties of the final product. Likewise, the appearance properties of the samples were also evaluated over a wide range of the scale (Supplementary Table 2).

The extrusion sample F2 was perceived dark and brown, while the other samples were light in colour (Supplementary Table 3). In the study of Saldanha do Carmo et al. (2019), dark and brown colour was connected to oat and pea extrudates with high expansion, whereas in the study of Liu et al. (2000) the decrease in lightness turned out to be due to weaker expansion caused by increased moisture as well as higher oat flour content. F2 and F21 were the oat extrudates evaluated most often having a grey colour, while F23, F24, and F20 were the ones least frequently connected to greyness. The extrudates showed some yellowish shade, except for F2, F15, F18, or F21, in which the assessors did not detect yellow colour.

All the oat extrudates had mild odour and flavour, and the differences of mean intensities between samples were minor, as previously stated in the literature (Sjövall et al., 1997). The only differences in odour were found in musty aroma. F15 and F18 were the most intense, while in other samples musty aroma was barely noticeable. A possible reason for the mildness and similarity of the odours of the extrudates may be the small sample amount in the sensory evaluation from which the odours could not be properly evaluated. F2 stood out from the other extrudates being intense in all evaluated flavour properties. The same extrudate was also the darkest in colour, suggesting that the physical conditions and the chemical properties of the sample were favourable for the Maillard reaction. Flour F2 was among the highest protein containing samples in the sensory analysis, but had relatively low fat content (7.05%) compared to the other samples. High-shear conditions have been shown to promote Maillard reaction (Cheftel, 1986). A sample with lower fat content would be expected to have higher shear than a high-fat one (Moraru & Kokini, 2003), which could then promote the formation of Maillard reaction products. Additionally, higher content of free fatty acids has led to reduced Maillard reaction during extrusion (Parker et al., 2000). Potentially, flours with higher total fat content could also have higher free fatty acid content. As a result of the Maillard reaction, browning and many flavour compounds, such as pyrazines, pyrroles and furans are formed in the oat extrudates causing typical oat flavour and different toasted aromas (Parker et al., 2000; Salmenkallio-Marttila et al., 2011; Starowicz & Zieliński, 2019)

In the consensus PCA (Fig. 4), principal component 1 (PC1) explained 71% and PC2 21% of the variance. Appearance and texture properties had stronger loadings on the first and second PC than odour or flavour properties. Crispness, pore size, uneven surface and thickness correlated with each other and had high positive loadings on PC1, whereas hardness, musty odour and dark particles had negative loading on PC1. Chewiness had positive loading on PC2 and grittiness, roasted odour, and flavour intensity had the highest negative loadings. On the scores plot (Fig. 4 A.), oat extrudates were divided into two groups and three separate samples. F15 and F18 formed the first group having highly negatively loading on PC1 and neutral loading on PC2 indicating these extrudates being hard, having some dark particles and being less crispy and thick. F7, F20, F23, F24, and F30 formed the second group of extrudates. They have positive loading on both PCs which indicates the extrudates have big pores and they are also crispy, thick, and easily chewable. F2 was also crispy and thick but then it has negative loading on PC2 meaning it had more intense flavour and odour and being grittier than the other extrudates. F2 also had uneven colour and was the darkest sample, which is in line with the study of Saldanha do Carmo et al.

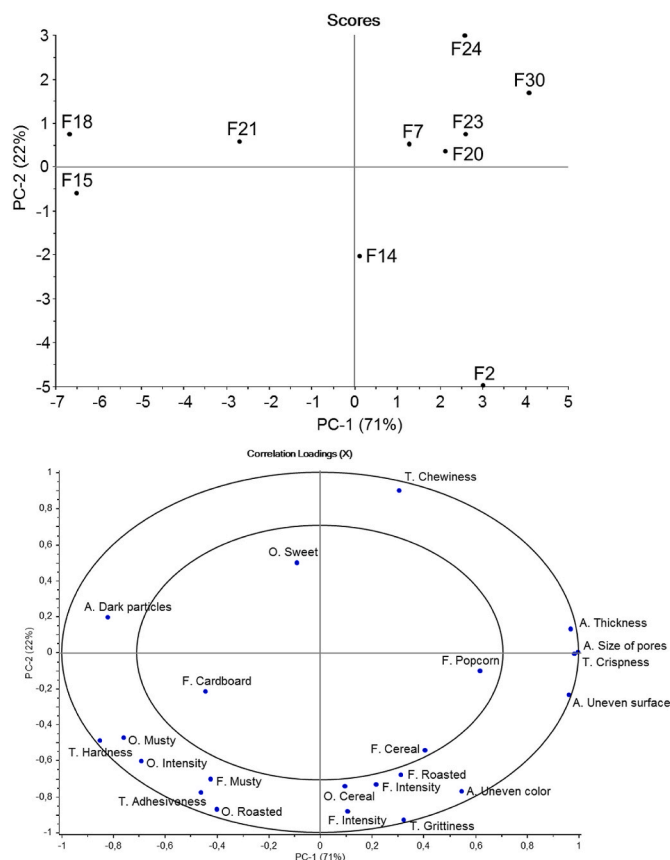


Fig. 4. Consensus PCA with scores and correlation loadings (A = appearance, F = flavor, O = odour and T = texture attribute) plots of the descriptive sensory profile of extruded oat samples. Data is averaged over 11 assessors and 2 replicates.

(2019) in which darkness and red colour of expanded snacks were correlated with stronger odour intensity and toasted aroma.

3.4. Linking sensory results to chemical and physical properties

Instrumental texture, macrostructure and sensory result data were combined to a partial least squares -regression (PLS) model (Fig. 5). In the model, 61% of the variation in the instrumental variables explained 84% of the variation in the sensory profile with two validated factors. Among the Y-variables, four sensory attributes, namely thickness of samples (Q^2 0.816 with two factors, Supplementary Table 4), size of pores (Q^2 0.807), crispy (Q^2 0.705) and hardness (Q^2 0.743), were well explained with model using two validated factors. The sensory attributes thickness of samples, size of pores and crispy characteristics were explained by the high expansion percentage and low density (Fig. 5A), while the perceived sensory hardness was explained by opposite instrumental results. Additionally, intensity of aroma and musty aroma attributes correlated TDF and fat contents, while roasted aroma and musty flavour correlated with protein content. The second factor shows especially the sample F2 together with uneven colour, hard particles and higher intensity of flavour.

Musty odour and flavour may arise in oat products due to lipid oxidation, and thus extrudates with higher lipid content would be more prone to these kinds of off-flavours (Heiniö et al., 2002). Moio et al. (2015) found that higher temperatures can increase the amount of lipid oxidation. On the other hand, previous studies have also found that higher extrusion temperature can also promote expansion of oat extrudates (Sandrin et al., 2018). Thus, choosing flour with lower lipid content, may allow using extrusion conditions that promote improved

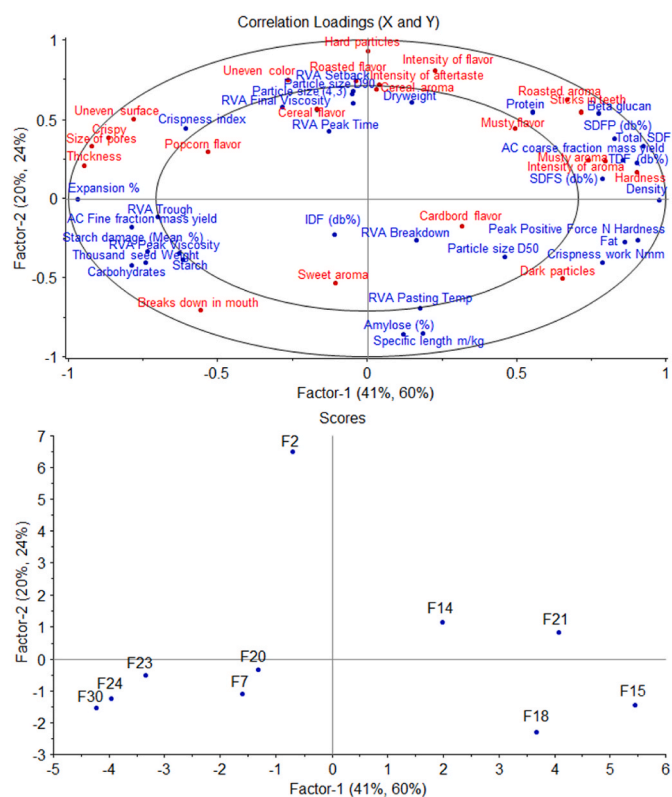


Fig. 5. Partial least squares regression model for interactions between instrumental variables (X-data with blue, $n = 32$) and sensory attributes (Y-data with red, $n = 22$). Above: loadings plot with variables; Below: scores plot with samples included in the sensory test ($n = 10$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

texture and flavour. Roasted aromas could presumably be caused by Maillard reaction products, which may be promoted by the higher protein content of certain flours.

3.5. Limitations of the study

In preliminary tests, extrusion conditions were optimized for one of the oat flours, that was as average in chemical composition as possible (F3). These extrusion conditions were subsequently used for the other 29 flours. Optimally, conditions would have been separately optimized for each of the 30 flours, although in practice this would not have been possible due to the vast amount of analysis required. Therefore, some of the flours could have performed better at different conditions than the ones chosen.

In sensory analysis, the number of samples was limited to 10 due to practical limitations. A higher number of samples could have increased the predictivity of the PLS-model.

4. Conclusions

Highly diverse structures and sensory properties were produced from the 30 oat flours studied in extrusion trials, depending on their chemical and techno-functional properties. In general, non-starch components, especially fat content, correlated significantly with density and hardness, while starch content correlated with expansion. Thus, fat content and starch content may be viewed as the most important quality indicators for extrusion. Based on the results of this study, rapid analyses such as thousand seed weight and RVA could be used to predict the performance of a particular flour during dry extrusion. However, further studies would be needed to validate these findings, e.g. by specifically

choosing flours with diverse TSW or RVA viscosity and testing them in extrusion, to observe how small changes in the respective characteristics are relevant for extrusion performance.

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CRediT authorship contribution statement

Markus Nikinmaa: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Sari A. Mustonen:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Lauri Huitula:** Investigation, Methodology. **Oskar Laaksonen:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Kaisa M. Linderborg:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing – original draft. **Emilia Nordlund:** Conceptualization, Supervision, Project administration, Funding acquisition. **Nesli Sozer:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lwt.2023.114457>.

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