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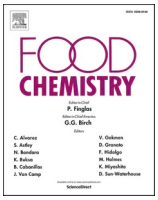

Variability of carbohydrate composition and pasting properties of oat flakes and oat flours produced by industrial oat milling process – Comparison to non-heat-treated oat flours

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ABSTRACT

This study characterised the starch and dietary fibre properties and their significance to the pasting characteristics of oat flakes and flours produced from 30 Finnish pure cultivar oats with or without the industrial scale milling process. Large variation in carbohydrate characteristics was observed, the insoluble dietary fibre content of flours was 2.4–5.7 % and soluble dietary fibre was 4.9–8.0 %. The oat milling process induced a significant amount of starch damage ($p < 0.05$), a fourfold increase from 1 % to 4 % in average was observed. The pasting properties of both flakes and flours were interlinked ($p < 0.05$) with the chemical composition of oats, i.e., high starch content of flours was connected to higher paste viscosity values. The milling process increased the peak, trough, setback, final and time to peak viscosities of oat flours. These results show the significance of oat milling process, including kilning, to the carbohydrate quality of oats.

1. Introduction

Oats have been traditionally used as flakes for porridge and as an ingredient in conventional bakery products, but recently also the use of oat flour as an ingredient for different food products, such as oat-based milk substitutes, has been increasing (Webster, 2011). The increased use of oats in different food products creates a need for scientific information on the variation of the chemical composition of oat materials, which would help the food industry to optimize their oat raw material selection for production of different types of oat products. Both starch and dietary fibre have significant impact on the technological properties of oats and oat ingredients, and therefore, understanding their quality and possible changes to them by oat processing is important.

Starch content of the oat groat can vary a lot depending on the growing location, oat variety and the proportions of other macromolecules and it is typically 50–60 % in dry matter basis (Doehlert & Moore, 1997; Jokinen et al., 2021; Shewry et al., 2008; Zhou et al., 1998).Oat groats contain 10–12 % dietary fibre in dry matter basis (Jokinen et al., 2021; Manthey et al., 1999; Rainakari et al., 2016). Oat dietary fibre is mainly β-glucan that represents at least 40 % of the IDF (water-insoluble dietary fibre) and 80 % of the SDF (water-soluble dietary fibre) (FDA, 1997; Wood, 2011). Especially β-glucan of oats has increased the interest towards oats as a food raw material due to its health-related properties. Furthermore, oat β-glucan is well known for its ability to from highly viscous gels, which affects the utilization of oats and oat β-glucan in food processing (Mäkelä et al., 2017; Wood, 1991). An important physicochemical property of starch is its pasting behaviour (Balet et al., 2019; Kasturi & Bordenave, 2014). The pasting properties of oat flour depend on the starch quality and properties, but also on the other components such as protein and dietary fibre (Choi et al., 2012; Liu et al., 2010). Both dietary fibre and starch content have been connected to the characteristics of oat flakes (Lapveteläinen et al., 2001).

Oats are used in the food industry mostly as flour or rolled oats. Oat flour is usually milled either from flakes or directly from groats, and the flour is often used as whole grain flour (Girardet & Webster, 2011). Oat milling process is different compared to the milling of other cereal grains as it includes a heat treatment step, namely kilning, which is performed to inactivate the endogenous lipid degrading enzymes. The oat milling process and heat treatment have been found to affect the physicochemical properties of oat flour and starch (Hoover, 2010; Hu et al.,

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2010; Nguyen et al., 2019; Zhou et al., 1999; Ziegler et al., 2018). For example, the oat milling process including kilning has been found to affect the pasting characteristics of oats (Zhou et al., 1999). In addition to heat, the mechanical forces present during the milling can cause damage to starch granules (Boyaci et al., 2004; Morgan & Williams, 1995). The role of starch damage for wheat flour quality has been clearly demonstrated, while only a little research is available regarding damaged starch content and formation in commercial oat flours (Eliasson, 2012; Hüttner et al., 2010).

Currently oats are delivered to mills as mixtures of different oat cultivars with differing quality properties, which is challenging for the food industry as predicting the end-product quality is more difficult. We have previously shown that pure cultivar oat batches exhibit significant variation in their chemical composition and grain quality (Jokinen et al. 2021), in their physical properties of oat flakes and flours (Jokinen et al. 2022) and in their baking quality (Sammalisto et al. 2021). Therefore, understanding the effects of the industrial scale oat milling process on carbohydrate quality and pasting properties of oat flakes and oat flours can improve the food applicability of oats. The aim of this research was to study the effects of oat milling in industrial scale on carbohydrate properties and quality of oat flakes and flours produced from 30 Finnish pure cultivar oat batches. Amylose content, amount of insoluble and soluble dietary fibre and damaged starch content of oat flours were analysed and correlated with the pasting properties of the oat flakes and flours. In addition, the obtained data was correlated with the data published previously by Jokinen et al., (2021), Jokinen et al., (2022) and Sammalisto et al., (2021) including the total starch, dietary fibre and β-glucan content of the samples. It was hypothesized that the industrial scale milling process will affect the pasting properties of the oat samples and that the pasting characteristics of industrially produced oat flours will be significantly different compared to oat flours produced in laboratory scale without the kilning step.

2. Materials and methods

2.1. Oat raw materials

Thirty batches of oat grains representing different oat cultivars were obtained from Boreal Plant Breeding Ltd., Plantanova Oy and Lantmännen Agro Oy. Three different crop years, 2017, 2018 and 2019 and 23 different cultivars, were represented. The oat cultivars were selected based on their availability and on the expectation that they would show differences in their chemical composition and physical properties. All the thirty oat batches were processed as pure cultivar. Three different types of oat samples were produced from the native oat grains: non-heat-treated oat flour, oat flakes and heat-treated oat flour (Fig. 1). Non-heat-treated oat flours were produced in laboratory scale by dehulling native oat grains with an oat dehuller (Rivakka, Nipere Oy, Finland) and grinding at 12 000 rpm with an ultra-centrifugal mill (Retsch ZM 200, Haan, Germany) using a 0.5 mm sieve. The non-heat-treated oat flours were stored below −18 °C until use. Oat flakes and heat-treated oat flours were produced from the oat grains in industrial scale at Vääksyn Mylly Oy (Asikkala, Finland). The process included drying, dehulling, kilning, flaking, and milling with a stone mill. The milling stone was replaced after processing of the 10 first oat samples which caused a difference in the particle size distribution of oat flour samples 1–10 and 11–30 (Jokinen et al., 2022; Sammalisto et al., 2021). Therefore, the heat-treated oat flour samples 11–30 were re-milled with a hammer mill (Hamermolln mono 6, Werkhuizen Schepens NV, Dendermonde, Belgium) equipped with a 0.5 mm sieve at approximately

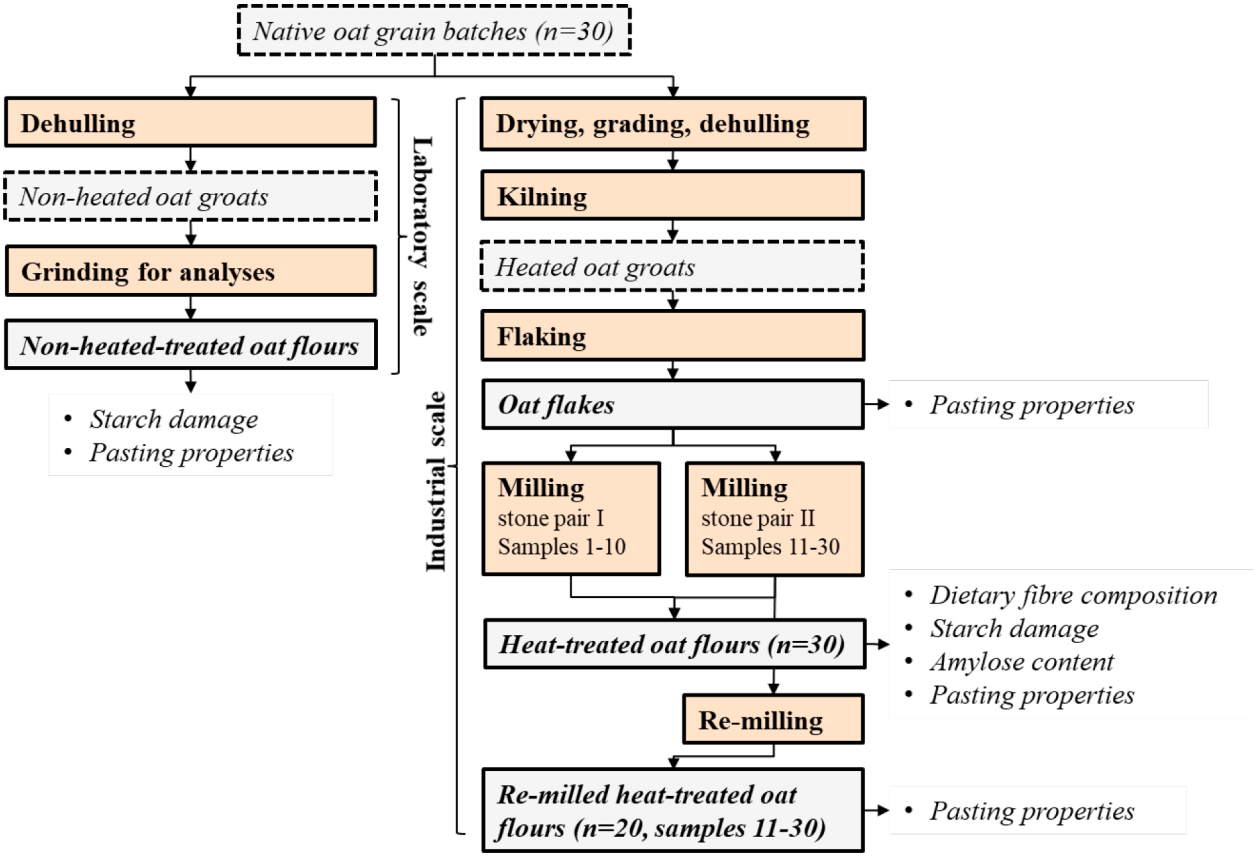

Fig. 1. Processing scheme of the oat raw materials. The raw materials are shown in the grey boxes and subsequent analyses with bullet points, with the processing steps in light orange. Analysed samples are outlined with solid lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

120 kg/h feed rate to obtain a similar particle size distribution as the oat flour samples 1–10 had.

2.2. Carbohydrate analysis

The total dietary fibre content of heat-treated oat flours was analysed with the AOAC Method 2011.25 using a semi-automated Dietary Fibre Analyser (ANKOM^{TDF}, Makedon, NY, USA). In this methodology, the total dietary fibre includes water-insoluble dietary fibre (IDF) and water-soluble dietary fibre (SDF), which includes water-soluble dietary fibre that precipitates in 78 % (v/v) ethanol (SDFP) and water-soluble dietary fibre that stays soluble in 78 % (v/v) ethanol (SDFS). The performance of the method was followed with an in-house standard sample. The damaged starch content of all the samples was determined using the Megazyme starch damage assay kit (AACC Method 76–31.01) including the sample blanks in the analysis. The accuracy of the method was followed with a reference wheat sample provided in the kit. The amylose content of oat flours was analysed with the Megazyme amylose/amylopectin assay kit with a minor modification, where the filtration step through Whatman® No. 1 filter paper was replaced with centrifugation at 1,850 × g for 10 min at 22 °C to sediment the other materials than starch. A maize starch control sample provided in the kit was analysed with each determination to follow the performance of the method. The total dietary fibre analyses were performed as duplicates and other analyses were performed as triplicates, averaged, and reported on a dry matter basis (dm).

2.3. RVA analysis of oat flakes and flours

Pasting properties of oat flakes, and non-heat-treated and heat-treated oat flour samples 1–30 and re-milled heat-treated oat flour samples 11–30 were analysed using Rapid Visco Analyser (RVA Super 4 by Newport Scientific, Warriewood, Australia) and the analysis was performed according to the Standard Newport Scientific method 1 as described by Crosbie and Ross (2007). In the beginning of the analysis, flakes or flours and water purified with reverse osmosis system were weighed and mixed in sample tins, yielding dry matter contents of 8 % for flakes and 12.3 % for flours. The RVA analysis of flakes and flours was initiated by mixing samples for 10 s at a paddle speed of 960 rpm followed by a 50 s holding period with a paddle speed of 160 rpm. The paddle speed was held at 160 rpm for the rest of the measurement. The mixing step was followed by a heating step from 50 to 95 °C for 222 s. The temperature was held at 95 °C for 150 s and then the sample was cooled back to 50 °C in 228 s and kept for 120 s at 50 °C. All samples were analysed in triplicate.

Pasting characteristics of flour samples were reported as described by the standard method. Due to the noisy character of the viscosity profiles of the flakes, the results for the flakes were extracted from the viscosity profiles in a different manner than for the flours. The initial viscosity at 50 °C was determined as the average viscosity between the first 32 and 60 s of the measurement. The pasting temperature was defined as the temperature at which a steep increase in viscosity took place during heating. The viscosity at 95 °C was calculated as the average of the viscosity values at the plateau observed at 95 °C. The final viscosity was determined as the average of the viscosity values during the last 60 s of the measurement. The setback was calculated as the difference between the final viscosity and the viscosity at 95 °C. In this publication, the apparent viscosities measured with RVA are referred to as viscosity.

2.4. Statistical analysis

To investigate the relationship between the chemical characteristics of oats and physical properties of oat grains, flakes and flours, the data obtained in the current study was correlated with the chemical composition data of the non-heat-treated and heat-treated oat flours published by Jokinen et al. (2021) and physical properties of the oat groats, oat flakes and heat-treated oat flours published by Sammalisto et al. (2021) and Jokinen et al. (2022). To evaluate the possible interaction between the baking quality and carbohydrate characteristics, the results of oat flour samples 11–30 were correlated with their baking performance published by Sammalisto et al. (2021). The results are represented as average values, and the numbers of replicate measurements are separately detailed. All results, average deviations and coefficients of variations were calculated using Excel spreadsheet software (Excel 2016, Microsoft, Redmond, US). Differences between the pasting properties of oat flour samples were analysed with one-way analysis of variance (ANOVA) with Tukey's honestly significant difference (HSD) ($p < 0.05$) post hoc test. Differences between carbohydrate and pasting properties of oat flake and flour samples were estimated with the Kruskal–Wallis one-way analysis of variance test ($p < 0.05$). The interactions between the different sample parameters were estimated based on the Pearson correlation coefficients. Sample grouping and differentiation were visually observed based on principal component analysis (PCA) regression. The Pearson correlation coefficients, ANOVA, Kruskal-Wallis test, and independent sample T-tests were carried out with the SPSS-software (IBM SPSS Statistics, version 26, IBM, New York, NY, USA). PCA was performed using The Unscrambler (CAMO Software AS, Oslo, Norway) version 10.5.1.

3. Results

3.1. Carbohydrate composition and quality of oat flours

Carbohydrate properties showed significant variation ($p < 0.05$) between the oat samples (Table 1, Appendix Table A.1.). The total dietary fibre content of the oat flours was approximately 11 % (dm) and varied between 8.5 and 13 % (dm). IDF, SDFP and SDFS contents of the oat flours were 4.8 %, 4.9 % and 1.4 % (dm) on average and represented 44, 43 and 14 % of the total dietary fibre content, respectively. Thus, water-soluble dietary fibre represented approximately 56 % of the total dietary fibre of the oat flours. The total dietary fibre in the oat flours was previously shown to contain 30–46 % β-glucan (Jokinen et al., 2021). The amylose content of the heat-treated oat flours varied between 19 and 29 % of total starch content (Table 1).

To evaluate the effect of the milling process on oat starch quality, the amount of starch damage in flours was determined before and after the milling process (Table 1). In addition to the thorough evaluation of the carbohydrate composition of the heat-treated oat flour, the impact of milling process on starch quality was evaluated by analysing the starch damage content of the non-heat-treated oat flours as well. Starch damage content of the non-heat-treated oat flours was 0.9 % (dm) on average whereas the starch damage content of the oat flours was 4.4 % (dm) on average, varying from 2.3 to 7.4 % (dm). The difference between damaged starch content of non-heat-treated and the heat-treated oat flours was 3- to 7-fold depending on the sample. The share of starch damage of total starch was 5.6–10.4 % in heat-treated oat flour samples 1–10 and 3.7–9.5 % in heat-treated oat flour samples 11–30.

3.2. Pasting properties of oat flakes and flours

The pasting properties of the oat flakes exhibited great variation between the samples (Appendix Table 2). Based on the Kruskal–Wallis one-way analysis of variance, there were significant differences ($p < 0.05$) between the samples in all parameters (Appendix Table A2). The initial viscosity value of the flakes was 120 mPa*s on average, and it exhibited the largest variation of all parameters (highest value being 5-fold in comparison to the lowest one). Values of viscosity at 95 °C, final viscosity and setback viscosity were 475, 1330 and 853 mPa*s, respectively, on average and the differences between the smallest and the largest values were almost 3-fold for each of these parameters. Differences between the flake samples were evident also based on the pasting

Table 1
Carbohydrate composition of non-heat-treated oat flour and heat-treated oat flours. SD = starch damage. Total dietary fibre (TDF) content of oat flours expressed as insoluble dietary fibre (IDF), soluble dietary fibre that precipitates in ethanol (SDFP) and soluble dietary fibre that stays soluble in ethanol (SDFS). Share of the dietary fibre fraction of the total dietary fibre is shown in brackets after the value.

	Non-heat-treated oat flour	Heat-treated oat flour						
	SD (% dm)	SD (% dm)	TDF (% dm)	IDF (% dm)	SDFP (% dm)	SDFS (% dm)	β-Glucan [a] (% dm)	Amylose (%/starch)
Average	0.9 x[b]	4.4 y	11.1	4.8 (44)	4.9 (43)	1.4 (13)	4.0 (36)	26
Min	0.7	2.3	8.5	2.4 (28)	3.6 (37)	0.7 (6)	2.9 (30)	19
Max	1.2	7.4	13.2	5.7 (51)	6.1 (54)	2.4 (21)	4.6 (46)	29

[a] Reprinted with permission from Jokinen et al. (2021). Copyright 2021 Jokinen et al. [b] Different letters, x and y, within each row and component indicate a statistically significant difference ($p < 0.05$) between the samples based on an independent sample *t*-test.

Table 2
Pasting properties of non-heat-treated oat flour samples, heat-treated oat flour samples 1–10 (stone pair I), heat-treated oat flour samples 11–30 (stone pair II) and re-milled heat-treated oat flour samples 11–30.

Sample type		Peak viscosity (mPa*s)	Trough viscosity (mPa*s)	Breakdown viscosity (mPa*s)	Final viscosity (mPa*s)	Setback viscosity (mPa*s)	Peak time (min)	Pasting temperature (°C)
Non-heat-treated flour Samples 1–10 (n = 10)	Average	3746a[a]	1816a	1930b	4273a	2456a	5.8a	84a
	Min	3048	1207	1726	3141	1853	5.6	81
	Max	4736	2377	2441	5489	3112	6.2	88
Non-heat-treated flour Samples 11–30 (n = 20)	Average	3610a	1869a	1742a	4541a	2672ab	5.9ab	87b
	Min	2638	1227	1124	3372	2145	5.7	82
	Max	4774	2391	2382	5498	3282	6.2	91
Heat-treated flour Samples 1–10 (n = 10)	Average	4614b	2690b	1923b	5943b	3253bc	6.1b	82bc
	Min	4256	2377	1505	4615	2160	5.8	75
	Max	5674	3177	2596	7981	5205	6.6	86
Heat-treated flour Samples 11–30 (n = 20)	Average	4506b	2773b	1733a	5743b	2971c	6.0c	85bc
	Min	3861	2063	1210	4795	2469	5.7	81
	Max	5316	3715	2424	6959	4058	6.3	89
Re-milled heat-treated flour Samples 11–30 (n = 20)	Average	4411b	2748b	1664a	6037b	3289c	6.3d	85c
	Min	3867	2165	1150	4483	2238	6.1	81
	Max	4937	3568	2231	7704	4822	6.6	90

[a] Different letters within each column indicate statistically significant difference ($p < 0.05$) between treatments based on Tukey's HSD test. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

curves, of which some examples are shown in Fig. 2A. Flake sample 10 showed especially low values of apparent viscosities compared to all other samples. Flake samples 4, 11, 13, 24 and 28 all exhibited final viscosity values above 1750 mPa*s and sample 4 had the highest value of 1850 mPa*s (Fig. 1., Appendix table A.2).

In general, the pasting properties of the 30 oat flour samples changed due to processing and exhibited large variation (Table 2). The milling process increased the peak viscosity, trough viscosity, setback viscosity, final viscosity, and time to peak viscosity, and did not affect the breakdown viscosity or pasting temperature (Table 2). The non-heat-treated samples exhibited significantly ($p < 0.05$) lower peak viscosity, trough viscosity and final viscosity values for all samples compared to heat-treated oat flour samples. Furthermore, pasting properties of the re-milled samples 11–30 were measured to understand if the re-milling had an impact on the pasting characteristics. It was observed that the re-milling of the oat flour samples 11–30 had significant ($p < 0.05$) influence on the time to reach peak viscosity (peak time) and pasting temperature of the oat flours while other parameters were unaffected.

Although there were differences in pasting properties of the differently milled oat flours as indicated by the one-way ANOVA, the

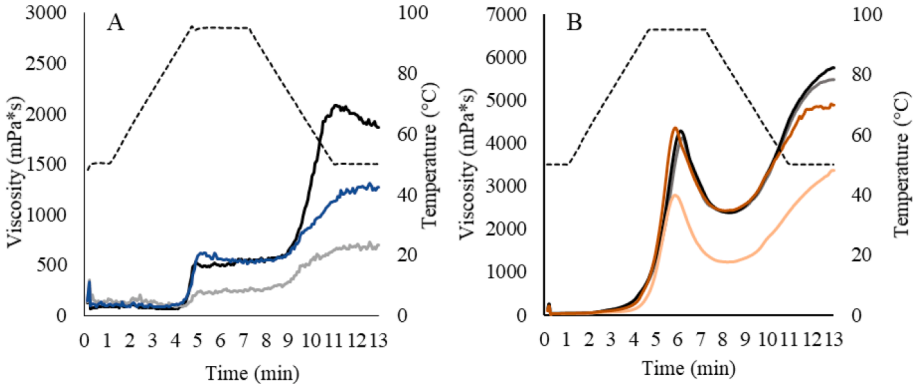

Fig. 2. Examples of RVA pasting profiles for oat flake (A) and flour (B) samples. A: Pasting properties of oat flake sample 4 (black line), sample 10 (grey line) and sample 12 (blue line). B: Pasting properties of flour samples 1 and 12 as non-heat-treated oat groats (grey line, sample 1; light orange line, sample 12) and as heat-treated oat flour after milling process (black line, sample 1; dark orange line, sample 12) The oat flake concentration was 8% (on dry matter basis) and oat flour concentration was 12.3 % (on dry matter basis). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

differences between the pasting properties of the non-heat-treated and heat-treated oat flour samples were very sample dependent (example curves in Fig. 2B). The difference in behaviour was not observed at all for one of the samples (sample 1), while for most of the samples the non-heat-treated samples showed clearly differing pasting behaviour compared to the heat-treated flour peak viscosity, trough viscosity and final viscosity values. Similar observation could be made for the heat-treated oat flour samples 11–30, that the difference between the pasting behaviour of the non-heat-treated, the heat-treated and the re-milled heat-treated flour were raw material specific (Appendix Figure A.1). The higher peak time values after the re-milling of the heat-treated oat flour samples 11–30 could be observed from the pasting curves. In addition, some of the samples exhibited deviating behaviour during the end of the RVA test by showing sudden increase and decrease in viscosity before settling to final viscosity (Appendix Figure A.1). This was interpreted to originate from flour paste sticking to the mixing paddle resulting in a sudden decrease of viscosity due to slipping of the paste in relation to the sample tin. This was observed especially in samples that reached high viscosities during the final cooling step of the experiment.

3.3. PCA analysis of the results

The principal component analysis (PCA) of the physical properties of oat flakes from Jokinen et al. (2022), chemical composition of heat-treated flours milled from flakes from Jokinen et al. (2021) and carbohydrate and pasting properties of oat flakes from the present study showed several relationships between the measured parameters. The visual projection of the correlation loadings in PCA of the flake properties and chemical composition of heat-treated oat flour is shown in Fig. 3. Pasting properties of the flakes grouped both with physical properties of the flakes as well as the chemical composition of the samples. Final viscosity, setback viscosity and viscosity at 95 °C were grouped with the amount of fines of the samples as well as the starch content, damaged starch content and share of damage starch of the total starch of the samples. Furthermore, pasting temperature and initial viscosity of the samples were located on the opposite side of the projection and grouped with protein content, β-glucan content, lipid content and ash content of the samples. Similar interactions were observed between the flake parameters and composition of oats by the Pearson correlation coefficients (Appendix Table A.6.).

Furthermore, pasting properties of the non-heat-treated flours grouped with the chemical composition of the samples (Fig. 4A). Breakdown viscosity grouped with the starch and damaged starch contents of the samples. Furthermore, pasting temperature of the samples was located on the opposite side of the projection and grouped with protein, lipid and ash contents of the samples. The PCA of the properties of the physical properties and chemical composition of heat-treated oat flours showed several interactions between the measured parameters (Fig. 4B). Pasting properties of the heat-treated oat flours grouped with the chemical composition of the samples. Peak viscosity and breakdown viscosity were grouped with the starch content, damaged starch content and share of damage starch of the total starch of the samples. Furthermore, pasting temperature and the peak viscosity of the samples were located on the opposite side of the projection and pasting temperature grouped with the insoluble dietary fibre content as well as with the particle size parameters. Peak time, setback viscosity and final viscosity were grouped with water holding capacity and with ash and β-glucan content of the heat-treated oat flours. The heat-treated flour samples 1–10 and 11–30 were clearly separated in the scores plot of the PCA projection, while no clear difference was observed between the samples 1–10 and 11–30 for flakes or non-heat-treated flours (Appendix, Figs. A.2-A.4). When the carbohydrate and pasting properties of heat-treated oat flour samples 11–30 were correlated with their baking performance, no significant interactions were observed based on Pearson correlation coefficients (data not shown). The hardness of oat groats (samples 1–10) was found to correlate positively with the damaged starch content of oat flours ($p < 0.01$, $r = 0.778$) and with the share of damaged starch in total starch of oat flours ($p < 0.05$, $r = 0.714$).

4. Discussion

This study was conducted to explore the carbohydrate characteristics and pasting properties of oat ingredients before and after the industrial oat milling process. Previous studies have mainly focused on understanding the carbohydrate properties and starch quality of oat samples milled in laboratory scale, whereas the carbohydrate quality and properties of oat flours produced in industrial scale that includes kilning have not been studied to same extent. Although there are some studies that have focused on exploring the interaction between the carbohydrate

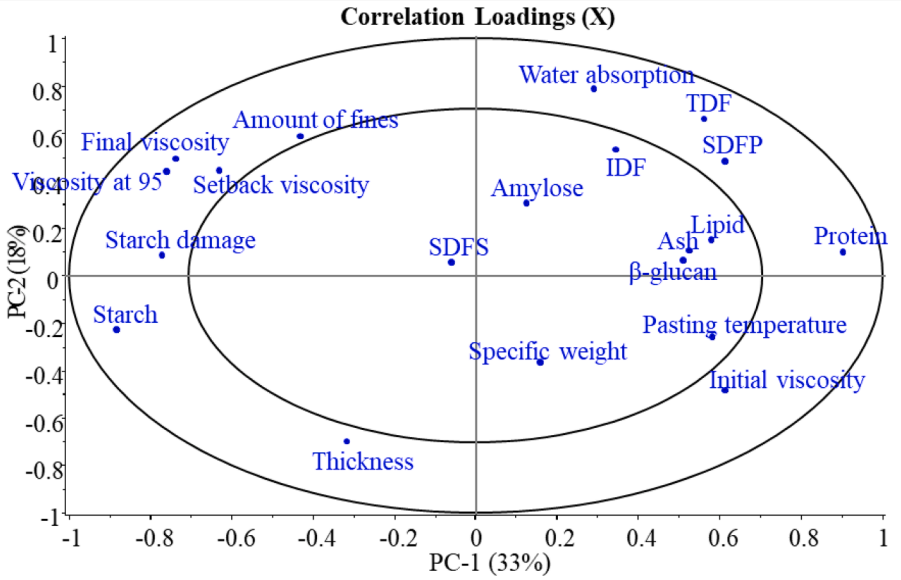

Fig. 3. Principal component analysis (PCA) correlation loadings of the oat flake properties and chemical composition of heat-treated oat flours. TDF = total dietary fibre, IDF = water insoluble dietary fibre, SDFP = water-soluble dietary fibre that precipitates in the presence of 78 % ethanol, SDFS = water-soluble dietary fibre that stays soluble in the presence of 78 % ethanol.

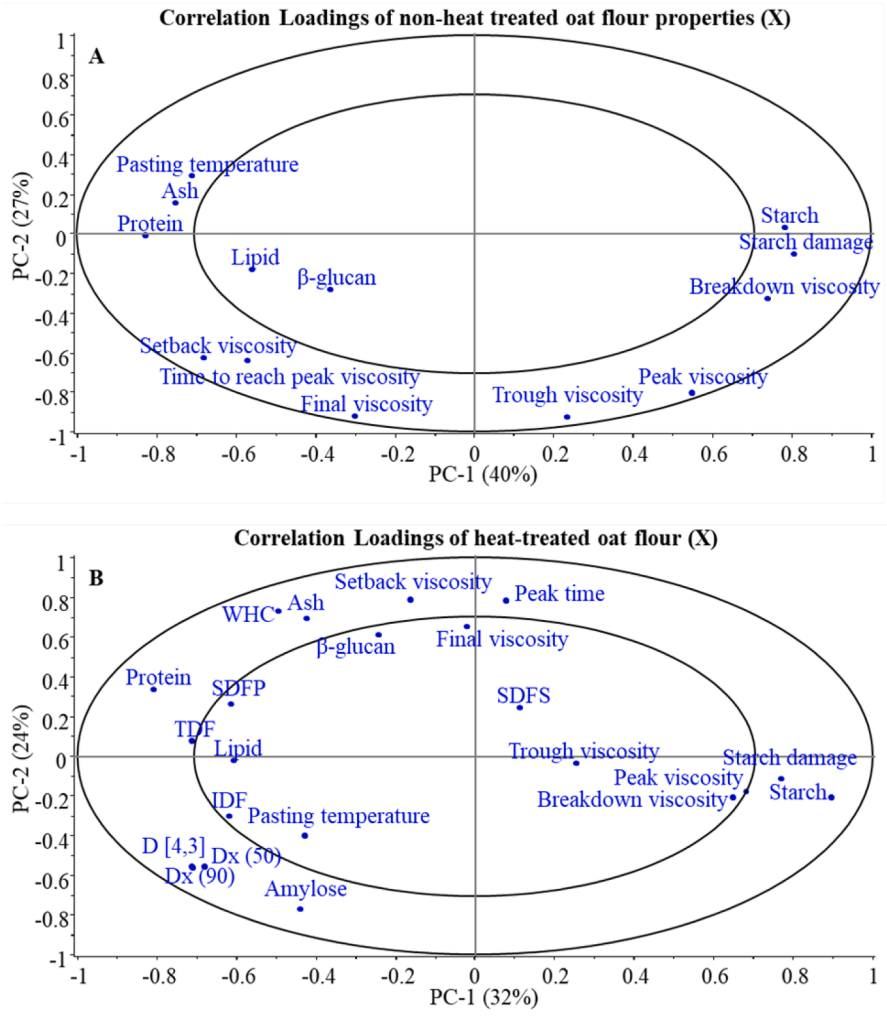

Fig. 4. A: Principal component analysis (PCA) correlation loadings of RVA pasting properties and chemical composition of the non-heat-treated flours. B: Principal component analysis (PCA) correlation loadings of the physical and chemical properties of the heat-treated oat flours. TDF = total dietary fibre, IDF = water insoluble dietary fibre, SDFP = water-soluble dietary fibre that precipitates in the presence of 78 % ethanol, SDFS = water-soluble dietary fibre that stays soluble in the presence of 78 % ethanol. WHC = water holding capacity, D_{50} = median particle diameter, $D_{4,3}$ = the mean particle diameter, D_{90} = particle diameter, of which 90 % of the particles are smaller.

properties of oats and the product quality, the variation of the behavior of different oat batches in the milling process has not been elucidated. We have previously investigated the connection between the native oat grain and oat flour characteristics (Jokinen et al., 2021) and demonstrated the variation of processability of the pure cultivar oat raw materials (Jokinen et al., 2022). Furthermore, Sammalisto et al. (2021) identified the factors related to the baking quality of the heat-treated oat flour samples 11–30. The current study demonstrated a significant variance in the carbohydrate properties of the 30 different oat batches before and after the oat milling process.

4.1. Carbohydrate characteristics of oat flours

Total dietary fibre contents of heat-treated oat flours found in the current study agree with the previous literature, although the shares of different dietary fibre fractions are inconsistent with the previous studies (Manthey et al., 1999; Rainakari et al., 2016). According to Manthey et al. (1999), total dietary fibre content of six oat varieties was 10.2–12.1 % (dm) and soluble dietary fibre presented 38–42 % and insoluble dietary fibre 58–62 % of total dietary fibre, which differ from what was seen in the current study where the lower share of insoluble dietary fibre (44 %) and higher share of soluble dietary fibre (56 %) was observed. Furthermore, Rainakari et al. (2016) reported higher IDF contents (6.7–8.1 % dm), similar SDFP contents (3.7–5.6 % dm) and at least two times smaller SDFS contents (0.2–0.5 %) in the oat flake samples than what was found in the current study (2.4–5.7 %, 3.6–6.1 %, and 0.7–2.4 %). The inconsistency between the current study and the previous studies may be explained by the changes in the definition of dietary fibre as well as by differences in the analysis methods. The AOAC method 2011.25 used in the current study includes the water-soluble dietary fibre that remains soluble in ethanol (SDFS, i.e., oligosaccharides) into soluble dietary fibre fraction as well, whereas Manthey et al. (1999) analysed the total dietary fibre content without the oligosaccharides. Although Rainakari et al. (2016) utilized the same analysis method as in the current study, the difference in the results may originate from the difference between the semi-automated method used in the current study and the manual method used by Rainakari et al. (2016) in addition to the natural variation between the different oat batches. The current results emphasize the importance of constant monitoring of the dietary fibre contents of cereal raw materials as the definition of dietary fibre and analytical methods to determine dietary fibre develop constantly.

In the current study, the damaged starch content of non-heat-treated flour samples was significantly lower (mainly below 1 %) than the damaged starch content of heat-treated flour (4.4 %). Furthermore, a large variation in the amount of starch damage was observed between the different oat batches, which demonstrates raw material specific behaviour. Although higher starch damage content was connected to higher starch content of oat flours, the ratio between the amount of starch damage and starch content was not constant.

This indicates that the damaged starch is also related to other factors than the starch content. Currently there is no literature available explaining the origin of starch damage in oats. In wheat, the amount of damaged starch depends on the harshness of the grinding as well as on

the hardness of the wheat grain as reviewed by Boyaci et al. (2004). In a study by Engelson and Fulcher, (2002), a relation between oat grain characteristics and overall groat damage during dehulling was observed. They reported that the β-glucan content and protein content of the oat grain influenced the amount of groat breakage occurring during dehulling. The current study suggests that the grain hardness could also be related with starch damage in oats, as starch damage in oat flour was shown to increase with an increase in groat hardness. Previous studies have shown that the oat milling process induces changes in the oat groat hardness and that the kilning can increase the hardness of oat groats (Gates et al., 2008). Furthermore, the groat hardness has been shown to increase with increasing starch content and to be oat batch related (Jokinen et al., 2022).

As milling causes starch damage, it may be estimated that almost all starch damage of non-heat-treated oat flours originated from the laboratory scale milling, and it can be assumed that there is almost no starch damage at all in the intact oat groats. Currently there is very limited amount of literature available regarding the starch damage content of commercial oat flours and the relation between the oat grain properties and the amount of starch damage occurring during oat milling and only Hüttner et al. (2010) have reported damaged starch contents of 1.6, 6.7 and 9.2 % in three commercial oat flours.

Role of carbohydrate quality for wheat flour quality has been clearly demonstrated, for example starch quality and starch damage content affect the baking quality of wheat flour as reviewed by Eliasson (2012). Meanwhile similar linkages are lacking for oats. Some connections have been reported regarding the role of total dietary fibre, β-glucan, starch, and starch damage content of oats on the end-product quality. For example, Hüttner et al. (2010) have reported that the amount of starch damage affects the rheological properties and baking quality of the oat. However, no significant interactions were observed in the current study between the baking quality and starch damage content of the oat flours. The significance of the starch damage content of oat flours for the quality of oat products remains to be confirmed.

4.2. Pasting behavior of oat flake and flour samples

Large variation of the oat flake pasting properties between the 30 samples was expected, as the current flake samples were found to exhibit a large variation in their physical properties (Jokinen et al., 2022). Oat flake pasting properties were connected to protein and starch content of oats as higher protein content was related to lower final viscosity, setback, and viscosity at 95 °C while starch content had the opposite influence. This could be observed in case of heat-treated oat flour sample 10 with an exceptionally high protein content (19.2 % dm) that exhibited the lowest viscosity. Furthermore, a higher share of fine particles of the flakes was connected to higher viscosity at 95 °C values, showing that a higher amount of fine particles in flakes increases the water-holding capacity of the flakes (Balet et al., 2019). In addition, a higher share of fine particles was connected to higher final and setback viscosities demonstrating an increased tendency of the flake suspension to retrograde. According to Lapveteläinen et al., (2001), thicker oat flakes with high amount of starch are connected to low maximum viscosity measured by amylograph, low water absorption and low protein and β-glucan content. In the current study, the thickness of flakes was indeed inversely correlated with the dietary fibre fractions of oats as well as with water absorption capacity of flakes. Nevertheless, no clear link between thickness and viscosity values measured by RVA were observed, and starch content was connected to higher final viscosity values instead of lower values.

The current non-heated and heated oat flour samples exhibited several interactions between the pasting characteristics and chemical composition of oats. Higher starch and damaged starch contents were related to higher peak, breakdown and trough viscosity values, while higher total dietary fibre, protein, lipid and ash showed opposite relationship. According to Liu et al. (2010), there might be a notable interaction between β-glucan and starch that affects the pasting properties of oat flours and they postulated that peak viscosity and trough viscosity are more starch-related whereas the final viscosity can be linked to β-glucan content. This would seem to apply to the current data as well, as higher starch content of oats was indeed related to higher peak and trough viscosities of flours while higher β-glucan content was connected to higher final viscosities of flours. In the current study, the higher amylose content of oat flours was connected to lower peak time, final and setback viscosities. Similar relation between amylose content and setback viscosity has been observed in heat-treated oats in the study by Nguyen et al. (2019) as well. The current study shows that many of the relationships reported in the literature between the oat flour pasting properties and chemical composition of oats observed in the laboratory scale apply to the oat flours produced in the industrial scale as well.

4.3. Impact of oat milling process on pasting behavior

In the current study, the pasting characteristics of oat samples were significantly different between the non-heat-treated flours produced in laboratory scale and the heat-treated oat flours produced in industrial scale, i.e., the oat milling process with characteristic kilning step affected the pasting characteristics of oats. The effect of the kilning step as a part of the milling process on oat pasting properties has also been studied by Zhou et al. (1999) who observed significant changes in the pasting properties of three Australian oat cultivars after small scale processing including steaming, kilning and rolling. The processing increased the peak viscosity, time to peak viscosity and final viscosity values and the changes were sample dependent, which was observed in the current study as well. Nevertheless, according to Nguyen et al. (2019), heat treatment increases the pasting temperature and decreases the breakdown, final and setback viscosity of oat flours, which is partly contradictory with the current results. This difference can be explained with different processing methods as in the study by Nguyen et al. (2019) the heat treatment included wet steaming at 100 °C for 40 min, dry heating at 125 °C for 10 min and drying at 112 °C for 30 min and milling was performed with cryogenic-milling process to avoid molecular degradation of starch granules. The current study utilized industrial scale milling process that included drying at 145 °C for 3 h and kilning at 150 °C for 40 s followed by a 15-min stabilization period at 110 °C and milling was performed with stone mill. Therefore, it can be considered that the processing conditions in the current study were more intensive than described by Nguyen et al. (2019) and yielded some molecular changes in the starch granules. As the kilning step is a part of the whole industrial scale process in the current study, the changes in the pasting properties cannot be considered to originate solely from the kilning step, but as a combination of the kilning and the other processing steps present in the milling process.

The peak viscosity can be linked with the water holding capacity of the material as reviewed by Balet et al. (2019). Furthermore, according to Hüttner et al. (2010), water holding capacity of oat flours is enhanced by the protein, β-glucan, and high damaged starch content and the small particle size of the flour. Jokinen et al. (2021) noted that the β-glucan and ash contents of the current heat-treated oat flours were significantly lower and starch contents higher compared to the current non-heat-treated flour samples. This was postulated to be due to the differences in the dehulling method in laboratory scale and in industrial scale and must be noted when interpreting the current results as well. In the current study, the higher peak viscosities were indeed connected to higher water holding capacity values and therefore the increase in the peak viscosity values could be also partly explained by the increased damaged starch content, but also with the slightly different amount of starch in the non-heat-treated and heat-treated oat flours. Higher final viscosity values after milling indicate that the milling process could increase the tendency of the oat starch to retrograde. It was expected that the particle size distribution of flours affects the pasting behaviour of flour. Thus, it was expected that the re-milling of oat flour samples

11–30 affects the pasting characteristics of these flours, but only some changes were observed, and the main effect was the increase in the time to reach peak viscosity values showing that the re-milling step slowed the swelling rate of the flour granules. The current results highlight the importance of understanding the effect of commercial milling process on the oat flour properties as laboratory scale processing without heat-treatment and different processing conditions than in industrial scale seem to yield very large variation in the oat flour characteristics. The difference in the pasting characteristics between the non-heat-treated and heat-treated flours is not related only to the heat treatment (kilning), but also to the other steps included in the industrial process. The current study shows that understanding the properties of oat flours produced in industrial scale oat milling process is important, as the industry rarely utilizes oats without the heat treatment.

5. Conclusions

In the current study, a large variation in the starch and dietary fibre content and quality of pure cultivar oats were observed. Furthermore, the effect of the industrial oat milling process on the amount of starch damage and pasting characteristics was demonstrated. The oat milling that includes the heat treatment was found to inflict a notable amount of starch damage and the starch damage content was oat batch dependent. In addition, the pasting properties of oats changed due to the milling process and showed similarities between the 30 samples although also batch specific behaviour was observed. The pasting properties of oat flakes and both non-heat-treated and heat-treated oat flours were mainly related to the chemical composition of oats but also linked to the physical properties of the flakes and flours. This study highlights the importance of studying the carbohydrate properties of oats produced in the industrial scale, as the industrial scale processing significantly affects the characteristics of oats. Furthermore, the importance of raw material selection as well as optimization of the heat treatment and processing conditions when producing oat-based ingredients are highlighted, as the different pure oat batches exhibited large variation in their carbohydrate properties and pasting behaviour in the constant milling conditions. However, the role of this variation for the quality of the oat-based food products remains to be confirmed.

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CRediT authorship contribution statement

Iina Jokinen: Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Pia Silventoinen-Veijalainen:** Conceptualization, Investigation, Writing – review & editing. **Martina Lille:** Validation, Investigation, Data curation, Writing – review & editing, Visualization. **Emilia Nordlund:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Ulla Holopainen-Mantila:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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

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