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Variation in the physical properties of oat groats, flakes and oat flake flour – Processability of thirty pure cultivar oat batches from Finland

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ABSTRACT

The aim of this study was to understand the processability of thirty pure cultivar oat batches and how the physical properties of oat groats and flakes affect the characteristics of oat flake flour. This was conducted by investigating the relationship between the chemical composition of oats and the physical characteristics of oat groats, flakes and flours produced by industrial scale milling process. It was clearly shown that the oat batches behaved differently in the milling process and that the physical characteristics of oat groats, flakes and flours were interrelated. For example, separation of bran and endosperm particles of oat flours by dry fractionation was connected to the chemical composition as well as particle size distribution of the flours. Furthermore, it was shown that flowability properties of oat flours affect the bran-endosperm separation of oat flour by dry fractionation. This study demonstrated the role of the oat raw material in the milling process as well as the relationship between the different mill products, which deepens the understanding of oat milling process and is important when aiming at producing oat products with high quality.

1. Introduction

Traditionally oats (*Avena sativa* L.) have been consumed for food as flakes for porridges and as bakery ingredients for biscuits and bread (Webster, 2011). Due to the growing amount of oat-based food products, the use of oat flour is increasing, and there is a need to improve the understanding about the properties of oat flour and oat flakes in order to produce high quality products and to increase the predictability of food processes. Compared to wheat, oat raw materials have not been as extensively optimized for different food industry applications.

Oat milling process includes cleaning, dehulling and heat treatment steps, after which the groats are typically flaked (Pomeranz, 1995). Kilning including steaming and heating is conducted in order to inactivate the lipid-degrading enzymes that may cause rancidity during storage (Ganßmann & Vorwerck, 1995). Oat flour may be milled either from flakes or directly from groats, and the flour is usually used as whole grain flour (Girardet & Webster, 2011). Furthermore, oats are often delivered to mills as mixtures of oats comprising of different cultivars grown in different locations and it has been shown that the chemical composition and properties of oats vary significantly (Jokinen et al., 2021; Lapveteläinen et al., 2001; Shewry et al., 2008). One of the major challenges in the oat milling process is related to the high lipid content of oats, which is related to the tendency of the material to accumulate to the surfaces of the milling equipment (Girardet & Webster, 2011).

Several physical attributes of grain, such as hardness of grains, have been shown to be important factors for wheat flour end quality after the milling process (Campbell et al., 2012). Studies concerning differences in physical properties and chemical composition of oats and oat mill product quality have been studied to some extent. Physical and chemical properties of oat flakes have been shown to be influenced by cultivar, thus it has been suggested that the oat flaking process would be optimized on a cultivar basis (Lapveteläinen et al., 2001; Rhymer et al., 2005). Similar oat cultivar or batch related connections have not been elucidated for oat flour properties and different oat-based food applications. As use of oats flour has been increasing in different food applications, it is important to understand how oat groat and flake

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properties affect the quality of oat flours.

Physical properties of oat flours, such as particle size and water holding capacity, affect their use in processing. For example, Sammalisto et al. (2021) demonstrated a connection between the median particle size and baking properties of oat flours. Furthermore, physical properties of oat flours also affect their utilization in dry processes, such as sieving or air classification, which can be utilized after the milling process in order to obtain ingredients with higher amount of starch, protein or β-glucan than in the original oat flour (Assatory et al., 2019; Sibakov et al., 2012; Wu & Doehlert, 2002; Wu & Stringfellow, 1995). Behaviour of flours and powders in processing depend on several factors such as moisture content, chemical composition, particle size and flowability of the flour. For example, it has been previously established for oats that lipid content is one of main factors affecting the fractionation properties of oat flour (Sibakov et al., 2011).

Relationship between the physical and chemical properties of oat grain and flakes in oat milling process have been studied, whereas there is a limited number of reports on the factors affecting the processability and physical properties of oat flours. Furthermore, understanding the relationship between the flake and flour properties would be important, since the flours are often produced from flakes in oat milling. We have previously investigated the connection between the native oat grain and oat flour characteristics (Jokinen et al., 2021) and identified the factors related to the baking quality of oat flours (Sammalisto et al., 2021). Therefore, this study aimed at investigating the impact of hardness of oat groat and physical properties of oat flakes on physical characteristics of the produced whole grain oat flour. The results produced in this study were correlated with the previous data by Jokinen et al. (2021) concerning the chemical composition of the 30 Finnish oat batches. As the chemical composition of these samples showed variation, it was hypothesized that the behaviour in the milling process and the physical properties of these samples will vary as well. In addition, it was hypothesized that hardness of oat groat and physical properties of oat flakes show significant relationship with the physical properties of the oat flours, including flour water holding capacity, particle size, bran-endosperm separation by air classification and flow properties.

2. Materials & methods

2.1. Materials

Thirty Finnish oat sample batches representing different oat cultivars were obtained from Boreal Plant Breeding Ltd., Peltosiemen Ltd., Vääksyn Mylly Ltd., Plantanova Ltd., Raisio plc and Lantmännen Agro Ltd. The samples were processed as pure cultivars and three different crop years, 2017, 2018 and 2019, were represented. The chemical composition of the whole grain oat flours has been published earlier by Jokinen et al. (2021) and corresponding oat sample codes were used in our study. All samples were analysed as heat-treated oat groats, oat flakes and whole grain oat flour, which were produced at Vääksyn Mylly Ltd. (Asikkala, Finland) (Fig. 1). The milling process included drying, de-hulling, kilning, flaking and milling with a stone mill, as described in Jokinen et al. (2021). The whole grain oat flour was milled from oat flakes. The milling stone was replaced after processing of the 10 first samples which caused difference in particle size of the samples 1–10 and 11–30. 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 120 kg/h feed rate.

2.2. Oat groat hardness

Oat groat hardness of oat groat samples 1–10 was determined with a method adapted from Gates, Dobraszczyk, et al. (2008) from heat-treated oat groats. Twenty replicate groats (placed crease down) were compressed into 50% deformation with a Texture Analyser (TA-XT2i, Stable Microsystems, Surrey, UK), with a 10 kg load cell. The compression was done at a speed of 1 mm/s using a cylindrical probe of 36 mm in diameter. The probe was held at 50% deformation for 5 s, and the maximum force during the measurement was considered groat hardness.

2.3. Oat flake properties

Oat flake analyses included measuring the water absorption of oat

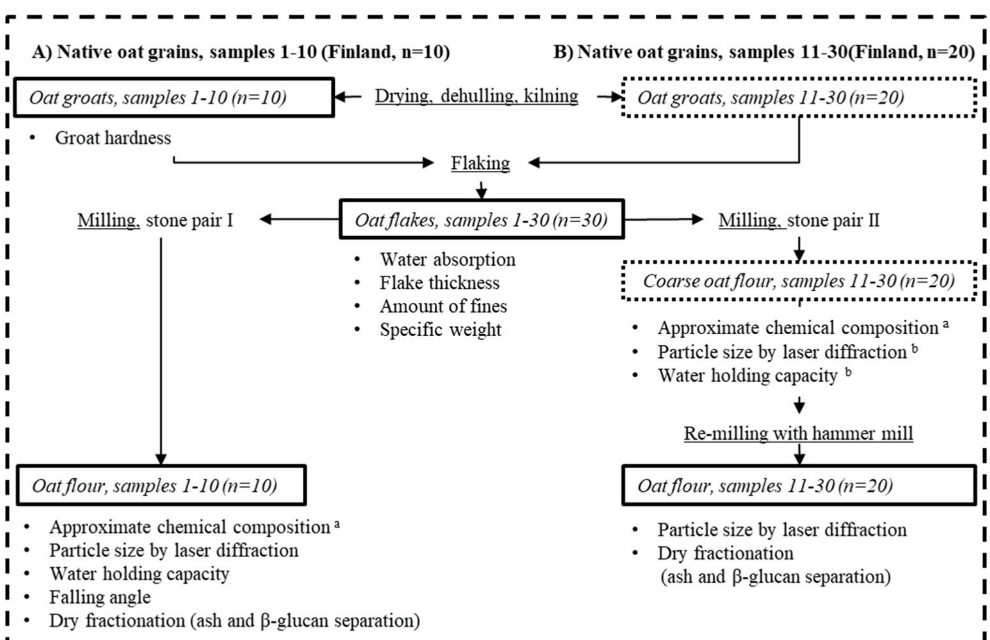

Fig. 1. Oat raw material processing and analysed properties. Processing steps are underlined, samples analysed are outlined with black line and analysed properties listed with bullet points. [a] Reprinted with permission from Jokinen et al. (2021). Copyright 2021 Jokinen et al. [b] Reprinted with permission from Sammalisto et al. (2021). Copyright 2021 Sammalisto et al.

flakes (AACC method 56–40), oat flake thickness with a micrometer (Mitutoyo 0–25 mm, 0.01 mm, Mitutoyo Corporation, Japan), specific weight, and the share of fines by separating particles that are less than 2.5 mm with a sieve shaker (CISA RP-08-S, CISA Cedaceria Industrial, Barcelona, Spain). The sieving measurement was carried out for 6 min at an amplitude of 2 mm. All measurements were performed in triplicates, but oat flake thickness was analysed from twenty replicate samples.

2.4. Oat flour properties

2.4.1. Particle size distribution of oat flours

Particle size distribution of the flours were analysed by laser diffraction method. The analysis based on laser diffraction was carried out using a Mastersizer 3000 with a dry feed unit (Aero S, Malvern Instruments Ltd, Malvern, Worcestershire, UK). The refractive index of the sample was 1.47 as defined by Alvarez et al. (2013), input pressure 3 bar and feed rate 30%. Values of D_{50}, D_{90} and $D_{4,3}$ were determined from three replicate measurements, and they represent volume-based results. D_{50} is the median particle diameter, while $D_{4,3}$ represents the mean particle diameter. D_{90} is the particle diameter, of which 90% of the particles are smaller. Analysis was performed in triplicate for each sample.

2.4.2. Water holding capacity of oat flours

Water holding capacities of the flour samples 1–10 were measured with AACC standard method (56–30, 2000) with small modifications. Between mixing and each centrifugation of the samples, samples were kept at room temperature for 20 min to allow a proper water absorption of the flour and to improve the repeatability. In the original method, incubation time was not specified. Analysis was performed in triplicate for each sample. Water holding capacities of the coarse flour samples 11–30 before re-milling have been published by Sammalisto et al. (2021).

2.4.3. Dry fractionation

Air classification of all of the thirty oat flours was performed using a Minisplit Air Classifier (British Rema Manufacturing company Ltd., Chesterfield, UK) with 2500 rpm air classifier wheel speed, 220 m^3/h air flow rate and a sample feed rate of approximately 1.7 kg/h. Oat flour samples 1–10 were classified directly after the industrial milling process and the flour samples 11–30 after re-milling with the hammer mill. In each sample set, 700 g of oat flour was air classified in duplicate, the masses of the two fractions were weighed and recorded and mass yield of each fraction was calculated with Equation (1).

$$\textit{Mass yield}\ (\%\ \ \mathrm{dm}) = \frac{\text{Dry weight of the fraction (g)}}{\text{Dry weight of the raw material (g)}} \times 100\% \tag{1}$$

Ash content of the combined duplicate coarse fractions from air classification was determined in a muffle furnace (Model P300 N11/HR, Nabertherm, Lilienthal, Germany) using a temperature program including increase to 103 °C for 3 h, hold at 103 °C for 4 h, increase to 550 °C in 9 h and hold at 550 °C for 7 h followed by cooling to ambient temperature. β-Glucan content of the combined duplicate coarse fractions was determined according to the AOAC Method 995.16 using a Megazyme assay kit (β-Glucan Assay Kit, Megazyme, Bray, Ireland). β-Glucan content of coarse fractions was determined in triplicates and ash content of coarse fractions in duplicates. β-Glucan and ash separation efficiencies (SE) were calculated to evaluate the component separation efficiency with Equation (2) adapted from Tyler et al. (1981) using the β-glucan and ash contents of the raw material flours published earlier by Jokinen et al. (2021).

$$\textit{Separation efficiency}\ (\%\ \ \mathrm{dm}) = \textit{Mass yield of fraction}\ (\%, dm) \times \frac{\text{Component content in the fraction (\%)}}{\text{Component content in the raw material (\%)}} \tag{2}$$

2.4.4. Flowability analysis

Flow properties of the oat flour samples 1–10 were determined by analysing the avalanche angle of the flours, which is defined as the maximum angle at which powder begins to flow. Measurement was conducted using a purpose-built device with a sample drum (50 mL volume, 41 mm diameter) rotating at 4 rpm as described by Calton et al. (2019). Each sample was analysed in 10 replicates.

2.5. Statistical analysis

In order to investigate the interaction 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 results previously published by Jokinen et al. (2021) and Sammalisto et al. (2021). The results are represented as average values, and the numbers of replicate measurements are separately detailed. All results, standard deviations and coefficients of variations were obtained using Excel spreadsheet software (Excel 2016; Microsoft, Redmond, US). The interactions between the different sample parameters were estimated based on the Pearson correlation coefficients. Differences between the flowability values of each sample were analysed with ANOVA with Tukey's honestly significant difference (HSD) ($p < 0.05$) posthoc test. Statistical difference between hardness of groats, flake properties, water

Table 1

Average ± standard deviation, minimum and maximum values of hardness of oat groats (n = 10) and water absorption, thickness, share of fines, and specific weight values of oat flakes (n = 30). Minimum and maximum values of hardness of groats and thickness of flakes are expressed as average values of 20 replicate measurements (n = 20). Minimum and maximum water absorption, share of fines and specific weight of flakes are expressed as average values of 3 replicate measurements (n = 3).

	Heat-treated groat (n = 10) Samples 1-10	Oat flake (n = 30) Samples 1-30			
	Hardness (N)	Water absorption (mL/g)	Oat flake thickness (mm)	Share of fines (%)	Specific weight (g/L)
Average	46.1 ± 8	1.2 ± 0.01	0.6 ± 0.01	10.2 ± 0.8	370 ± 3
Min	35	1.0	0.5	3	330
Max	56	1.5	0.7	27	413
CV (%) [a]	10–24%	0.2–3.2%	1.5–3.9%	1.5–19%	0.2–1.9%

[a] CV = coefficient of variation.

holding capacity and particle size values of flours and dry fractionation values of flours of each sample were estimated with a Kruskal–Wallis one-way analysis of variance test ($p < 0.05$). Independent sample T-tests ($p < 0.05$) were performed to compare the parameters of oat flour samples 1–10 and samples 11–30. The Pearson correlation coefficients, ANOVA, Kruskal-Wallis test and independent sample T-tests were carried out with SPSS-software (IBM SPSS Statistics, version 26, IBM, New York, NY, USA).

3. Results

3.1. Oat groat and flake properties

Oat groat hardness varied between 34.5 and 55.8 N, and the average was 46.1 N (Table 1, Appendix Table A1). Hardness values showed significant ($p < 0.05$) variation between the samples. Oat flake water absorption values were between 1.0 and 1.5 mL/g, oat flake thickness values were between 0.5 and 0.7 mm, share of fines was 3–27% and specific weight values were between 330 and 413 g/L (Table 1, Appendix Table A2). All flake parameters exhibited statistically significant differences ($p < 0.05$) between the different samples.

3.2. Oat flour properties

3.2.1. Physical oat flour properties

Water holding capacity values of the oat flour samples ranged between 1.0 and 1.6 mL/g flour, with the average of 1.2 mL/g and the values were significantly different ($p < 0.05$) between the samples (Table 2., Appendix Table A3). Water holding capacities of the coarse oat flour (samples 11–30) ranged between 1.1 and 1.5 mL/g flour (Sammalisto et al., 2021). Due to the differences in the particle sizes between the two sample sets from the mill, samples 11–30 were re-milled with a hammer mill prior to dry fractionation to allow comparison of all 30 samples in air classification. Particle size values of oat flour samples 1–10 were significantly different ($p < 0.05$) compared to the particle size values of re-milled samples 11–30 (Table 2, Appendix Table A3). The average of D_{50} values for the oat flours of the flour samples 1–10 was 51 μm and average of D_{50} values for the oat flours of the flour samples 11–30 was 54 μm. $D_{4,3}$-values were 138 μm and 130 μm and D_{90}-values were 387 μm and 361 μm for the samples 1–10 and 11–30, respectively. The particle size distribution of the coarse flours (sample flours 11–30 before re-milling) has been published by Sammalisto et al. (2021).

3.2.2. Dry fractionation and flow properties

To evaluate the flowability of the oat flours, avalanche angle values were measured from the oat flours of the samples 1–10 (n = 10) and those varied from 39.5 to 51.9° (Appendix Table A4). Based on the avalanching behaviour of the oat flours during the measurement, all exhibited cataracting flow regime (Fig. 2.). The aim of the dry fractionation was to obtain a coarse fraction representing 20–30% of the original sample and a fine fraction representing 70–80% of the original sample (Sibakov et al., 2012) targeting separation of bran (coarse) and starchy endosperm (fine) parts of the groat. In the flour samples 1–10, mass yields of the fine and coarse fractions obtained by air classification from oat flours were 71.7–79.8% and 16.8–25.0%, respectively (Table 3, Appendix A5). For the flour samples 11–30, the mass yields of fine and coarse fractions were 66.5–78.7% and 17.7–31.1%, respectively. A significant difference ($p < 0.05$) between mass yields of the 1–10 samples and the re-milled samples 11–30 was observed (Table 3). Original β-glucan content of the oat flours published by Jokinen et al. (2021) varied between 2.9 and 4.6% and the β-glucan contents of the coarse fractions varied from 9.7 to 13.8%. β-Glucan separation efficiencies to coarse fraction varied between 50.4 and 87.7%. Ash content of the oat flours was 1.6–2.3% while the ash content of fractions varied between 4.2 and 5.3% and ash separation efficiencies to coarse fraction were 43.6–63.3%. β-Glucan and ash content of the coarse fractions of samples 1–10 and 11–30 were significantly different ($p < 0.05$).

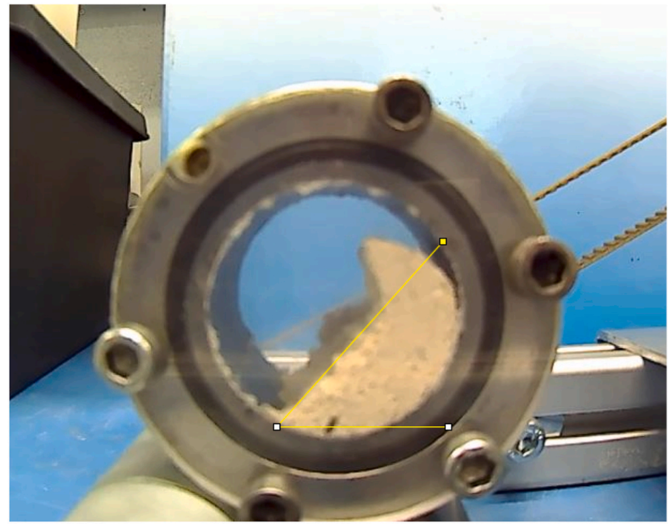

Fig. 2. Example of a freeze-frame of oat flour during avalanche test. Angle of avalanche is shown in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. Statistical analysis

Pearson's correlation coefficients were calculated between the physicochemical properties of oat flours, hardness of groats and physical properties of oat flakes and oat flours (chemical composition of flours by Jokinen et al. (2021) and water holding capacity and particle size distribution with laser diffraction by Sammalisto et al. (2021)). Correlations between the physical properties of oat flakes, water holding capacity of oat flours 1–10 and particle size distribution data of the two sample sets were analysed separately, due to the difference in the milling method. Several interactions were observed between the chemical composition of oat flours, hardness of groats and physical properties of the oat flour samples 1–10 and 11–30 (re-milled coarse flour set)

Table 2
Average ± average standard deviation, minimum and maximum values of particle sizes of oat flour samples 1–10 (n = 10) obtained directly from the mill and of the oat flour samples 11–30 (n = 20) after re-milling with a hammer mill analysed by laser diffraction. D_{50} is the median particle diameter, while $D_{4,3}$ represents the mean particle diameter and D_{90} is the particle diameter, of which 90% of the particles are smaller.

	Oat flour samples 1–10 (n = 10)				Oat flour samples 11–30 (n = 20)			
	Average	Min	Max	CV (%) [b]	Average	Min	Max	CV (%)
D_{50} (μm)	51 ± 1a [a]	44	62	1–5	54 ± 2b	44	75	2–8
$D_{4,3}$ (μm)	138 ± 3b	129	148	0–3	130 ± 5a	113	163	1–8
D_{90} (μm)	387 ± 7b	355	417	0–3	361 ± 14a	310	454	1–8

[a] Different letters within each row indicate statistically significant difference ($p < 0.05$) between samples based on an independent sample *t*-test.
[b] CV = coefficient of variation.

Table 3
Average ± average standard error, minimum and maximum values of mass yields of fine fractions and mass yield and properties of coarse fractions produced by air classification from oat flours (n = 30) at an air classifier wheel speed of 2500 rpm and airflow of 220 m^3/h. Minimum and maximum mass yield values are expressed as average values of two replicate air-classifications (n = 2).

	Samples	Fine fraction	Coarse fraction				
		Mass yield (% dm)	Mass yield (% dm)	β-glucan (% dm)	SE of β-glucan (%) [b]	Ash (% dm)	SE of ash (%)
Average	1–10	75.6 ± 0.9b[a]	20.9 ± 0.5a	12.4 ± 0.1b	62.5b	4.7 ± 0.0b	49.3a
Min	1–10	71.7	16.8	10.9	50.4	4.2	43.6
Max	1–10	79.8	25.0	13.8	76.8	5.3	54.5
CV (%) [c]		0–3	0–9	0		0–3	
Average	11–30	72.7 ± 1.2a	23.6 ± 0.6b	11.5 ± 0.1a	68.8a	4.2 ± 0.0a	51.3a
Min	11–30	66.5	17.7	9.7	58.9	3.6	46.4
Max	11–30	78.7	31.1	13.7	87.7	5.2	63.3
CV (%)		0–6	0–20	0		0–5	

[a] Different letters within each column indicate a statistically significant difference ($p < 0.05$) between the samples based on an independent sample *t*-test.
[b] SE = separation efficiency.
[c] CV = coefficient of variation.

Table 4
Pearson correlation coefficients of hardness of oat groats and chemical and physical properties of oat flours. D_{50} is the median particle diameter, while $D_{4,3}$ represents the mean particle diameter and D_{90} is the particle diameter, of which 90% of the particles are smaller. WHC = water holding capacity.

	Hardness	WHC	Angle of avalanche	Starch[a]	Protein[a]	Lipid[a]	Ash[a]	TDF[a]	β-glucan[a]
Samples 1–10 (n = 10)									
Hardness	–	-.817**	–	.794**	-.779**	–	-.864**	–	–
WHC	-.817**	1.0	.637*	-.865**	.890**	–	.920**	–	.828**
Angle of avalanche	–	.637*	1.0	–	–	–	.776**	–	–
D_{50}	.817**	–	–	.732*	-.651*	–	-.764*	–	–
$D_{4,3}$	–	–	–	–	–	–	.776**	–	–
D_{90}	–	.637*	–	–	–	–	–	–	.654*
Samples 11–30 (n = 20)									
D_{50}	na		na	–	–	–	–	–	.455*
$D_{4,3}$	na		na	–	–	–	–	–	–
D_{90}	na		na	–	–	–	–	–	–

-. Correlation is not significant at the 0.05 level (2-tailed). na. not analysed.
Correlation is significant at the 0.01 level (2-tailed).
Correlation is significant at the 0.05 level (2-tailed).
[a] Reprinted with permission from (Jokinen et al., 2021). Copyright 2021 Jokinen et al.

(Table 4). Groat hardness correlated positively ($p < 0.01$) with starch content and median particle size diameter value (D_{50}) of the oat flour samples 1–10, whereas it showed a negative correlation ($p < 0.01$) with protein content, ash content and water holding capacity of the oat flour samples 1–10.

Regarding physical properties of the flours, water holding capacity of the oat flour samples 1–10 showed significant positive correlation ($p < 0.01$) with protein, ash and β-glucan content of oat flours while significant negative correlation ($p < 0.01$) with starch content of oat flours. Angle of avalanche of the oat flour samples 1–10 showed positive correlation ($p < 0.01$) with ash content of the sample flours 1–10. Significant negative correlations were observed between D_{50} values of the oat flour samples 1–10 and protein ($p < 0.01$) and ash ($p < 0.05$) contents of the flour samples 1-01, while starch content of the samples 1–10 showed a positive correlation ($p < 0.01$) with D_{50} values of flour samples 1–10. Mean particle size diameter value ($D_{4,3}$) of oat flour samples 1–10 showed positive correlation ($p < 0.01$) with ash content. Particle size value D_{90} correlated positively with β-glucan content of the flour samples 1–10 ($p < 0.05$). Particle size distribution values of oat flour samples 11–30 did not show any significant correlations with the chemical composition of the flours except a weak positive correlation ($p < 0.05$) between D_{50} value and β-glucan content of oats.

Hardness of oat groat samples 1–10 did not exhibit any significant correlation with the physical properties of oat flakes, whereas interactions were observed between the chemical composition of oat flours and physical properties of the flours and flakes (Table 5). Water absorption values of oat flakes exhibited significant positive correlation ($p < 0.01$) with total dietary fibre content of oats, weak positive correlation ($p < 0.05$) with protein content and weak negative correlation ($p < 0.05$) with starch content of oat. Among the oat flake properties, oat flake thickness correlated negatively with oat flake water absorption ($p < 0.001$). Water holding capacity of oat flour samples 1–10 correlated negatively ($p < 0.01$) with thickness of flakes. In the samples 1–10, the share of fines in the flakes correlated positively with D_{50} ($p < 0.05$) while oat flake thickness correlated negatively with D_{90} ($p < 0.05$). No other correlations were observed between the particle size values of the oat flour samples 1–10 and oat flake properties. Particle size distribution of the coarse oat flours showed weak positive correlation ($p < 0.05$) with the specific weight of the flakes and no interactions were observed between physical properties of oat flakes and particle size distribution values of the re-milled oat flour samples 11–30.

In air classification, mass yields of fine and coarse fractions, as well as ash and β-glucan contents and their separation efficiencies showed several significant relationships with chemical composition and particle size properties of oat flours and physical properties of oat flakes (Table 6, Appendix Table A6). Groat hardness of the oat groat samples 1–10 exhibited significant negative correlation ($p < 0.01$) with mass yield of the coarse fraction and separation efficiencies of ash and β-glucan (Appendix Table A6). Starch content of the oat flours showed negative correlation ($p < 0.01$) with mass yield of coarse fraction. Protein and lipid content of flours correlated positively ($p < 0.01$) with mass yield of coarse fraction. Total dietary fibre content of the flour showed positive correlation ($p < 0.01$) with the mass yield of the coarse fraction, negative correlation ($p < 0.05$) with the ash content of the coarse fraction and positive correlation ($p < 0.05$) with the β-glucan separation efficiency to the coarse fraction. β-Glucan content of flours

Table 5
Pearson correlation coefficients between physical properties of oat flakes, hardness of oat groats and chemical and physical properties of oat flours. D_{50} is the median particle diameter, while $D_{4,3}$ represents the mean particle diameter and D_{90} is the particle diameter, of which 90% of the particles are smaller.

		Oat flake properties			
		Water absorption	Share of fines	Thickness	Specific weight
Oat groats (n = 10)	Hardness	–	–	–	–
Oat flake (n = 30)	Water absorption	1	–	-.611**	–
properties	Share of fines	–	1	–	–
	Thickness	-.611**	–	1	.372*
	Specific weight	–	–	.372*	1
Oat flour (n = 30)	Starch [a]	-.430*	–	.444*	–
Composition [a]	Protein [a]	.426*	-.399*	-.410*	–
	Lipid [a]	–	–	–	–
	Ash [a]	–	–	–	–
	Total dietary fibre [a]	625**	–	-.513**	–
	β-glucan [a]	–	–	-.396*	–
Oat flour samples 1–10 (n = 10)					
properties	Water holding capacity	–	–	-.853**	
	D_{50}	–	.680*	–	–
	$D_{[4.3]}$	–	–	–	–
	D_{90}	–	–	-.771**	–
Coarse oat flour samples 11–30 (n = 20)					
properties	Water holding capacity [b]	–	–	–	–
	D_{50} [b]	–	–	–	.490*
	$D_{[4.3]}$ [b]	–	–	–	.546*
	D_{90} [b]	–	–	–	.547*
Oat flour samples 11–30 (n = 20) properties	D_{50}	–	–	–	–
	$D_{[4.3]}$	–	–	–	–
	D_{90}	–	–	–	–

-. Correlation is not significant at the 0.05 level (2-tailed).
Correlation is significant at the 0.01 level (2-tailed).
Correlation is significant at the 0.05 level (2-tailed).
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correlated positively with β-glucan content of coarse fractions. Particle size distribution values $D_{[4,3]}$ and D_{90} were positively correlated ($p < 0.05$) with the mass yield of the coarse fraction as well as separation efficiency values of the ash and β-glucan. Angle of avalanche correlated positively ($p < 0.05$) with ash and β-glucan content of coarse fraction and water holding capacity of the flours showed positive correlation ($p < 0.05$) with mass yield, β-glucan content and β-glucan separation efficiency of coarse fraction (Appendix Table A6).

Table 6
Pearson correlation coefficients of parameters measured from the coarse fraction obtained by air classification, oat flour particle size D_{50}, $D_{4,3}$ and D_{90} value and chemical composition of flours (n = 30). D_{50} is the median particle diameter, while $D_{4,3}$ represents the mean particle diameter and D_{90} is the particle diameter, of which 90% of the particles are smaller.

		Coarse fraction				
		Mass yield	Ash	Ash SE	β-glucan	β-glucan SE
Flour	Starch [a]	-.619**	–	–	–	-.507**
	Protein [a]	.656**	–	.383*	–	.509**
	Lipid [a]	.570**	-.466**	–	–	.391*
	Ash [a]	.419*	.433*	–	–	–
	TDF [a]	.582**	-.379*	.423*	–	.497**
	β-glucan [a]	–	–	–	.665**	–
	D_{50}	–	–	.440*	–	–
	$D_{[4,3]}$	.385*	–	.556**	–	.403*
	D_{90}	.430*	–	.563**	–	.441*

-. Correlation is not significant at the 0.05 level (2-tailed).
Correlation is significant at the 0.01 level (2-tailed).
Correlation is significant at the 0.05 level (2-tailed).
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4. Discussion

This study was conducted to understand processability of various oat batches and how the different characteristics of oat groats and flakes are connected to the physical properties of oat flours. Previous studies have mainly focused on finding linkages between oat grains and oat flakes, whereas the factors affecting the physical properties of oat flours have not been studied to same extent. Although there are some studies that have focused on finding the linkages between the oat cultivar and the product quality, the variation of the behaviour of different oat batches in the milling process has not been elucidated.

In the current study, groat hardness was shown to be related to the chemical composition of oat groats, as higher starch content was connected to higher hardness values of groats, and higher protein and ash contents to lower hardness values of groats. Grain hardness is a generally used indicator of wheat milling quality as it is related to particle size distribution, chemical composition of the subsequent flour and bread making quality in wheat (Campbell et al., 2012). It was observed in the previous study by Sammalisto et al. (2021), that the particle size properties of the oat flours affect the baking quality, whereas similar linkages have not been discovered for oat groat hardness. In wheat, the hardness of grain has been connected to presence or absence of endosperm-specific proteins called as puroindolines (Morris, 2002). Contrary to the current findings, Doehlert and McMullen (2000) reported that higher β-glucan content of groats was connected to higher hardness values of groats and that protein and starch content of groats were not related to hardness. However, Doehlert and McMullen (2000) used single kernel characterization system (SKCS) to evaluate the groat hardness whereas the method used by Gates, Dobraszczyk, et al. (2008) and the current study is based on compression measurement by Texture Analyser. Therefore, the results are not completely comparable.

Apart from measuring methods, the differences observed in correlations with grain hardness might originate from the differing processing conditions during milling. According to Gates, Dobraszczyk, et al. (2008), heat treatment and moisture content of the groats have a significant impact on the behaviour of oat groats during compression and may yield softer or harder oat groats depending on the treatment conditions. They observed that the maximum force required for compression of groats increased when heat treatment temperature increased from 80 to 110 °C. They postulated that this was due to the water-induced stiffening related to the swelling of the groat structure that reduces the amount of air cells and other discontinuities. The milling process utilized in the current study 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, which can be considered intensive compared to the conditions previously described in the literature where temperatures rarely exceed 115 °C (Duque et al., 2020; Gates, Dobraszczyk, et al., 2008; Girardet & Webster, 2011). Regardless of the differences in the kilning conditions, the observed hardness values of oat groats showed similar variation as in the previous study by Gates, Dobraszczyk, et al. (2008), where the maximum force, i.e. hardness in the current study, varied between 49 and 62 N in kilned oat groats. This highlights that raw material as well as the heat treatment affect the hardness of the oat groats after the kilning, as the kilning conditions were constant in the current study.

Oat flake properties, water absorption, thickness and specific weights, showed statistically significant differences among the thirty oat samples and were in accordance with the previous studies by Gates, Sontag-Strohm, et al. (2008) and Lapveteläinen et al. (2001). Particularly, the share of fines varied considerably, mainly between 3 and 16% for most of the samples and even 27% for one sample. The high share of fines observed in the current study indicates extensive flake breakage during the flaking process. For example, the values reported in one study by Gates, Sontag-Strohm, et al. (2008) were below 3%, where the oat flake breakage was connected to intensity of the heat treatment. The kilning conditions utilized in the current study presumably facilitated the formation of substantial share of fine flake particles in some of the samples during the flaking process. When the chemical composition was evaluated against the flake properties, higher protein content was connected to lower values of the share of fines and flake thickness. In a previous study by Lapveteläinen et al. (2001), protein content of oat groats did not correlate with any of the oat flake properties. The current findings show that the effect of the heat treatment on the amount of flake breakage depends on the protein content of the raw material as the flaking process was constant for all of the samples.

The previous literature regarding the correlations between the oat flake properties is inconsistent with the current findings in many respects. For example, according to Lapveteläinen et al. (2001) thicker oat flakes are connected to lower amount of the share of fines in the flakes, which was not observed in the current study. Then again, Gates, Sontag-Strohm, et al. (2008) observed that thicker oat flakes are related to higher specific weight of the flakes, which is in agreement with the current study. Gates, Sontag-Strohm, et al. (2008) did not observe a significant correlation between flake thickness and water absorption of oat flakes, which was observed in the current study. Nevertheless, our study focused on the variation in the properties of different pure cultivar samples in constant processing conditions whereas Gates, Sontag-Strohm, et al. (2008) studied the effect of the different processing conditions on one raw material consisting of different oat cultivars. It is apparent, that the differences in the milling process conditions of oat flakes affect the end properties of the flakes and thus make comparison of the previous findings with the current work challenging. The contradictory results also highlight the impact of milling process on the oat flake quality, suggesting that the milling conditions should be optimized depending on the raw material.

Physical properties of oat flours showed significant correlations with both chemical composition of the oat flours and physical properties of the oat groats and oat flakes. Particle size distributions of thirty oat flour samples showed large variation. In the current study, groat hardness showed a significant positive correlation with the D_{50} value of the oat flours from the flour samples 1–10 revealing that the milling of the harder groats resulted in larger median particle size of the flour. When considering particle size distribution in wheat milling, hard wheats yield more middle size ranged particles and less small and larger particles whereas softer wheats yield more small sized particles, some middle-sized particles and a tail of larger bran particles (Campbell et al., 2012). Based on the results of the current study, this phenomenon does not apply to oats. However, it is important to note, that the milling process and chemical composition of oats are very different compared to wheat, especially by the heat treatment applied to oat groats. Some connections were found between the amount of fine particles and thickness of flakes and the particle size distribution of oat flours, but they were inconsistent between the samples 1–10 and 11–30, which can be expected to originate from the change of the milling stone. As particle size distribution of oat flours has been shown to be connected to the baking properties of oats, the role of the different raw materials should be considered when producing oat flours intended for certain food use (Hüttner et al., 2010; Sammalisto et al., 2021).

Dry fractionation by air classification was applied to understand the behaviour of the whole oat flours when producing fine starchy endosperm-rich and coarse beta-glucan- and bran-rich fractions from whole grain oat flours. Ash and β-glucan are mainly located in the bran layers of oat groats and therefore their separation to the fractions can be used to estimate the enrichment of bran layers into the coarse fraction (Rainakari et al., 2016; Shewry et al., 2008; Sibakov et al., 2012). In the current study, β-glucan was clearly enriched into the coarse fraction and ash was enriched to some extent based on the separation efficiency values, suggesting that bran was separated into the coarse fraction, thus the results are in line with previous reports for oats (Sibakov et al., 2011). The separation efficiency values were significantly different between the different samples and exhibited large variation, although the dry fractionation parameters were constant. This further confirms that processes utilized for oats should be optimized on oat raw material basis.

Grain and seed hardness have been observed to affect the dry fractionation result in wheat as well as in legumes (Létang et al., 2002; Tyler, 1984). In this work, the harder the groat, the lower the mass yield of coarse fraction as well as the separation efficiencies of the ash and β-glucan into the coarse fraction in the oat flour samples 1–10 were. This observation is logical as higher hardness values were related to higher starch content of the oats and thus indicate a higher endosperm share of oats yielding lower mass yields of coarse fraction. Particle size distribution of the flour is one of the important factors affecting the separation in dry fractionation (Assatory et al., 2019). This was observed also in the current study as flours with larger mean particle diameter and higher amount of larger particles increased the mass yields of the coarse fractions as well as the separation efficiency of ash and β-glucan to the coarse fraction.

Angle of avalanche was determined to evaluate of oat flour samples 1–10 which can be used to estimate the behaviour of flours in processing. Values observed in the current study for the samples 1–10 are similar as described in the literature for other food materials (Calton et al., 2019; Montes et al., 2019). Calton et al. (2019) have reported avalanche angle values of 41–56° for protein and starch rich powders and Montes et al. (2019) values of 40–68° for differently processed coffee and cocoa powders. Based on the avalanching behaviour of the oat flours during the measurement, all exhibited cataracting flow regime, i.e. flour build-up of the leading edge before collapsing to the bed surface, which shows that the flours resisted flow under these conditions (Boateng & Barr, 1996; Calton et al., 2019). Flow properties of the powders depend on several attributes such as shape and size of the particles, as well as density and moisture content of the material (Montes et al., 2019). In general, lower angle of avalanche values are related to good flowability. Surprisingly, particle size distribution values of the flour samples 1–10 did not show any significant correlations with the angle of avalanche values. Angle of avalanche showed a weak positive correlation with water holding capacity of the oat flour samples 1–10 which indicates that flours with higher water holding capacity have poorer flowability. Furthermore, higher ash and β-glucan content of the coarse fraction were connected to increased angle of avalanche values, but not with to the mass yield of the coarse fraction of the samples 1–10. This indicates that separation of bran layers in dry fractionation may be improved in flours with poorer flowability properties.

As oat lipid content is known for affecting the processing and milling behaviour of oats, it was expected that dry fractionation and flowability properties of the flours would be affected by the lipid content of oats (Girardet & Webster, 2011; Sibakov et al., 2012; Wu & Doehlert, 2002; Wu & Stringfellow, 1995). Lipid content of oat flours was found to be related to dry fractionation properties in the current study, as high lipid content was connected to lower mass yields of fine fraction and higher mass yields of coarse fraction. Lipids have been shown to prevent the dispersion of the flour particles in air in different legumes (Assatory et al., 2019). If the dispersion of the flour particles is limited, it can be expected that the smaller particles are not separated as effectively to fine fraction and thus end up in the coarse fraction, as observed in the current study. While dry fractionation of the flours was related to the lipid content of oats, no significant interaction was observed between the lipid content of oat flour and flowability properties, i.e. the angle of avalanche test.

5. Conclusions

The current study demonstrated the significant differences in the processing behaviour of thirty pure cultivar oat batches. Additionally, relations between oat groat hardness, oat flake properties, and oat flour properties were identified. It was observed that the milling process of oat batches resulted in great variation in the physical characteristics of oat flakes and flours. For example, the amount of flake breakage, i.e. amount of fines, showed great variation between the batches although the flaking process was constant, and the higher breakage was related to lower protein content. Furthermore, it was shown that the physical properties of the different mill products, i.e., groats, flakes and flours were mainly related to the chemical composition of the raw material but also interrelated. The hardness of oat groat and physical properties of the oat flakes were connected to the chemical composition and physical properties of the subsequent oat flours. In addition, it was shown that behaviour of oat flours in dry fractionation is connected to hardness of groats and affected by the particle size distribution of the flours. Flours with poorer flowability properties were connected to increased bran-endosperm separation in dry fractionation. This study highlighted, that the oat batches exhibit significant variation in their processibility and physical properties and therefore process optimisation should be made based on the raw material. In addition, further efforts are required to predict the behaviour of oat in milling process and the connection of the raw material to the quality of oat-based food products.

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CRediT authorship contribution statement

I. Jokinen: Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Preparation, Visualization, Iina Jokinen and Saara Sammalisto, have had equal contribution to the work presented in this manuscript. All authors have read and agreed to the published version of the manuscript. **S. Sammalisto:** Validation, Investigation, Writing – original draft, Preparation, Data curation. **P. Silventoinen-Veijalainen:** Conceptualization, Investigation, Writing – review & editing. **T. Sontag-Strohm:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition. **E. Nordlund:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **U. Holopainen-Mantila:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Appendix A. Supplementary data

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References

Alvarez, P. A., Mongeon, V. J., & Boye, J. I. (2013). Characterization of a gluten reference material: Wheat-contaminated oats. *Journal of Cereal Science, 57*, 418–423. https://doi.org/10.1016/j.jcs.2013.01.006

Assatory, A., Vitelli, M., Rajabzadeh, A. R., & Legge, R. L. (2019). Dry fractionation methods for plant protein, starch and fiber enrichment: A review. *Trends in Food Science & Technology, 86*, 340–351. https://doi.org/10.1016/j.tifs.2019.02.006

Boateng, A. A., & Barr, P. V. (1996). Modelling of particle mixing and segregation in the transverse plane of a rotary kiln. *Chemical Engineering Science, 51*(17), 4167–4181.

Calton, A., Ma, H., Nordlund, E., Poutanen, K., & Sozer, N. (2019). Instant properties of ingredients used for point of consumption production of high-moisture food structures selectively fortified with protein and dietary fibre. *Journal of Food Engineering, 263*, 204–212. https://doi.org/10.1016/j.jfoodeng.2019.06.020

Campbell, G. M., Webb, C., & Owens, G. W. (2012). Milling and flour quality. In S. P. Cauvain (Ed.), *Breadmaking: Improving quality* (2nd ed., pp. 188–215). Woodhead Publishing.

Doehlert, D. C., & McMullen, M. S. (2000). Genotypic and environmental effects on oat milling characteristics and groat hardness. *Cereal Chemistry, 77*(2), 148–154. https://doi.org/10.1094/CCHEM.2000.77.2.148

Duque, S. M. M., Leong, S. Y., Agyei, D., Singh, J., Larsen, N., & Oey, I. (2020). Understanding the impact of pulsed electric fields treatment on the thermal and pasting properties of raw and thermally processed oat flours. *Food Research International, 129*. https://doi.org/10.1016/j.foodres.2019.108839

Ganßmann, W., & Vorwerck, K. (1995). Oat milling, processing and storage. In R. W. Welch (Ed.), *The oat crop* (1st ed., pp. 369–408). Dordrecht: Springer. https://doi.org/10.1007/978-94-011-0015-1.

Gates, F. K., Dobraszczyk, B. J., Stoddard, F. L., Sontag-Strohm, T., & Salovaara, H. (2008). Interaction of heat-moisture conditions and physical properties in oat processing: I. Mechanical properties of steamed oat groats. *Journal of Cereal Science, 47*, 239–244. https://doi.org/10.1016/j.jcs.2007.04.003

Gates, F. K., Sontag-Strohm, T., Stoddard, F. L., Dobraszczyk, B. J., & Salovaara, H. (2008b). Interaction of heat-moisture conditions and physical properties in oat processing: II. Flake quality. *Journal of Cereal Science, 48*, 288–293. https://doi.org/10.1016/j.jcs.2007.09.009

Girardet, N., & Webster, F. H. (2011). Oat milling: Specifications, storage, and processing. In F. H. Webster, & P. J. Wood (Eds.) (2nd ed.,*, Vol. 2. Oats chemistry and technology* (pp. 301–319). AACC International Press.

Hüttner, E. K., Bello, F. D., & Arendt, E. K. (2010). Rheological properties and bread making performance of commercial wholegrain oat flours. *Journal of Cereal Science, 52*, 65–71. https://doi.org/10.1016/j.jcs.2010.03.004

Jokinen, I., Pihlava, J.-M., Puganen, A., Sontag-Strohm, T., Linderborg, K. M., Holopainen-Mantila, U., & Nordlund, E. (2021). Quality factors of industrially produced oat flours in relation to the composition of the native grains. *Foods, 10* (1552). https://doi.org/10.3390/foods10071552

Lapveteläinen, A., Alho-Lehto, P., Sinn, L., Laukkanen, T., Lindman, T., Kallio, H., Kaitaranta, J., & Katajisto, J. (2001). Relationships of selected physical, chemical, and sensory parameters in oat grain, rolled oats, and cooked oatmeal - a three-year study with eight cultivars. *Cereal Chemistry, 78*(3), 322–329. https://doi.org/10.1094/CCHEM.2001.78.3.322

Létang, C., Samson, M. F., Lasserre, T. M., Chaurand, M., & Abécassis, J. (2002). Production of starch with very low protein content from soft and hard wheat flours by jet milling and air classification. *Cereal Chemistry, 79*(4), 535–543. https://doi.org/10.1094/CCHEM.2002.79.4.535

Montes, B. E. C., Martínez-alejo, J. M., Lozano-perez, H., Gumy, J. C., Zemlyanov, D., & Carvajal, M. T. (2019). A surface characterization platform approach to study flowability of food powders. *Powder Technology, 357*, 269–280. https://doi.org/10.1016/j.powtec.2019.08.072

Morris, C. F. (2002). Puroindolines: The molecular genetic basis of wheat grain hardness. *Plant Molecular Biology, 48*, 633–647. https://doi.org/10.1023/A:1014837431178

Pomeranz, Y. (1995). Industrial uses of oats. In R. W. Welch (Ed.), *The oat crop* (1st ed., pp. 480–503). Dordrecht: Springer. https://doi.org/10.1007/978-94-011-0015-1.

Rainakari, A. I., Rita, H., Putkonen, T., & Pastell, H. (2016). New dietary fibre content results for cereals in the Nordic countries using AOAC 2011.25 method. *Journal of Food Composition and Analysis, 51*, 1–8. https://doi.org/10.1016/j.jfca.2016.06.001, 2016.

Rhymer, C., Ames, N., Malcolmson, L., Brown, D., & Duguid, S. (2005). Effects of genotype and environment on the starch properties and end-product quality of oats. *Cereal Chemistry, 82*(2), 197–203.

Sammalisto, S., Laitinen, M., & Sontag-Strohm, T. (2021). Baking quality assessment of twenty whole grain oat cultivar samples. *Foods, 10*(2461). https://doi.org/10.3390/foods10102461

Shewry, P. R., Piironen, V., Lampi, A.-M., Nyström, L., Rakszegi, M., Fras, A., Boros, D., Gebruers, K., Courtin, C. M., Delcour, J. A., Andersson, A. A. M., Dimberg, L., Bedo, Z., & Ward, J. L. (2008). Phytochemical and dietary fiber components in oat varieties in the healthgrain diversity screen. *Journal of Agricultural and Food Chemistry, 56*(21), 9777–9784. https://doi.org/10.1021/jf801880d

Sibakov, J., Myllymäki, O., Holopainen, U., Kaukovirta-Norja, A., Hietaniemi, V., Pihlava, J. M., Lehtinen, P., & Poutanen, K. (2012). Minireview: β-Glucan extraction methods from oats. *Agro Food Industry Hi-Tech, 23*(1), 10–12.

Sibakov, J., Myllymäki, O., Holopainen, U., Kaukovirta-Norja, A., Hietaniemi, V., Pihlava, J. M., Poutanen, K., & Lehtinen, P. (2011). Lipid removal enhances separation of oat grain cell wall material from starch and protein. *Journal of Cereal Science, 54*, 104–109. https://doi.org/10.1016/j.jcs.2011.04.003

Tyler, R. T. (1984). Impact milling quality of grain legumes. *Journal of Food Science, 49* (3), 925–930. https://doi.org/10.1111/j.1365-2621.1984.tb13243.x

Tyler, R. T., Youngs, C. G., & Sosulski, F. W. (1981). Air classification of legumes. I. separation efficiency, yield, and composition of the starch and protein fractions. *Cereal Chemistry, 58*(2), 144–148.

Webster, F. H. (2011). Oat utilization: Past, present and future. In F. H. Webster, & P. J. Wood (Eds.), *Oats chemistry and technology* (2nd ed., pp. 347–361). AACC International Press.

Wu, Y.v., & Doehlert, D. C. (2002). Enrichment of β-glucan in oat bran by fine grinding and air classification. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 35*(1), 30–33. https://doi.org/10.1006/fstl.2001.0806

Wu, Y., & Stringfellow, A. (1995). Enriched protein- and β-glucan fractions from high-protein oats by air classification. *Cereal Chemistry, 72*(1), 132–134.