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Milling and differential sieving to diversify flour functionality: A comparison between pulses and cereals

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ABSTRACT

In this study, pulse (pea, lentil) and cereal (barley, oats) seeds were firstly milled into whole flours, which were then sieved into coarse and fine flours. The particle sizes of the three generated flour streams followed a descending order of coarse > whole > fine, consistent with the observation under scanning electron microscopy (SEM). Among the four crops, the three flour streams showed the same rank order of fine > whole > coarse in starch and damaged-starch contents but the opposite order in ash and total dietary fiber contents. Thus, those functional properties closely related to starch occurring in flour, such as L^* (brightness), starch gelatinization enthalpy change (ΔH), and gel hardness, followed the same order of fine > whole > coarse. By contrast, protein contents of the three flour streams did not vary in pea and lentil but showed a trend of coarse > whole > fine in barley and oats, which could partially explain generally comparable foaming and emulsifying properties of the three streams of pulse flours as well as an order of coarse > whole > fine in oil-binding capacity (OBC) of cereal flours, respectively. The different particle sizes and chemical compositions of the three flour streams only resulted in a descending order of fine > whole > coarse in the pasting viscosities of the pulse flours but did not lead to such a clear trend in the cereal flours, which could be partly attributable to the different microscopic structures of the pulse and cereal seeds and their corresponding flours. This research clearly demonstrated that particle size, chemical composition, and microscopic structure were important variables determining the specific techno-functional properties of pulse and cereal flours.

1. Introduction

Pulses are defined as dried, edible seeds of legume plants, which include peas, lentils, faba beans, dry beans, and chickpeas (Hoover, Hughes, Chung, & Liu, 2010). Pulses are consumed as whole or split seeds in many regions of the world due to their favorable nutritional value. Pulses are a good source of complex carbohydrates (*e.g.*, resistant starch and other dietary fibers), proteins, minerals, vitamins, and phytochemicals (Chibbar, Ambigaipalan, & Hoover, 2010). Previous studies have well documented that regular intake of pulses helps humans maintain health and manage diseases, such as reducing the risks of type-2 diabetes, cardiovascular diseases, and gastrointestinal illnesses (Rebello, Greenway, & Finley, 2014). *In vivo* human feeding studies have provided evidence supporting the low glycemic effect of pulse flours (Gbenga-Fabusiwa et al., 2019; Marinangeli & Jones, 2011). Cereals are grains or seeds of plants in the grass family, which are consumed as staple foods globally, such as wheat, maize, rice, barley, and oats (Bender, 2006). Cereal-based foods are the primary sources of starches, proteins, dietary fibers, vitamins, and minerals for large populations in different parts of the world (Adom, Sorrells, & Liu, 2003; Bhatty, 1999). A large body of scientific evidence has indicated that the consumption of cereals is important for humans to support and maintain health and well-being and that whole grains are more desirable for lowering the incidence of chronic diseases (*e.g.*, type-2 diabetes, obesity, and cardiovascular illnesses) (Anderson, 2003; McKevith, 2004). In the food industry, considerable portions of pulses and cereals are processed into flours, which are essential ingredients for the preparation of bakery products, snacks, pastas and noodles, soups, and many others (Asif, Rooney, Ali, & Riaz, 2013; Yuan, Liu, Reimer, Isaak, & Ai, 2021).

Pulses and cereals have been illustrated to differ in their seed structures and compositions. First of all, pulses are dicotyledonous, whereas cereals are monocotyledonous (Tiwari & Singh, 2012).

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Secondly, after the removal of seed coat (*e.g.*, by dehulling), pulse cotyledon consists of more protein and dietary fiber but less starch than cereal cotyledon (Stone, Nosworthy, Chiremba, House, & Nickerson, 2019). Thirdly, microscopy imaging has revealed that starch granules are compactly embedded in protein and fiber matrices in pulse cotyledon, while such compact entrapment of starch granules is largely absent in cereal cotyledon, especially in the starchy endosperm (Setia et al., 2019; Shapter, Henry, & Lee, 2008). More importantly, the embedment of pulse starch granules in the described matrix structure tends to restrict their swelling for viscosity development during heating and to limit their enzymatic susceptibility (Dhital, Bhattarai, Gorham, & Gidley, 2016; Setia et al., 2019). In the current literature, however, there is a lack of comprehensive understanding of how the noted different seed structures and compositions affect the functional attributes of pulse and cereal flours.

Milling and sieving are frequently used jointly to generate flours with diversified functional attributes. According to previous studies, milling and sieving lead to flours with different particle sizes, which is an important parameter that impacts the proximate compositions and techno-functional attributes of flours. For instance, Ahmed, Taher, Mulla, Al-Hazza, and Luciano (2016) prepared lentil flours with various particle sizes through roller milling and subsequent sieving using a series of screens: 210, 149, 105, 74, and 63 μm. The research observed that, as the particle size decreased, the starch contents of the lentil flours increased but the protein and ash contents decreased. Bourré et al. (2019) milled yellow pea using various screen openings (1.27, 1.00, 0.79, and 0.5 mm) to obtain flours with different particle sizes. The authors found that pea flour with a smaller particle size contained more starch, while the protein contents of the prepared flours were generally comparable. In the work of Dhen et al. (2016), soy flour was sieved in a sifter to separate into three fractions: coarsest ($>$ 156 μm), intermediate (132–156 μm), and finest ($<$ 132 μm). The researchers demonstrated that the protein, lipid, and ash contents of soy flours increased when the particle size decreased. Thus, discrepancy was identified regarding how varying particle sizes influenced the chemical compositions of resulting flours, which could be attributed to that different crops were used and different milling and sieving methods were employed. With regard to functional properties, finer flours have been reported to exhibit lower gelatinization temperatures but higher peak viscosities than the corresponding coarse flours with larger particle sizes (Ahmed, Taher, et al., 2016; Ai, Jin, Kelly, & Ng, 2017). Prior research has illustrated that water-holding (WHC) and oil-binding capacity (OBC) of barley, rye, wheat, and pea flours were influenced by different particle sizes, but the trends varied among studies (Drakos et al., 2017; Protonotariou, Drakos, Evageliou, Ritzoulis, & Mandala, 2014; Ren, Setia, Warkentin, & Ai, 2021). Moreover, previous research only focused on one crop type – pulses, cereals, or pseudocereals – within one study in examining the particle size impact. However, it will be more meaningful to directly compare pulse and cereal flours varying in particle sizes generated from the same processing conditions, particularly considering the aforementioned distinct differences in their cotyledon structures and compositions.

In the present study, pea, lentil, barley, and oats were selected as representative pulses and cereals to prepare flours with different particle sizes by simple milling and subsequent sieving. The sieving step was expected to efficiently separate the milled whole flours into two streams: coarse flour consisting of larger particles better preserving the original structure of cotyledon; and fine flour consisting of smaller particles having more disrupted structure (*e.g.*, more ruptured protein and fiber matrix and more obvious starch damage) (Ahmed, Taher, et al., 2016; Protonotariou et al., 2014). The physicochemical properties of the obtained whole, coarse, and fine pulse and cereal flours were comprehensively characterized and then related to their proximate compositions as well as particle size distributions and morphologies. Since the applied milling and differential sieving method is time-efficient and cost-effective and provides a high flour yield, the insightful findings from this research regarding the "structure–function" relationships of the whole, coarse, and fine flour streams from pulses and cereals will be valuable for the agri-food industry to produce flours possessing diverse functional profiles for a broad range of food products.

2. Materials and methods

2.1. Materials

Certified seeds of pea (CDC Meadow variety), lentil (CDC Richlea variety), barley (CDC Clear variety; hulless type), and oats (Summit variety) were purchased from Penwest Seeds Company (Three Hills, AB, Canada), Simpson Seeds Inc. (Moose Jaw, SK, Canada), Lakeside Seeds (Wynyard, SK, Canada), and Ardell Seeds ltd. (Vanscoy, SK, Canada), respectively. In the agri-food industry, they are popular cultivars used for producing flours from the respective crops. Total Starch Assay Kit, Starch Damage Assay Kit, and potato amylose standard for amylose content measurement were acquired from Megazyme International ltd. (Co. Wicklow, Ireland). Maize amylopectin standard for amylose content measurement was procured from Sigma-Aldrich Canada Co. (Oakville, ON, Canada). Canola oil was purchased from a local grocery store. Other chemicals were reagent grade and acquired from Sigma-Aldrich Canada Co. or Fisher Scientific Company (Ottawa, ON, Canada).

2.2. Pre-treatments of seeds and preparation of flour streams

2.2.1. Dehulling of oat seeds

The obtained oats were firstly dehulled using an impact dehuller (Model 14S, Entoleter, Hamden, CT, U.S.A.) at a rotation speed of 2,113 rpm with one pass. The dehulled seeds and seed hull were then separated using a Clipper seed cleaner (Model M-2B, A.T. Ferrell Company Inc., Bluffton, IN, U.S.A.). The dehulled oat seeds were collected for the following kilning step.

2.2.2. Kilning of hulless barley and dehulled oat seeds

The hulless barley and dehulled oat seeds were kilned to enhance the storage stability by steaming them in a rotating steam kettle (Prairie Agricultural Machinery Institute, Humboldt, SK, Canada) at 100 °C and a rotor speed of 12 rpm for 8.0 min under ambient pressure. After the heat stabilization, the seeds were cooled to room temperature and then dried in a forced-air oven at 50 °C for 16–20 h to reach a moisture level $<$ 12%. The kilned barley and oat seeds were stored at −30 °C for future use. The kilning process was carried out in two independent batches for each crop.

2.2.3. Milling of seeds into whole flours

The pea, lentil, and heat-stabilized barley and oat seeds were milled using a Micron Powder Systems hammer mill (Hosokawa Micron Powder Systems, Summit, NJ, U.S.A.) through a two-step method at a rotor frequency of 20 Hz. The grains were firstly milled to pass through a 5.0-mm screen, followed by a second milling step to pass through a 2.0-mm screen. The collected non-fractionated flours were designated as "whole flours" in the subsequent experiments. The weights of the used seeds and the derived whole flours were recorded, and the yields of the whole flours were calculated as:

$$\%\text{Yield of whole flour from milling} = (\text{Weight of whole flour collected from milling}) / (\text{Initial weight of seeds used for milling}) \times 100\%$$

The milling process was carried out in two independent batches for each crop (*i.e.*, n = 2 for data reporting).

2.2.4. Differential sieving of whole flours into coarse and fine streams

An automatic sieve shaker (Model AS 200, Retsch GmbH, Haan, Germany) equipped with a 0.15-mm sieve was used to separate the whole flours into two different streams: the portion passing through the

sieve was collected and designated as "fine flour", and the portion remaining on the top of the sieve was collected and designated as "coarse flour". Consequently, three streams of flours, namely "whole", "coarse", and "fine", were generated from each crop type. According to our preliminary tests, the 0.15-mm sieve was chosen for two reasons: (1) the sieving efficiently yielded reasonable percentages of coarse and fine flours from the whole flours of the four crops (shown in Table 1); and (2) the generated whole, coarse, and fine flours from the same crop exhibited apparently diverse functional attributes. These two points are critical for future commercialization of the developed pulse and cereal flours. This sieving step was performed separately on the collected whole flours from the two independent batches of milling as described above (*i.e.,* n = 2 for coarse and fine fractions from each crop type). The yields of coarse and fine flours from sieving were calculated as:

%Yield of coarse/fine flour from sieving = (Weight of collected coarse/fine flour from sieving) / (Initial weight of whole flour used for sieving) × 100%

The whole, coarse, and fine flour streams from the four crops were stored at −30 °C before subsequent analyses.

2.3. Particle-size distributions of flours

Particle-size distributions of the whole, coarse, and fine flours were determined using Malvern Scirocco 2000 Mastersizer (Malvern Panalytical, Saint-Laurent, QC, Canada). Briefly, the flour (~2 g) was suspended in 20 mL distilled water under magnetic stirring at 250 rpm for 5 min. The flour suspension was then loaded to the dispersion cell dropwise using a disposable pipette. The particle-size distribution and volume-weighted mean particle size (D[4,3]) were recorded by Mastersizer 2000 Version 5.54 Software (Malvern Panalytical) after the laser obscuration reading fit into a range of 10–20%. The refractive indices of flour and dispersant were set at 1.50 and 1.33, respectively.

2.4. Morphologies of flours

The flour sample was sprinkled on a carbon tape that was attached to an aluminum stub, and the sample was then coated with gold using a Q150T ES coater (Quorum Technologies Inc., Puslinch, ON, Canada). The microscopic structure of flour was examined under a field-emission scanning electron microscope (SEM, SU8010, Hitachi High Technologies Canada Inc., Rexdale, ON, Canada). The scanning conditions were set to 3.0 kV of acceleration voltage and 10 μA of probe current. Representative images of each sample were captured at three different magnifications: 150 ×, 500 × and 1500 ×.

2.5. Proximate analysis of flours

Moisture contents of the whole, coarse, and fine flours were determined using AACC Method 44–15.02 (AACC, 2000). Starch contents of the flours were measured using AACC Method 76–13.01 with Megazyme Total Starch Assay Kit (AACC, 2000). Damaged-starch contents of the flours were quantitated using AACC method 76–31.01 with Megazyme Starch Damage Assay Kit (AACC, 2000). Dumas combustion method using a Nitrogen/Protein Analyzer (CN628, LECO Corporation, St. Joseph, MI, U.S.A) was employed to measure nitrogen contents of the flours. Protein contents were calculated by multiplying the nitrogen contents with a conversion factor of 6.25 according to AACC Method 46–30.01 (AACC, 2000). Lipid contents of the flours were quantitated using a Goldfisch Fat Extractor (Labconco Corp., Kansas City, MO, U.S.A.) according to AOAC Method 945.16 (AOAC, 2016). Ash contents of the flours were measured following AACC Method 08–01.01 (AACC, 2000). Total dietary contents of the flours were determined using AOAC Method 2011.25 (AOAC, 2016). This experiment was completed with one replicate on each batch of flour (*i.e.*, n = 2 for data reporting) by the Medallion Labs (Minneapolis, MN, U.S.A.). Amylose contents of the flours were determined using an iodine colorimetric method (Chrastil, 1987). Amylose contents were determined on a "dry flour basis" and converted to a "dry starch basis" using the following equation:

%Amylose content, dry starch basis = (%Amylose content, dry flour basis) / (% Starch content, dry flour basis) × 100%

To achieve accurate measurements of starch and amylose contents using the indicated methods, flour samples are required to pass through a sieve with openings of 0.5 mm (Ai et al., 2017). Consequently, the whole and coarse flours in this study were re-milled using a Laboratory Mill 3100 (PerkinElmer Inc., Waltham, MA, U.S.A.) installed with a 0.5-mm sieve prior to those two tests.

Table 1
Yields of whole pea, lentil, barley, and oat flours from milling and corresponding coarse and fine flours from differential sieving.[a]

Flour	Yield of whole flour from milling (%)[b]	Differential sieving	
		Yield of coarse flour (%)[c]	Yield of fine flour (%)[c]
Pea	92.8 ± 0.9a	39.3 ± 0.2a	60.0 ± 0.1c
Lentil	90.4 ± 3.1a	46.4 ± 2.2b	53.0 ± 1.9b
Barley	90.5 ± 0.7a	63.1 ± 0.5c	35.6 ± 0.5a
Oats	91.8 ± 2.3a	36.5 ± 2.6a	61.0 ± 1.2c

[a] Data are presented as average ± standard deviation (n = 2); in the same column, data with the same letter are not significantly different at $p < 0.05$.
[b] %Yield of whole flour from milling = (Weight of whole flour collected from milling) / (Initial weight of seeds used for milling) × 100%.
[c] %Yield of coarse/fine flour from sieving = (Weight of collected coarse/fine flour from sieving) / (Initial weight of whole flour used for sieving) × 100%.

2.6. Color of flours

Color parameters of the whole, coarse, and fine flours were measured using Hunterlab MiniScan XE Colorimeter (Hunter Association Laboratory Inc., Reston, VA, U.S.A.) equipped with an illuminant A and 10° observer as described by Liu, Yin, Pickard, and Ai (2020). The device was standardized with black and white tiles. The flour was transferred into a transparent plastic petri dish covered with a lid before the measurement. The color of the flour was described using three parameters: L^* for brightness from black (0) to white (100), a^* for green (−) to red (+), and b^* for blue (−) to yellow (+).

2.7. Thermal properties of flours

Thermal properties of the whole, coarse, and fine flours were measured using a differential scanning calorimeter (DSC 8000, PerkinElmer Inc.). The flour (~10 mg) was precisely weighed into a stainless-steel pan (PerkinElmer Inc.), and three volumes of distilled water (v/w) was added to fully hydrate the sample. The pan was hermetically sealed and kept at room temperature for at least 2 h before the measurement. The sample was heated from 10 to 140 °C at a ramping rate of 10 °C/min. After the first scan, the sample was immediately cooled to 10 °C at 40 °C/min and rescanned to detect the dissociation of amylose–lipid complexes (ALC) (Ai, Nelson, Birt, & Jane, 2013). The thermograms of the flour were analyzed using Pyris Software (Version 13.3.1.0014, PerkinElmer Inc.). Onset (T_o), peak (T_p), and conclusion (T_c) temperatures and enthalpy change (ΔH) of the endothermic peaks were calculated.

2.8. Pasting properties and gelling ability of flours

Pasting properties of the whole, coarse, and fine flours were determined using a Rapid Visco Analyser (RVA 4800, PerkinElmer Inc.). A flour slurry (28.5 g total weight containing 10.6% dry solids) was prepared and loaded to the instrument. The sample was analyzed using the

following temperature profile: (1) equilibrating at 50 °C for 1 min; (2) heating to 95 °C at a rate of 6 °C/min; (3) holding at 95 °C for 5 min; (4) cooling to 50 °C at a rate of 6 °C/min; and (5) keeping at 50 °C for 2 min (Liu et al., 2019).

Immediately after the RVA run, the cooked flour paste was transferred into a plastic container (inner diameter = 33.0 mm, height = 38.0 mm) and kept at room temperature for 2.0 h for gelling to take place. TA. XT.Plus Texture Analyzer (Texture Technologies Corp., South Hamilton, MA, U.S.A.) installed with TA-10 Probe (diameter = 12.7 mm) was used to determine the flour gel hardness with the following settings (Liu et al., 2019): trigger force = 0.5 g, penetration speed = 0.5 mm/s, and penetration depth = 10.0 mm.

2.9. Water-holding and oil-binding capacity of flours

Water-holding capacity (WHC) of the whole, coarse, and fine flours was determined according to AACC Method 56–20.01 (AACC, 2000). Oil-binding capacity (OBC) of the flours was measured following the method of Setia et al. (2019). WHC and OBC were calculated on a dry basis (db) of the flours.

2.10. Foaming properties of flours

Foaming capacity (FC) and foaming stability (FS) of the whole, coarse, and fine flours were determined using the method reported by Bai, Stone, and Nickerson (2018). In brief, the flour (0.5 g) was suspended in 49.5 g distilled water, followed by adjusting the pH to 7.0 using 0.1 M HCl or 0.1 M NaOH. The suspension was magnetically stirred at 250 rpm overnight prior to the test. On the next day, the pH of the suspension was readjusted to 7.0, and 15.0 mL of the suspension was transferred to a 400-mL beaker. The suspension was homogenized using an IKA homogenizer (T10, IKA, Wilmington, NC, U.S.A.) at a speed of level 3 for 1.0 min and subsequently level 4 for 4.0 min. The generated foam was transferred into a 100-mL graduated cylinder immediately, and the initial volume of the foam was recorded as V1. After 30.0 min of sitting at room temperature, the volume of the remaining foam was recorded as V2. FC and FS were calculated using the following equations:

$$\text{FC (\%)} = \text{V1 / (15 mL initial volume)} \times 100\%$$

$$\text{FS (\%)} = (\text{V1} - \text{V2}) / \text{V1} \times 100\%$$

2.11. Emulsifying properties of flours

Emulsion activity (EA) and emulsion stability (ES) of the whole, coarse, and fine flours were measured according to the method reported by Setia et al. (2019) with slight modifications. Briefly, the flour (4.25 g) was suspended in 75.0 g distilled water, and the pH of the suspension was adjusted to 7.0 using 0.1 M HCl or 0.1 M NaOH. The suspension was magnetically stirred at 250 rpm overnight before the test. On the next day, the pH of the suspension was readjusted to 7.0, and 75.0 mL canola oil was added to the suspension. The same IKA homogenizer was used to homogenize the sample at a speed of level 4 for 1.0 min. An aliquot (~30 mL) of the resultant emulsion was transferred into a 50-mL centrifuge tube, followed by centrifugation at 1,300 g for 5.0 min. The heights of the emulsified layer and the entire emulsion in the tube were recorded, and the EA was calculated using the following equation:

$$\text{EA (\%)} = \text{(Height of emulsified layer) / (Height of entire emulsion)} \times 100\%$$

The remaining emulsion in the beaker was heated in a water bath at 80 °C for 30.0 min and then cooled to room temperature. An aliquot (~30 mL) of the resulting emulsion was transferred into a 50-mL centrifuge tube, followed by centrifugation at 1,300 g for 5.0 min. The heights of the emulsified layer and the entire emulsion in the tube were recorded, and the ES was calculated using the following equation:

$$\text{ES (\%)} = \text{(Height of emulsified layer) / (Height of entire emulsion)} \times 100\%$$

2.12. Statistical analysis

The kilning, milling, and sieving of the pulse and cereal grains to produce whole, coarse, and fine flours were performed in two independent batches (*i.e.*, n = 2 for data reporting). For each batch of sample, all the analyses were conducted in duplicate (*i.e.*, n = 4 for data reporting) unless specifically indicated. The data were reported as average ± standard deviation. Statistical differences among the data were performed using one-way ANOVA with Tukey's HSD test at a significance level of 0.05 using IBM SPSS Software Version 25 (IBM Corporation, Armonk, NY, U.S.A.).

3. Results and discussion

3.1. Yields of whole flours from milling and coarse and fine flours from differential sieving

After milling, the yields of whole flours ranged from 90.4% to 92.8% for the four different crops (Table 1), indicating good recovery rates of flours from this step. Upon sieving using a 0.15-mm sieve, the yields of coarse and fine flours showed broad ranges of 36.5%-63.1% and 35.6%-61.0%, respectively. Among the four crops, barley exhibited the highest yield of coarse flour but the lowest yield of fine flour, which could be linked to the largest particle size of the whole barley flour as displayed in Fig. 1. Additionally, the total yields of both coarse and fine flours from the four crops were remarkably high, 97.5%-99.4%, suggesting negligible loss of flour during sieving.

3.2. Particle-size distributions and morphologies of flours

The particles in the whole flour samples of the four crops exhibited a bimodal distribution (Fig. 1): the first peak (30.2, 26.3, 30.2, and 34.7 μm in the four flour samples, respectively) mainly corresponded to individual starch granules; and the second one (478.6, 363.1, 549.5, and 724.4 μm, respectively) mainly corresponded to aggregated particles consisting of starch, protein, and fiber (marked by rectangles in Fig. 2) (Liu et al., 2020). D[4,3] of the whole flour samples was in a descending order of barley > oats > lentil > pea.

The 0.15-mm sieving was effective in separating the above-mentioned two main types of particles in the whole flours: the fine stream of pea, lentil, and barley primarily consisted of individual starch granules, along with some protein and fiber debris; by contrast, the coarse counterparts predominantly comprised aggregated particles (Figs. 1 and 2). Consequently, the particle-size distribution curves of the fine and coarse flours obtained from sieving were obviously different from those of the corresponding whole flours, and the D[4,3] of the three flour streams from the same crop followed an ascending order of fine < whole < coarse. For the flours within the whole, coarse, and fine groups, D[4,3] of pea and lentil samples were consistently smaller than those of the barley and oat samples. Moreover, distinct differences were observed in the morphologies of the large, aggregated particles among the coarse pulse and cereal flours: (1) Those of pea and lentil aggregated particles had fewer starch granules, as compared to the coarse barley and oat flours; and (2) Pea and lentil starch granules were more compactly entrapped in protein and fiber matrices (marked by up arrows in Fig. 2), while such compact entrapment of starch granules by protein and fiber was largely absent in the coarse barley and oat flour particles. The described differences in particle morphology between coarse pulse and cereal flours generally reflected the differences in the microscopic

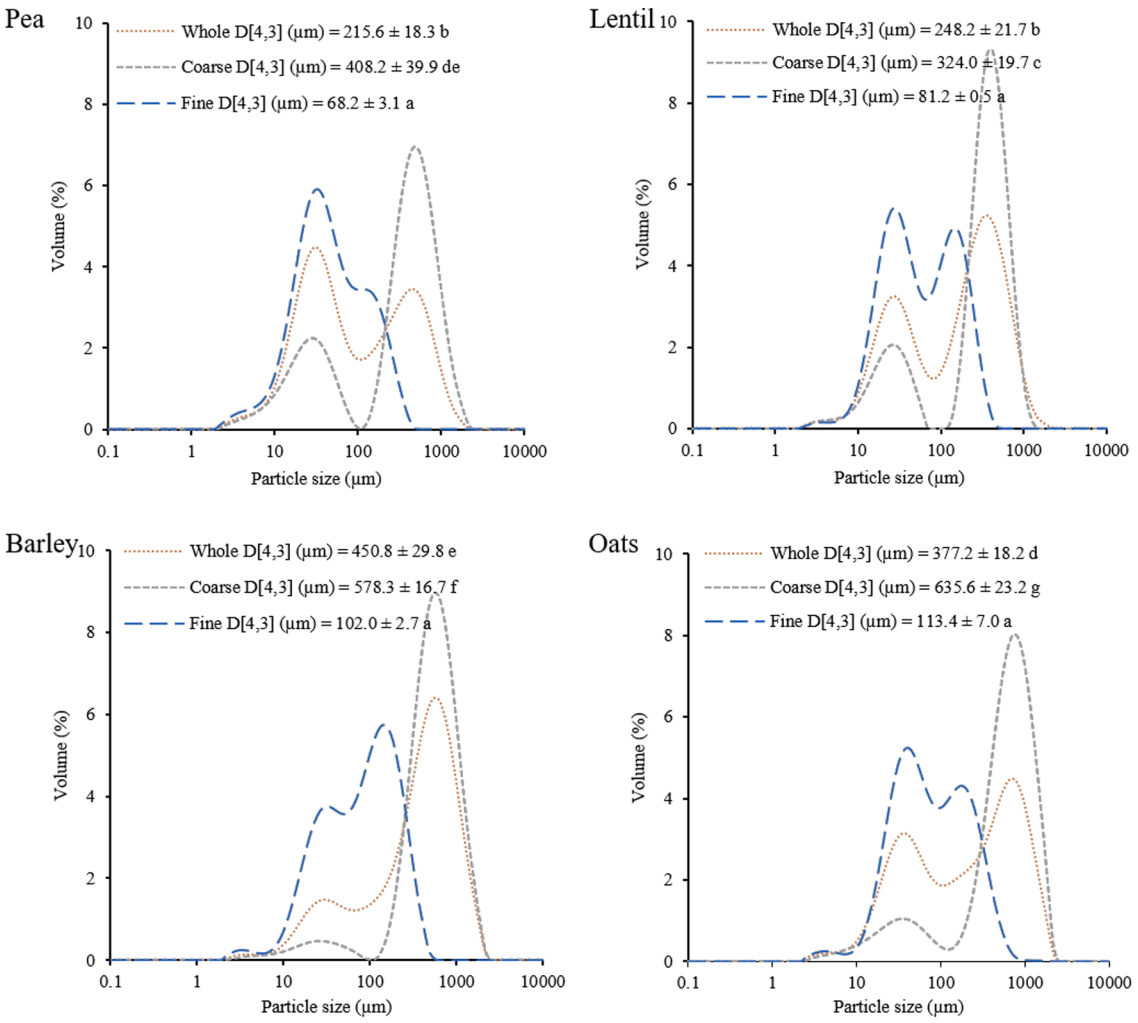

Fig. 1. Particle-size distributions of pea, lentil, barley, and oat flours from three different streams. D[4,3] are presented as average ± standard deviation (n = 4). Data with the same letter are not significantly different at $p < 0.05$ among all the samples.

structures of their seeds (Setia et al., 2019; Shapter et al., 2008).

Of all the four crops, it is noteworthy that oat starch granules exist in two forms in the grains: (1) single granules having approximately 2–15 μm in diameter (marked by stars in Fig. 2); and (2) clusters composed of compound granules having approximately 20–150 μm in diameter (marked by ovals) (Bechtel, 1981; Falsafi et al., 2019). Some of such clusters were preserved in the fine flour of oats, which explained its largest D[4,3] among all the four fine fractions.

3.3. Chemical compositions of flours

Starch contents of the three flour streams followed a descending order of fine > whole > coarse for all the four crops (Table 2), which are in agreement with the results reported by Ahmed, Taher, et al. (2016). The trend is also consistent with the presence of starch granules in the different streams as illustrated in SEM images (Fig. 2). Damaged-starch contents of the fine, whole, and coarse streams also fit into the same trend for all the studied crops, which could be explained by that more mechanical force was required to break cotyledon structure to achieve the fine particles and that the large particles better retained the original cotyledon structure. The milling and sieving, however, did not result in any significant difference in the amylose contents of starch (dsb) in the three flour streams of the same crop.

Protein contents of the three flour streams from pea and lentil were largely comparable, but they exhibited a trend of coarse > whole > fine for cereal flours, particularly for oats (Table 2). For the same crop, the difference in the lipid contents of the three resultant streams was largely insignificant. Among the different crops, the lipid concentrations of the different flours were in an ascending order of lentil < pea < barley < oats, and the remarkably higher lipid levels of oat samples correspond well with the results reported by other researchers (Liu, Bailey, & White, 2010; Sharma & Gujral, 2010; Stone et al., 2019). Ash contents of the three flour streams from the same botanical source displayed an increasing order of fine < whole < coarse, suggesting that minerals were more concentrated in the coarse fraction, which is in good accordance with the findings of Ahmed, Taher, et al. (2016). An obvious impact of particle size on the total dietary fiber contents of the flour streams was observed as the values followed an ascending order of fine < whole < coarse for all the four crops, suggesting that the coarse stream could be a more promising source of dietary fiber from the respective crops.

As clearly presented in Table 2, the pulse flours of the three different streams in general consisted of less starch (except for the coarse oat flour) and lipid but more protein, ash, and dietary fiber than the corresponding cereal flour streams. In addition, the starches in the former group contained more amylose (dsb) than those in the latter group. The noted differences in the proximate compositions of the pulse and cereal flours agree well with the observation in previous studies (Li et al., 2019; Stone et al., 2019), and the impacts on their physicochemical properties were comprehensively discussed in the following sections.

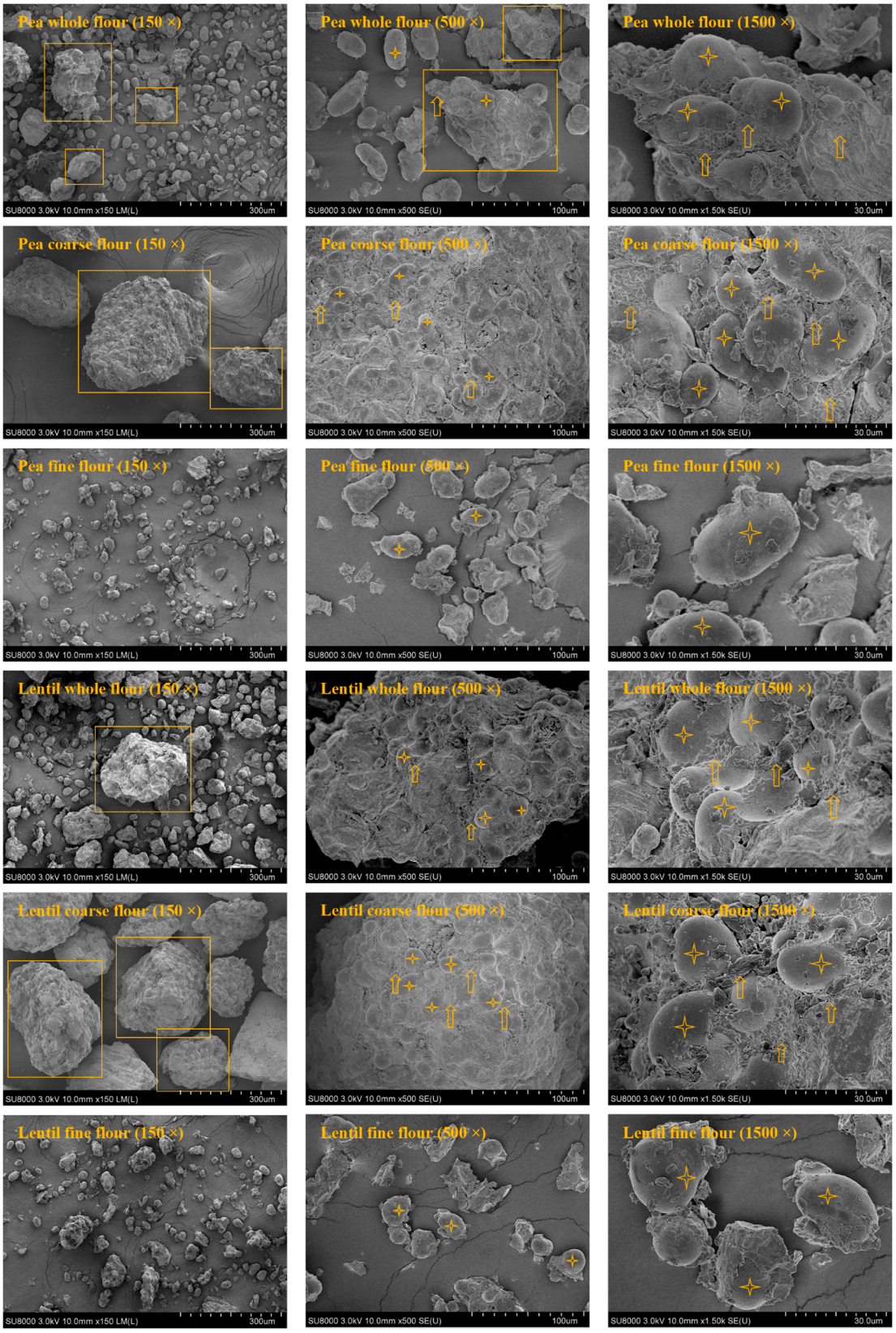

Fig. 2. Scanning electron microscopy (SEM) images of pea, lentil, barley, and oat flours from three different streams. Magnification at which the image was captured is shown in parentheses. Rectangles indicate aggregated particles formed with starch, protein, and fiber; up arrows indicate protein and fiber matrices; stars indicate starch granules; ovals indicate clusters of compound granules.

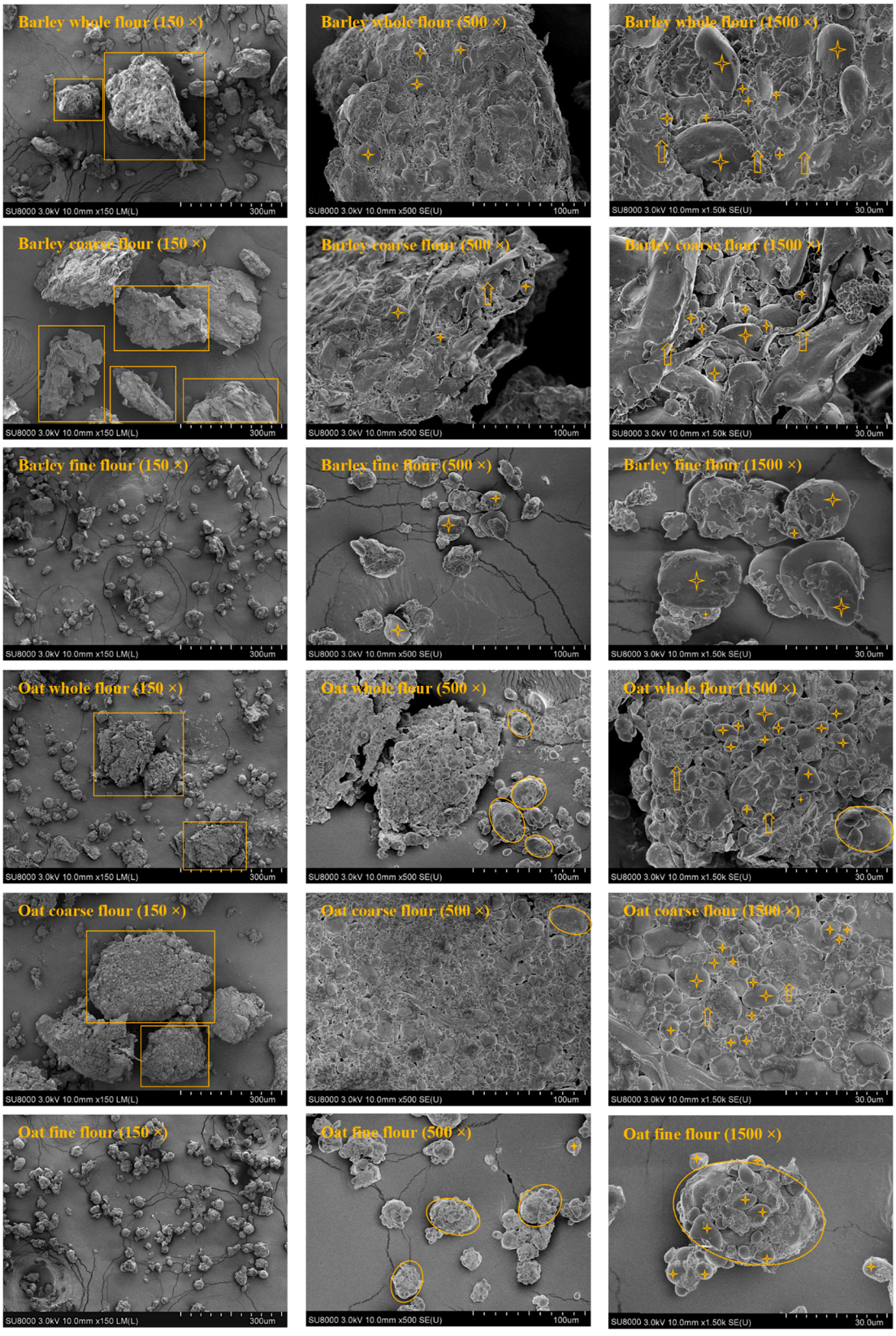

Fig. 2. (*continued*).

3.4. Color of flours

Overall, the color parameters of the three streams from the same crop followed the same trend: with the reduction in particle size, the L^* value increased while the a^* and b^* values decreased (Table 3). The enhanced L^* values in the fine flours were attributable to: (1) This stream contained more starch but less ash and dietary fiber than the whole and coarse counterparts (Table 2); and (2) The smaller particle size of fine

Table 2
Chemical compositions of pea, lentil, barley, and oat flours from three different streams on a dry flour basis.[a]

Flour	Starch (%)	Damaged starch (%)	Amylose (%)	Amylose (%, dsb)[b]	Protein (%)	Lipid (%)	Ash (%)	Total dietary fiber (%)[c]
Pea								
Whole	49.8 ± 1.3c	0.77 ± 0.01b	17.9 ± 0.7cd	36.0 ± 1.4cd	21.4 ± 1.4f	1.36 ± 0.10b	2.33 ± 0.13e	27.7 ± 2.3e
Coarse	40.1 ± 0.6a	0.29 ± 0.03a	14.4 ± 0.5b	35.8 ± 1.2cd	21.8 ± 0.3fg	1.25 ± 0.05b	2.51 ± 0.02g	36.5 ± 2.3f
Fine	53.1 ± 0.5d	1.29 ± 0.04c	20.6 ± 0.3ef	38.8 ± 0.7d	22.7 ± 0.4g	1.36 ± 0.09b	2.15 ± 0.03d	16.7 ± 0.4bc
Lentil								
Whole	49.5 ± 0.8c	0.81 ± 0.01b	18.1 ± 0.8cd	36.6 ± 2.0cd	24.5 ± 0.2h	0.66 ± 0.03a	2.37 ± 0.01ef	23.0 ± 0.2d
Coarse	43.5 ± 1.2b	0.25 ± 0.02a	15.3 ± 0.2b	35.1 ± 1.2c	24.7 ± 0.1h	0.60 ± 0.07a	2.46 ± 0.01fg	27.8 ± 0.0e
Fine	51.5 ± 1.0cd	1.48 ± 0.04d	17.8 ± 0.1cd	34.6 ± 0.3c	25.1 ± 0.4h	0.76 ± 0.02a	2.33 ± 0.01e	19.1 ± 0.9bcd
Barley								
Whole	62.2 ± 0.7f	3.00 ± 0.04g	19.1 ± 0.9de	30.8 ± 1.4b	11.4 ± 0.2ab	2.36 ± 0.07d	1.56 ± 0.02b	19.1 ± 0.6bcd
Coarse	57.7 ± 0.3e	2.02 ± 0.06e	16.1 ± 1.9bc	27.9 ± 3.3ab	12.1 ± 0.2b	2.32 ± 0.06cd	1.83 ± 0.00c	21.0 ± 0.6cd
Fine	73.3 ± 1.4h	4.66 ± 0.10h	21.9 ± 1.1f	29.9 ± 1.0ab	11.0 ± 0.2a	1.91 ± 0.10c	1.15 ± 0.02a	10.4 ± 0.2a
Oats								
Whole	59.9 ± 1.4ef	1.91 ± 0.04e	16.1 ± 0.5bc	26.9 ± 0.4a	15.5 ± 0.2d	7.66 ± 0.17e	1.44 ± 0.08b	15.1 ± 0.3b
Coarse	42.8 ± 1.0b	1.56 ± 0.09d	11.3 ± 0.5a	26.4 ± 1.0a	19.8 ± 0.1e	8.37 ± 0.41f	2.14 ± 0.04d	21.2 ± 0.1d
Fine	67.0 ± 0.9g	2.25 ± 0.14f	17.8 ± 1.1cd	26.6 ± 1.4a	13.7 ± 0.3c	7.94 ± 0.33e	1.18 ± 0.04a	8.8 ± 1.3a

[a] Data are presented as average ± standard deviation (n = 4); in the same column, data with the same letter are not significantly different at $p < 0.05$.
[b] %Amylose content, dry starch basis = (%Amylose content, dry flour basis) / (%Starch content, dry flour basis) × 100%.
[c] Data are presented as average ± standard deviation (n = 2); in the same column, data with the same letter are not significantly different at $p < 0.05$.

Table 3
Hunter color parameters of pea, lentil, barley, and oat flours from three different streams.[a]

Flour	L^*	a^*	b^*
Pea			
Whole	86.4 ± 0.7fg	2.1 ± 0.3ef	21.0 ± 1.3cd
Coarse	79.5 ± 0.5cd	4.5 ± 0.3h	31.4 ± 0.2e
Fine	88.5 ± 0.1h	1.6 ± 0.0cd	20.9 ± 0.3cd
Lentil			
Whole	80.8 ± 0.6d	1.1 ± 0.1b	18.1 ± 0.8c
Coarse	70.3 ± 1.6a	1.6 ± 0.4cd	21.8 ± 4.5d
Fine	84.9 ± 0.2ef	0.5 ± 0.1a	18.0 ± 1.3c
Barley			
Whole	84.9 ± 0.2ef	1.3 ± 0.0bc	10.0 ± 0.1a
Coarse	79.1 ± 0.6bc	2.3 ± 0.1f	13.1 ± 0.3ab
Fine	87.9 ± 0.3gh	0.9 ± 0.0ab	9.7 ± 0.2a
Oats			
Whole	83.9 ± 0.2e	1.8 ± 0.0de	13.5 ± 0.1b
Coarse	78.0 ± 0.5b	2.9 ± 0.1g	17.8 ± 0.5c
Fine	84.7 ± 0.1e	1.6 ± 0.0cd	13.1 ± 0.2ab

[a] Data are presented as average ± standard deviation (n = 4); in the same column, data with the same letter are not significantly different at $p < 0.05$.

flour contributed to a larger total surface area, thus allowing more reflection of light (Ahmed, Al-Jassar, & Thomas, 2015). The reported results correspond well with the work of Kaiser, Barber, Manthey, and Hall (2019) and Drakos et al. (2017). Compared with the cereal flours, the pulse flours exhibited considerably greater b^* values (*i.e.*, more yellowness), which could be associated with the nature of the seeds.

3.5. Thermal properties of flours

The DSC thermograms of the pulse flours showed a major peak followed by an overlapping minor shoulder in the first scan (Figure S1 and Table 4): the first major peak exhibiting T_p at 70.7–73.6 °C mainly resulted from starch gelatinization, while the minor shoulder displaying T_p at 90.4–92.0 °C mainly resulted from protein denaturation (Ren et al., 2021). The second scan of pulse flours revealed the absence ALC, which is consistent with previous work (Liu et al., 2019). The DSC thermograms of the cereal flours showed a major peak followed by a separate minor peak in the first scan: (Figure S1 and Table 4): the first major peak exhibiting T_p at 65.4–70.2 °C and ΔH of 4.2–7.5 J/g primarily represented starch gelatinization, while the second minor peak displaying T_p at 95.0–101.2 °C primarily represented the dissociation of ALC, which was confirmed by the occurrence of a similar peak having T_p at 100.2–103.1 °C in the second scan (Liu et al., 2019). The ALC dissociation peak of the oat flours exhibited a wider temperature range (~88–105 °C) and a greater ΔH (0.5–0.7 J/g) in comparison with those of the barley flours (~98–106 °C and 0.2–0.3 J/g, respectively) in the second scan, suggesting more ALC formation in the former. Moreover, the oat flours distinctly showed a third peak having T_p at 115.6–116.0 °C in first scan, which represented the denaturation of protein according to Moisio, Forssell, Partanen, Damerau, and Hill (2015).

Generally, for the same crop type, the starch gelatinization temperatures in the first scan did not vary significantly among the three flour streams (Table 4); however, the cereal flour with finer particles consistently exhibited a higher ΔH value (*i.e.*, fine > whole > coarse). Ai et al. (2017) suggested that flour with a smaller particle size could achieve more complete starch gelatinization, which thus required more ΔH for this thermal transition. In addition, the larger ΔH of finer flour could be associated with the higher starch content as compared to the other two streams (Table 2). Compared with the pulse flours, the barley and oat flours exhibited lower starch gelatinization temperatures, consistent with the differences in the gelatinization temperatures of isolated starches from these crops (Falsafi et al., 2019; Gao, Vasanthan, & Hoover, 2009; Li et al., 2019).

3.6. Pasting properties of flours

For both pulse crops, the three flour streams explicitly showed pasting viscosities of fine > whole > coarse (Fig. 3 and Table S1), corresponding well with the trends reported by Gu et al. (2021). The lowest viscosity development in the coarse pea and lentil flours could be explained by the following two important factors: (1) The coarse flours comprised significantly less starch than the corresponding whole and fine flours (Table 2), and starch is known to be the leading component responsible for viscosity development of flour during pasting (Yuan et al., 2021); and (2) The starch granules were densely packed in protein and fiber matrices in coarse flours (Fig. 2), which was demonstrated to restrict the swelling of starch granules to provide less viscosity (Dhital et al., 2016; Setia et al., 2019).

In contrast, the different particle sizes did not have the same influence on the pasting properties of the barley and oat flours as noted above for the pea and lentil flours (Fig. 3 and Table S1). The fine barley and oat flours showed higher peak viscosities than the whole and coarse counterparts, which could be mainly ascribed to the markedly greater starch contents of the fine flours (Table 2). Overall, the fine cereal flours displayed trough and final viscosities similar to those of the whole and coarse counterparts. Interestingly, despite the observed significant

Table 4
Thermal properties of pea, lentil, barley, and oat flours from three different streams.[a,b]

Flour	First scan						Second scan			
	Gelatinization of starch				Dissociation of amylose–lipid complexes	Denaturation of protein	Dissociation of amylose–lipid complexes in rescan			
	T_o (°C)	T_p (°C)	T_c (°C)	ΔH (J/g)	T_p (°C)	T_p (°C)	T_o (°C)	T_p (°C)	T_c (°C)	ΔH (J/g)
Pea										
Whole	64.5 ± 0.8cd	71.4 ± 0.3f	78.0 ± 0.6de	N.A.[c]	N.D.[d]	91.5 ± 0.3b	N.D.	N.D.	N.D.	N.D.
Coarse	63.7 ± 0.4bc	70.7 ± 0.3ef	79.6 ± 0.5fg	N.A.	N.D.	92.0 ± 0.3b	N.D.	N.D.	N.D.	N.D.
Fine	63.6 ± 0.3b	71.1 ± 0.1f	78.8 ± 0.4ef	N.A.	N.D.	91.3 ± 0.1b	N.D.	N.D.	N.D.	N.D.
Lentil				N.A.	N.D.		N.D.	N.D.	N.D.	N.D.
Whole	66.7 ± 0.4e	73.5 ± 0.5g	81.6 ± 0.5h	N.A.	N.D.	90.4 ± 0.5a	N.D.	N.D.	N.D.	N.D.
Coarse	67.4 ± 0.2e	73.4 ± 0.1g	80.4 ± 0.4g	N.A.	N.D.	90.5 ± 0.3a	N.D.	N.D.	N.D.	N.D.
Fine	67.3 ± 0.4e	73.6 ± 0.3g	81.9 ± 0.4h	N.A.	N.D.	90.5 ± 0.3a	N.D.	N.D.	N.D.	N.D.
Barley										
Whole	64.3 ± 0.1bcd	69.6 ± 0.1cd	76.5 ± 0.2c	6.4 ± 0.3cd	100.7 ± 0.4bc	N.D.	98.4 ± 0.6b	102.8 ± 0.1c	106.5 ± 0.4c	0.3 ± 0.0a
Coarse	64.6 ± 0.4d	70.2 ± 0.3de	77.7 ± 0.7d	5.4 ± 0.3b	101.2 ± 0.5b	N.D.	98.4 ± 0.5b	102.5 ± 0.4c	105.7 ± 0.8bc	0.2 ± 0.0a
Fine	63.8 ± 0.1bcd	69.3 ± 0.3c	76.3 ± 0.3c	7.5 ± 0.4e	101.7 ± 0.7b	N.D.	98.8 ± 0.4b	103.1 ± 0.3c	106.3 ± 0.2bc	0.3 ± 0.1a
Oats										
Whole	60.3 ± 0.1a	65.4 ± 0.2a	71.7 ± 0.2a	5.8 ± 0.4bc	99.0 ± 0.4ab	115.8 ± 0.2c	88.5 ± 0.4a	101.2 ± 0.3b	105.4 ± 0.4bc	0.7 ± 0.0c
Coarse	60.8 ± 0.2a	66.2 ± 0.1b	72.8 ± 0.2b	4.2 ± 0.1a	98.0 ± 1.9a	116.0 ± 0.1c	89.1 ± 0.3a	100.2 ± 0.5a	104.0 ± 0.7a	0.5 ± 0.0b
Fine	60.3 ± 0.5a	65.6 ± 0.3a	71.8 ± 0.2a	6.8 ± 0.1d	98.7 ± 0.4ab	115.6 ± 0.4c	88.8 ± 0.2a	101.7 ± 0.0b	105.3 ± 0.4b	0.6 ± 0.1c

[a] Data are presented as average ± standard deviation (n = 4); in the same column, data with the same letter are not significantly different at $p < 0.05$.
[b] T_o: onset temperature; T_p: peak temperature; T_c: conclusion temperature; ΔH: enthalpy change.
[c] N.A.: Not available because of the overlapping between starch gelatinization peak and protein denaturation peak.
[d] N.D.: Not detectable.

differences in their D[4,3] (Fig. 1) and starch contents (Table 2), the pasting profiles of the coarse barley and oat flours were generally comparable to those of their respective whole flours. This observation could be associated with the following factors: (1) The starch granules in coarse barley and oats streams were not embedded in dense protein and fiber matrices as in pea and lentil samples (Fig. 2), and thus the presence of more protein and dietary fiber in the coarse cereal flours did not restrict the swelling of the granules during pasting; and (2) β-glucan tended to be concentrated in the coarse stream during differential sieving (Ahmed, 2014), and this polysaccharide, occurring at a high level in barley and oat grains, could contribute to viscosity development of their coarse flours, thereby offsetting the differences with the whole counterparts during RVA analysis.

Despite the fact that the pulse flours had higher starch gelatinization temperatures than the cereal flours (Figure S1 and Table 4), the former showed noticeably lower pasting temperatures than the latter (Fig. 3 and Table S1), which could primarily result from the existence of ALC in the cereal flours because such single-helical complexes are known to restrict granular swelling of starch during heating to elevate the pasting temperatures of starch and flour (Liu et al., 2019; Yuan et al., 2021). Overall, the studied pulse flours exhibited significant lower pasting viscosities in comparison with the cereal flours, which could be attributable to less starch and the entrapment of starch in protein and fiber matrices of the former as discussed above as well as more amylose in the pulse starches (dsb; Table 2) (Li et al., 2019).

3.7. Gel hardness of flours

In general, strength of the gels developed from the three flour streams of the same crop exhibited a descending order of fine > whole > coarse (except for pea; Fig. 4), indicating that the fine streams had a tendency to form a stronger gel after cooking and storage. The observed trend is in good accordance with that reported by Nura, Kharidah, Jamilah, and Roselina (2011), in which the gel hardness of rice flour was negatively correlated with its particle size. According to previous studies, starch is the main contributor to the gelling ability of flour but the presence of protein, dietary fiber, and other components is detrimental for gel formation (Joshi, Aldred, Panozzo, Kasapis, & Adhikari, 2014; Yuan et al., 2021), which explained the greatest gel strength of fine flour among all the three streams (Table 2). Further research is needed to understand why the gelling ability of the fine pea flour did not fit into this trend.

For the same flour stream of the four studied crops, the pulse flour gels generally exhibited higher hardness than those of cereal flours (65.9–163.9 g *versus* 30.3–61.5 g; Fig. 4), except for the coarse pea flour gel (27.9 g), although the pulse flours were composed of less starch but more protein, dietary fiber, and ash than the corresponding cereal streams (Table 2). The findings could be attributed to the remarkably stronger gelling ability of the pulse starches than the cereal starches (Li et al., 2019; Liu et al., 2019). The poorest gelling capability of the coarse pea flour could be related to its smallest starch content but largest dietary fiber and ash contents of all the flour samples (Table 2).

3.8. WHC and OBC of flours

WHC and OBC are important functional properties of food ingredients as they determine the textural properties, mouthfeel, and yield of final products (Ai et al., 2017; Lin & Zayas, 1987). Within the same crop, the coarse flour exhibited the largest WHC value followed by the whole and fine streams, indicating that WHC of the flours were reduced as the particle sizes decreased (Table 5), which could be partly linked to the reduced dietary fiber contents (Table 2) (Ahmed, Al-Attar, & Arfat, 2016). Our observation is in good accordance with the finding of Ahmed, Taher, et al. (2016). However, Rao et al. (2016) reported the opposite trend, in which WHC of sorghum flours increased as the particle sizes decreased. Within the same stream, the flours of pulses and cereals showed comparable WHC, except for the coarse group, where the coarse oat flour exhibited a noticeably greater WHC value (2.30 g/g) than the other three coarse flours (1.51–1.74 g/g). The highest WHC of the coarse oat flour could be partly explained by its largest D[4,3] as illustrated in Fig. 1.

OBC of the three flour streams from the same pulse crop were comparable (Table 5), indicating that their OBC were not significantly affected by the different particle sizes, which was primarily attributed to the comparable protein contents of the different pulse flour streams (Table 2) (Ren et al., 2021; Stone et al., 2019). In contrast, OBC of the

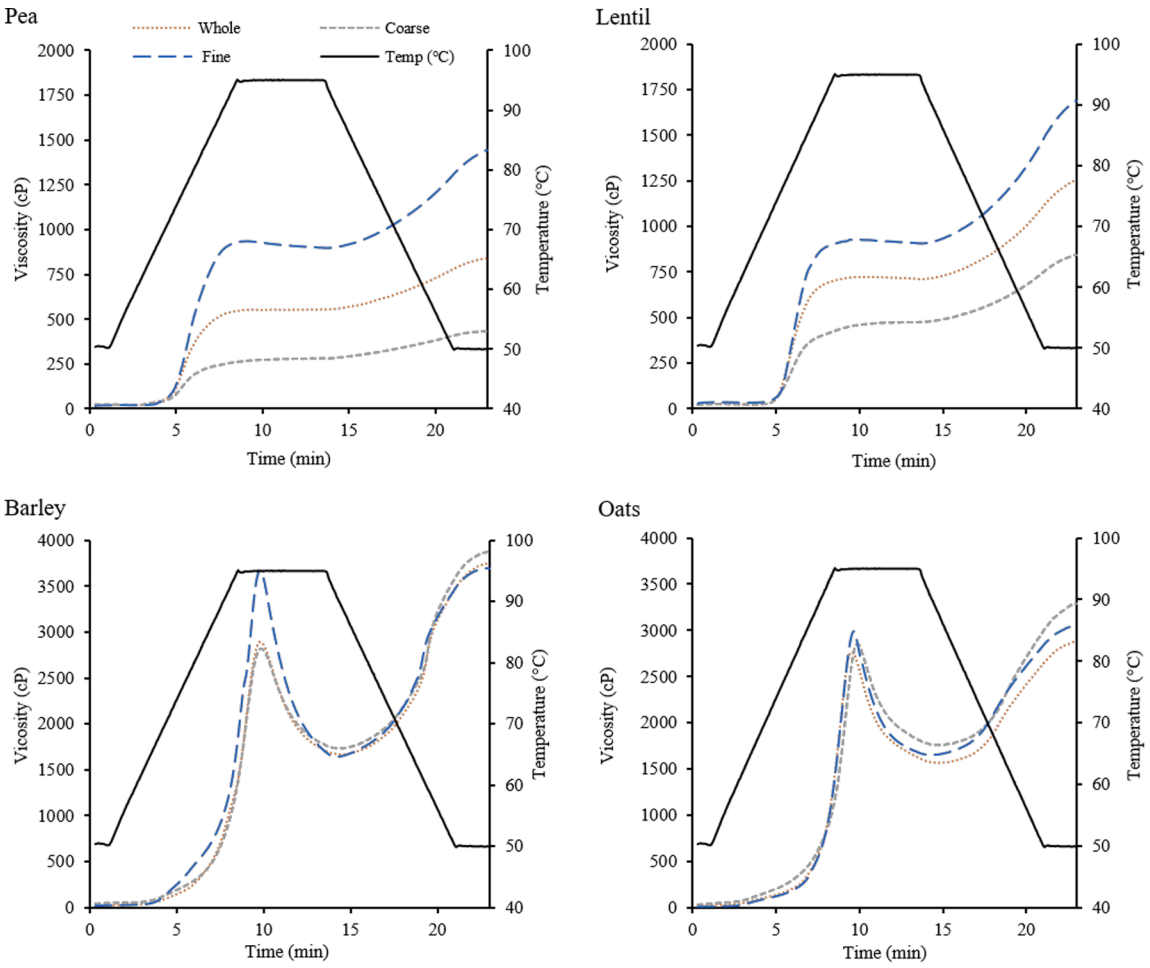

Fig. 3. Pasting properties of pea, lentil, barley, and oat flours from three different streams. Flour suspensions (28.5 g total weight) with 10.6% concentration (w/w, dry flour basis) were used for the measurement using Rapid Visco Analyser.

cereal flours were remarkably influenced by the particle sizes. For the same cereal crop, OBC of the three flour streams followed a descending order of coarse > whole > fine, suggesting that OBC of the cereal flours decreased as the particle sizes decreased, agreeing well with the data reported by Protonotariou et al. (2014), Rao et al. (2016) and Drakos et al. (2017). The lower OBC value of the fine cereal streams could be partially ascribed to their lower protein content when compared with the whole and coarse counterparts as presented in Table 2.

3.9. Foaming and emulsifying properties of flours

Foaming and emulsifying properties of flour ingredients are mainly related to the protein component (Ma et al., 2011; Stone et al., 2019). The FC values of the pea and lentil flours were 378–404% and 303–350%, respectively (Table 5). Generally, the three flour streams of the same pulse showed comparable FC values, which suggested an insignificant impact of particle size on the foaming properties of pulse flours, probably due to the similar levels of protein of the three streams (Table 2) (Stone et al., 2019). With respect to FS, a lower value indicated greater foam stability. Pea and lentil flours had FS values of 6.1–11.6% and 7.6–9.5%, respectively (Table 5). The fine pea flour exhibited slightly greater FS than the whole and coarse counterparts, indicating lower stability of the foam developed from the former. In contrast, the particle sizes did not show significant influence on the stability of foams generated from the lentil flours.

Within the same pulse group, both EA and ES of the three flour streams did not show a noticeable difference, except for the whole lentil flour, which exhibited a higher ES value than its coarse and fine counterparts. The results suggested that the emulsifying properties of the pulse flours were not distinctly influenced by the particle sizes, which was possibly attributed to the comparable protein contents of the three streams from the same pulse group (Table 2) (Stone et al., 2019).

Foaming and emulsifying properties could not be determined for the cereal flours due to the lack of foam and emulsion formation (Table 5). The phenomenon could be ascribed to: (1) relatively low protein contents of the cereal flours (11.0–19.8%; Table 2); (2) the existence of prolamin as the leading protein component in the cereal flours, which had noticeably poorer solubility than that of albumin and globulin proteins predominantly present in the pea and lentil flours (Stone et al., 2019); and (3) the greater lipid contents of the cereal flours, especially oats, thereby reducing the migration of proteins to the interface (Table 2) (Lam, Warkentin, Tyler, & Nickerson, 2017).

4. Conclusions

In the current study, pulses (pea, lentil) and cereals (barley, oats) were firstly milled into whole flours, which were subsequently sieved into coarse and fine flours. Both particle-size analysis and SEM observation confirmed the order of coarse > whole > fine in the flour particle sizes. For all the four crops, the three flour streams displayed the same rank order of fine > whole > coarse in their starch and damaged-starch contents but the reverse order in their ash and total dietary fiber contents. Consequently, the functional attributes closely associated with starch present in flour, such as L^* value, starch gelatinization ΔH, and

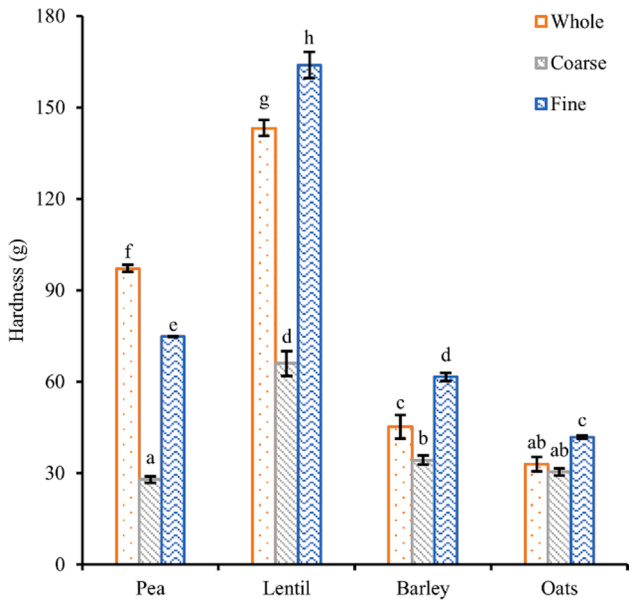

Fig. 4. Hardness of gels prepared with pea, lentil, barley, and oat flours from three different streams. Flour suspensions (28.5 g total weight) with 10.6% concentration (w/w, dry flour basis) were cooked using RVA 4800 following the same conditions used for pasting property determination. After cooking, the flour pastes were poured into a plastic container with lid and stored at room temperature for 2.0 h before the determination of hardness. Data with the same letter are not significantly different at $p < 0.05$ among all the samples.

Table 5
Functional properties of pea, lentil, barley, and oat flours from three different streams.[a,b]

Flour	WHC (g/g, db)	OBC (g/g, db)	FC (%)	FS (%)	EA (%)	ES (%)
Pea						
Whole	1.36 ± 0.03b	1.49 ± 0.06d	378 ± 17cd	6.1 ± 1.9a	42.4 ± 2.3a	62.3 ± 4.3ab
Coarse	1.73 ± 0.10d	1.45 ± 0.03d	390 ± 15d	6.9 ± 2.7ab	41.0 ± 1.8a	59.4 ± 1.0ab
Fine	1.23 ± 0.01a	1.49 ± 0.04d	404 ± 21d	11.6 ± 1.1b	40.9 ± 0.7a	62.4 ± 3.8ab
Lentil						
Whole	1.45 ± 0.03bc	1.02 ± 0.03ab	350 ± 22bc	9.5 ± 3.3ab	41.1 ± 1.8a	65.4 ± 3.1b
Coarse	1.74 ± 0.03d	0.94 ± 0.01a	303 ± 16a	7.6 ± 1.7ab	41.8 ± 1.8a	56.1 ± 5.0a
Fine	1.17 ± 0.02a	0.99 ± 0.00ab	333 ± 6ab	8.8 ± 1.5ab	39.9 ± 1.0a	55.0 ± 2.5a
Barley						
Whole	1.17 ± 0.02a	1.68 ± 0.06e	N.D.	N.D.	N.D.	N.D.
Coarse	1.51 ± 0.01c	2.10 ± 0.07f	N.D.	N.D.	N.D.	N.D.
Fine	1.12 ± 0.03a	1.44 ± 0.04d	N.D.	N.D.	N.D.	N.D.
Oats						
Whole	1.47 ± 0.02c	1.15 ± 0.02c	N.D.	N.D.	N.D.	N.D.
Coarse	2.30 ± 0.03e	1.69 ± 0.06e	N.D.	N.D.	N.D.	N.D.
Fine	1.19 ± 0.11a	1.08 ± 0.05bc	N.D.	N.D.	N.D.	N.D.

[a] Data are presented as average ± standard deviation (n = 4); in the same column, data with the same letter are not significantly different at $p < 0.05$; N.D.: not determinable.

[b] WHC: water-holding capacity; OBC: oil-binding capacity; FC: foaming capacity; FS: foam stability; EA: emulsion activity; ES: emulsion stability.

gelling ability, also fit into the same order of fine > whole > coarse. In contrast, protein contents of the three flour streams did not significantly differ in pea and lentil but showed a trend of coarse > whole > fine in barley and oats. Thus, comparable foaming and emulsifying properties were observed for the three streams of pulse flours, and OBC of the barley and oat flours exhibited a consistent trend of coarse > whole > fine. The noted different particle sizes and chemical compositions among the three flour streams only caused a descending order of fine > whole > coarse in the pasting viscosities of the pulse flours but did not lead to such a clear trend in the cereal flours.

A close comparison between the pulses and cereals revealed that the pulse flours generally contained less starch and lipid but more protein, dietary fiber, and ash than the cereal flours of the same stream and that the starches in the pulse flours comprised more amylose. Moreover, in the coarse pulse flours that better preserved the original structure of cotyledon, the starch granules are entrapped in compact protein and fiber matrices, but such a dense structure surrounding starch granules was generally absent in the coarse cereal flours. Due to the noted differences in the proximate compositions and structures, the pulse flours exhibited stronger foaming, emulsifying, and gelling ability but lower pasting viscosities as compared to the cereal flours of the same stream. The highlighted impacts of particle size, chemical composition, and microscopic structure on the characterized functional properties of the pulse and cereal flours will be meaningful for the agri-food sector to use different crops as well as to manipulate milling and sieving processes to create flours with diverse techno-functional characteristics. The research and development activities will significantly expand industrial applications of this important category of ingredients in human foods, pet foods, animal feeds, and other similar products.

CRediT authorship contribution statement

Fan Cheng: Data curation, Formal analysis, Investigation, Software, Validation, Writing – original draft, Writing – review & editing. **Ke Ding:** Investigation, Validation. **Hanyue Yin:** Investigation, Validation. **Mehmet Tulbek:** Conceptualization, Funding acquisition, Investigation, Resources. **Claire Maria Chigwedere:** Investigation, Validation, Writing – review & editing. **Yongfeng Ai:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing.

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 material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2022.112223.

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