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Pea and lentil flour quality as affected by roller milling configuration

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Abstract

This study examined the effects of roller mill configuration on pulse flour quality. Dehulled yellow pea and green lentil were ground to flour using a laboratory roller mill characterized by its flexibility to control particle size reduction while maintaining a constant feed rate. The milling diagram length (long, six passes vs. short, four passes) and sieve sizes (large, 300 μm vs. tight, 180/150 μm) were adjusted for a total of four milling configurations. Each flour stream was characterized with respect to its physical properties and chemical composition. No notable differences were identified between pea and lentil based on how the milling configuration influenced flour characteristics. Overall, combining streams to produce a whole flour did not affect the chemical composition but resulted in variability for physical characteristics as indicated by a tendency toward increased levels of damaged starch with the shorter milling diagram. Damaged starch content was found to be indirectly associated ($p < 0.05$) with the particle size distribution, where the highest concentrations were noted in flours with median distributions below 30 μm. When individual streams were compared across milling configurations, the stream itself was rarely found to significantly influence flour physicochemical properties. However, the variation exhibited in particle-size distribution, protein, starch, ash, and damaged starch content could have practical relevance given the many significant ($p < 0.05$) correlations with functional properties that could subsequently affect the end-use applicability of flours. This would imply that specialized flours could be made with the intention of being used for defined food applications.

Highlights

- Changes in milling configuration produced pulse flours with a range of physical and functional properties.
- Flour streams from a particular milling configuration demonstrated a wide range of physical and chemical characteristics, for example, starch damage and protein content.
- Smaller particle size was associated with a higher degree of starch damage.
- Variations in chemical and physical characteristics of flour streams were related to differences in their functional properties.

KEYWORDS
damaged starch, flour functionality, lentil flour, particle size, pea flour, roller mill

1 | INTRODUCTION

The world population is increasing steadily, and food supply will be a major challenge for the 21st century (Chéreau et al., 2016). Plant-based foods provide an opportunity to address this challenge; it follows that pulses will play an important role in food market evolution as the world progresses toward more sustainable food sources (McDermott & Wyatt, 2017). Pulses are high in protein having an amino acid profile complementary to that of cereals and contribute to environmental sustainability through their low carbon and water footprints and their importance in crop rotations (McDermott & Wyatt, 2017; Todorov et al., 1996). The Food and Agriculture Organization (FAO) projects global pulse consumption to increase by 21 million tons over the period 2013–2025 (Rawal & Navarro, 2019); 68% of this increase in consumption will be in the form of food (Rawal & Navarro, 2019). In order to grow the pulse industry on a global level, a greater understanding of ingredient, that is, flour, specifications for targeted end-use applications, is required, as is the case with cereal flour production (Campbell, 2007; Prabhasankar et al., 2000). The ultimate aim of the pulse flour industry is to advance knowledge on how best to adjust the milling process in order to deliver flours that are of a desired and consistent quality despite annual and batch-to-batch variations in raw material quality and composition.

A literature review compiled in 2018 outlined the status of pulse flour milling research (Scanlon et al., 2018). This review identified that although studies have demonstrated acceptable pulse flour use in a range of applications, there is limited information on how to manipulate pulse milling to produce flours optimized for specific food product applications. The authors summarized research gaps that need to be addressed in order to obtain the same level of technical expertise that exists in the wheat milling industry (Campbell, 2007). Several research gaps are directly related to pulse flour processing. Is there a desired particle size and how to produce it? What are the target flour specifications and the corresponding by-products? What is the influence of starch damage and how to monitor this characteristic?

Multiple technologies, including impact, hammer, roller, stone, and attrition milling, have been shown to be effective in producing pulse flours (Maskus et al., 2016). Within studies on each of these processes, there was large variation in sample origin, preparation, and milling configuration. It follows that the milling technology itself and the applied process settings, as well as differences in the raw material due to seed variety or growth environment, will have an effect on flour properties, which might be attributed to changes in the particle-size distribution (PSD) and level of starch damage (Maskus et al., 2016). Variability in these flour properties will have an effect on the respective end-use applications (Scanlon et al., 2018).

Unlike other milling technologies, roller milling facilitates the production of a diversity of flours (Campbell, 2007; Prabhasankar et al., 2000; Sakhare et al., 2014) Also, a roller mill requires lower specific energy consumption compared with other technologies such as pin and attrition mills. Several studies have investigated the milling of pulse products using roller mills (Mittal et al., 2012; Sakhare et al., 2014; Sakhare et al., 2015; Thompson et al., 1976; Zinn et al., 2002). The production of a specific flour using roller mills can be performed more gradually as a result of the multiple roll and sifter passes. It follows that many adjustments to the milling process are possible, providing greater control over particle-size reduction and generation of flours with a variety of functional characteristics. This has created interest in the use of roller milling technology to control variability and manage diversity in pulse flour quality.

All streams from any given milling process may yield flours of variable composition and quality (Prabhasankar et al., 2000). Additionally, the roller milling of pulses will be affected by many parameters including dehulling, tempering, roll gap, sieve openings, milling diagram length, fluting profile, roll differential speed, and feed rate. The aim of this study was to assess the utility of roller milling for the production of pulse flours with quality characteristics that might be optimal for particular applications. The study was designed to highlight whether variations in processing parameters, specifically pulse type (pea or lentil), milling diagram length, and sieve openings, were sufficient to produce flours differing significantly in their physical and chemical characteristics and, therefore, in end-use quality.

Dehulled samples of pea and lentil were milled using a laboratory-scale roller mill with variations in two processing parameters, namely, milling diagram length and sieve openings. The effect of mill flow configuration on the physical and chemical properties of the flour streams produced was analyzed. A subsequent study will relate differences in flour quality to end-use applicability.

2 | MATERIALS AND METHODS

2.1 | Raw material

Samples of yellow pea (CDC Spectrum) and green lentil (CDC Greenstar) harvested in 2019 were sourced from a producer in Limerick, Saskatchewan, Canada. Whole pea (24.4% protein on dry basis, 10.7% moisture) was dehulled and split with a stone mill (MTI 70, Saint donat sur l'herbasse, Moulins Alma Pro®) spaced at 6 mm, and then passed through a zig-zag classifier (MZM 1-40, Augsburg, Germany, Hosokawa-Alpine®) set at 3.6 m/s. Lentil (24.8% protein on dry basis, 9% moisture) was dehulled by a combination of a knife mill (SM300, Haan, Germany, Retsch®) set at 1200 rpm equipped with a 6-mm sieve and the zig-zag classifier set at 3.6 m/s. Nondehulled seed was collected with a seed cleaner (RKS SLN, Kitzingen, Germany, Pfeiffer®) and returned to the dehulling process. The dehulled seed of pea and lentil represented 89.9% and 85.0%, respectively, of the initial sample mass; with 8.9% and 14.6% collected as hull and 1.2% and 0.4% lost during the process (dust and humidity). After dehulling, the residual hull on the seed was manually sorted as 0.3% for lentil and 0.6% for pea. The residual hull material was collected as a by-product stream from the milling process.

2.2 | Roller milling

A number of parameters that may be adjusted during the roller milling process have an effect on final product quality, including milling diagram length, roll fluting profiles, speed differential, sieve openings, and stream recycling (Campbell & Bedford, 1992). The aim of this study was to produce flours differing in composition and quality by adjusting two of these process parameters, namely, milling diagram length and sieve openings.

Milling was performed using a laboratory roller mill (MLU 202, Uzwil, Switzerland, Buhler®) with four different configurations, as highlighted in Figure 1 and described below:

- Long milling diagram/large opening: three break roll sets (B1–B3) and three reduction roll sets (C1–C3), sieve openings of 300 μm;
- Long milling diagram/tight opening: three break roll sets (B1–B3) and three reduction roll sets (C1–C3), sieve openings of 180 μm (B1, C1, and C2) and 150 μm (B2, B3, and C3);

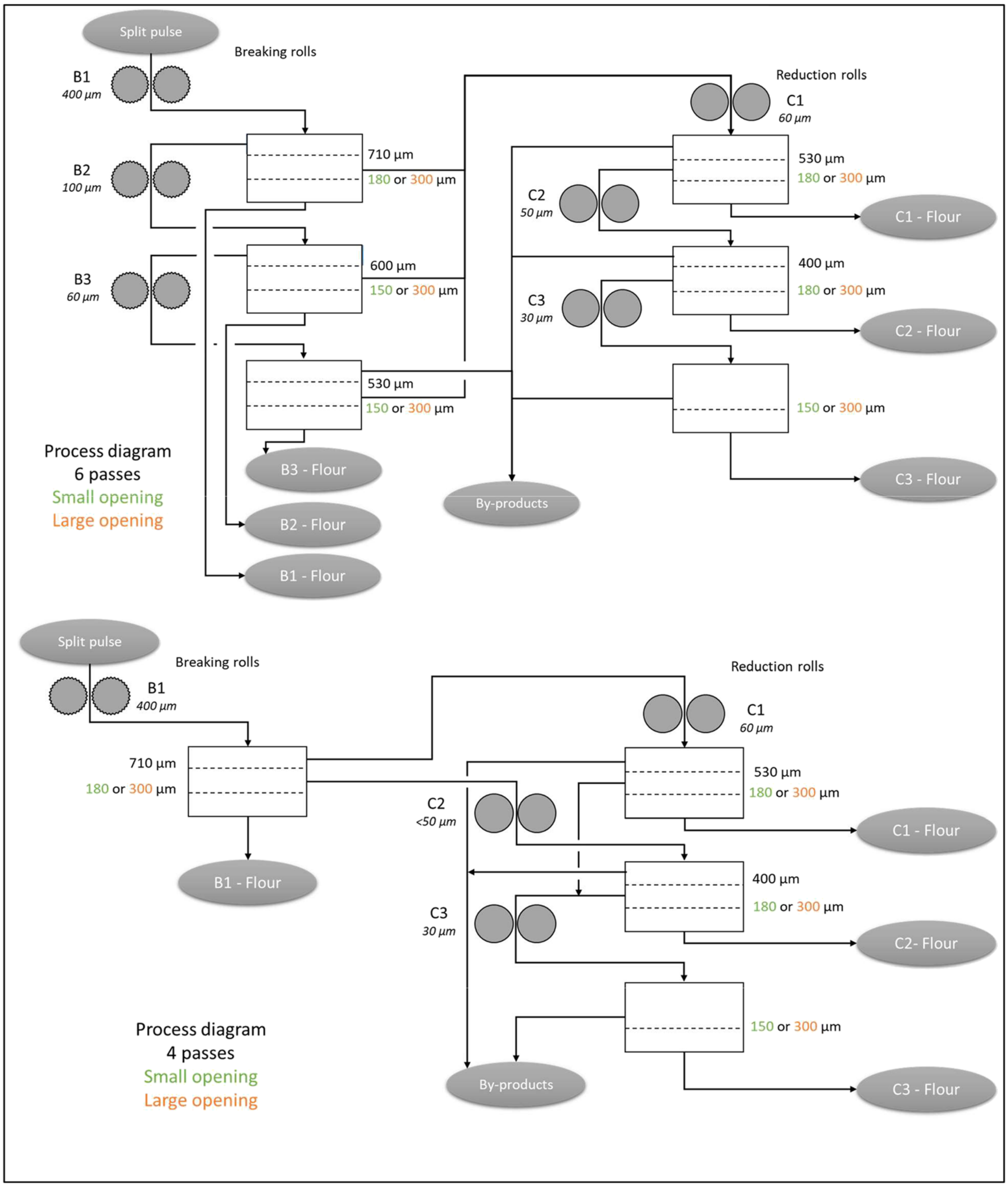

FIGURE 1 Roller milling diagrams employed in the production of pea and lentil flours

- Short milling diagram/large opening: one break roll set (B1) and three reduction roll sets (C1–C3), sieve openings of 300 μm;
- Short diagram/tight opening: one break roll set (B1) and three reduction roll sets (C1–C3), sieve openings of 180 μm (B1, C1, and C2) and 150 μm (C3).

The roll gaps and upper sieve openings for the three corrugated break rolls (B1–B3) and the three smooth reduction rolls (C1–C3) were as follows: B1 with a 400-μm gap and 710-μm upper sieve, B2 with a 100-μm gap and 600-μm upper sieve, B3 with a 60-μm gap and 530-μm upper sieve, C1 with a 60-μm gap and 530-μm upper sieve, C2 with a 50-μm gap and 400-μm upper sieve, and C3 with a 30-μm gap and no upper sieve. Milling was conducted using 36-kg samples at a constant feed rate (6 kg/h) with temperature controlled to <30°C to ensure that no flour heating occurred.

These four diagrams produced 52 streams, among which 40 were flours and 12 were by-products composed mostly of hull.

2.3 | Analysis

The 40 flours were characterized in terms of their yield and chemical, physical, and functional properties. Most analyses were done in duplicate (only density was done in triplicate). Nitrogen content was determined by the Kjeldahl method (TecatorTM with Kjeltec 8400, Hillerød, Denmark, Foss® system) according to procedure NF EN ISO 5983-2 and using a nitrogen to protein conversion factor of 6.25. Moisture and ash content were measured using a Prepash system (Dietikon, Switzerland, Precisa®) according to Sluiter et al. (2008). The test consisted of drying at 105°C until a constant weight was achieved, followed by calcination at 550°C. Total starch and damaged starch contents were determined by enzymatic methods using Megazyme®Kit K-SDAM 06/18 (AACC method 76-31.01 and ICC method No.164) and Kit K-TSTA-50A 04/19 (AOACC Method 996.11 and AACC method 6-13.01), respectively. Damaged starch was expressed on a starch basis.

PSD was determined by laser diffraction in a dry condition (Mastersizer 3000, Worcestershire, United Kingdom, Malvern®) according to ISO procedure 13320:2020. Dispersion was conducted at four bars with refraction and adsorption indices of 1.5 and 0, respectively. Particle-size and shape distributions were evaluated by image analysis (Morphology G3, Worcestershire, United Kingdom, Malvern®) where at least 10,000 particles were dispersed on a microscope slide and characterized. Powder heterogeneity was expressed as SPAN, calculated as follows: SPAN = $(d_{90}–d_{10})/d_{50}$; with d_{90}, d_{50}, and d_{10} being the sizes at which 90%, 50%, and 10% of the particles had a diameter below this value.

Methods for evaluation of functional properties were adapted from protocols previously described in the literature (Maskus et al., 2016). Viscosity evaluations were performed on a Rapid Visco Analyzer RVA 3D + (Watham, United States, PerkinElmer, Inc.). Four grams (3.6-g dry matter) of sample was dispersed in 25 ml of deionized water. The following temperature and mixing profile was applied: t_0 → 0 min, 50°C and 960 rpm/t_1 → 0.1 min, 50°C and 160 rpm/t_2 → 1 min, 50°C and 160 rpm/t_3 → 4.42 min, 95°C and 160 rpm/t_4 → 7.12 min, 95°C and 160 rpm/t_5 → 11 min, 50°C and 160 rpm. Three viscosity parameters were calculated from the resulting curve, namely, maximum viscosity, the hold on trough (obtained after total dispersion and thus the loss of granular structure just before cooling) and the final viscosity (obtained at the end of cooling).

Foaming properties were evaluated with a Foamscan (Lyon, France, Teclis Scientific) using a 0.1% protein solution. Foam was formed by bubbling air into the solution using a frit (P3) at a flow rate of 200 ml/min for 30 s. Foam volume and its stability were then recorded over 10 min, using egg white as a reference.

Emulsifying properties of flours were measured by producing an oil-in-water emulsion. A dispersion of 1% flour in water was mixed with oil at a proportion of 75/25 (dispersion/oil) followed by sonication at room temperature with a Branson 450 Digital Sonifier (Connecticut, USA, Branson Ultrasonics ©) using a 13-mm probe with 10 cycles of 10 s over 2 min set to 40% magnitude. Size distribution of the oil droplets was then measured on a particle-size analyzer (Mastersizer; Malvern, United Kingdom, Malvern Panalytical) with two dispersants (water and SDS). A refractive index of 1.46 was used for sunflower oil and 1.33 for water, and an absorption index of 0.01 was used for sunflower oil. Emulsion stability was assessed by comparison of initial droplet size distribution and after 7 days (percentage difference).

Water holding capacity was measured by adding flour to 10 ml of water at a concentration of 20 mg/ml of dry matter. Suspensions were mixed for 1 h with stirring, followed by centrifugation at 15,000*g* for 10 min. Water holding capacity was expressed as the ratio of the water content of the hydrated sample and the original sample weight.

Powder bulk density was evaluated using a 250-ml graduated cylinder. Aerated bulk density was measured as the density obtained immediately after adding the flour to the graduated cylinder, and tapped bulk density as the value obtained after 1 min of manual vibration. Hausner index, indicative of flowability, was calculated as follows (Thakur et al., 2019):

$$H = \frac{\rho_t}{\rho_a}$$

where ρ_t = tapped density and ρ_a = aerated density. A Hausner index below 1.2 was considered to indicate high flowability.

2.4 | Streams calculation

Blending of flour streams is a common practice during roller milling as the chemical composition of flours follows additive laws. The concentration of a particular parameter for a particular flour combination was calculated as follows:

$$Y_{\text{combined flour}} = \sum_{i}^{B1 \rightarrow C3} x_i . Y_i$$

where

- i is flour stream(s) selected: B1, B2, B3, C1, C2, and/or C3
- Y_i is the concentration of the selected parameter (ex: protein, damaged starch, particle size, etc.)
- x_i is the percentage of flour in the blend

Entire streams were blended in order to avoid having an infinite number of flour combinations.

2.5 | Statistical analysis

Mean differences among streams were assessed using Tukey–Kramer groupings for parameters identified as significant with Type III analysis of variance at a significance level of $p < 0.05$. Relationships among flour properties were assessed using Pearson's correlation coefficient. Statistical analysis was conducted using SAS v9.4 (SAS Institute, Cary, North Carolina, USA). Physicochemical properties of individual flour streams and blends were also assessed by using principal component analysis (PCA) and Pearson's correlations calculated using Xlstat software (version 2016.1.1.; Paris, France, Addinsoft).

3 | RESULTS AND DISCUSSION

3.1 | Stream production

As presented in Figure 1, dehulled pea and lentil were milled using four milling configurations obtained by adjusting the milling diagram length and flour sieve sizes, thereby producing a total of 40 flour streams. Analysis of variance (ANOVA) results demonstrated that moisture and damaged starch content differed significantly ($p < 0.05$) among streams, whereas no effect was found for all remaining physicochemical properties (results not shown). Despite the lack of significance in some samples, differences among all streams will be discussed in order to gauge their practical relevance. The composition and yield for each stream are presented in Tables 1 and 2 for pea and lentil, respectively.

TABLE 1 Yield, composition, and physicochemical properties of roller-milled pea flour streams

Milling configuration	Flour stream	Yield (%)	Moisture (%)	Ash (%DM)	Protein (%DM)	Starch (%DM)	Damaged starch (% starch)	Particle size (d_{10}, µm)	Median particle size (d_{50}, µm)	Particle size (d_{90}, µm)	SPAN[a]
Long diagram/ tight opening	B1	11.3	10.7	2.5	22.6	57.9	4.8	14.7	43	162	3.4
	B2	6.4	10.5	2.7	23.3	53.9	3.8	15.3	49	151	2.8
	B3	0.6	10.5	2.6	22.3	59.7	4.2	13.9	36	139	3.5
	C1	69.2	9.9	2.9	25.2	52.6	4.5	13.9	60	158	2.4
	C2	8.8	9.5	3.1	26.5	48.3	5.2	11.9	52	147	2.6
	C3	1.0	9.8	3.2	28.1	46.0	7.9	11.4	38	142	3.5
Long diagram/ large opening	B1	16.6	10.0	2.6	24.1	52.0	4.0	16.1	71	267	3.6
	B2	20.9	9.9	2.9	25.3	49.2	2.6	21.9	158	305	1.8
	B3	1.4	9.7	3.0	24.5	48.7	3.6	20.6	151	295	1.8
	C1	58.6	9.5	3.0	24.7	49.0	6.5	12.1	53	148	2.6
	C2	1.3	9.0	2.8	24.9	48.5	9.9	7.2	31	137	4.2
	C3	0.2	9.0	2.8	25.8	47.3	16.0	4.5	23	61	2.5
Short diagram/ tight opening	B1	11.4	10.7	2.5	22.9	53.4	5.1	15.2	45	174	3.5
	C1	42.4	10.3	2.7	24.4	52.2	7.2	13.2	45	158	3.2
	C2	38.8	10.1	2.8	25.1	49.9	6.9	12.9	48	135	2.5
	C3	2.0	10.2	3.0	27.3	45.5	6.6	11.1	44	128	2.7
Short diagram/ large opening	B1	18.4	10.7	2.6	24.1	54.5	3.8	17.1	86	290	3.2
	C1	39.3	10.4	2.9	25.3	52.5	5.4	13.0	57	193	3.2
	C2	38.6	10.5	2.9	25.7	52.1	6.8	10.7	41	129	2.9
	C3	2.4	9.6	3.1	26.6	49.8	10.7	8.9	33	132	3.8
Average		**19.5**	**10.0**	**2.8**	**24.9**	**51.2**	**6.3**	**13.3**	**58**	**173**	**3.0**
Standard deviation		*21.0*	*0.5*	*0.2*	*1.5*	*3.7*	*3.1*	*4.1*	*36*	*65*	*0.6*

[a]SPAN is the width of the particle-size distribution calculated as follows $SPAN = (d_{90} - d_{10})/d_{50}$.

TABLE 2 Yield, composition, and physicochemical properties of roller-milled lentil flour streams

Milling configuration	Flour stream	Yield (%)	Moisture (%)	Ash (%DM)	Protein (%DM)	Starch (%DM)	Damaged starch (% starch)	Particle size (d_{10}, µm)	Median particle size (d_{50}, µm)	Particle size (d_{90}, µm)	SPAN[a]
Long diagram/ tight opening	B1	8.5	9.2	2.7	25.2	55.1	5.4	14.9	58	180	2.9
	B2	8.4	9.1	2.7	24.8	56.4	4.8	14.2	55	160	2.6
	B3	0.6	9.2	2.6	23.6	58.8	5.2	14.7	43	140	2.9
	C1	71.6	8.6	2.8	25.9	54.2	5.2	9.9	75	172	2.2
	C2	9.6	8.6	2.9	27.2	50.5	6.1	11.7	61	158	2.4
	C3	0.5	8.9	3.1	29.5	45.7	9.4	7.0	32	116	3.4
Long diagram/ large opening	B1	14.8	9.0	2.7	24.0	51.8	3.8	17.4	96	293	2.9
	B2	20.4	8.9	2.8	26.0	54.4	2.6	23.5	167	317	1.8
	B3	1.2	8.7	2.9	26.0	50.6	1.9	25.8	169	309	1.7
	C1	60.4	8.5	2.8	25.3	51.3	5.8	10.9	61	156	2.4
	C2	1.2	8.2	2.7	25.0	51.0	10.2	5.7	29	116	3.8
	C3	0.1	7.9	2.8	24.8	51.0	15.4	4.0	22	132	5.8
Short diagram/ tight opening	B1	8.9	9.3	2.7	24.5	54.4	5.5	15.9	56	184	3.0
	C1	36.5	8.9	2.7	26.1	55.5	7.8	11.4	47	162	3.2
	C2	48.1	8.7	2.8	26.5	53.0	8.3	11.4	44	126	2.6
	C3	2.5	8.8	2.8	28.5	41.9	14.9	6.6	30	93	2.9
Short diagram/ large opening	B1	16.0	9.6	2.8	25.7	55.8	3.4	20.4	120	359	2.8
	C1	42.4	9.0	2.8	26.3	55.3	7.5	11.5	47	160	3.2
	C2	38.8	9.0	2.7	26.4	54.3	8.2	10.5	40	113	2.5
	C3	2.0	9.6	2.9	27.0	51.8	14.3	6.6	27	83	2.8
Average		**19.6**	**8.9**	**2.8**	**25.9**	**52.6**	**7.3**	**12.7**	**64**	**176**	**2.9**
Standard deviation		*22.1*	*0.4*	*0.1*	*1.4*	*3.8*	*3.9*	*5.8*	*43*	*79*	*0.8*

[a]SPAN is the width of the particle-size distribution calculated as follows $SPAN = (d_{90} - d_{10})/d_{50}$.

The sum of the yields for all flour streams of a given milling configuration did not equal 100% due to the production of by-products. However, the by-product yield was always less than 0.5%, with the exceptions of middlings (fine by-product) produced from pea using the long milling diagram/tight opening (1.8%) and bran (coarse by-product) produced from lentil using the short milling diagram/tight opening (3.6%). The higher amounts of by-products for these configurations were attributed to an overload of certain sieves due to the constant feed rate applied. The 20 streams produced for each pulse type (pea or lentil) exhibited large differences in yield. However, pulse type itself did not have a large effect on the amount of flour obtained for a particular stream. Therefore, for both pea and lentil, the majority of flour was derived from the C1 stream, followed by B1, B2, and occasionally C2. It follows that B3, C3, and usually C2 were low yielding streams (Tables 1 and 2). These differences in stream yields were expected, because they are well known in cereals (Campbell, 2007; Prabhasankar & Haridas Rao, 2001) and in pulses (Sakhare et al., 2014, 2015).

Ash, starch, and protein content of flour streams ranged from 2.5% to 3.2% and 2.6% to 3.1%, 45.5% to 59.7% and 41.9% to 57.8%, and 23.3% to 28.1% and 23.6% to 29.5% for pea and lentil, respectively, demonstrating moderate differences among streams (Tables 1 and 2). Although streams were not found to be significantly different in composition ($p < 0.05$), except for moisture and damaged starch content, the variation in protein content among streams may have practical relevance as pea and lentil having initial seed protein concentrations of 24.4% and 24.8% (dry basis), respectively, produced flour streams differing in protein concentration by up to 5% (Tables 1 and 2). Blending of flour streams is a commercial strategy commonly used to produce wheat flours with desired physicochemical properties (Campbell, 2007; Mittal et al., 2012; Sakhare et al., 2014). The roller milling process thus is a useful tool for adjusting the protein content of pulse flours and providing opportunities to optimize protein requirements for particular end-uses.

Damaged starch content displayed significantly ($p < 0.05$) higher values for streams collected at C3 ($\bar{xc} = 11.9\%$) than at B2 ($\bar{xc} = 3.5\%$) for both pea and lentil. Similar results were reported by Price et al. (2021), where the final fourth middlings stream produced from roller milling of pea displayed significantly ($p < 0.05$) higher levels of starch damage than all other streams. Variability in flour PSD was large (CV > 50%); however, no significant differences were found among streams. Particle-shape distribution was assessed for the majority of samples; however, because no significant differences in particle shape were detected, the data are not presented.

TABLE 3 Pearson correlation matrix of compositional and functional parameters for roller-milled pea (highlighted grey, below diagonal line) and lentil (highlight green, above diagonal line) flours

Variables	Protein	Ash	Starch	Damaged starch	Median particle size	SPAN	Water holding capacity	Emulsions capacity (water)	Emulsion stability	Foam volume	Foam stability	Final viscosity	Aerated density	Tapped density	Hausner index
Protein	–	**0.784***	**−0.702****	0.401	−0.152	−0.126	−0.249	−0.319	−0.063	−0.298	−0.003	**−0.826*****	−0.153	−0.205	0.037
Ash	**0.867*****	–	**−0.573****	0.205	0.093	−0.093	−0.124	0.065	−0.045	−0.241	0.108	**−0.645****	−0.112	−0.202	0.027
Starch	**−0.837*****	**−0.768*****	–	**−0.538***	0.181	−0.136	0.297	−0.067	0.286	0.220	−0.338	**0.709****	0.381	0.409	−0.220
Damaged starch	0.427	0.258	**−0.448***	–	**−0.748****	**0.660****	−0.387	−0.048	**−0.444***	0.050	**0.503***	**−0.786*****	**−0.841*****	**−0.572****	**0.705****
Median particle size	−0.086	0.083	−0.091	**−0.580****	–	**−0.606****	0.187	0.120	0.255	−0.153	−0.155	**0.541***	**0.742****	0.319	**−0.704****
SPAN	−0.156	−0.328	0.301	0.243	**−0.641****	–	−0.280	0.231	−0.069	0.118	0.341	−0.413	**−0.839*****	−0.430	**0.848*****
Water holding capacity	0.057	−0.285	−0.257	**−0.471***	**0.613****	**−0.675****	–	0.370	0.069	−0.126	−0.358	0.399	0.249	0.088	−0.266
Emulsion capacity (water)	−0.405	−0.218	0.152	−0.113	0.150	−0.274	0.392	–	−0.137	0.283	0.350	0.245	−0.160	0.049	0.310
Emulsion stability	−0.338	−0.336	0.088	−0.255	0.133	−0.084	0.123	−0.094	–	0.114	−0.412	0.312	**0.483***	**0.514***	−0.260
Foam volume	−0.034	−0.058	0.017	0.124	−0.250	0.130	0.027	0.245	0.111	–	**0.587****	0.255	−0.050	0.387	0.339
Foam stability	**0.473***	0.352	**−0.462***	**0.762*****	−0.321	0.119	−0.347	−0.108	−0.094	**0.487***	–	0.179	−0.356	−0.095	0.435
Final viscosity	**−0.775*****	**−0.607****	**0.671****	**−0.707****	**0.520***	−0.127	0.274	0.209	0.257	−0.065	**−0.537***	–	**0.754****	**0.574***	**−0.481***
Aerated density	−0.358	−0.151	0.314	**−0.705****	**0.758****	0.313	0.317	0.008	−0.026	−0.248	**0.514***	**0.716****	–	**0.689****	**−0.846*****
Tapped density	−0.401	−0.332	**0.468***	**−0.597****	**0.481***	0.014	−0.117	0.024	−0.071	−0.333	−0.413	**0.548*****	**0.788*****	–	−0.207
Hausner index	0.167	−0.099	−0.041	**0.518***	**−0.652****	**0.468***	**−0.663****	−0.028	−0.040	0.038	0.418	**−0.578****	**−0.754****	−0.195	–

Note: Values in bold are significant correlations.

$^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.0001$.

3.2 | Links between process parameters and flour quality

Table 3 presents the Pearson correlation coefficients among pea and lentil flour stream constituents. For both pea and lentil, a negative correlation existed between protein content and starch content (−0.84, $p < 0.001$ and −0.70, $p < 0.01$), whereas a positive correlation was found between protein content and ash content (0.87, $p \leq 0.0001$ and 0.78, $p \leq 0.0001$), respectively. The results indicate that flour streams enriched in protein and ash contained relatively less starch. The inverse relationship between starch and protein is not surprising given the phenomenon that occurs during air classification (Pelgrom et al., 2013). In this process, the protein-rich fractions are found to be lower in starch and higher in ash. This is explained by the disintegration of the cotyledon and the concomitant release of fine particles (<10 μm) rich in protein, whereas starch granules and/or agglomerates of protein and starch constitute fractions with particles larger than 10 μm (Moller et al., 2021). In this study, no correlation was found between protein content or starch content and particle size (Table 3). Production of protein-rich streams was thus a consequence of the roller milling configuration that led generally to particle-size reduction without a substantial change in particle composition.

Table 3 shows that for both pea and lentil, a clear negative correlation existed between particle size and damaged starch content ($p < 0.01$). This indicates that a flour with a smaller average particle size will exhibit a higher level of damaged starch. The same relationship was found for stone milling (Monnet et al., 2019) and is well known for rice and wheat milling (Thakur et al., 2019). Figure 2 demonstrates that this relationship is not linear but rather is characterized by a threshold near an average particle size of 35–40 μm, below which the damaged starch content increases markedly to above 10% (on a starch basis). For coarser flours (above 40 μm), the level of damaged starch averaged below 8%, with levels closer to 4% for flours with an average particle size over 100 μm. In this study, the average particle size was utilized as an aggregate value to study the effect of particle size. Conclusions were similar when considering other criteria such as d_{90} (Tables 1 and 2); however, the threshold value was closer to 120 μm. Considering the PSD of starch granules, known to be between 10 and 40 μm in pea (Pelgrom et al., 2013), it is possible that an increased level of damaged starch is linked to the proportion of flour milled that is closest in particle size to the size of an individual starch granule. This hypothesis was recently studied by Monnet et al. (2019), where the authors pointed out the fragmentation mechanisms within the pea kernel structure.

Table 4 presents the physicochemical composition of pulse flours (all streams combined) according to the milling configuration applied. As only one milling replicate was analyzed for each pulse type and configuration, significant differences among mean values could not be

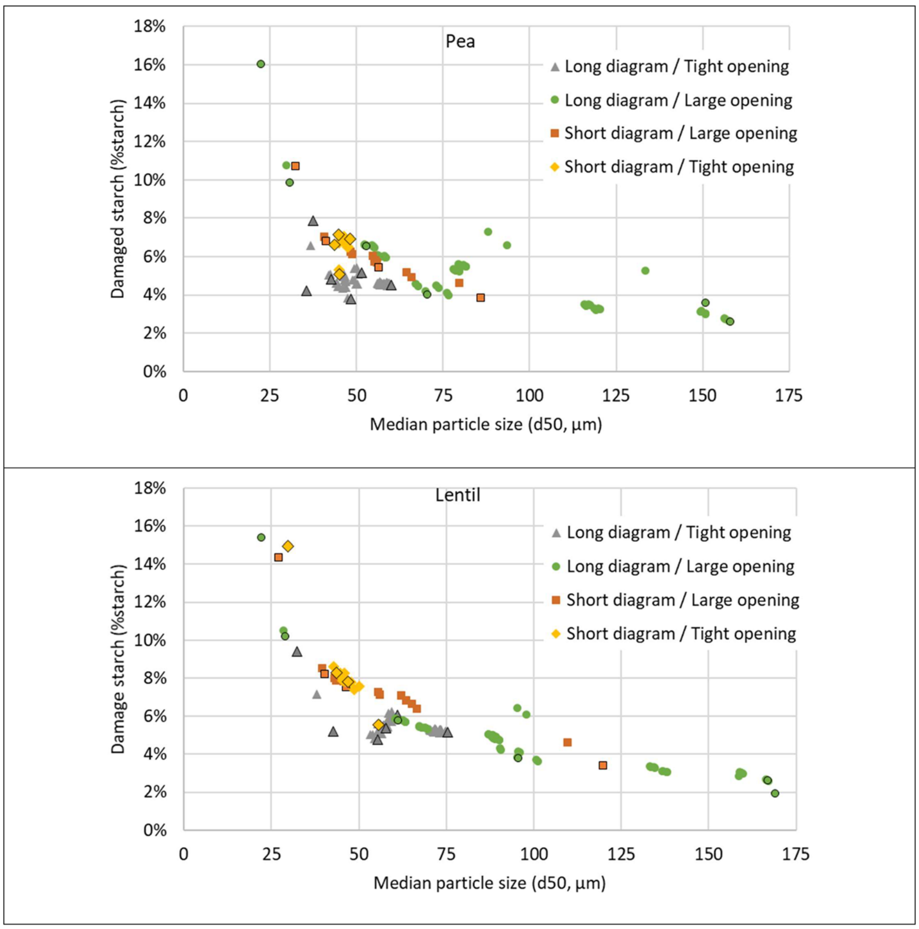

FIGURE 2 Correlations between damaged starch content and particle size for roller-milled pea and lentil flour streams and combinations of flour streams. Data point outlined in black represent individual flour streams and those not outlined in black represent combinations of flour streams

TABLE 4 Composition and physicochemical properties of roller-milled pea and lentil flour streams

Milling configuration	Moisture (%)	Protein (%DM)	Ash (% DM)	Starch (% DM)	Damaged starch (% starch)	Particle size (d_{10}, μm)	Median particle size (d_{50}, μm)	Particle size (d_{90}, μm)	Particle size (d_{97}, μm)
Pea									
Long diagram/ tight opening	10.0	24.9	2.9	52.9	4.6	13.9	56.1	156.7	203.9
Long diagram/ large opening	9.6	24.7	2.9	49.5	5.3	14.9	79.0	202.8	238.0
Short diagram/ tight opening	10.2	24.6	2.8	51.3	6.8	13.3	46.3	149.9	199.5
Short diagram/ large opening	10.5	25.3	2.8	52.7	5.8	12.8	55.5	184.6	245.9
Average	**10.1**	**24.9**	**2.9**	**51.6**	**5.6**	**13.7**	**59.2**	**173.5**	**221.8**
Standard deviation	*0.4*	*0.3*	*0.1*	*1.6*	*0.9*	*0.9*	*13.9*	*24.6*	*23.5*
Lentil									
Long diagram/ tight opening	8.7	25.9	2.8	54.1	5.3	10.9	70.3	169.8	214.7
Long diagram/ large opening	8.6	25.3	2.8	52.0	4.8	14.6	89.3	211.5	246.1
Short diagram/ tight opening	8.8	26.2	2.8	53.8	8.0	11.7	45.6	144.2	200.5
Short diagram/ large opening	9.1	26.3	2.8	54.9	7.3	12.4	55.5	172.1	251.9
Average	**8.8**	**25.0**	**2.8**	**53.7**	**6.4**	**12.4**	**65.2**	**174.4**	**228.3**
Standard deviation	*0.2*	*0.5*	*0.0*	*1.2*	*1.5*	*1.6*	*19.0*	*27.8*	*24.7*

determined. However, results suggest that the configuration itself had an influence on the level of damaged starch. For example, flours produced with the long milling diagram had a tendency for lower average damaged starch content than flours produced with the short milling diagram, ranging from 4.6% to 5.3% for the long diagram compared with 5.8% to 8.0% for the short diagram across sieve opening size and pulse type. Parameters related to the PSD also were highly variable across configurations (CV > 10%). However, no clear trends were identified across milling treatments as the chemical composition of pulse flours displayed low variability across milling configurations, demonstrated by the low coefficients of variation (<3.0%). This observation suggests that chemical composition (i.e., protein, ash, and starch content) of the whole, combined flour cannot be affected significantly by the milling configuration, but the physical properties of individual flour streams (i.e., damaged starch content and particle size) are entirely a consequence of milling. In addition, no distinct differences were noted between pea and lentil whole flours or streams, suggesting that a given milling configuration will produce similar flour streams across pulse types.

A study by Maskus et al. (2016) compared pea flour production via roller milling with other milling technologies including hammer, stone, and pin milling. The authors reported a coarser particle size for flours produced with roller mills, characterized by a d_{90} of 835 μm (in comparison with the maximum d_{90} value obtained here of 359 μm, but 176 μm on average). This indicates that the flours produced in this study contained particles that were relatively finer but similar in damaged starch content (an average of ~5.6% damaged starch in the previous study). The referenced study also reported lower protein (22.1%) and starch (49.6%) contents than for the whole flours described in Table 4, although the differences are not large and may be attributed to differences in the composition of the samples milled.

PCA of flour physicochemical characteristics was selected to further emphasize the relationships between pea and lentil flour parameters given the multicollinearity of the data. Figure 3 presents PCA of the physicochemical characteristics for 156 pea and lentil flours that were derived through individual flour stream blending. This was done to assess the possible range in compositional parameters that could be produced with the milling configurations employed. All possible flour stream combinations of a given configuration were combined so that a total of 136 flour blends were calculated. In an effort to minimize the number of possible combinations, the quantity of flour used in each calculated blend was reflective of the actual yield each stream produced via the milling process. For example, if stream B2 yielded 3.6 kg of flour, then only this mass of 3.6 kg was used in calculations for the compositional parameters of the resulting blended flours that included B2. During PCA, only protein, ash and starch content, median particle size (d_{50}), and SPAN were retained for the analysis as d_{90} and d_{10} were redundant with median particle size (d_{50}).

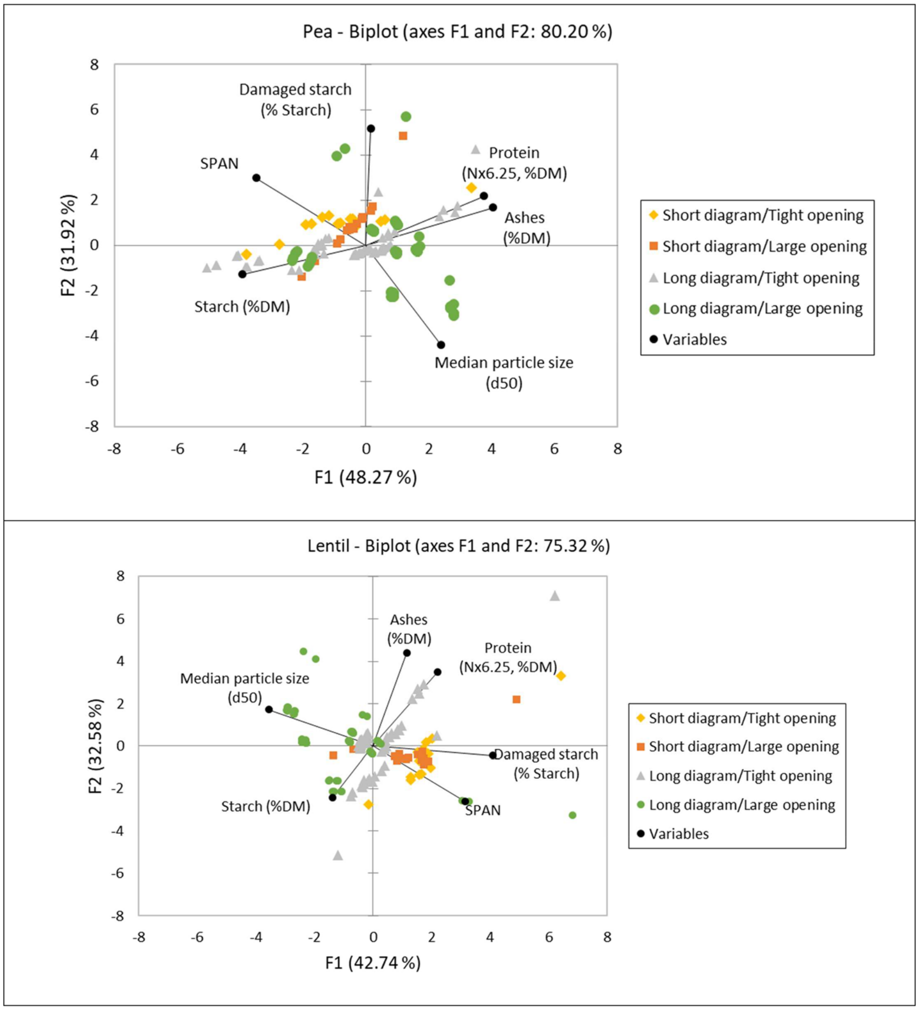

FIGURE 3 Principal component analysis describing relationships among compositional and physicochemical parameters for roller-milled pea and lentil flour streams and combinations of flour streams

PCA of both pea and lentil using two principal components accounted for 80.2% and 75.3% of the respective flour variability (Figure 3). No individual milling configuration appeared discriminant from another based on the distribution of flour streams across treatments. However, there are individual flour streams that can be distinguished from the others, indicating the presence of extreme flours based on their physicochemical composition. This observation suggests that it is possible to produce a large diversity of individual flour streams using a single milling technology and further emphasizes the potential of flour blending as a tool to produce flours with specific physicochemical characteristics.

3.3 | Effect of flour composition on functionality

One of the objectives of this study was to assess if variability in flours resulting from roller milling would have an effect on their end-use applicability as ingredients. To this end, the 20 pea and lentil flour streams were characterized in terms of their laboratory scale functionality. The aim was to highlight whether differences in physicochemical characteristics would affect the behavior of the flours in terms of their emulsion capacity, viscosity, foam capacity, flowability, and water holding capacity.

The functional characteristics of the 20 pea and lentil flour streams are presented in Tables 5 and 6. All parameters for which differences were noted across individual milling streams were considered. Maskus et al. (2016) presented similar values for pea flour pasting properties (specifically, an RVA final viscosity of 211 RVU) and water absorption capacity (1.4–2.2 g/g). In the present study, foam stability after 10 min was slightly lower than that reported by Maskus et al. (2016) (84%), which can be attributed to small differences in the methodology. Certain properties such as foam volume, Hausner index, tapped density, and aerated density displayed relatively low variability (generally with CV < 5%). Conversely, emulsion properties, water holding capacities, RVA values, and foaming properties were highly variable (with CV > 10%).

A Pearson's correlation matrix was calculated to highlight relationships between the functional properties of flour streams and their physicochemical properties (Table 3). All RVA parameters (maximum, trough, and final viscosity) were strongly correlated to one another ($r > 0.97$, $p < 0.001$) and were similarly correlated with other physicochemical characteristics (results not shown). Therefore, only final

TABLE 5 Functional properties of roller-milled pea flour streams

Milling configuration	Stream	Water holding capacity (g g^{-1})	Emulsions capacity (water, µm)	Emulsions capacity (SDS, µm)	Emulsion stability (%)	Foam volume (ml)	Foam stability (%)	High viscosity (peak, RVU)	Final viscosity (RVU)	Hold on trough (RVU)	Aerated density (g cm^{-3})	Tapped density (g cm^{-3})	Hausner index
Long diagram/ tight opening	B1	1.62	41	32	79	117	7	158	293	154	0.481	0.644	1.34
	B2	1.88	43	37	86	119	14	160	290	156	0.493	0.641	1.30
	B3	1.27	41	34	81	109	12	167	293	160	0.486	0.702	1.45
	C1	2.18	37	31	84	111	12	146	268	142	0.484	0.646	1.34
	C2	2.23	35	28	79	111	6	137	232	128	0.448	0.597	1.33
	C3	1.40	17	11	63	108	28	114	172	105	0.438	0.640	1.46
Long diagram/ large opening	B1	1.81	41	33	80	108	4	164	299	159	0.462	0.658	1.42
	B2	2.23	37	31	83	111	7	155	300	153	0.542	0.665	1.23
	B3	2.12	38	36	93	105	15	161	301	155	0.554	0.702	1.27
	C1	2.00	36	28	77	110	1	153	273	145	0.480	0.607	1.26
	C2	1.62	39	30	77	113	30	137	224	127	0.467	0.641	1.37
	C3	1.44	40	29	73	113	79	126	199	116	0.397	0.588	1.48
Short diagram/ tight opening	B1	1.62	17	30	176	111	10	164	295	158	0.465	0.638	1.37
	C1	1.49	33	8	24	105	2	151	272	145	0.512	0.680	1.33
	C2	1.62	30	35	117	103	0	142	248	135	0.462	0.625	1.35
	C3	1.66	29	27	94	119	57	139	224	128	0.464	0.645	1.39
Short diagram/ large opening	B1	1.46	16	16	99	109	8	163	299	158	0.544	0.700	1.29
	C1	1.63	21	11	52	107	5	149	269	143	0.515	0.693	1.35
	C2	1.63	19	10	54	107	3	141	247	134	0.469	0.640	1.37
	C3	1.44	14	8	59	113	69	162	260	153	0.461	0.611	1.33
Average		**1.72**	**31.10**	**25.09**	**0.82**	**110**	**0.19**	**149**	**263**	**143**	**0.48**	**0.65**	**1.35**
Standard deviation		*0.29*	*10.10*	*10.19*	*0.30*	*4*	*0.23*	*14*	*37*	*16*	*0.04*	*0.03*	*0.07*

Note: ND indicates where insufficient sample was available for complete characterization.

TABLE 6 Functional properties of roller-milled lentil flour streams

Roller milling configuration	Stream	Water holding capacity (g g^{-1})	Emulsions capacity (water, μm)	Emulsions capacity (SDS, μm)	Emulsion stability (%)	Foam volume (ml)	Foam stability (%)	High viscosity (peak, RVU)	Final viscosity (RVU)	Hold on trough (RVU)	Aerated density (g cm^{-3})	Tapped density (g cm^{-3})	Hausner index
Long diagram/ tight opening	B1	2.21	38	30	78	111	9	171	281	163	0.500	0.661	1.32
	B2	3.14	40	31	77	112	4	184	293	175	0.518	0.676	1.31
	B3	1.41	34	27	78	143	90	180	313	172	0.524	0.737	1.41
	C1	1.88	36	30	82	111	8	180	291	175	0.561	0.728	1.30
	C2	1.80	34	35	103	111	5	153	241	147	0.532	0.682	1.28
	C3	1.47	34	27	79	111	20	112	180	105	0.466	0.664	1.43
Long diagram/ large opening	B1	1.75	32	28	87	109	6	178	287	168	0.526	0.661	1.26
	B2	1.88	38	30	78	111	6	180	294	175	0.558	0.684	1.22
	B3	1.76	39	31	80	113	93	176	286	168	0.574	0.705	1.23
	C1	1.85	37	30	81	108	4	179	272	169	0.518	0.692	1.34
	C2	1.46	45	31	70	113	89	143	238	136	0.479	0.677	1.41
	C3	1.54	49	34	69	115	87	ND	ND	ND	0.401	0.632	1.58
Short diagram/ tight opening	B1	1.48	24	16	66	105	0	173	274	160	0.505	0.643	1.27
	C1	1.64	20	22	112	108	6	169	275	162	0.531	0.706	1.33
	C2	1.62	22	13	58	107	5	156	247	147	0.492	0.685	1.39
	C3	1.42	21	13	60	113	85	134	221	125	0.480	0.651	1.36
Short diagram/ large opening	B1	1.55	20	19	96	106	5	175	285	165	0.540	0.678	1.26
	C1	1.45	16	18	112	109	5	158	253	150	0.523	0.692	1.32
	C2	1.62	18	10	57	109	8	150	238	141	0.492	0.651	1.32
	C3	1.50	27	13	51	113	82	125	210	117	0.477	0.627	1.31
Average		**1.72**	**31.05**	**24.23**	**0.79**	**112**	**0.31**	**162**	**262**	**1534**	**0.51**	**0.68**	**1.33**
Standard deviation		*0.39*	*9.61*	*8.00*	*0.17*	*7.74*	*0.38*	*20.9*	*34.0*	*20.81*	*0.04*	*0.03*	*0.08*

Note: ND indicates where insufficient sample was available for complete characterization.

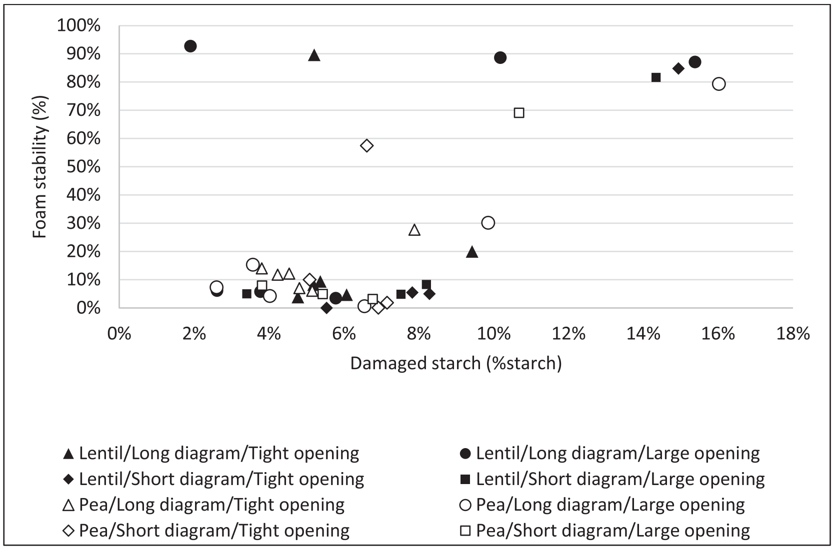

FIGURE 4 Correlations between damaged starch content and foam stability for roller-milled pea (white points) and lentil (black points) flour streams and combinations of flour streams

viscosity data were used in the correlation analysis. Also, results for emulsification capacity in water or in SDS were strongly correlated ($r > 0.87$, $p < 0.001$); hence, data for emulsification in water only are reflected in Table 3.

Emulsion capacity and foam volume were weakly correlated with any of the physicochemical parameters analyzed. Therefore, variability in values for these properties cannot be explained by the present study. Table 3 demonstrates the independency of most of the functional properties analyzed as they correlate weakly with one another. The majority of the exceptions are for those parameters measured during the same test, such as foam stability and foam volume, which were positively correlated. The same observation is valid for tapped density, aerated density, and Hausner index; all three of which also were correlated to the RVA trough and final viscosities.

Of the correlations presented in Table 3, those found to be significant ($p < 0.05$) for both pea and lentil flour streams include the following: foam stability with damaged starch content; final viscosity with protein, ash, starch, and damaged starch content; aerated density with damaged starch content; average particle size and Hausner index with damaged starch content; and average particle size and SPAN.

The final viscosity was inversely related to damaged starch, ash, and protein content but directly related to starch content and mean particle size. Due to the absence of a correlation between damaged starch (itself correlated with median particle size) and protein content (which was correlated with starch content and ash content), pasting properties appear to be affected by both physical and chemical parameters. This multiparameter response indicates the complexity with which all physicochemical properties of a flour can affect its functionality.

Aerated density and Hausner index, both relevant to flour handling, were significantly affected by particle size and damaged starch content. Due to the relationship between particle size and damaged starch, it may be assumed that particle size is the main explanation for this observation. Results indicate that if a higher flour density is desired, too fine of a powder should be avoided to control the level of starch damage. It follows that flowability (Hausner index < 1.2) of a flour is better when the particle size is relatively coarse (>60 μm) and narrowly spread (low SPAN).

Damaged starch content also was found to be significantly correlated with foam stability, although the relationship between the parameters is complex (Figure 4). It appears that if the damaged starch content is below 10%, the foam is not stable. Above 10%, improved stability is observed, until above 12% starch damage where the foam becomes stable. This behavior is hypothesized to be the result of the increased viscosity that arises alongside a certain degree of damaged starch that is required to stabilize the foam. However, three flour streams did not follow this trend as they exhibited foam stability with starch damage below 8% (Figure 4). These three flours were derived from the B3 and C3 streams, both of which were low yielding under every milling configuration. One explanation could be that these low yielding streams were contaminated with other compounds/particles (such as hull) that imparted increased viscosity useful in stabilizing the foams. The B3 and C3 streams correspond to the final flour collection before by-product removal.

4 | CONCLUSION

The objective of this study was to assess the flexibility of roller milling for the production of flours with specific quality characteristics that may be useful for particular end-use applications. The results fully demonstrated that a variety of flour streams could be produced using the roller mill configurations applied. Streams varied with respect to their particle size and protein, starch, and damaged starch contents. The potential to create flours with varying physicochemical characteristics could be even higher at industrial scale, considering that this study focused on only two process parameters (milling diagram length and sieve openings), whereas commercially, many additional factors can be altered to influence final product quality. Further research is required to examine the influence of these additional milling process parameters and how they may affect the applications of a flour.

Despite the high degree of variability among flour streams produced, results from this study showed that combining all flour streams from any given milling configuration will produce whole flours having similar chemical characteristics. The physicochemical characteristics of a particular flour stream across milling configurations were alike for both pea and lentil and therefore, may also apply to the milling of other pulse types using the same settings. A shortened milling diagram with tighter sieve openings increased the severity of the mechanical treatment during flour production, resulting in a tendency for increased levels of damaged starch. For the production of flours with lower levels of starch damage, a longer and therefore more gradual milling diagram with larger sieve openings should be applied. An alternative approach is the blending of similar flour streams. For example, the second break (B2) roll streams exhibited lower levels of damaged starch and could be combined to produce flours with low starch damage and higher pasting properties, whereas the final reduction (C3) roll streams could be mixed to produce flours with relatively high damaged starch contents. This study also showed that stream blending would be a useful strategy for creating flours that meet particular end-use specifications. The next step in this research is the undertaking of food application trials designed to help develop ideal flour specifications.

Finally, this study demonstrated that the physicochemical properties of streams translated to differences in the functional characteristics of the flours. The behavior of the functional properties of a flour was complex, with only a few parameters being clearly related to the physicochemical characteristics studied. In particular, pasting properties were favorable when both protein and damaged starch contents were low. Additionally, foam stability increased with a higher level of damaged starch, and flowability was improved for flours found not to be too fine (>60 μm) and having narrow SPAN. Food application studies are required to aid in understanding the effect of these functional attributes and how they relate to the final product. Considering the inherent flexibility of roller milling for producing flour streams with particular characteristics, food incorporation studies are very important to highlight ideal flour specifications for a given application.

CONFLICT OF INTEREST

Authors JC and TD are employees of Pulse Canada.

FUNDING INFORMATION

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ETHICS STATEMENT

This research did not involve any ethics issues to be considered.

AUTHOR CONTRIBUTIONS

Conceptualization: JCM, AM, RT, and TD. Methodology: JCM, AM, RT, and TD. Project Administration: TD and JCM. Investigation: JCM. Formal Analysis: JCM and JC. Writing – original draft: JCM and JC. Writing – review & editing: JCM, JC, AM, RT, and TD.

DATA AVAILABILITY STATEMENT

Source data are available upon request.

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