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Bulk and flow characteristics of pulse flours: A comparative study of yellow pea, lentil, and chickpea flours of varying particle sizes

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ABSTRACT

The demand for pulses is increasing due to their numerous nutritional, sustainability, and agronomical advantages. However, studies on the bulk and dynamic flow properties of pulse flours, which are crucial for adequate handling and processing, are scarce. This study was performed to investigate the flow properties of yellow pea, lentil, and chickpea flours and compare them with wheat flour. Pulse flours of different particle sizes were produced using a laboratory roller mill through adjusting the settings of the roll gap opening and sieve arrangement and employing 75, 150, and 200 μm bottom sieves for small, medium, and large-sized flours, respectively. The flour flow properties were analyzed using a Hosokawa powder tester and FT4 powder rheometer. Chickpea flours had the lowest bulk density and the highest aeration ratio and were more compressible and cohesive among all the pulse flours and wheat flour. The small-sized flour for each pulse grain was more cohesive than the large-sized flours. For nearly all tests, chickpea and small-sized yellow pea flours were characterized as non-flowing powders, while medium and large-sized lentil flours showed relatively good flow properties comparable to wheat flour. Overall, pulse flours had lower bulk density and were classified as poor flowing flours compared to wheat flour. The production of small-sized pulse flours is not recommended because of their low bulk density, high compressibility, and poor flow properties. Adjustments to equipment will be necessary for the incorporation of pulse flours into modern industrial platforms. This study will aid the milling and baking industries in preparing for pulse grain processing and benefit transportation companies in evaluating pulse flours for proper handling.

1. Introduction

Pulses are protein-rich grains that originate from the regions around the middle and Far East. In America, lentils, yellow peas, and chickpeas are the most produced pulse grains (USDA, 2017). Pulses are nutritious and contain more protein than common cereals such as wheat, rice, and maize. They are also rich in vitamins and minerals that are necessary for the body's core mechanisms. Having non-digestible carbohydrates and fibers, pulses are a low glycemic food source, which means they can be good food for people with diabetes or those wanting low-carb food (Fujiwara et al., 2017). Because of all the above benefits, the demand for pulses has been increasing (Rajpurohit and Li, 2023; Goldstein and Reifen, 2022). Individuals who have celiac disease or gluten sensitivity are also driving the growing demand for gluten-free food, of which pulses are a part (Asif et al., 2013; Bessada et al., 2019; Han et al., 2010). In 2016, the FAO FSN Forum (2016) suggested incorporating pulses into commonly consumed food products. Since then, more scientists have started to adopt pulses for the baking industry (Bourré et al., 2019; Paladugula et al., 2021). A study by Nkurikiye et al. (2023) showed that the incorporation of chickpea, lentil, and yellow pea flours in refined wheat flour was feasible. They found that lower levels of incorporation did not have significant effect on the physical properties of the bread, and the nutritional attributes of the wheat bread were improved. The incorporation of new grains in baking requires the production of flour. Scientists started to develop milling methods for pulses since then. As an example, Pulivarthi et al. (2021) developed a milling method for yellow peas and lentils where they used roller mill to produce pulse flours of different particle sizes with approximately the same proximate composition.

When considering the utilization of flour on an industrial level, the flow properties play a crucial role in determining the handling of flour during transportation and processing in plant facilities. Assessing flow

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properties is crucial in determining if flow aids are needed, and if so, what kind, to facilitate ease of handling (Fathollahi et al., 2020). It has been found that moisture content, particle size, and chemical composition have a significant impact on the flow properties of flour due to interaction forces existing between different molecules and particles (Siliveru et al., 2017). The variations in flour composition exert different effects on the flour's flow characteristics.

To date, the flow properties of pulses have not been extensively studied due to their minimal presence in modern industries. In most places where pulses are produced, they are processed in pulse grain-specific facilities that are not suitable for the current economy, which encourages multipurpose equipment (Donke et al., 2017; Schneider, 2002). However, with research, equipment can be adjusted to run pulses as well. Handu et al. (2022) studied three varieties of chickpea flour, one of which was commercial, and found that the chickpea flour was in the hardened (poor flowing) category on the powder flowability classification. This means that adjustments should be made to equipment for the chickpea flour to flow better.

Based on the limited research available on the flowability properties of pulse flours, this study was conducted to determine the flow functionality of lentil, yellow pea, and chickpea flours and to understand the effect of flour particle size on their flowability. The results from this study could serve the scientific community and related industry to adapt pulse flours to current facilities and/or design processing and handling equipment to better handle pulse flours.

2. Materials and methods

2.1. Pulse grain materials

Lentils and Kabuli chickpea grains were purchased from Amazon online store (Food to live store). Yellow pea grains were purchased from Amazon online store (D'allesandro gourmet ingredients store). All the grains were kept at room temperature until they were used. All-purpose wheat flour was purchased from a local store.

2.2. Milling pulse grains

Lentil, chickpea, and yellow pea were milled using a laboratory scale Ross roller mill (Model 915, Ross Machine and Mill Supply, Oklahoma City, OK, USA) following the procedure developed by Pulivarthi et al. (2021). A few modifications were made to the procedure to accommodate chickpea milling. The grains were tempered overnight to a moisture content of 13%. The rolls gap opening and sieve arrangement were adjusted to produce flours of different particle sizes. For all the grains, bottom sieve of 75, 150, and 200 μm was used to produce small (S), medium (M), and large (L)-sized flours, respectively. Fig. S1 shows details of the small-sized chickpea milling flow sheet. For other flours, the same milling flowsheet was followed with some minor adjustment as listed in Table S1. The flour yield was measured by dividing the weight of flour obtained by the original weight of the grains.

2.3. Flour characterization

Particle size and particle distribution analysis was performed using the QICPIC particle analyzer (Sympatec GmbH System-partikel-technik, Clausthal-Zellerfeld, Germany) equipped with an RODOS/L dispenser. The M3(1–341 μm) camera lens was used. A 5 g sample of flour was placed on the feeder, and the feeding rate was set to 35%. The flour sample was purged with dry compressed air at a pressure of 3 bar. X_{10}, X_{50}, X_{90}, and volumetric mean diameter (VMD) were recorded.

2.4. Scanning electron microscopy

The morphology of the flour was determined using a Hitachi scanning electron microscope (SEM, S-3500N, Hitachi Scientific Instruments, Mountain view, CA, US). A 10 kV power was used at × 100 and × 500 magnification. The flours were sprinkled on carbon tape and coated with platinum using a sputtering technique before capturing images.

2.5. Proximate composition and starch damage

Ash, protein, moisture, and crude fat content were determined following the AACC method 08-01.01, 46-30.01, 44-17.01, and 30-10.01 (AACC International, 1961; AACC Approved Methods of Analysis, 1961; AACC Approved Methods of Analysis, 1999; AACC Approved Methods of Analysis, 2003), respectively. The total carbohydrate content was calculated using equation (1) below:

$$Total\ carbohydrates\ (\%) = 100 - (Ash + crude\ fat + Moisture + Protein) \tag{1}$$

All the proximate composition data are reported in dry basis.

Flour starch damage was measured using an SDmatic TM equipment (Chopin Technologies, Villeneuve la Garenne, France) following the AACC 76–33.01 method (AACC Approved Methods of Analysis, 2007). In short, 1.5 g of citric acid powder, 3 g of potassium iodide powder, and one drop of 0.1N sodium thiosulphate solution were mixed with 120 ml of distilled water in the SDmatic glass reaction vessel. Then, 1 g of flour sample was added to the sample holder and the test was initiated. The SDmatic automatically measured the starch damage in the flour sample.

2.6. Bulk properties

A Hosokawa Powder tester PT-R (Hokosawa Micron B.V., Japan) was used to measure the aerated bulk density (ρ_b), tap density (ρ_t), and angle of repose (AoR) of the flours. The powder tester was equipped with a steel cylindrical container with a 750 μm screen at the bottom and a large-mouthed funnel below. 110 g of flour was placed into the equipment container and vibrated at an amplitude of 1 mm for 30 s. The mass of the remaining flour was measured to calculate bulk density. The tap density was measured by tapping the extended container 180 times, and the mass of the flour remaining in the original container was used to measure the tap density (Barretto et al., 2023). Carr's compressibility index (CCI) and Hausner's ratio (HR) were measured using equations (2) and (3) respectively.

$$\text{Carr's compressibility index (CCI) } (\%) = \left(\frac{(\rho_t - \rho_b)}{\rho_t}\right) \times 100 \tag{2}$$

$$Hausner's\ ratio\ (HR) = \frac{\rho_t}{\rho_b} \tag{3}$$

The angle of repose was measured by mounting a small glass funnel and a stainless-steel table to the powder tester. First, 110 g of the flour was placed in the container and vibrated at an amplitude of 1 mm for 30 s. Then, the flour was allowed to flow on the stainless-steel table until it formed a dune. The built-in laser calculated the dimensions of the flour dune and computed the angle of repose (Berton et al., 2002).

True density of the flour was measured using a helium gas pycnometer AccuPync II 1340 (Micromeritics, Norcross, Georgia). In this method, the flour was placed in a chamber and helium gas was passed through it to fill the pores and empty spaces. The ratio of weight of the flour and the volume occupied indicated the true density.

2.7. Dynamic flow test (stability, aeration, and variable flow rate)

The flow properties of the pulse flours were measured using an FT4 Powder Rheometer (Freeman Technologies, Tewkesbury, Gloucestershire, UK). The FT4 powder rheometer consists of a vertical glass container and a rotating blade, and it measures the force required to cause the powder to flow as imposed by the moving blade (Bian et al., 2015). Dynamic, shear, and bulk flow tests can be conducted with this equipment. The dynamic flow test measures the energy required to move the blade through the flour vertically from the top, while the shear flow test analyzes the behavior of the flour under different handling and storing conditions. The bulk flow test measures the changes in volume when a series of increasing stress is applied to the flour sample (Karde et al., 2015).

The parameters measured in the dynamic flow test were flow rate index (FRI), basic flow energy (BFE), and stability index (SI). The stability index (Eq. (4)) is the measure of stability of a powder and measures the changes due to the flow of flour. A 25 mm × 10 ml split cylinder was used with a 23.5 mm blade for the dynamic flow test on the FT4 Powder Rheometer. The sample was filled in the glass cylinder and conditioned using the blade followed by a test cycle at a blade tip speed of 100 mm/s. The resistance on the blade from the top to bottom represents the flow energy. To measure the SI, seven consecutive tests (test 1 to 7) were performed at the same speed of 100 mm/s. SI which shows how the flour particle arrangement changes due to flow was measured according to equation (4). After test 7, four additional test runs (test 8 to 11) were performed with the blade speed reducing gradually from 100 to 10 mm/s, and to measure the flow rate index (equation (5)). Tests 8, 9, 10, and 11 were measured at a speed of 100, 70, 40 and 10 mm/s respectively. The changes between test 8 and 11 indicated the flour flow properties changes in relation to reducing blade speed (Freeman, 2007).

$$Stability\ index\ (SI) = \frac{Total\ energy\ consumed\ at\ test\ 7}{Total\ energy\ consumed\ at\ test\ 1} \tag{4}$$

$$Flow\ rate\ index\ (FRI) = \frac{Flow\ energy\ at\ test\ 11}{Flow\ energyat\ test\ 8} \tag{5}$$

Aeration was measured by introducing airflow from the base of the vessel filled with flour. The flow energy was measured by varying air velocity. The following equation (6) was used to calculate the aeration ratio (AeR) (Divya and Ganesh, 2019; Handu et al., 2022; Jan et al., 2016).

$$Aeration\ ratio\ (AeR) = \frac{E_r}{E_o} \times 100 \tag{6}$$

AeR- Aeration ratio, E_r- Residual flow energy during full aeration (air velocity 10 mm/s), E_o- Flow energy during fixed bed conditions (air velocity 0 mm/s).

2.8. Bulk flow tests (permeability and compressibility)

This test was performed using a vented piston and a 25 mm × 10 ml split cylindrical glass vessel attachment with the FT4 Powder Rheometer. The flour was placed in the glass vessel and compressed with pressure ranging from 1 to 15 kPa. The conditioned bulk density (CBD) of the sample was recorded by the powder rheometer before starting the test, and the powder rheometer was also used to measure the density after compression; those two parameters were used to equate the compressibility index (CI) (Chikosha et al., 2014). Poorly flowing flour had higher compressibility index. The CI was measured using the following equation (7).

$$Compressibility\ index\ (CI)\ (\%) = \frac{Density\ after\ compression}{CBD} \times 100 \tag{7}$$

Permeability quantifies a flour's ability to allow fluids to pass through it. The airflow resistance was measured by the powder rheometer as air was blown into the powder at a speed of 2 mm/s for the permeability test (Barretto et al., 2021; Karde et al., 2015).

Flow tests were conducted at room temperature and pressure, while the moisture content was monitored to minimize its effect on the flow tests by ensuring that the pulse flours moisture content was practically similar for impartial comparison.

2.9. Data analysis

All the measurements were conducted in triplicates. The experimental data were analyzed using the Statistical Analysis Software (SAS Studio). The mean differences were determined by analysis of variance, and Tukey-Kramer grouping was used with a significance level of $p < 0.05$.

4. Results and discussion

4.1. Pulse and wheat flours physical properties

The milling process produced pulse flours with yields ranging from 80.0 to 86.9% (Table S1). Lentil had a lower flour yield due to its smaller size compared to chickpea and yellow pea, as well as other genetic and physical properties, which is consistent with the observations made by Pulivarthi et al. (2021).

Looking at the particle size distribution, the milling process successfully produced pulse flours of different particle size as intended (Table 1). The X_{10} suggests the largest particle in the ten percentage (10%) of the total flour volume. For all the pulse flours, the small sized flours had smaller particles compared to large-sized ones. A similar trend was also observed for the 50 (X_{50}) and 90 (X_{90}) percentiles of the flour. Medium-sized pulse flours had a particle size distribution similar to that of wheat flour. The volumetric mean diameter (VMD) also indicated a significant difference in particle size between the three flours for each pulse. Statistically, small-sized pulse flours had the lowest VMD, while large-sized lentil flour had the highest VMD among the pulse flours. Furthermore, the medium-sized lentil and yellow pea flours and large-sized chickpea flour showed VMD comparable to wheat flour. Overall, the data from flour characterization indicate that the method of producing medium-sized pulse flours yields flours with particle sizes similar to commercial wheat flour.

Fig. 1 shows scanning electron microscopy (SEM) images of medium-sized pulse flours and wheat flour. The SEM images revealed a higher degree of particle agglomeration in chickpea flours compared to lentil, yellow pea, and wheat flour. Additionally, SEM images in Fig. S2 demonstrate that flours of different particle sizes exhibit distinct

Table 1
Particle size analysis of pulse flours and wheat flour.

Flour type	X_{10} (μm)	X_{50} (μm)	X_{90} (μm)	VMD (μm)
Wheat	21.77 ± 1.97^{abc}	88.64 ± 2.63^{c}	169.86 ± 11.49^{bc}	93.71 ± 0.37^{d}
S Lentil	15.16 ± 0.11^{cd}	65.24 ± 2.40^{d}	142.34 ± 13.93^{bc}	73.6 ± 4.15^{e}
M Lentil	24.81 ± 1.02^{ab}	122.31 ± 5.33^{b}	178.76 ± 1.53^{bc}	109.6 ± 2.72^{c}
L Lentil	29.73 ± 0.98^{a}	147.68 ± 1.92^{a}	245.89 ± 13.07^{a}	145.87 ± 4.29^{a}
S Yellow pea	15.47 ± 1.90^{cd}	65.08 ± 4.29^{d}	127.02 ± 0.11^{c}	70.00 ± 1.99^{e}
M Yellow pea	19.70 ± 0.42^{bcd}	93.32 ± 0.06^{c}	179.90 ± 9.80^{bc}	95.90 ± 0.99^{d}
L Yellow pea	24.71 ± 5.31^{ab}	121.67 ± 8.93^{b}	248.11 ± 32.22^{a}	127.77 ± 5.29^{b}
S Chickpea	12.76 ± 1.17^{d}	67.06 ± 9.23^{d}	130.06 ± 12.66^{c}	69.0 ± 0.53^{e}
M Chickpea	14.04 ± 0.76^{cd}	67.93 ± 2.79^{d}	162.09 ± 1.33^{bc}	79.7 ± 0.76^{e}
L Chickpea	18.21 ± 1.03^{bcd}	100.61 ± 4.84^{c}	190.14 ± 3.78^{b}	102.69 ± 3.44^{cd}

Means with different superscript letters within each column denote significant differences ($p < 0.05$).

S- Small, M-Medium, L-Large.

X_{10}-largest particle in 10% of the sample, X_{50}-largest particle in 50% of the sample, X_{90}-largest particle in 90% of the sample.

VMD- Volumetric Mean Diameter.

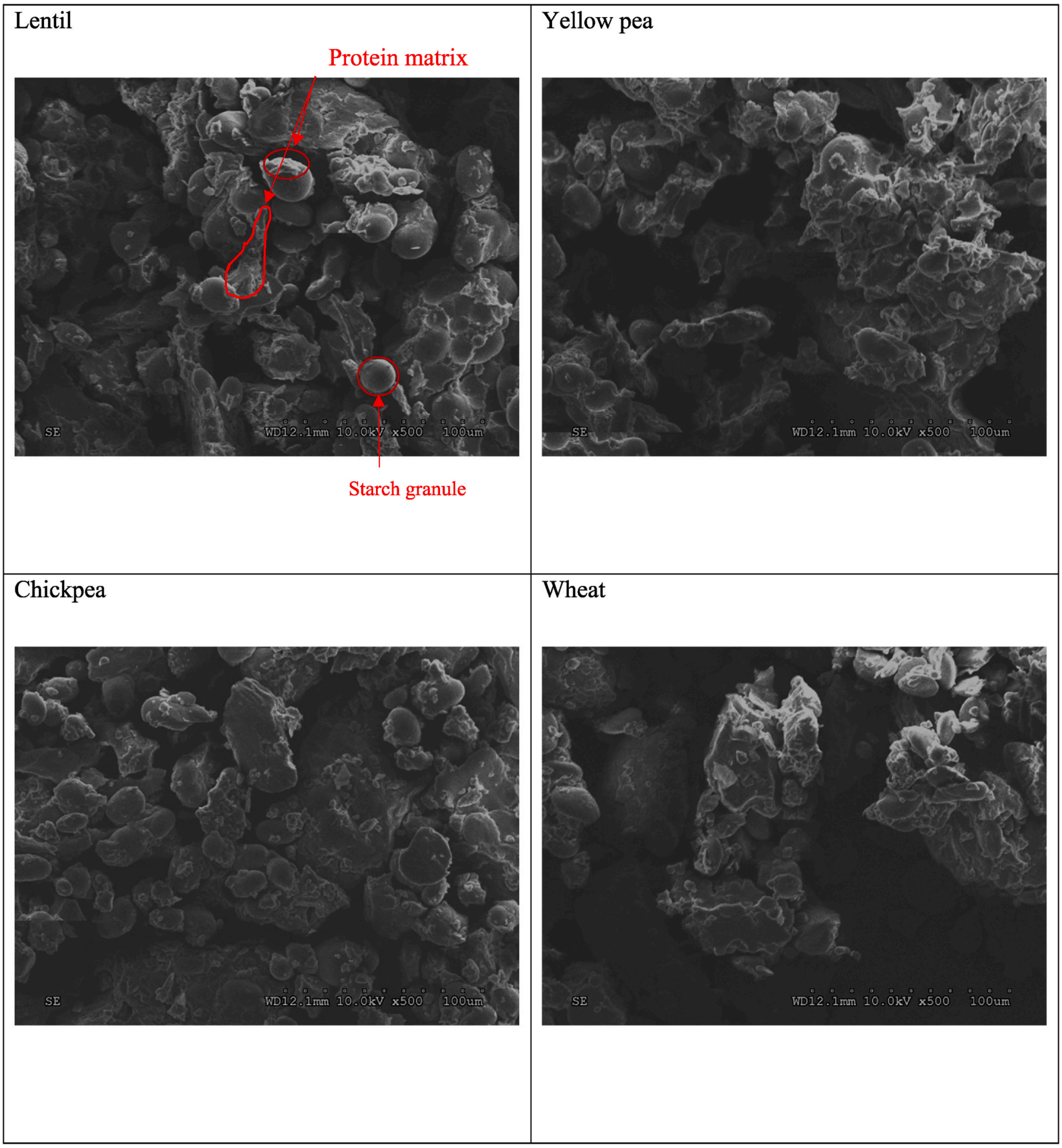

Fig. 1. Scanning electron microscopy of medium-sized pulses flours and wheat flour.

morphologies. The particles from large-sized flours were bulky compared to particles of small-sized flours, and this was due to fewer processing steps involved in producing large-sized flours. When looking at the different size flours of the same grain, chickpea flour particles displayed minimal differences in morphology compared to lentil and yellow pea. Chickpea flours were all agglomerated and relatively very similar while lentil and yellow pea flours showed significant morphological changes across different sized flours. This observation is in accordance with particle size analysis results reported above, where the particle size difference in chickpea flour was less pronounced compared to lentil and yellow pea flours.

The moisture content of the pulse flours was around 10%, which is suitable for this study as moisture content significantly affects the flowability properties of flour (Siliveru et al., 2017). The wheat flour moisture content was 13.56%, which is typical for commercial wheat flour (Table S2). The ash content was higher in chickpea flour than in yellow pea and lentil flours. When comparing the protein content among the flours, lentil's protein content was higher (~25%), while the protein content of other pulses was between 20 and 22%. Chickpea flours had a higher crude fat content (>7.74%) than wheat (1.64%), lentil (~1.90%), and yellow pea (~2.10%). Studies have shown that crude fat content tends to significantly affect the flow properties of powder (Leturia et al., 2014).

The total carbohydrate showed some differences (Table S2). The proximate composition obtained in this study was in accordance with those reported by the USDA database (USDA, 2019) for pulses. Chickpea and yellow pea flours had the highest total carbohydrate content (65%) among the pulses, while the total carbohydrate content for all lentil flours was around 61%. The total carbohydrate content of wheat flour was around 75%. The lower content of total carbohydrate and high fiber content make pulses a low glycemic index food source (Singh et al., 2021).

The starch damage of pulse flours increased as the flour particle size reduced (Fig. S2). Generally, small-sized yellow pea flours showed higher starch damage while large-sized chickpea flour showed the minimal starch damage among the tested flours. The increased starch damaged observed when the flour particle size reduced was due to numerous flour runs through the pair of rolls.

4.2. Bulk properties of pulse and wheat flours

Each grain type showed an increase in bulk density as particle size increased (Table 2). The large-sized lentil flour had the highest bulk density (596.0 kg/m^3), while all chickpea flours had very low bulk density (<370 kg/m^3). This was due to the presence of more air gaps between the particles in chickpea flour. The bulk density of lentil flours ranged from 455 to 596 kg/m^3, which was comparable to the bulk density of wheat flour (563.2 kg/m^3). The current data indicates that more volume is required to store or transport yellow pea and chickpea flour than wheat or lentil flours (Nawaz et al., 2015).

The tap density values indicated that lentil and yellow pea flours had higher densities (712–776 kg/m^3) compared to chickpea flour, which had smaller tap density (582–620 kg/m^3). This suggests that chickpea flour particles were cohesive enough to resist the release of air gaps during tapping. Moreover, the Carr's compressibility index values for chickpea flour were significantly higher (40.15–45.15%) than those for lentil and yellow pea flours (23.00–38.00%), indicating that chickpea flour particles were more compressible after tapping due to the presence of more air pockets. This is consistent with the aeration ratio values presented in Table 3, which show that chickpea flours had higher aeration ratios compared to other pulse flours, indicating increased compressibility.

The true density data generally indicate the density of the particles excluding air space. Among the flours tested (Table 2), chickpea flours showed significantly lower true density. This means that, chickpea materials are less dense due to their higher content of crude fat. The true density findings depict that apart from chickpea flours, yellow pea and lentil flours had almost similar true density ($p > 0.05$) initially, but different milling process caused different bulk densities.

In addition to particle size, the higher fat content in chickpea flour could be another factor that caused greater compressibility. A study conducted by Bian et al. (2015) reported on the flow properties of soft and hard wheat flour, showing that soft wheat flour had more compressibility than hard wheat flour. Although, soft wheat flour had a similar particle size to hard wheat flour, it contained a significantly higher fat content (1.21%) compared to the hard wheat flour (0.39%). These study findings support the idea that fat content is an important factor for the observed compressibility differences. The medium and large-sized lentil flours showed similar bulk, tapped density, and Carr's compressibility index properties comparable to wheat flour. Large-sized lentil flour was less compressible among the pulse flours since it showed a lower compressibility index (23%).

Hausner's ratio (HR) is another important parameter used to predict the flow of powder materials. Lower HR values indicate excellent flowing powders. Medium and large-sized lentil flour showed lower HR values than other pulse flours, indicating that they are better flowing powders compared to smaller-sized lentil flours, yellow pea, and chickpea flours. Chickpea flour had the highest HR values (Table 2). Among the flours used in this study, wheat flour had the lowest HR value, indicating that it is the best flowing flour. The combination of HR and Carr's compressibility index is often used to predict powder flowability. According to Carr's (1965) classification of powders, wheat flour and medium and large-sized lentil flours are classified as passable, large-sized yellow pea flour is poor flowing, while small-sized lentil and medium-sized yellow pea are classified as very poor flowing. All the chickpea flour and small yellow pea flour are non-flowing. The findings from this study suggest that special practices should be considered when incorporating pulse flours in modern industries.

The angle of repose (AoR) is another parameter used to predict the flow of powder materials. Wheat flour, large-sized lentil flour, and medium-sized chickpea flour were classified as very cohesive flours based on their AoR values (Table 2), while all other pulse flours were classified as non-flowing flours. The wheat, large lentil, and medium chickpea flours had AoR values of 58.75°, 62.95°, and 63.15° respectively, indicating that they are very poor flowing powders according to Carr's classification. The AoR data showed higher variation compared to Carr's compressibility and Hausner's ratio, which was caused by the crumbling of the flour dune structure.

In a recent study conducted on three chickpea varieties by Handu et al. (2022), the angle of repose for all flours were ranging from 41 to 44°, indicating that those whole chickpea flours were easily flowing powders. The observed angle of repose values indicate that the flours used in that study are better flowing than any flour used in this study regarding the angle repose. However, this could be due to the physical nature of the flour used since they used a hammer mill to grind the chickpeas, producing coarse flours and wider particle size distribution than the refined pulse flours from a roller mill used in this study. Large particle-sized flours are often associated with better flowing properties (Jan et al., 2018), suggesting that larger particles of chickpea flour could improve its flow properties.

4.3. Dynamic flow properties

Dynamic flow data are listed in Table 3. Basic flowability energy (BFE) represents the energy required to initiate powder movement. Lower BFE values indicate powders that require less energy to initiate flow. In the current study, smaller-sized lentils and yellow peas flours had significantly lower BFE compared to larger-sized flour, indicating that they require less energy to initiate the movement (Figs. S3–S5). Based on this parameter, they are more easily flowing than large-sized

Table 2
Bulk and bulk flow properties of pulse flours and wheat flour.

Flour type	Bulk density (kg/m^3)	Tapped density (kg/m^3)	True density (kg/m^3)	Carr's compressibility index (%)	Hausner's ratio	Angle of repose (°)
Wheat	563.2 ± 2.76^{b}	723.0 ± 4.24^{bcd}	1462.4 ± 1.86^{a}	22.17 ± 0.12^{g}	1.28 ± 0.01^{h}	58.75 ± 0.75^{d}
S Lentil	455.5 ± 0.71^{e}	712.5 ± 2.12^{d}	1456.1 ± 0.86^{bc}	35.05 ± 1.20^{cd}	1.56 ± 0.01^{d}	67.35 ± 0.92^{bc}
M Lentil	565 ± 1.41^{b}	765.5 ± 2.12^{a}	1452.4 ± 0.32^{c}	24.10 ± 2.55^{f}	1.35 ± 0.01^{f}	71.10 ± 4.38^{ab}
L Lentil	596 ± 1.41^{a}	776.5 ± 4.95^{a}	1453.9 ± 0.06^{bc}	23.00 ± 0.28^{f}	1.30 ± 0.01^{g}	62.95 ± 1.48^{c}
S Yellow Pea	445 ± 1.41^{e}	715.0 ± 7.07^{cd}	1455.1 ± 2.18^{abc}	38.05 ± 0.07^{bc}	1.61 ± 0.01^{d}	77.50 ± 1.13^{a}
M Yellow Pea	497.0 ± 0.00^{d}	729.5 ± 0.71^{bc}	1458.4 ± 1.25^{ab}	31.30 ± 0.71^{de}	1.47 ± 0.00^{e}	71.25 ± 1.20^{ab}
L Yellow Pea	513.0 ± 1.41^{c}	736.0 ± 7.07^{b}	1452.8 ± 1.72^{c}	30.50 ± 0.71^{e}	1.43 ± 0.01^{e}	76.80 ± 2.26^{a}
S Chickpea	315.0 ± 7.07^{h}	582.5 ± 4.95^{f}	1428.5 ± 3.59^{e}	45.15 ± 0.35^{a}	1.85 ± 0.03^{a}	66.00 ± 0.99^{bc}
M Chickpea	370.5 ± 0.71^{f}	619.5 ± 0.71^{e}	1437.5 ± 0.25^{d}	40.15 ± 0.07^{b}	1.67 ± 0.01^{c}	63.15 ± 1.48^{c}
L Chickpea	348.0 ± 2.83^{g}	598.5 ± 2.12^{f}	1431.6 ± 0.52^{e}	41.50 ± 0.71^{ab}	1.72 ± 0.01^{b}	68.00 ± 1.56^{bc}

Means with different superscript letters within each column denote significant differences ($p < 0.05$).
S- Small, M-Medium, L-Large.
Carr's index classification: Excellent (<10); Good (11–15); Fair (16–20); Passable (21–25); Poor (26–31); Very poor (32–37); Non-flowing (>38).
Hausner's ratio classification: Excellent (1.00–1.11); Good (1.12–1.18); Fair (1.19–1.25); Passable (1.26–1.34); Poor (1.35–1.45); Very poor (1.46–1.59); Non-flowing (>1.60).

Table 3
Dynamic flow properties of pulse flours and wheat flour.

Flour type	Basic flowing energy (mJ)	Stability index	Flow rate index	Aeration ratio	Aerated energy at 10 mm/s (mJ)
Wheat	711.31 ± 5.91^{b}	1.04 ± 0.02^{a}	0.99 ± 0.04^{bc}	2.74 ± 0.14^{c}	12.45 ± 2.14^{h}
S Lentil	402.52 ± 3.90^{c}	1.02 ± 0.01^{bc}	1.71 ± 0.02^{a}	8.39 ± 0.79^{bc}	34.97 ± 1.50^{ef}
M Lentil	730.22 ± 28.57^{b}	0.97 ± 0.02^{cd}	0.93 ± 0.02^{e}	3.98 ± 0.17^{c}	16.29 ± 2.36^{g}
L Lentil	953.01 ± 31.98^{a}	0.90 ± 0.00^{d}	0.97 ± 0.01^{e}	2.01 ± 0.37^{c}	36.66 ± 1.82^{e}
S Yellow pea	531.52 ± 27.36^{c}	1.02 ± 0.03^{bc}	1.66 ± 0.01^{a}	11.06 ± 0.14^{b}	33.51 ± 0.95^{f}
M Yellow pea	715.42 ± 36.73^{b}	1.01 ± 0.01^{bc}	1.20 ± 0.01^{c}	14.51 ± 2.01^{b}	63.14 ± 14.54^{d}
L Yellow pea	790.92 ± 43.36^{b}	1.02 ± 0.02^{bc}	1.05 ± 0.01^{d}	12.13 ± 1.53^{b}	99.48 ± 2.54^{c}
S Chickpea	802.97 ± 29.82^{ab}	1.16 ± 0.01^{a}	1.30 ± 0.00^{b}	28.62 ± 1.41^{a}	254.32 ± 20.25^{a}
M Chickpea	790.24 ± 10.01^{b}	1.01 ± 0.04^{bc}	1.26 ± 0.04^{bc}	25.47 ± 3.29^{a}	170.18 ± 25.08^{b}
L Chickpea	763.93 ± 90.39^{b}	1.05 ± 0.01^{b}	1.28 ± 0.01^{b}	22.75 ± 2.15^{a}	250.53 ± 41.83^{a}

Means with different superscript letters within each column denote significant differences ($p < 0.05$).
S- Small, M-Medium, L-Large.

flours. The BFE values of chickpea flours were higher and not significantly different across different particle sizes, possibly due to their cohesive nature. The particle size of flour is responsible for the observed trend in yellow pea and lentil flours, while in chickpea flours, it is believed that the fat content increased the resistance to flow, requiring more energy to initiate movement. The small-sized lentil flour shows a much better flowability (402.52 mJ) than other tested flours, while the large-sized lentil flour had the worst flowability (953.01 mJ). It is believed that the high surface area in small-sized flours is responsible for lower BFE observed, as the blade moves more particles in a single move in small-sized flours than in large-sized flours. Barretto et al. (2021) also observed lower BFE for fine flour than large-sized teff flour. When comparing pulses to wheat flour, the wheat flow energy is similar to that of medium-sized yellow pea and lentil flours (Fig. 2).

After test 7, the tip speed was reduced, which increased the flow energy required for all the chickpea and yellow pea flour types along with the small-sized lentil flour. The increase of flow energy after test 7 usualy indicates cohesive flours (Freeman, 2007). This implies that wheat, medium, and large-sized lentil flours showed non-cohesive behavior compared to the chickpea flours.

The stability index (SI) represents the ability of the flour to maintain its flow during transport. According to Table 3, wheat, medium, and large-sized lentil flours had a lower SI (<1), indicating lower stability during flow. In contrast, yellow pea, chickpea, and large-sized lentil flours had a SI higher than 1, indicating better flow stability. For yellow pea flours, the differences in particle size did not affect the SI. However, lentils and chickpeas showed a decrease in stability index as their particle size increased. Chickpea flours generally exhibited higher stability than other grains used in this study, possibly due to their higher fat content, which increased cohesiveness and stability. Overall, all the flours tested in this study were found to be very stable during flow.

The flow rate index (FRI) is another important parameter to identify the flowability of the flour. It shows the flow energy required for a powder to flow as the tip speed of the blade is reduced. Lower FRI values indicate powders that require less energy to flow and are therefore more easily flowing. Cohesive powders tend to have higher FRI values as they are more responsive to changes in speed. Among the flour tested, wheat flour, medium and large-sized lentil flours had values below 1 which indicates they are good flowing flours compared to yellow pea and chickpea flours (Table 3). The FRI value for small-sized lentil and yellow pea flours are significantly higher, indicating that they are cohesive flours with poor flowability.

The aeration ratio is a measure of how well a flour allows fluids to pass through. Cohesive flours typically have a high aeration ratio. In this study, lentil flours exhibited non-cohesive behaviors (AeR < 9), while chickpea flour was more cohesive (AeR > 22) (Table 3). There was no significant variation in aeration ratio between flours of different particle sizes of the same pulse grain. Comparing the pulse flours to the wheat flour used in this study, only lentil flours showed similar aeration properties to wheat flour, and both lentil and wheat flours exhibited non-cohesive behavior, which is desired in a production plant. The aeration ratio data was consistent with the amount of energy required for maximum aeration (10 mm/s). Wheat flour required less energy (12.45 mJ), while cohesive flour like chickpea required 250 mJ at the same air velocity. This data confirms that chickpea flour is cohesive while lentil flour is non-cohesive, and this is attributed to the higher fat

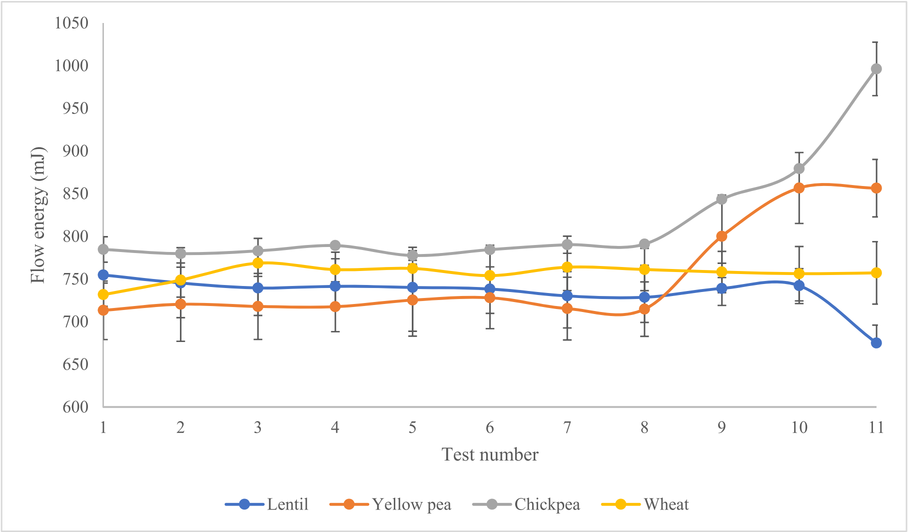

Fig. 2. Flow energy of medium-sized pulse and wheat flours.

content in chickpea flour, which increased the cohesiveness. Fig. 3 illustrates that chickpea flour required more flow energy at higher speeds than medium-sized lentil and yellow pea flours, providing further evidence that chickpea flour is cohesive. Non-cohesive powders generally consume less flow energy at high air velocities (Freeman, 2007). Differences in particle size among flours of the same pulse grain did not significantly affect the results of the aeration tests (Figs. S6–S8).

4.4. Bulk flow properties

During the permeability test, a constant airflow is passed through the flour and the pressure drop across the powder bed is measured. A greater pressure drop indicates a less permeable powder. In this study, the medium-sized yellow pea flour consistently showed a larger pressure drop compared to the other medium-sized pulse flours and wheat flour, suggesting a lower permeability of the former (Fig. 4). The small-sized flours were significantly less permeable than medium and large-sized flours for both yellow pea and lentil. All the chickpea flours showed no significant difference in permeability among different particle sizes (Figs. S9–S11). The permeability test also revealed that the medium-sized lentil and yellow pea flours were practically as permeable as the wheat flour used in this study.

The compressibility test is used to measure how resistant a flour is to compression, with higher values indicating high compressibility. This parameter is greatly influenced by the porosity of the flour, where flours having more air gaps tend to be more compressible (Freeman, 2007). In this study, chickpea flours have showed to be more compressible (Fig. 5), which can be explained by their higher aeration ratio (>22) and crude fat content (>6%). These factors contributed significantly to the higher compressibility of chickpea flour compared to the other pulse flours and wheat flour used in this study (Fig. 5).

Interestingly, among different particle-sized flours of the same grain, small-sized lentil and yellow pea flours were found to be more compressible than medium and large-sized flours (Figs. S12–S14). The bulk density of wheat flour used in this study was 563.2 kg/m^3, which is comparable to medium-sized lentil and yellow pea flours. Additionally, the compressibility of medium-sized lentil flour was found to be very comparable to the control wheat flour. As observed with other parameters, chickpea flours were not significantly different in compressibility among different particle sizes, and medium-sized lentil flour was very comparable to the control wheat flour.

5. Conclusion

In conclusion, this study highlights the flow properties of various particle-sized pulse flours and compares them to wheat flour. Chickpea flour was found to be highly cohesive and non-flowing, with high compressibility, which could pose challenges for transportation and storage. On the other hand, medium and large-sized lentil flours showed better flow properties that are comparable to wheat flour. The study suggests that the high fat content in chickpea flour may have contributed to its poor flowability. It is recommended to conduct further research on flow aids or adjustments that could enhance the flowability of pulse flours. Additionally, comparing pulse flours' flowability to other major grain flours, instead of pharmaceutical and industrial powders, would provide more relevant results. The study also emphasizes the need to investigate the pulse flours flowability properties when they are aided by other compounds. More research is needed on flour treatment, such as defatting feasibility, as flour composition significantly affects flow properties. Overall, these findings could have implications for the pulse flour industry and the development of innovative processing methods.

CRediT authorship statement

Eric Nkurikiye: Conceptualization, Investigation, Methodology, Data curation, Writing -Original Draft, writing -review and editing. Manoj Kumar Pulivarthi: Conceptualization, Investigation, Methodology, writing -review and editing. Annika Bhatt: Investigation, Writing -review and editing. Kaliramesh Siliveru: Conceptualization, Methodology, Writing -review and editing, Supervision. Yonghui Li: Conceptualization, Methodology, Writing -review and editing, Supervision, Project administration, Funding acquisition.

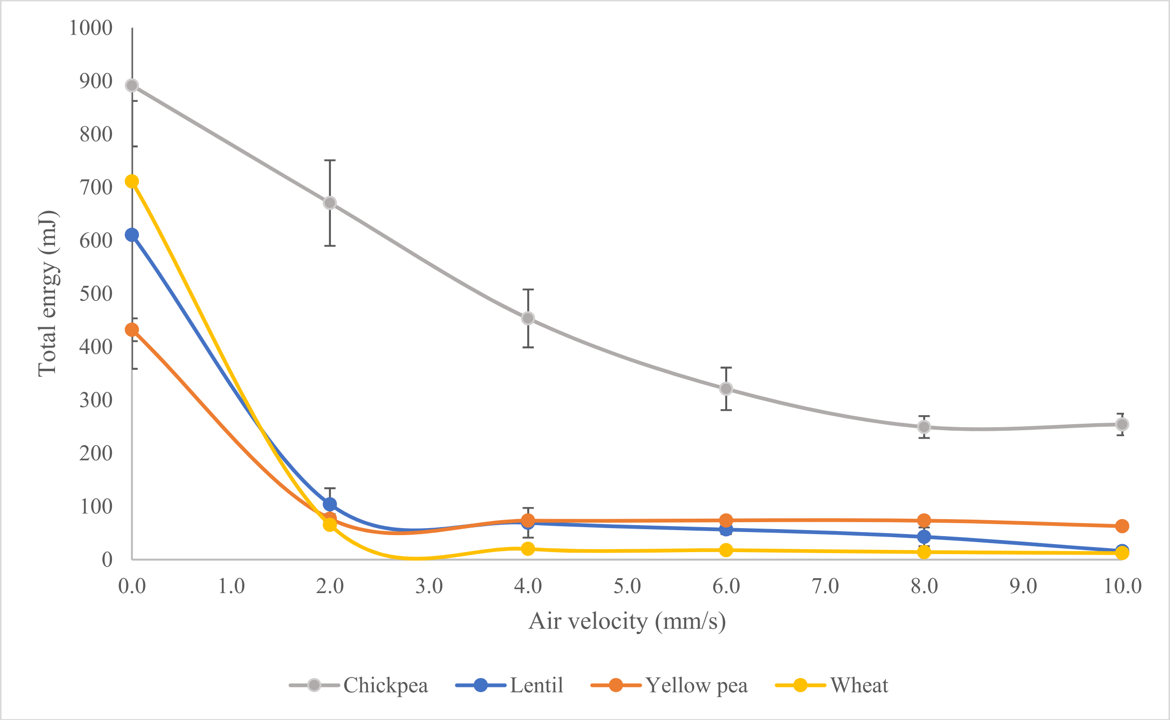

Fig. 3. Aeration energy at different air speed for medium-sized pulse flours and wheat flour.

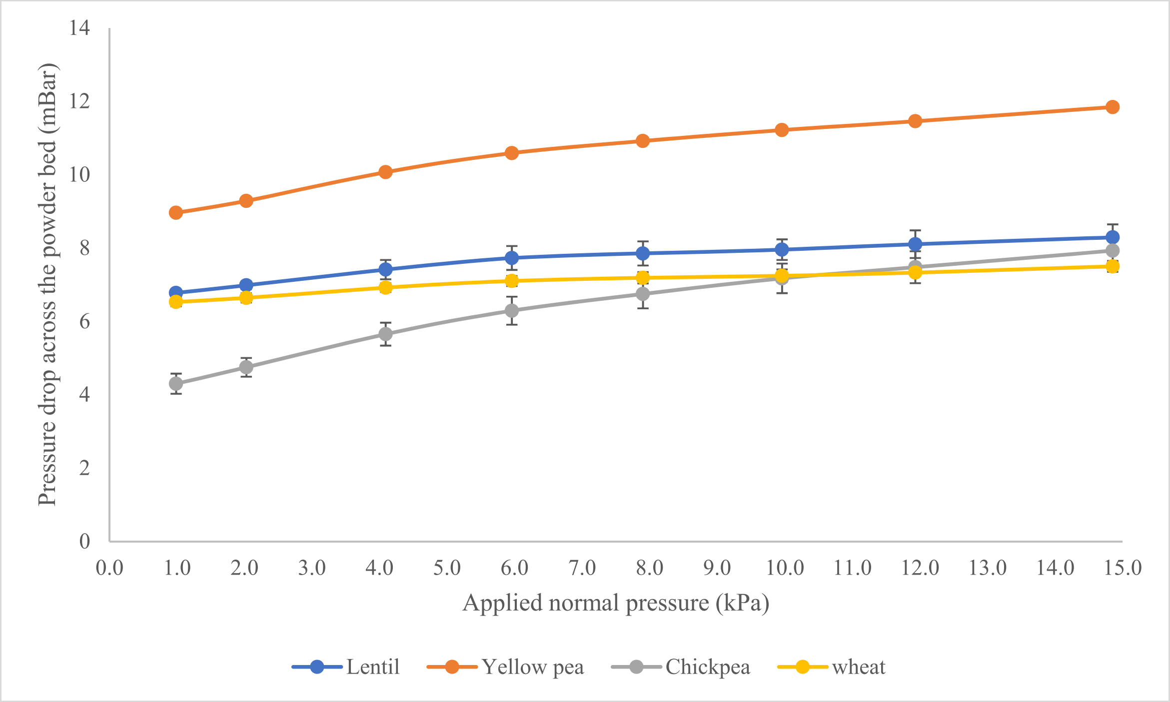

Fig. 4. Pressure drop across the powder bed as the pressure increases for medium-sized pulse flours and wheat flour.

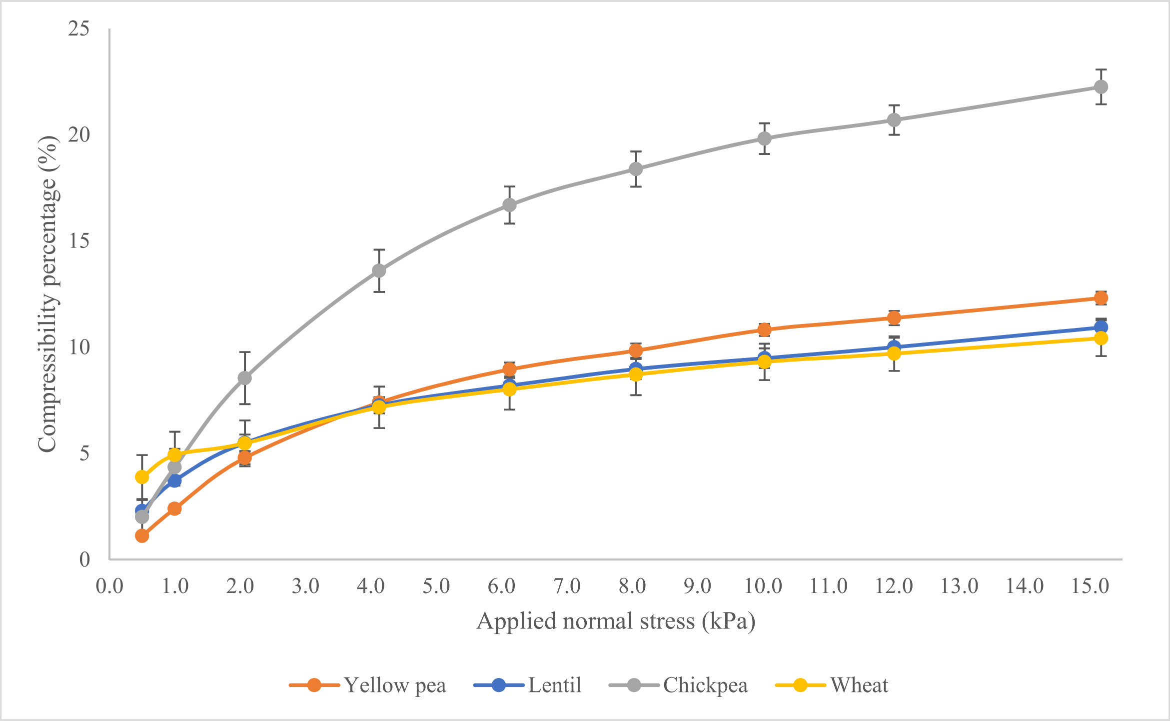

Fig. 5. Compressibility of medium-sized pulse flours and wheat flour.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jfoodeng.2023.111647.

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