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Mechanical attributes of Swedish pea cultivars

Santanu Basu [a,*], Stina Gustafsson [a], Puneet Kumar [b], Subir Kumar Chakraborty [b], Roger Andersson [a]

[a] Department of Molecular Sciences, Swedish University of Agricultural Sciences, Box 7015, SE-750 07 Uppsala, Sweden
[b] ICAR-Central Institute of Agricultural Engineering, Bhopal, 462038, India

A R T I C L E I N F O

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A B S T R A C T

Mechanical or textural attributes of pulses like Swedish pea are important for milling process development like dehulling, splitting of cotyledons or making flour. This research is an attempt to gain better understanding of the compression and fracture behavior, cotyledon splitting and dehulling phenomena of Swedish pea cultivars (Ingrid, Clara and Balder) harvested from different years (2018, 2019 and 2020) in relation to chemical compositional profile and physical attributes. Physical attributes of Swedish pea were highly associated with specific cultivar types and environmental growth conditions. Majority of the chemical components (starch, dietary fibers) in pea samples were not significantly different between the cultivars or harvest years. Only protein content (16.9–19.6 % range) differed significantly between the cultivars and harvest years. Environmental conditions of the harvest year or cultivar types could not cast any significant difference in fracture or dehulling related parameters. Cotyledon splitting phenomena were significantly linked to different size and shape related parameters and starch content (47.6–50.0 % range). This study applies fracture mechanics principles to classify Swedish pea cultivars in terms of different mechanical attributes. Our work will help plant breeders to find scientific insight for gene targeting for future crop development with better milling efficiency and pulse milling industry to adopt pea cultivar specific dehulling and milling process development.

1. Introduction

Knowledge about mechanical properties of plant seeds in relation to processing is important for efficient dehulling and milling process design. Plant seeds like pulses need three major milling operations: dehulling, splitting and milling. Dehulling means removal of the seed-coat from the cotyledon to produce whole polished seed. Splitting means cleaving the dicotyledonous pulse seed into two splits. Milling refers to fracturing and subsequent breaking of a whole seed or seed cotyledons into milled flours (Wood and Malcolmson, 2021). Milling behaviors of the pulse seeds vary usually with the different chemical compositional profiles (Gupta and Das, 2000; Wood et al., 2014a, 2014b, 2014c; Singh et al., 2017) or physical attributes (Bhattacharya et al., 2005; Oomah et al., 2010). Developing efficient milling operations (dehulling, splitting or milling into flours) are important for the pulse milling industry. Milling performance is linked to topography of the cotyledon and adjoining seed coat surfaces and polysaccharide composition in these regions for pulses (Wood et al., 2017, 2021). Compression and fracture behavior of any biological material like seed is also dependent on the orientation of the seed or direction of force application (Meyers et al., 2008; Noraphaiphipaksa et al., 2016; Singh et al., 2017).

Peas are important in Swedish cuisine and have been historically native crops in Sweden since Neolithic times. Different cultivars of Swedish pea are grown for food and animal feed purposes. There is growing interest in the Nordic region in selecting and developing pea cultivars with better compositional profiles (especially higher protein content), early maturity and cold tolerance (Leino et al., 2013). This is largely driven by the emerging plant protein industry, which aims to utilize peas not just as food or feed, but as a source of high-value protein, starch, and fiber fractions for a variety of industrial and nutritional applications. However, little scientific knowledge exists on the effect of genotype, environmental factors, and postharvest storage period, on the physical profile (seed shape, size and weight distribution) and chemical composition (starch, dietary fiber, and protein profile) of Swedish peas as well as their mechanical attributes (Leino et al., 2013; Carlson-Nilsson et al., 2021). Mapping the mechanical attributes like forces or work required for dehulling, splitting of cotyledon or fracture of Swedish pea cultivars in relation to the physical profile and chemical compositions

* Corresponding author.
E-mail address: santanu.basu@slu.se (S. Basu).

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(starch, protein, and fiber profile) will help us to develop better dehulling and milling processes.

Although there are research works regarding the compression and fracture behaviors of various seeds, compression and fracture behavior of pea has not been studied comprehensively (Lysiak, 2007 and Pelgrom et al., 2013). Understanding mechanical attributes of pea is important because of growing interest in using pea seeds for a biorefinery process to extract suitable ingredients for food industry. The knowledge about the dehulling, compression and fracture behaviors of Swedish pea in relation to chemical compositional profile, shape, size, and weight has not yet been scientifically explored. The present study aimed to examine the effect of harvest year on the dehulling, splitting, compression and fracture attributes of three different Swedish pea cultivars (Ingrid, Clara and Balder).

2. Materials and methods

2.1. Materials

Swedish pea (Pisum sativum L.) varieties (Ingrid, Clara, Balder) belonging to harvest season 2018, 2019 and 2020 were used for the study. All pea varieties were commercial cultivars in Sweden; no genetic modification or selection manipulation was involved in choosing the pea cultivars. Pea varieties were harvested from a farm located near Lund in south of Sweden, and dried to 14 % moisture content, then stored in paper bags under farmhouse storage by Lantmännen, Sweden until the present study.

All chemicals used were from Sigma-Aldrich unless otherwise specified.

2.2. Physical properties

Seed samples were visually inspected and those with visible cracks or deformation were not used for mass, length, width, and thickness measurements. The mass was measured for 100 intact seeds by a digital balance (Model AB-204S, Mettler Toledo AB, Sweden) with a sensitivity of 0.1 mg and average value is reported. Length (L), width (W) and thickness (T) were measured randomly for 100 seeds with a digital vernier caliper (Cocraft, China) with an accuracy of 0.03 mm. Different size and shape related parameters like sphericity, volume, arithmetic and geometric mean diameter were also calculated as explained in Table 1.

Bulk density of the peas was measured according to Singh and Goswami (1996). A 500 mL beaker of known weight was filled with peas at a constant rate from approximately 15 cm height. The contents were then weighed, and the bulk density was calculated from the mass of seeds in relation to the volume of the container. True density was measured according to (Karababa 2006) with some modifications. A 100 mL graduated measuring cylinder was filled with 50 mL of distilled water and 25 g of pea was added. The change in volume was noted and the seed density was calculated as the ratio of the weight of the seeds and the volume change. Experiments were done in triplicate and mean values are reported. Moreover, the porosity which is the void space between the seeds were calculated in percentage from the bulk density and true density values.

2.3. Chemical composition

All pea seeds were pre-milled in a Tecator machine (Cemotec, Sweden) to decrease the particle size and further milled in a laboratory cylone mill (Retsch, Germany) to pass through 0.5 mm sieve. These milled samples were used for compositional analysis. Total dietary fiber was measured according to the Uppsala method (Theander et al., 1995). Crude protein content was determined by the Kjeldahl method, according to the Nordic Committee on Food Analysis (1976), using a 2520 digestor, Kjeltec 8400 analyser unit and 8460 sampler unit (all from

Table 1
Physical and mechanical parameters used for principal component analysis (PCA) with their abbreviations and description.

Term with unit	Abbreviation in the text	Description or formula
Length, mm	L	Length was the largest measured dimension of the seed
Width, mm	W	Width was the largest dimension normal to the direction of the length measurement
Thickness, mm	T	Thickness was the largest dimension normal to the direction of the length and width measurements
Arithmetic mean diameter, mm	AMD	$\mathrm{AMD}=\frac{L+W+T}{3}$
Geometric mean diameter, mm	GMD	$\mathrm{GMD}=(\mathrm{L}\cdot\mathrm{W}\cdot\mathrm{T})^{1/3}$
Surface area, mm^2	–	$\text{Surface area}=\frac{\pi.GMD.L^2}{(2.L-GMD)}$
Sphericity, unitless	–	$\text{Sphericity}=\frac{GMD}{L}$
Volume, mm^3	–	$\text{Volume}=\frac{\pi.\ (GMD^2).L^2}{6.(2.L-GMD)}$
Shape factor, unitless	–	$\text{Shape factor}=\frac{Volume}{Surface\ area}$
Bulk density, g/cm^3	–	Bulk density is a ratio of mass of the seeds to bulk volume, including airspace between the seeds.
True density, g/cm^3	–	True density is a ratio of mass of the seed to true volume of the seeds, without air space between the seeds
Porosity (%), unitless		$\text{Porosity}=\left(1-\frac{Bulk\ density}{True\ density}\right).100$
100 seed wt, g	100seedwt	Weight of 100 unbroken seeds
Fracture force, N	FracF	Maximum force required to initiate the fracture of the seed, measured with the Shimadzu autograph AGS-X when longitudinal axis of the seed was normal to the direction of loading
Fracture strain, %	FracStrain	Strain value at the fracture force, measured with the Shimadzu autograph AGS-X (Japan)
Time to fracture, s	FracTime	Time required to reach the fracture force value
Deformation before fracture, mm	DeformFrac	Distance traversed to reach the fracture force value
Essential work of fracture, N mm	EWFrac	Essential work of fracture is the amount of work needed to create a unit area of a crack or new surface in a seed. It is measured by calculating the area under the force-displacement curve from the pea compression experiment till the force reaches the fracture force value.
Dissipation work of fracture, N mm	DWFrac	Dissipation work of fracture is a measure of nonessential work required for fracture in the plastic deformation zone (behind the fracture process zone). It is measured by calculating the area under the second part of the force –displacement curve as shown in Annexure Fig. 2.
Slope of fracture force versus strain curve at 1 % strain, N	F-StrSL1	It is calculated by measuring the slope from the force-strain graph at 1 % strain value.
Slope of fracture force versus strain curve at 3 % strain, N	F-StrSL2	It is calculated by measuring the slope from the force-strain graph at 3 % strain value.
Slope of fracture force versus strain curve at 5 % strain, N	F-StrSL3	It is calculated by measuring the slope from the force-strain graph at 5 % strain value.
Cotyledon splitting force, N	CotySplitF	Force required to split the cotyledon into two parts (peak value), measured with the cotyledon splitting probe with texture analyzer
Time to split the cotyledon, s	CotySplitTime	Time required to split the cotyledon into two parts, obtained from texture

(continued on next page)

Table 1 (*continued*)

Term with unit	Abrreviation in the text	Description or formula
		analyzer data when cotyledon splitting force is maximum
Essential work for cotyledon splitting, N mm	EWCotySplit	It is measured by calculating the area under the force-displacement curve till the force reaches the cotyledon splitting force value.
Dissipation work for cotyledon splitting, N mm	DWCotySplit	It is measured by calculating the area under the second part of the force –displacement curve from the cotyledon splitting experiment as shown in Annexure Fig. 2.
Dehulling force, N	DehulF	Force required to remove the hull (peak value), measured with the dehulling probe with texture analyzer
Time to dehull, s	DehulTime	Time required to dehull the seed, obtained from texture analyzer data when force is maximum
Essential work for dehulling, N.mm	EWDehul	It is measured by calculating the area under the force-displacement curve till the force reaches the dehulling force value.
Dissipation work for dehulling, N.mm	DWDehul	It is measured by calculating the area under the second part of the force –displacement curve from the dehulling experiment as shown in Annexure Fig. 2.

Foss, Denmark). Protein content was estimated from nitrogen content (N x 6.25). The starch content in the milled flour samples from pea seeds was determined by selective hydrolysis with thermostable α-amylase and amyloglucosidase (Åman et al., 1994) and measuring the amount of glucose released using D-Glucose assay (GOPOD: glucose oxidase/peroxidase) kit of Megazyme (Bray, Ireland).

2.4. Textural properties

Three different forces (fracture force, cotyledon splitting force and dehulling force) were measured for the individual pea seed samples (Fig. 1). All measurements were performed at room temperature (22±2 °C).

2.4.1. Fracture force measurement

Compression and fracture behavior of pea seeds were studied with Shimadzu Autograph AGX-S (Japan) with TRAPEZIUM X data processing software. 10 KN load cells were used and crosshead speed 0.05 mm/s was used for all uniaxial compression and fracture experiments. Pea samples were placed in horizontal direction (longitudinal axis of the seed or kernel normal to the direction of loading) and a double-sided tape was used to fix the pea position on the platform. From the force-deformation raw data, we calculated fracture strain, time to fracture and the slopes at different strain values (1, 3 and 5 %). Several other fracture related parameters were also calculated from the force-time data (Table 1 and Fig. A1) to understand the compression and fracture phenomena in Swedish pea. One important point considered during compression and fracture study was that the pea microstructure was undergoing continuous changes. However, when a pea was sufficiently crushed to the point that initial porosity is nearly exhausted by progressive deformation, the stress started rising steeply indicating the beginning of densification regime due to complete compression of the seeds. Essential work of fracture (EWFrac) and dissipation work of fracture (DWFrac) was calculated from the area under the force-deformation curve up to that deformation or strain (Fig. A1). Total work of fracture is sum of essential work of fracture and dissipation work of fracture (Pardoen et al., 2002). Minimum five whole pea seeds of each cultivar were taken from each sample group and their mean values were utilized for actual data analysis.

2.4.2. Cotyledon splitting and dehulling force measurement

A texture analyzer (TA-XT Plus, Stable Micro Systems, Surrey, United Kingdom) attachment was developed in the Research Workshop at ICAR-Central Institute of Agricultural Engineering, Bhopal, India specifically for the purpose of measuring the cotyledon splitting force and dehulling force of a pea seed. The detail description of the dehulling probe, sample holder and frame attachment is described in the Kumar et al. (2022) paper and the diagram of the setup is presented in the Annexure (Fig. A2). The probe and holder setup (illustrated in Fig. A2) enabled controlled dehulling without disturbing cotyledon alignment. During the experimentation, the sample holder was fastened at the fixed platform while the dehulling probe was attached to the texture analyzer. The dehulling probe was operated in compression mode with pre-test, test and post-test speed of 2 mm/s, 1 mm/s and 10 mm/s, respectively. Five whole pea seeds were taken from each sample group for experiments and their mean values were calculated.

Cotyledon splitting force (CotySplitF): The hull from five pea seeds were removed manually without disturbing the gummy layer at the cleavage. The pearled (hull removed) grains were placed in the sample holder one at a time with their plane of cleavage aligned in vertical orientation and parallel to movement of probe (Kumar et al., 2022). The horizontally movable sample holder plate was adjusted so that probe should exert force only on one cotyledon and without touching the plane of cleavage. The cotyledon separation force (CotySplitF) and time to split the cotyledon (TimeSplit) were obtained from the force-time data for further analysis.

Dehulling force (DehulF): The dehulling force was measured by placing five whole pea seeds, one grain at a time in the sample holder. The grain was aligned in such a way that axis of hilum was vertical and parallel to direction of applied force (Kumar et al. (2022). Dehulling probe, attached on the texture analyzer would move vertically downward at a fixed speed (0.01 mm/s). Sample holder was positioned in such a way that dehulling probe would only remove the hull without disrupting the cotyledons. The dehulling force (DehulF) and time to dehull (TimeDehul) values were obtained through texture analyzer data output as a mean of the five measurements.

2.5. Statistical analysis

Statistical analysis was performed using Minitab version 19.2. General linear model procedure for analysis of variance (ANOVA) was performed using the seed cultivars and year of harvest as factors. Tukey's comparison test was used to distinguish significant differences between group means, with significance level set at 95 % confidence level. No interaction effect between cultivar and harvest year was estimated since only one sample of each cultivar was collected each year. Multivariate analysis of the data was done to understand the association between physical properties, chemical composition with mechanical attributes of the Swedish pea samples. Principal component analysis (PCA) score and loadings plots were used to visualize relationships between variables using the software SIMCA 17 (Sartorius Stedim Data Analytics AB, Sweden).

3. Results and discussion

3.1. Physical attributes

The average weight and size of the pea seeds varied significantly ($P < 0.05$) depending on the cultivar (Table 2). 100 seed weight ranged from 20.88 to 28.79 g, with Clara being the lightest and Ingrid being the heaviest. The average weight of the seeds from the harvest year 2018 was significantly lower compared to peas cultivated and harvested in the year 2019 and 2020. Further, the average length varied from 7.17 mm (Clara) to 8.07 mm (Ingrid). Ingrid had significantly higher length, width and thickness compared to Clara and Balder ($P < 0.05$). Clara had the lowest mean values for length, width and thickness (and volume),

Table 2
Physical parameters associated with Swedish pea seeds, like 100 grain weight (HGW), length (L), width (W), thickness (T), volume (V), sphericity (Sp), bulk density, true density and porosity.

Parameters	Cultivar			Year		
	Ingrid	Clara	Balder	2018	2019	2020
Hundred grain weight, g	28.79 ±4.61^{a}	20.88 ±4.10^{c}	23.69 ±4.56^{b}	22.35 ±5.09^{b}	25.52 ±6.03^{a}	25.48 ±4.7^{a}
Length, mm	8.07 ±0.54^{a}	7.17 ±0.50^{c}	7.36 ±0.48^{b}	7.28 ±0.62^{b}	7.61 ±0.59^{ab}	7.71 ±0.61^{a}
Width, mm	7.07 ±0.59^{a}	6.52 ±0.45^{b}	6.87 ±0.45^{c}	6.62 ±0.50^{b}	6.88 ±0.56^{a}	6.95 ±0.54^{a}
Thickness, mm	6.12 ±0.44^{b}	5.95 ±0.51^{c}	6.3 ± 0.47^{a}	5.95 ±0.49^{b}	6.18 ±0.46^{a}	6.25 ±0.48^{a}
Volume, mm^3	187 ±29^{a}	148 ±28^{b}	170 ±29^{a}	153 ±29^{b}	171 ±31^{a}	179 ±33^{a}
Sphericity	0.87 ±0.04^{c}	0.91 ±0.03^{b}	0.93 ±0.03^{a}	0.91 ±0.04^{a}	0.90 ±0.04^{a}	0.90 ±0.04^{a}
Bulk density, g/cm^3	0.90 ±0.01^{a}	0.89 ±0.01^{ab}	0.88 ±0.01^{b}	0.88 ±0.01^{b}	0.89 ±0.01^{a}	0.89 ±0.01^{a}
True density, g/cm^3	1.39 ±0.04^{a}	1.46 ±0.01^{a}	1.39 ±0.02^{a}	1.41 ±0.06^{a}	1.42 ±0.04^{a}	1.41 ±0.04^{a}
Porosity	35.6 ± 1.2^{b}	39.4 ± 1.0^{a}	36.6 ± 1.1^{ab}	37.8 ± 2.6^{a}	37.1 ± 1.7^{a}	36.8 ± 2.2^{a}

*Values are expressed as means by variety and means by year of cultivation (interactions were not evaluated). Values in the same row with different letters represent a significant difference ($P < 0.05$), although, by variety only and year only.

compared to the other cultivars. A significant difference in shape was found between Ingrid, Balder and Clara, where Balder was the roundest, followed by Clara, while Ingrid was the least round cultivar. There was also a significant ($P < 0.05$) difference between the size of the different peas from 2018 compared to the peas from 2019 to 2020. Majority of the measured parameters for seeds from 2018 was found to be consistently smaller apart from the shape related parameters like sphericity. It is important to mention here that in the year 2018; Sweden had an extremely warm and dry crop growing season (SMHI, 2021). Difference in seed physical attributes (size, shape, volume, weight, etc.) varied significantly between the pea cultivars. The difference in seed size and weight of pea samples comes from various environmental (temperature, drought, fertilizer amount, etc.) and genetic factors of different Swedish pea cultivars (Leino et al., 2013; Carlson-Nilsson et al., 2021; Gustafsson, 2022).

Bulk density of pea seeds ranged from 0.86 to 0.90 g/cm^3. Analysis of variance showed that Balder has a significantly lower bulk density compared to Ingrid, while no statistically significant difference could be detected for Clara ($P < 0.05$). True density ranged from 1.39 to 1.46 g/cm^3, with Ingrid and Balder showing the same true density, while Clara showed a higher value. Although, there was no significant difference. Porosity ranged from 35.6 (Ingrid) to 39.4 % (Clara). Interestingly, Swedish pea samples behaved like a hard sphere with random close packing and have very close packing density values to the theoretical values obtained for random sphere packing (Wu et al., 2003). When analyzing the parameters by year, there was no statistically significant difference for true density or porosity. However, the ANOVA showed that the bulk density of samples from 2018 was significantly lower compared to 2019 and 2020 ($P < 0.05$).

In Fig. 2, biplot originating from the PCA is shown for physical attributes of seeds. Bulk density, true density and porosity data was not included in the PCA as the other parameters (sphericity, thickness, width, volume and length) were measured for 100 seeds, and each point in the PCA plot represented one seed. Loadings (sphericity, thickness, width, volume and length) are combined with the scores of each individual pea, coloured by cultivar. A total of 79.6 % of the variance were contributed to the first and second principal component (PC), where PC1 and PC2 explained 53.3 % and 26.3 % of the variance respectively. Length, width, volume and weight seem to be the parameters influencing PC1 and were closely related to each other, whereas sphericity and thickness appears to be influencing PC2 the most. Further, there seems to be no correlation between sphericity and volume. Sphericity appeared to be the least linked with the other dimensional parameters like length, width and thickness. There was a positive correlation between seed width and volume.

3.2. Chemical composition

Detail compositional profiles (starch, protein, total dietary fiber content and detail dietary fiber profile) of the pea cultivars for different years are presented in Table 3. Clara and Ingrid had significantly different starch content. There was no significant differences found in the starch content among the pea cultivars over the years. The starch content varied from 47.7 % for Ingrid to 50.0 % for Clara (dry matter basis). When looking at the average of starch expressed as means by year, the range was smaller, 48.5–48.9 % of dry matter, for 2020 and 2018 respectively.

The total dietary fiber content of the Swedish pea varieties ranged from 12.1–13.2 % of dry matter. The total dietary fiber content for pea cultivar Clara was slightly lower compared to the values reported by Ferawati et al. (2019). However, the study conducted was for Clara harvested in the year 2016, and many environmental factors may be responsible for the difference. The main dietary fiber components in all the pea samples were, in the following descending order, glucose, arabinose, xylose and uronic acid residues. Only trace amounts of Klason lignin was found, indicating that it is probably present in the hulls in small amounts. Clara had a significantly lower percentage of arabinose residues compared to Ingrid and Balder, otherwise there were no significant differences found in the sugar residues, uronic acid and Klason lignin in the dietary fiber profile of the different pea varieties (Table 3). The content of galactose residues was significantly lower in 2018 compared to 2020, 0.58 and 0.65 % of dry matter, respectively.

Protein content of the pea samples varied significantly between the cultivars, Ingrid had highest protein content and Clara had the lowest protein amount. The total protein content was significantly lower for all pea cultivars for the year 2018 compared to 2019 and 2020. This may be related to environmental factors like drought for the year 2018. For the starch and dietary fiber content, there was not any statistically significant variation for the pea cultivars between the years. Apart from starch, protein and dietary fibres, remaining components in the Swedish pea samples are moisture, fat and galactoligosaccharides (not determined). Moisture and fat did not differ much in different harvest years (data not shown). However, environmental conditions like draught not only disturb plant physiology but also affect nutritional profile and seed morphological characteristics at a varied level.

Pea seeds are mechanically considered as neither a fully brittle or plastic material. From the overall composition, we can say that pea seeds are complex composite material, composed of different crystalline, semi-crystalline and non-crystalline amorphous components. The major component starch is present in a semi-crystalline form in the pea seed, while cell wall polysaccharides present in pea are broadly of four types, cellulose, hemi-cellulose, pectin and lignin. These components will have a very different hierarchical assembled arrangements due to different ways of organization of different cell wall polysaccharides, with starch and proteins in the pea seeds. Cellulose the main cell wall component in pea, are made up of β-D-glucose units, having extensive H-bonded network to pack the cellulose molecules into linear bundles and create regions of crystalline structure. However, hemicelluloses (mainly xyloglucans) are heteropolymers, made up of different sugar molecules, and do not form any crystalline regions. Similarly, protein bodies also do not contribute to crystallinity. Pectin, a heteropolysaccharide, is abundant in the middle lamella as well as in the primary cell wall of pea, helps in

Table 3
Starch, protein and total dietary fiber (TDF, as sum of sugar residues and Klason lignin) content in whole pea presented in % of dm (values expressed as means by variety as well as means by year of cultivation).

	Starch	Protein	TDF	Rha	Ara	Xyl	Man	Gal	Glc	UA	KL
Cutivar											
Ingrid	47.6 ± 0.5^{b}	19.6 ± 1.0^{a}	12.1 ± 0.3^{a}	0.21^{a}	3.39^{a}	1.19^{a}	0.31^{a}	0.61^{a}	5.85^{a}	1.00^{a}	0.18^{a}
Clara	50.0 ± 1.4^{a}	16.9 ± 0.8^{c}	12.2 ± 0.8^{a}	0.22^{a}	2.93^{b}	1.23^{a}	0.29^{a}	0.63^{a}	6.25^{a}	1.01^{a}	0.13^{a}
Balder	48.5 ± 0.9^{ab}	18.8 ± 1.8^{b}	13.2 ± 0.3^{a}	0.18^{a}	3.46^{a}	1.25^{a}	0.28^{a}	0.59^{a}	6.19^{a}	0.99^{a}	0.22^{a}
Year											
2018	48.8 ± 0.8^{a}	17.9 ± 2.5^{b}	12.8 ± 0.7^{a}	0.22^{a}	3.25^{a}	1.21^{a}	0.29^{a}	0.58^{b}	6.09^{a}	0.97^{a}	0.16^{a}
2019	48.9 ± 2.1^{a}	18.7 ± 1.7^{a}	12.4 ± 0.5^{a}	0.20^{a}	3.23^{a}	1.19^{a}	0.29^{a}	0.59^{ab}	6.06^{a}	0.99^{a}	0.21^{a}
2020	48.4 ± 1.4^{a}	18.7 ± 0.9^{a}	12.3 ± 1.0^{a}	0.19^{a}	3.32^{a}	1.27^{a}	0.29^{a}	0.65^{a}	6.14^{a}	1.03^{a}	0.16^{a}

*Standard deviation values are only shown for starch, protein and total dietary fibers. Values in the same column followed by different letters are significantly different at $P < 0.05$.
**Analysis of fructan was not performed for these samples.
Abbreviation used, Rha: Rhamnose, Ara: Arabinose, Xyl: xylose, Man: Manose, Gal: galactose, Glc: Glucose, UA: Uronic acid, KL: Klason lignin.

cell adhesion and separation. Lignin, which is present in a very small amount in the peas, also acts like a glue between the cell wall polysaccharides, and do not contribute to crystallinity. Lastly, water, fat and air will be also present in a pea seed and distributed in the bio-composite material like pea seed.

3.3. Textural attributes

3.3.1. Compression and fracture phenomena

The mechanical attributes of a seed largely depend on the geometrical properties, chemical compositional profile and the hierarchical structuring of protein, fiber, starch, lipid, moisture and other molecules present in different morphological forms. The representative compression and fracture behavior of a pea seed in the horizontal position as well as different calculated parameters from single pea compression data are shown in the Fig. 1 and A1. After an initial very small unstable zone, when the probe touches the pea seed and the sample realigns, the compressive force increased in a linear manner for all pea seeds with deformation till they are ruptured. The increasing rise of force value with time/deformation in the first part of the curve represented stiffness of the pea seeds. Maximum force is the fracture force where the seeds undergoes first rupture and further it leads to propagation of multiple cracks leading to breakage of the seeds into pieces. There is a sudden drop in the values of forces with few rising peaks with further

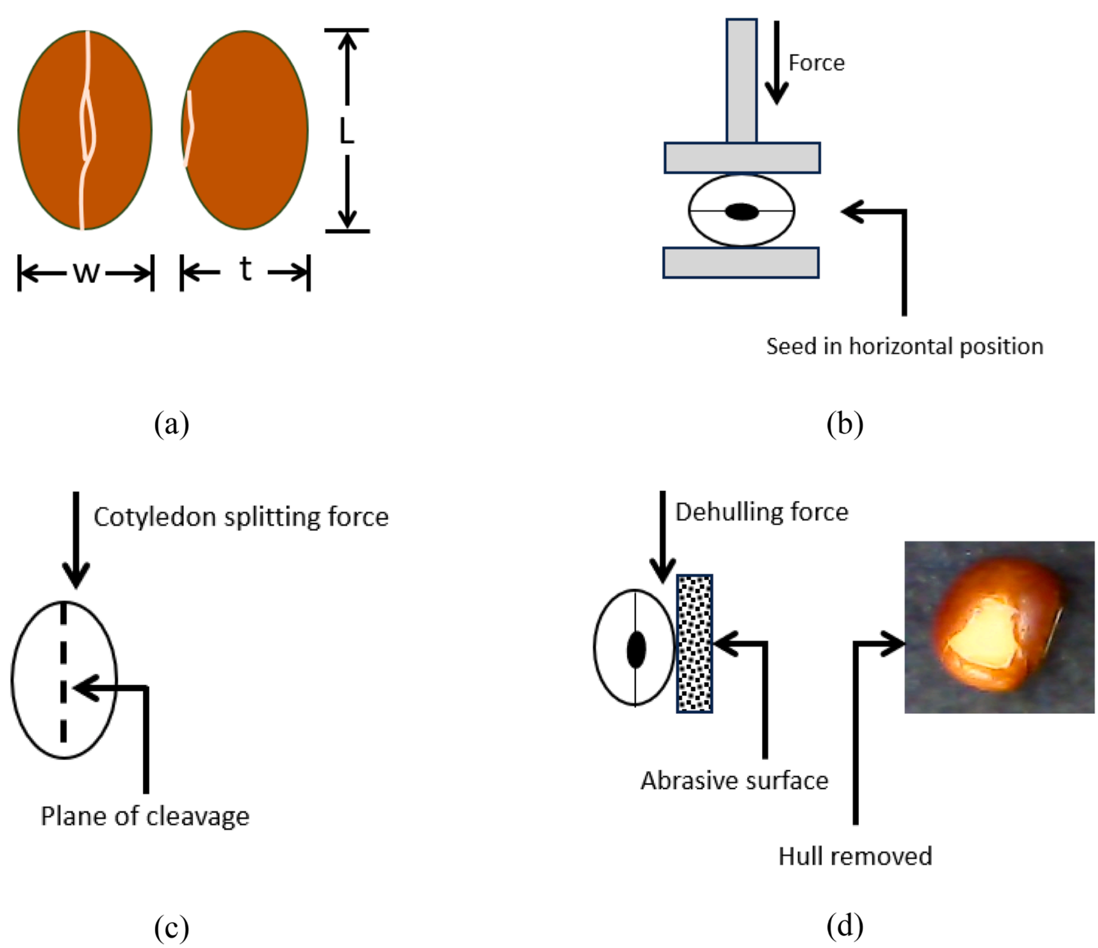
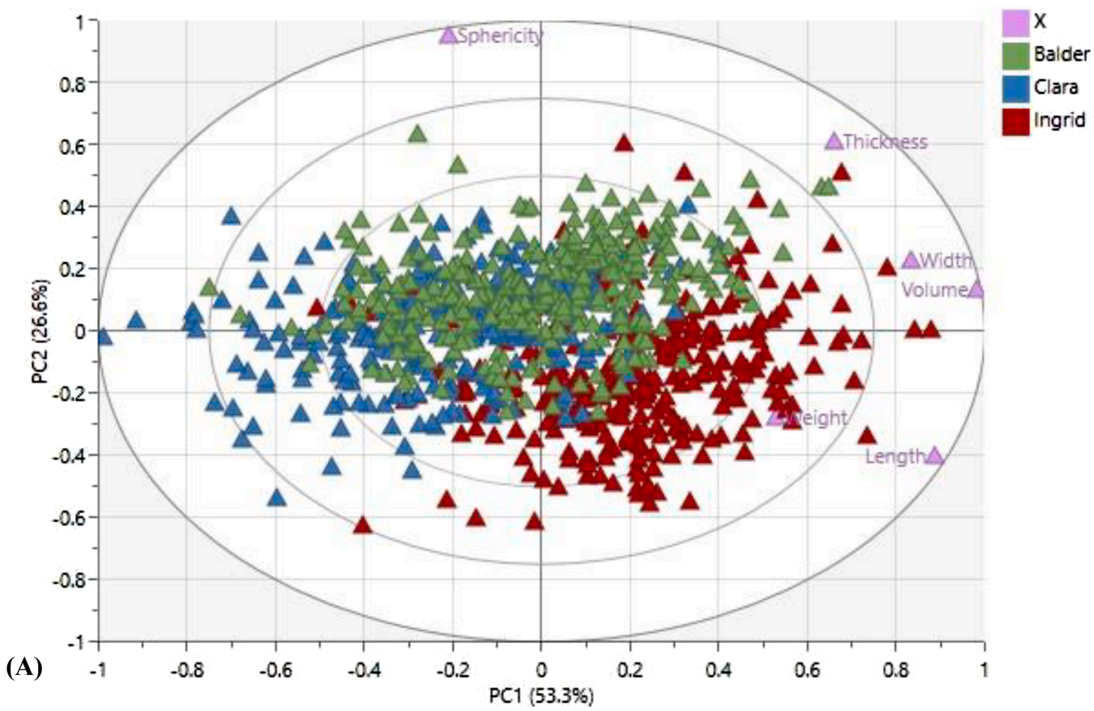


Fig. 1. Details of the grain while quantification of different mechanical attributes (a) Dimensional details of the grain (b) Compression and fracture (c) Cotyledon splitting (d) Hull removal.



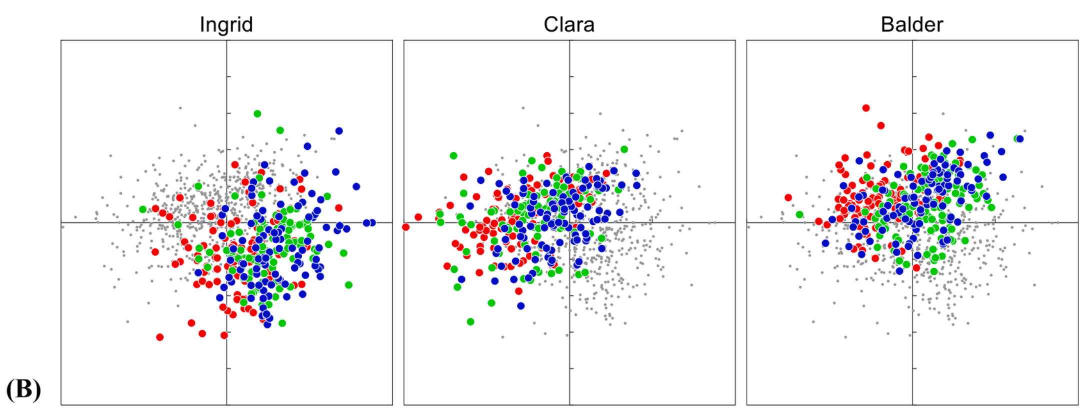


Fig. 2. A) Biplot, containing loadings (X), in pink (triangles) with labels of each variable, as well as scores of each pea, colored by variety. A total of 79.9 % of the variance was covered by the first PC (along the x-axis) and second PC (along the y-axis), depicted in the plot. B) Cultivar specific year wise distribution pattern of pea seeds (2018-red, 2019-green, 2020-blue) and grey dots represent rest of the seeds.

progression of deformation. The microscopic mechanism of fracture propagation in biological material like pea is due to cell wall collapse and buckling of the cell walls (Meyers, 2008). With further deformation, the cellular microstructure is crushed and stress starts rising steeply again indicating the starting of the densification regime (change in porosity) which means complete compression of cell wall (Vural and Ramachandran, 2004). One important point to note here that biological material like pea seeds are anisotropic (Meyers, 2008) thus, their compression-fracture phenomena also depends on the direction of force application or orientation of the pea seed undergoing compression. In this study, compression and fracture data were obtained in the axial direction only. The mechanical properties observed likely reflect the morphological structure—such as the seedcoat, hilum, and cotyledon—as well as the underlying chemical composition. (Wood et al., 2014 a, 2014b, 2014c). Understanding anisotropy in food has become important with the rising interest in the product specific structure and texture creation (Oppen et al., 2022; Van Vliet et al., 2011). However, fundamental studies of microstructural evolution of seed during compression and role of anisotropy in seed crack propagation are rather limited (Hasseldine et al., 2017, 2019). Exploring dehulling and seed crushing behavior in relation to anisotropic properties will help in pulse milling equipment design in future.

The different mechanical attributes of the Swedish pea seeds are reported in Table 4. It is important to note here that compression and fracture related parameters were measured with Shimadzu autograph and cotyledon splitting and dehulling parameters were measured with texture analyzer. There was wide variation in the measured mechanical attributes within the same pea seed samples. We found no significant effect of year of harvest or cultivar in the compression or fracture related attributes (fracture force, time to fracture, deformation to fracture, etc.). All pea samples fractured between 0.35 and 0.49 mm deformation distance of the seeds while undergoing uniaxial compression. The fracture strain values for Swedish pea samples varied between 5.02 and 7.32 % and found to be slightly negatively correlated with total protein content and width of the pea seeds ($r = -0.71$, $P < 0.05$). However, we did not find any correlation with fracture force and total protein amount, or protein-starch ratio in the pea samples. Hence, the texture results were not affected by the protein content variation of the pea seeds across the

Table 4
Textural parameters measured from compression, cotyledon splitting and dehulling experiments (values expressed as means by cultivar variety and means by year of cultivation).

Cultivar or Year	Fracture Force, N	Fracture strain, %	Time to fracture, s	Deformation to fracture, mm	Essential work of fracture (EWFrac), N mm	Dissipation work of fracture (DWFrac), N mm	Cotyledon splitting force, N	Time to split cotyledon, s	Dehulling force, N	Time to dehul, s
Ingrid	383.3 [a]	5.6 [a]	7.9 [a]	0.38 [a]	57.1 [a]	159.4 [a]	282.9 [a]	7.8 [a]	16.7 [a]	3.7 [ab]
Clara	375.9 [a]	6.4 [a]	8.3 [a]	0.42 [a]	68.9 [a]	120.9 [a]	192.9 [b]	6.4 [b]	15.1 [a]	2.3 [b]
Balder	411.4 [a]	5.5 [a]	7.5 [a]	0.37 [a]	66.8 [a]	133.7 [a]	225.1 [b]	7.0 [ab]	16.7 [a]	4.0 [a]
Year										
2018	384.5 [a]	6.0 [a]	7.9 [a]	0.39 [a]	64.5 [a]	119.8 [a]	208.0 [b]	6.6 [b]	15.2 [a]	3.9 [a]
2019	408.1 [a]	5.9 [a]	8.1 [a]	0.40 [a]	68.8 [a]	147.6 [a]	244.9 [ab]	7.9 [a]	16.3 [a]	3.1 [a]
2020	377.9 [a]	5.6 [a]	7.7 [a]	0.38 [a]	59.6 [a]	146.7 [a]	248.1 [a]	6.8 [b]	17.7 [a]	2.9 [a]

*Values in the same column with different letters represent a significant difference ($P < 0.05$), although, by variety and year only. Tukey's pair wise comparison was made on average values of at 95 % confidence level. Data of essential work of cotyledon splitting/dehulling and dissipation work of cotyledon splitting/dehulling not reported.

years (2018, 19, 20) under consideration. The general assumption is that protein bodies present in seed acts like a soft wrap, and homogenizes the stress distribution in the seed. Higher protein content in the pea seeds can help in dissipating the fracture process with its viscoelastic properties (Ji and Gao, 2004). Thus higher protein in a seed will generally allow higher deformation before the seeds are fractured. Our results did not follow such trend and may be due to the fact that the variation in protein content was too small. We can say that for a complex composite material like pea seed which has very different morphological arrangement of the tissues from outer seedcoat to inner part of the cotyledon, the fracture behavior is rather complicated.

Compression and fracture behavior of the Swedish pea cultivars were found to depend on the shape of the pea seeds (Fig. 3a) and displayed a clear clustering effect with sphericity values. The highest average value of fracture force was found for Balder (mean value 437.7 N, year 2019) and the lowest value was found for Clara (mean value 351.9 N, year 2018).

Essential work of fracture varied between 57.6 (Ingrid, year 2018) to

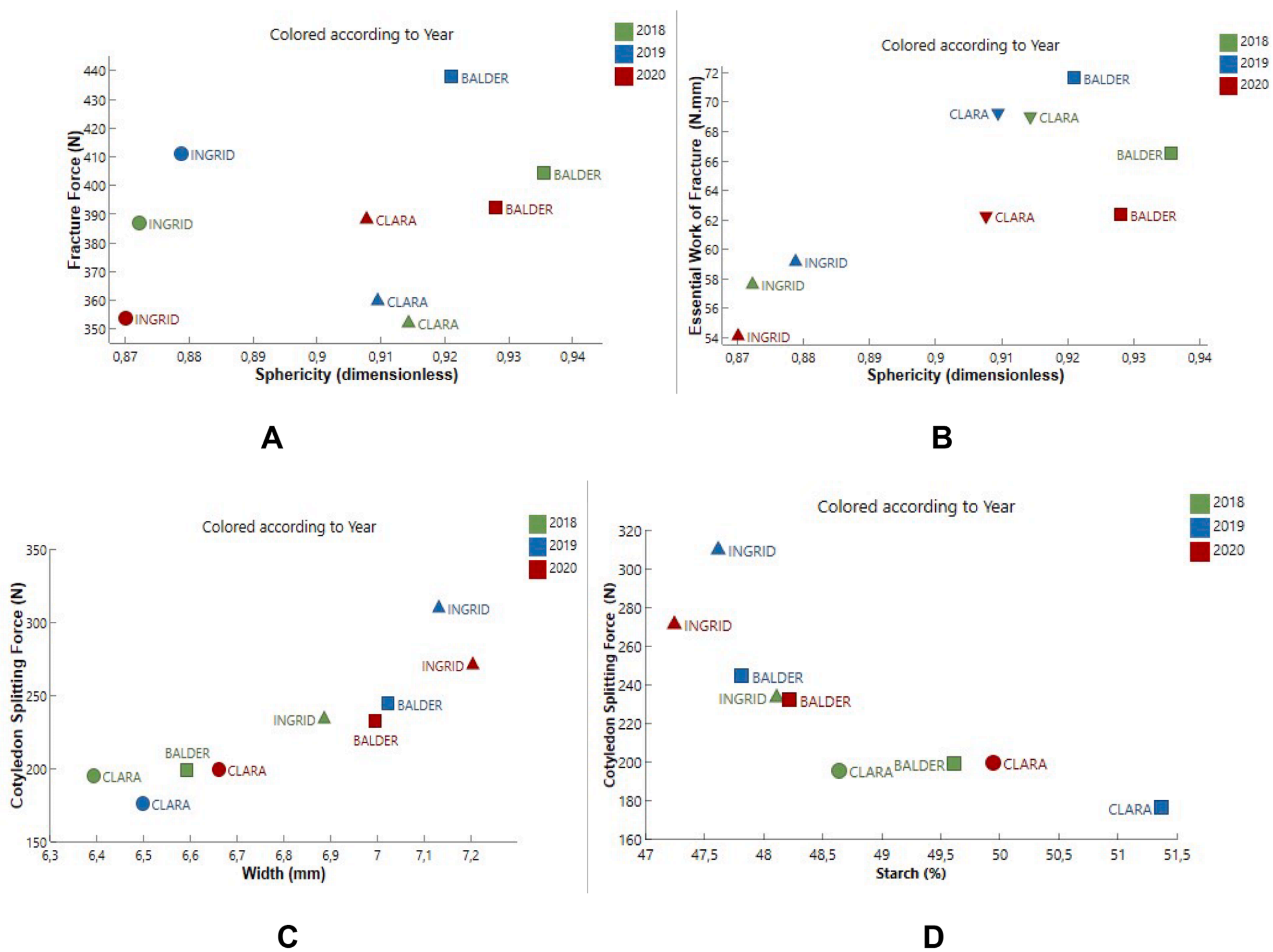


Fig. 3. Correlation profile of different mechanical attributes a) Fracture force versus sphericity, b) Essential work of fracture versus sphercity, c) Cotyledon splitting force versus seed width, d) Cotyledon splitting force versus starch %.

71.6 N.mm (Balder, year 2019). Non-essential work of fracture deriving from the plasticity or dissipation mechanism, was found to be much higher in comparison to the essential work of fracture for all pea samples. Essential work of fracture represents a material property (toughness) and is linked to rupture/fracture. Essential work of fracture is used to create new surface, whereas dissipation work of fracture (or non-essential work of fracture) is a geometry dependent parameter of pea seeds. Dissipation work of fracture represents the irreversible deformation and structural breakdown process throughout the seeds and not only limited to fracture zone (Bárány et al., 2010). Essential work of fracture was found to be positively correlated with sphericity of the pea seeds ($r = 0.77$, $P < 0.014$) and negatively linked with length of the pea seeds ($r = -0.78$, $P < 0.012$) (Fig. 3b). Balder having better spherical shape was found to have higher essential work of fracture (higher toughness). Ingrid seed samples had average length much higher compared to Clara and Balder. Ingrid seeds displayed lower essential work of fracture values (lower toughness). However, the dissipation work of fracture was found to be much higher in relation to essential work of fracture for Ingrid. Dissipation work of fracture is more linked to the crack propagation phenomena and did not have any association with any measured or calculated physical or chemical parameters. The slope at 3 % strain value (F-StrSL2) was strongly correlated with the measured fracture force values ($r = 0.93$, $P < 0.0003$), while slope at 5 % strain (F-StrSL3) was found to be positively correlated with dehulling force values ($r = 0.93$, $P < 0.0003$).

3.3.2. *Cotyledon splitting and dehulling phenomena*

Cotyledon splitting and dehulling of the pulses are linked to ease of milling. Some legume cultivars are easy to dehull and split, while some cultivars are difficult to mill and need preconditioning (treatment with water, oil or enzymes) for efficient milling operation (Wood and Malcolmson, 2021). Cotyledon splitting force was found to be negatively correlated with total starch content in the pea seeds ($r = -0.82$, $P < 0.006$) and had strong positive association with the length, width and volume of the pea seeds ($0.86 < r < 0.87$, $P < 0.003$) (Fig. 3c and 3d). Cotyledon splitting force and time to split the cotyledons were significantly higher ($P < 0.05$) for Ingrid pea cultivar compared to Clara and Balder (Table 4). For Ingrid, we also found consistently higher protein content in all the years compared to Clara and Balder. In the year 2018, all the pea samples had significantly lower protein content compared to pea seeds harvested from the year 2019 and 2020 ($P < 0.05$). Cotyledon splitting force and time for cotyledon splitting was significantly lower for the pea seeds harvested from the year 2018 compared to 2019 and 2020 ($P < 0.05$). We could comprehend pea cotyledon as a storage tissue where starch granules and protein bodies are embedded (Möller et al., 2021; Schutyser et al., 2015; Pelgrom et al., 2013). Our data indicated that the relative proportion of starch in relation to protein in pea seeds therefore had an influence in the cotyledon splitting parameters. However, we did not find any correlation between cotyledon splitting related parameters and total dietary fiber content or any specific fibre component. We measured dietary fiber profile of the whole seed. It is suggested to analyze dietary fiber profile of the seedcoat and cotyledon separately to find any association of fibers with cotyledon splitting phenomena.

Essential work for cotyledon splitting values were also significantly higher ($P < 0.05$) in Ingrid as compared to Clara and Balder (data not shown). It is important to understand that cotyledon splitting force and essential work of cotyledon splitting are relevant parameters for pulse milling pre-treatment strategy. These parameters represents the force required and work to be performed to cleave a single seed along the axial junction where two cotyledons are glued with each other.

Dehulling is the first step of milling, the average time to dehull the Swedish pea samples ranged between 2.3 s (Clara) to 4 s (Balder). Clara variety took significantly shorter time compared to Ingrid and Balder ($P < 0.05$) for dehulling. However, no significant difference was found in the dehulling force values measured between the different cultivars or harvest years. Essential work for dehulling was found to be significantly smaller for the Clara variety compared to Ingrid and Balder, while dissipation work of dehulling did not vary between the cultivars (data not shown).

3.4. *Association of year of harvest with textural attributes of pea cultivars*

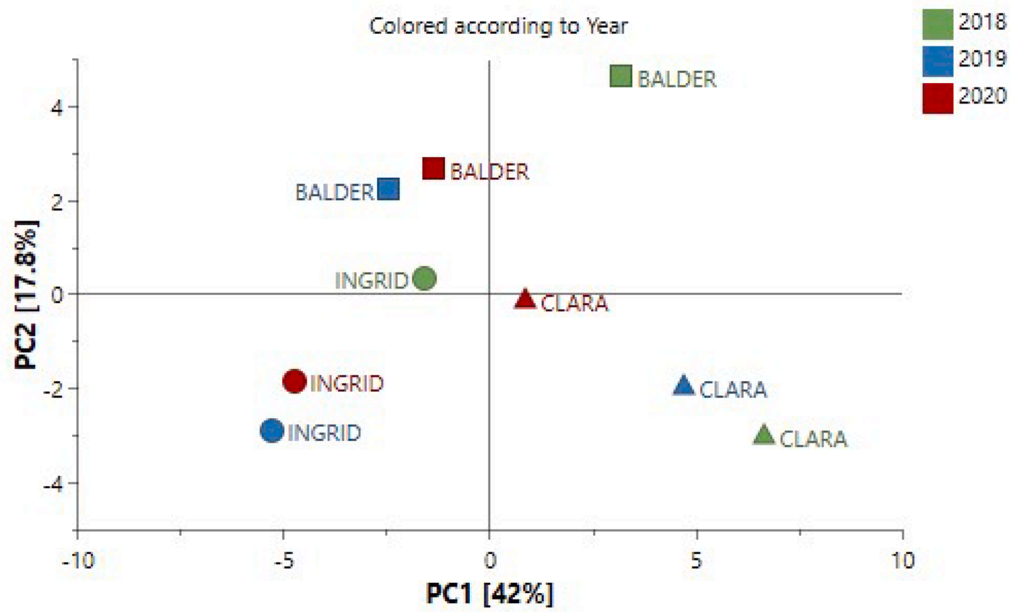
Principal component analysis was used as an exploratory method for finding the variation among the three Swedish pea cultivars (Ingrid, Clara and Balder) harvested in different years (2018, 2019, and 2020). First two principal components (PC1 and PC2) explained 59.8 % of the total variance of the data and showed a clear separation between the different pea cultivars (Fig. 4). The pea seeds (particularly Ingrid and Balder) harvested from the year 2018 was slightly different from the other batches (2019 and 2020 harvest year). This may be attributed to the environmental condition of the crop growth prevalent in Sweden for the year 2018 (hot and dry summer).

From the loading plot, we could see several cotyledon splitting related parameters (cotyledon splitting force, essential work of fracture for cotyledon splitting, time to split cotyledon) were positively associated with many size and shape related parameters (length, width, arithmetic and geometric mean diameter, shape factor, volume of seed and 100 seed weight). However, many of the fracture and dehulling parameters (fracture force, fracture strain, time to fracture, dehulling force, time to dehull, etc.) did not vary distinctly between the cultivars. We also did not find any strong positive or negative association between sizes or shape related attributes with any fracture or dehulling related parameters. Fracture force and dehulling force were correlated with the slope of fracture force versus strain curve at 3 and 5 % strain levels, F-StrSL2 and F-StrSL3 respectively.

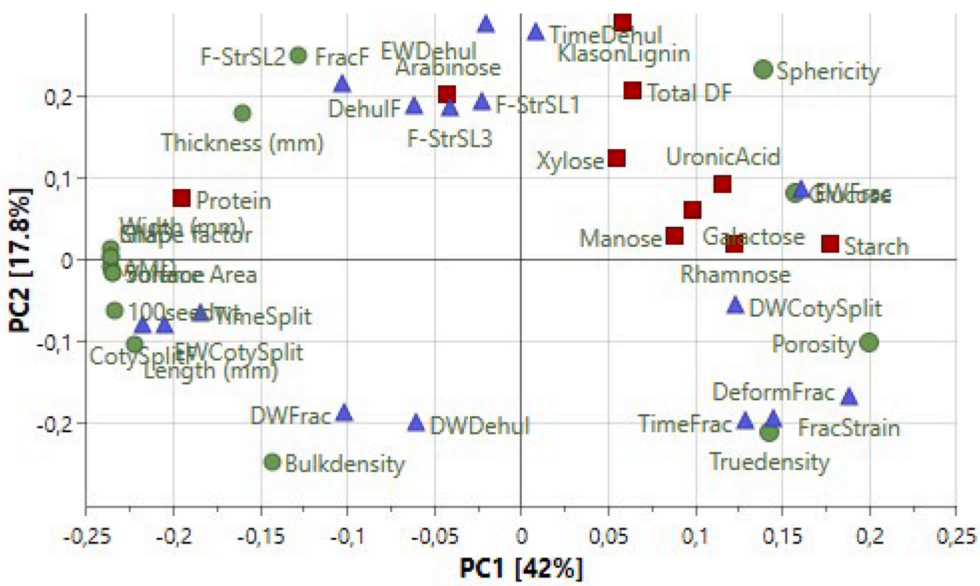
It would be scientifically interesting to investigate in future whether the cotyledon splitting forces or essential work of cotyledon splitting of pulse seeds are linked to efficient clean split production (or broken production). In depth understanding of pulse seed tissue composition and organization in different parts of the seed (seedcoat, inner and outer cotyledon) on fracture or cotyledon splitting or dehulling beahvior will find potential practical application in future. It will be interesting to explore pea cultivar microstructure using microscopy (e.g., SEM or X-Ray-Microtomography) to validate the proposed mechanisms of fracture propagation, such as cell wall collapse or porosity evolution. The present study was done only with 14 % moisture content of the seed samples, therefore investigating the influence of moisture content will also provide crucial information. PCA plot based on mechanical attributes in relation to physical attributes and chemical compositional profile of seeds could be used by plant breeders for identifying and selecting cultivars with better milling efficiency. This approach can also help in future breeding program with specific gene targeting in some pea cultivars to improve their dehulling or cotyledon splitting efficiency.

4. Conclusions

This study revealed that the differences in physical attributes and chemical compositional profile between Swedish pea samples are cultivar specific. Environmental conditions of the harvesting year also had a strong influence on the physical attributes and compositional profile of the peas, and rather limited influence in the mechanical attributes of the Swedish pea. Cotyledon splitting related parameters were influenced by the pea cultivar or harvest year or component like starch or physical size and shape. Further studies linking dehulling loss or broken produced or flour attributes with different mechanical attributes of Swedish pea will be useful. Thus, better understanding of the mechanical attributes of seed (dehulling, splitting and compression-fracture behavior) will eventually help to achieve efficient milling process design or dry fractionation process development or better pre-treatment strategy for seed coat removal before milling in future. As dehulling efficiency and milling performances are major industrial parameters for pulse milling industry, selecting cultivars based on



(A)



(B)

Fig. 4. Principal component analysis (PCA) plots for all parameters. A) Score plot for Swedish pea samples, B) Loading plot of all measured or calculated parameters in the study. Physical parameters (green circle), chemical compositional parameters (square brown) and mechanical attributes (blue triangle).

mechanical attributes like our approach will be promising direction in future. Plant breeders can also use this approach for achieving better milling efficiency for specific gene selection. Our textural study with Swedish pea is an attempt also to deviate from the standard ways of doing texture profile analysis (TPA) by food scientists. Understanding food texture by using principles of fracture mechanics will further aid in future to develop food texture scientific area.

Ethical statement

The authors declare that no human or animal subjects were involved in the experiments conducted for this paper.

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CRediT authorship contribution statement

Santanu Basu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stina Gustafsson:** Methodology, Investigation, Formal analysis. **Puneet Kumar:** Methodology, Investigation. **Subir Kumar Chakraborty:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis. **Roger Andersson:** Writing – review & editing, Visualization, Supervision, Software, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

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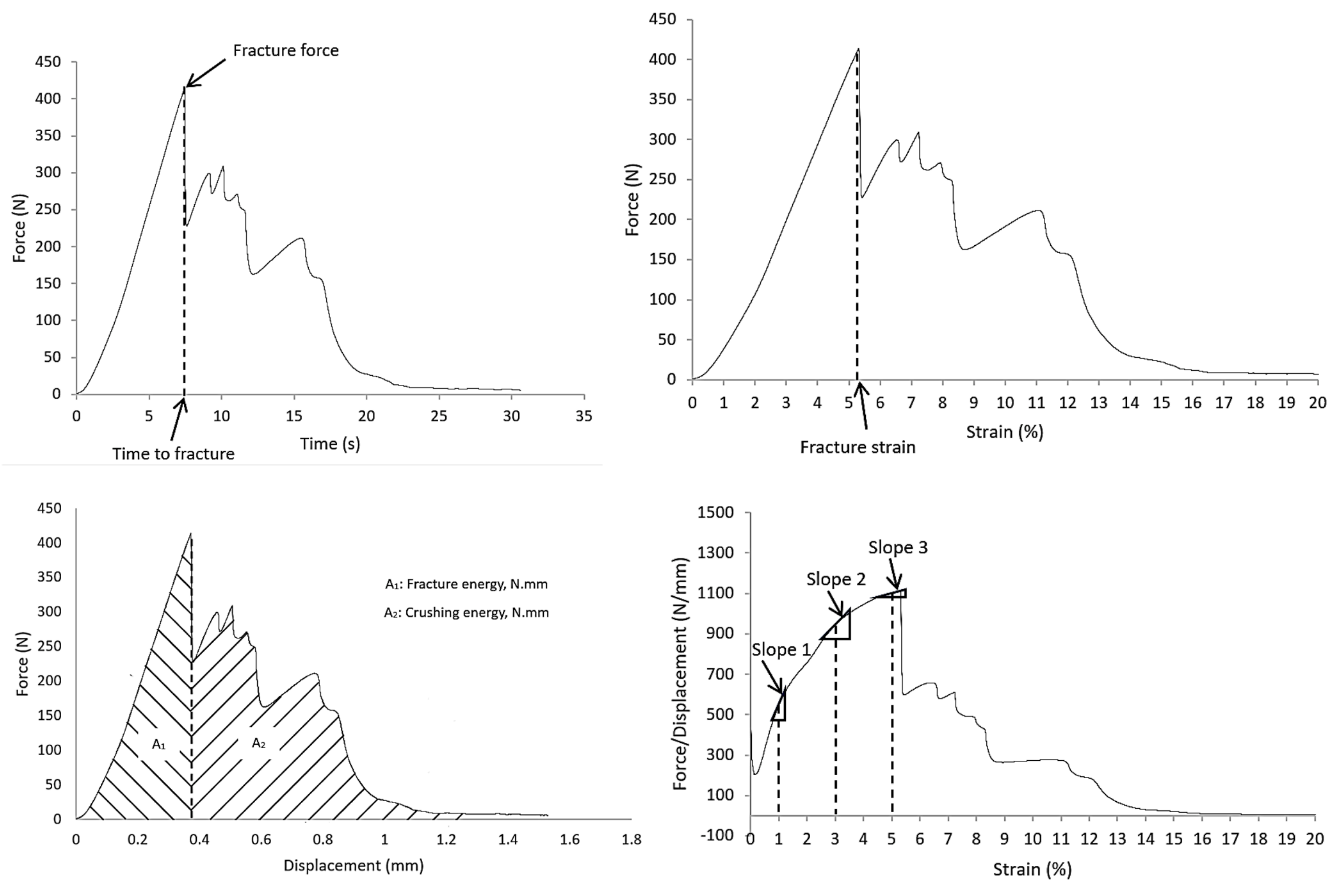
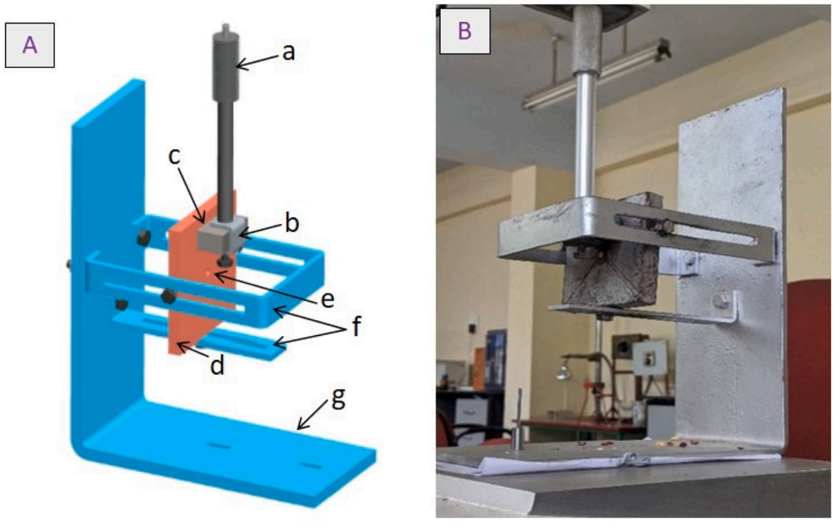
Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2025.100711.

Appendix



Annexure Fig. A1. Fracture parameters measured from force-displacement data.



Annexure Fig. A2. (A) Schematic representation of set-up for measurement of dehulling forces (a) Spindle attachment of texture analyzer (b) emery stone holder (c) emery stone (d) sample holder (e) slot for holding the grain (f) frame to provide three point supports to sample holder (g) main frame bolted to the texture analyzer platform. (B) The developed attachment positioned for the texture analyzer.

Data availability

Data will be made available on request.

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