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A new method for rapeseed hulls purification – Proof of concept☆

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Abstract – The loss of fats in the hulls is one of the main obstacles limiting the industrial implementation of rapeseed dehulling. The main reason resides in the shape of rapeseed outer cotyledons which resemble to the hulls' shape and make it difficult to separate. The purpose of this study is to propose a new method for the purification of rapeseed hulls. After primary separation by aspiration, the mixture of hulls and kernels is passed between a pair of flat rolls where kernels are flattened and stick to the metal while the hulls do not. We exploited this property to adapt a small laboratory flaker with two counter-rotating cylinders of 65 mm diameter with scrapers that make the kernels fall away from the hulls. Process optimization by tunning experimental conditions (hulls moisture content, roller spacing, roller speed and feed rate) allowed the determination of the optimal operating conditions. Experiments showed that wetting improves the purity of the hulls but reduces the one of the recovered kernels. A gap of 0.1 mm was necessary. In addition, it was shown that the sorting quality depends on the ratio flow-rate / rotation-speed. The best performances are reached around $1\,\mathrm{g.s^{-1}.rpm^{-1}}$. In these conditions, the hulls and kernels purity were 96% and 94% respectively. This preliminary work has allowed us to prove the concept. The next step will be to develop a pilot plant to validate the process efficiency on a larger scale (100 kg/h).

Keywords: rapeseed / dehulling / purification / kernels / hulls

Résumé – Nouvelle méthode de purification des pellicules de colzaé. L'un des verrous limitant le développement de la pratique industrielle du dépelliculage du colza est la perte de matière grasse dans les pellicules. En effet, morceaux fins de cotylédons et pellicules ayant des formes et des densités assez proches, les procédés de séparation sur colonne d'air sont assez peu efficaces. L'objet de cette étude est de proposer une méthode de purification des pellicules de colza basée sur la différence des propriétés d'adhérence entre amandes et pellicules lorsque ces matériaux sont passés entre deux cylindres métalliques. Les amandes collent sur le métal alors que les pellicules ne tiennent pas. Nous avons exploité cette propriété pour adapter un petit aplatisseur de laboratoire disposant de deux cylindres contrarotatifs de 65 mm de diamètre avec des racleurs qui font tomber les amandes à distance des pellicules. Après avoir testé l'effet de la teneur en eau des pellicules, de l'écartement des cylindres, de leur vitesse de rotation et du débit d'alimentation, nous avons pu mettre en évidence des paramètres optimaux de fonctionnement. Le mouillage améliore la pureté des pellicules mais dégrade celle des amandes récupérées. Un écartement de 0.1 mm est nécessaire. Par ailleurs, il a pu être montré que les meilleures performances étaient atteintes vers $1\,\mathrm{g.s^{-1}.tr.min^{-1}}$. Dans ces conditions, des puretés de 96% et 94% ont été obtenues pour les pellicules et les amandes respectivement. Ce travail préliminaire a permis de faire la preuve du concept. L'étape suivante consistera à développer un appareil pilote permettant de valider l'efficacité du procédé à une plus large échelle (100 kg/h).

Mots clés : colza / dépelliculage / purification / pellicules / amandes

1 Introduction

France has decided to strengthen its autonomy in terms of plant proteins but cannot produce enough soybeans to satisfy the most demanding livestock systems in terms of protein concentration (dairy cows, broilers), so it must innovate to find acceptable substitutes (Terres Univia, 2020). Rapeseed meal is penalized by its high fiber content related to presence of seed coat residues. Since the seed contains about 18% of hulls and about 44% of oil, after extraction of the latter, the meal is composed of about 30% of hulls and has a protein content of only 33–34% (Tormo *et al.*, 2020). Removing 85% of the seeds' hulls would bring the protein content of the meal to 40% (11.5% water and 1.8% oil) and reduce its NDF, ADF, and ADL content by 50, 57, and 76% respectively (Carré *et al.*, 2016). Even if the protein content of dehulled rapeseed meal does not reach that of soybean meal ($>$ 46% protein), the qualitative leap is sufficient to make it a raw material of great interest for animal feed. This interest has been confirmed by CEREOPA using the Prospective Aliment model in the framework of the VOCALIM project. This study simulates the effect on the French market in 2023 of 450 000 t of dehulled rapeseed meal (39.5% protein), 100 000 t of protein-enriched rapeseed meal (38% protein) and 200 000 t of sifted sunflower meal (43% protein). The model, based on a detailed knowledge of the functioning of the animal feed sector, substitutes one raw material for another according to the specifications of the different types of animal production in order to minimize the cost of feed. This study clearly showed that the composition of dehulled rapeseed meal is better suited to the poultry sector, which would capture 74% of the supply, while the sifted rapeseed meal with higher fiber content would be massively adopted by the swine sector (Lambert *et al.*, 2021). This adoption would make it possible to avoid importing non-GMO meals (soybean and sunflower). To achieve this position, the price of dehulled rapeseed meal would have to be at 95% of standard soybean meal, which is roughly in line with the predicted values from a study we published in this same journal (Carré *et al.*, 2015). According to this study, this level of price improved the crushing margin from 65.5 € to 81.2 €, which leaves enough to compensate for the additional costs related to dehulling. Nevertheless, this study showed the importance of controlling the residual oil content of the hulls. For three different economic contexts, characterized by decreasing oil prices, only one could tolerate oil content of hulls up to 18%. In the second, the dehulling became unprofitable as soon as the oil content of hulls reached 13%, and for the last, characterized by the highest oil prices, the tolerance was null, profitability being possible only for hulls with less than 9% oil. As a reminder, let us recall that rapeseed hull, unlike sunflower hull or soybean hull, contains around 8% oil (Carré *et al.*, 2016). This oil is present in a cell base located on the inner side of the integument. These thick-walled cells make this oil not very extractable and this contributes to the fact that rapeseed meal always has a higher oil content than sunflower and soybean meals (2.4% *versus* 1.1% and 1.5% for rapeseed, sunflower "35" and soybean meals, Tormo *et al.*, 2020, 2021; Heuzé *et al.*, 2020).

It should be noted that the tolerable oil content in rapeseed hulls is about 12% and that this corresponds to the presence of

Fig. 1. View of hull pieces and cotyledons of similar shape and thickness.

kernels residues that should not exceed 7% of the mass of industrial hulls.

At the origin of the difficulty to avoid oil residues in the hulls fraction comes from the shape of the embryo (kernel) in the seed. The outer cotyledon envelops the inner cotyledon in the manner of nested cups. Figure 1 shows the similarity of shape between pieces of cotyledon and pieces of hulls extracted by separation in an air stream. This similarity makes it difficult to clean the hulls and obtain an acceptable oil content.

The usual method for obtaining satisfactory quality is to separate the hulls from kernels residues with air columns, which is probably not very effective for sorting this product. Doubling the process is required to avoid losses resulting in high capital and energy costs. Currently, the dehulling of rapeseed is almost never carried out on an industrial scale.

During experiments carried out in our laboratory, we observed, by passing a mixture of kernels and rapeseed hulls on a small benchtop flaker, that the kernels tended to adhere to the rollers while the hulls did not. This led to the idea of exploiting this property of the kernels to separate them from the hulls by modifying the apparatus to include a scraping device and recovering the almonds and hulls separately.

Regarding the novelty of the process, a patent research was done using Espacenet, with key words like "hulls" "sorting" "cleaning". Twenty-six original patents (Supplementary Material Tab. S1) related to rapeseed dehulling methods were analyzed. In result it was not possible to find any reference to the principle of separation proposed in this work among these patents. Table 1 summarizes the typology of these patents according to the separation method, the seeds cracking technology and a possible preparation step. Most patents use air separation alone or in combination with sieving. The separation can be carried out by aspiration, winnowing or by mean of classification columns but the principle remains transportation of the hulls by an air flow. Sieves can be used, prior to aspiration to avoid the presence of small particles likely to be transported with the hulls, or after air separation to remove the fines that contain kernels residues. Electro separation uses the difference in electrostatic charges in hulls and kernel to deviate the flow of the hulls. Optical sorting is generally used as a finishing step to remove residual hulls or

Table 1. Recapitulation of the patent related to rapeseed dehulling and fraction sorting.

Brevet	Preparation	Seed cracking	Separation principle
CN112492980A		ND	Air
CN209952960U		ND	Air
CN106350205A	Negative temp; air 100–120 °C	Pneumatical transport + impacts	Air
CN101099428 (A)		Batter	Air
CN203144369U		Pneumatical transport + impacts	Air (cyclones)
CN203380112U		ND	Air + sieves
CN101438849 (A)		Batter	Air column
EP2550106A1		Impacts	Air column + sieves
US6326035B1		Impactor	Aspiration + sieve
CN106111516A		ND	Aspiration
CN207735250U		ND	Brush + air
GB2005526A		Wet milling	Cyclones
DE4041994 (A1)		Gap 2 clinders	Electroseparation
WO2014060494A1	Heat + drying	Cracking mill	ND
CN104293480A	Sonication	ND	ND
CN1458252A		ND	ND
CN104877756A	Microwaves	ND	Optical sorting
US3732108A		Solvent	Shifting (dry)
CN212910850U		batter	Sieve
CN103555414 (A)	Drying	Mill	Sieve + air column
CN2243334Y		Conical device	Sieve + aspiration
CN202808747U		Gap 2 cylinder	Sieve + aspiration
CN209722076U		ND	

ND: not described.

undehulled seeds. Hydro-cyclone has been proposed in patent GB2005526A for a separation at the extraction stage after disaggregation of the seeds in the solvent.

The seeds cracking can be divided in two general methods: impact methods and breaking between two corrugated surfaces where at least one is moving. Impacts can be supplied with pneumatic transportation, propelling against a target (impactors), passage in a rotating batter, etc. Pretreatment aim at facilitating the separation of the fractions. High temperature can both dry the seeds and weaken the hulls. Drying shrinks the kernel and limits the adherence between hulls and kernels. Sonication generates cavitation in liquid media and cavitation attacks the walls of the hulls. Microwaves enhance the effect of thermal treatment by rapid vaporization of water which could help the detachment of kernels from hulls.

Another research combining classification "B07B13"[1] with key words "adhesion" or "stick" from which a selection of the seventeen most relevant patents is reported in Table S2. Patent US3288283 describes an apparatus composed of two horizontal cylinders separated by a small distance with at least one of the cylinders having a deformable surface. Clay and phosphate mixture are driven between the rolls; clay is flattened and adheres to one of the surfaces while phosphate does not. A scrapper then removes the clay. That patent is very similar to our system except for the point where it requires a soft coating of the cylinders to function. It is related to a former patent (US 1609688) where rubber coated rolls are used to eliminate garlic seeds and other soft material from wheat, wheat grain having enough resistance to pass the cylinder without deformation while soft seeds are crushed, juice is expressed and absorbed by addition of absorbing dust. A less similar patent concerns the sorting of different plastics wastes. Patents AU663807B2, US5660282A1, and EP2060330A2 describe processes where polymers are heated to their melting point in order to make them able to stick to a conveying belt or cylinder after being pressed while other polymers remain solid and do not adhere. Other systems, using the principle of different adhesion capacity of materials for sorting, have been patented but they do not require the notion of pressure to make one of the components holding to the surface.

2 Material and methods

2.1 Purification device

Figure 2a shows a sketch of the rotating benchtop flaker (1). It has been equipped with tangential scrapers (21, 22) that are in contact with the cylinders (11, 12). The rotation is ensured by a variable speed motor in direct drive on one of the axes of the cylinders while the second one is moved in the opposite direction by a gear (22a). The size of the cylinders is 65 mm in diameter and 200 mm in length. The spacing can be adjusted from zero to several millimeters. The speed could vary from 0 to 1500 rpm.

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[1] Grading or sorting solid materials by dry methods, not otherwise provided for; Sorting articles otherwise than by indirectly controlled devices.

Table 2. Experimental design used.

Test	Feed rate	Rotational speed (RPM)	Gap between rolls (mm)	Water content (%)
1	≈ 350 tr/min	350	0.1	9.85
2	≈ 350 tr/min	350	0.1	17.55
3	≈ 350 tr/min	350	0.2	9.85
5	≈ 350 tr/min	800	0.1	9.85
6	≈ 350 tr/min	800	0.1	17.55
7	≈ 350 tr/min	800	0.2	9.85
8	≈ 350 tr/min	800	0.2	17.55
9	≈ 350 tr/min	1200	0.1	9.85
10	≈ 350 tr/min	1200	0.1	17.55
11	≈ 350 tr/min	1200	0.2	9.85
13	≈ 3 kg/h	350	0.1	9.85
17	≈ 3 kg/h	800	0.1	9.85
21	≈ 3 kg/h	1200	0.1	9.85
25	> 3.5 kg/h	350	0.1	9.85
26	> 3.5 kg/h	350	0.1	17.55
29	> 3.5 kg/h	800	0.1	9.85
33	> 3.5 kg/h	1200	0.1	9.85

158
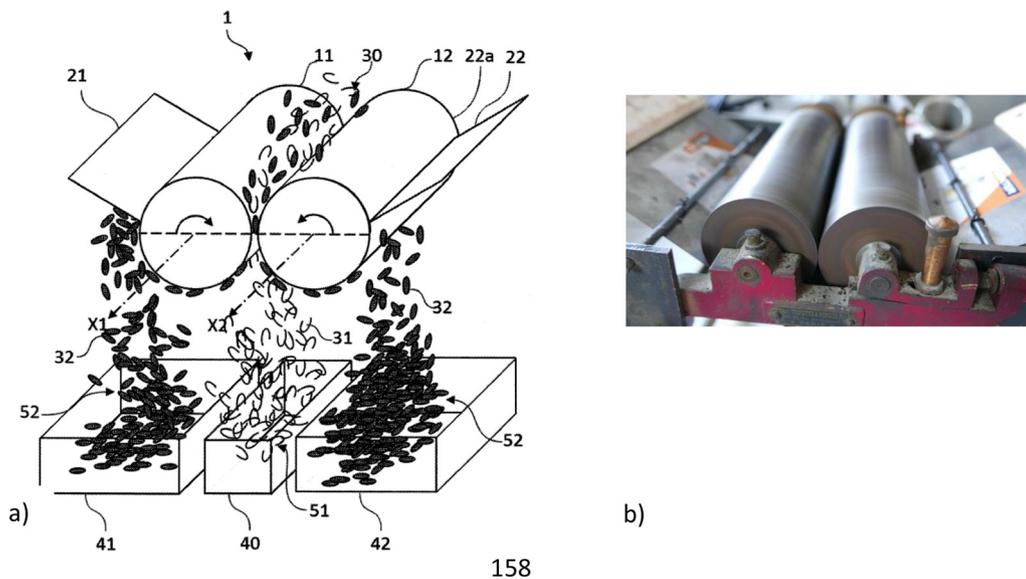
Fig. 2. (a) Sketch of the device; (b) View of the benchtop flaker equipped with tangential scrapers.

The cylinders were fed with rapeseed hulls (30) by means of a 60 mm wide vibrating trough whose vibration frequency was adjustable to control the feed rate. Under the cylinders, differentiated receptacles (40, 41, 42) allowed to recover product samples (31, 32) after separation for weighing and oil content measurement.

2.2 Water content conditioning

Moisture conditioning of the hulls was performed using a spray bottle. Forty-five grams of water were added to 445 g of initial hulls. The homogenization of the moisture content of the hulls was obtained by stirring the product for two hours in a rotating 2 L cylindrical container (60 RPM). Moisture content controls were performed by thermogravimetry on a Sartorius MA160 desiccant balance.

Rotational speed was measured with a Bioblock Scientific – Digital Tacho DT-2234 optical tachometer.

2.3 Optical purity measurement

In addition to the determination of oil content, the degree of purity of the hulls was measured by image analysis using the following method.

2.3.1 Image acquisition

In order to standardize and avoid lighting problems, the image acquisition was done using a desktop scanner (Cannon LIDE 100) set at a resolution of 600 DPI. The images were acquired in JPEG format. The acquisition is done by placing the sample to be analyzed directly on the glass of the scanner.

2.3.2 Definition of the optical purity

The principle of the optical purity measurement is to consider that the percentage of the analyzed image area, occupied by clear pixels, represents the rate of presence of kernels.

2.3.3 Procedure

The images are analyzed using the free software "ImageJ". This software allows to filter the images according to the characteristics of the color. The thresholds were set to measure the areas corresponding to the hulls.

When the cutoff was set, the software calculates the area occupied by the selected pixels.

Although the samples are slightly flattened by the scanner cover, there are still shadows in the image that may cause us to underestimate the kernel content. Since it is not possible to set thresholds that would identify these shaded areas to remove them from the analysis, we considered that this bias would be constant and would not affect our purity assessments.

2.4 Measurement of oil content

Oil content was measured by low resolution NMR spectrography according to NF EN ISO 10565. The instrument available to be used is the Bruker Minispec MQ 20H/10R.

2.5 Experimental design

In order to determine the impact of the parameters governing the operation of the device, the effect of roll spacing, feed rate, roll speed and hull water content were tested (Tab. 2).

A number of parameter combinations proved unfeasible, so the numbering of the experiments is not continuous. In particular, it turned out that the wide gauge was not suitable for reasons that are easy to understand and only four experiments were performed at this gauge.

In addition, the feed rate proved difficult to control, as did the rotation speed. As a result, the observed values varied to a fairly large extent.

2.6 Initial hulls

Initial hulls were obtained by fluidized bed sorter aspiration of a commercial rapeseed batch after dehulling. The sorter was adjusted to minimize the presence of hulls in the kernels. The oil content of the hulls was 22.2%, their optical purity 78.8%. Considering an intrinsic oil content of the hulls of 8% and 57% for the pure kernels, the pure kernel content of the mixture must be 28% to match the observed oil content. Since the optical purity of the mixture does not take into account the probable difference in density of the fractions, it is normal that the two values did not overlap (Fig. 3).
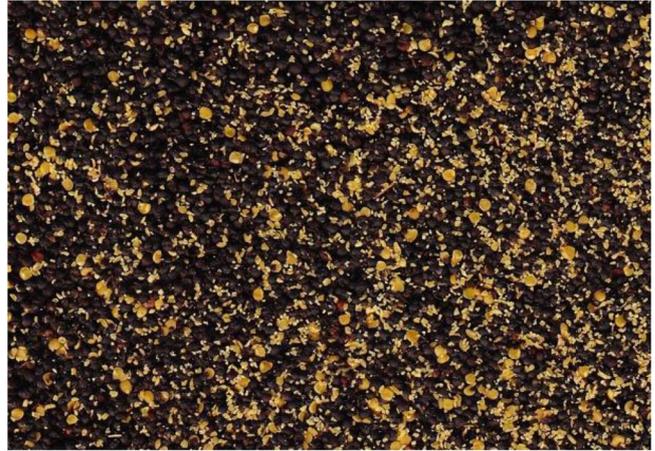

Fig. 3. View of the initial hulls.

3 Results

Table 3 presents all the results obtained. As can be seen, for the high-water content and wide spacing modalities, few tests were carried out due to the poor quality of the results obtained.

The first column shows the flow rates that varied widely within each modality. The control of the vibrator flow rate being ensured by the positioning of an eccentric weight, it was difficult to reproduce this positioning with precision, with the result that the observed flow rates varied from 0.59 kg/h to 3.99 kg/h.

The second column indicates the speed of rotation of the cylinders. As for the flows, we observe some variability within the modalities, this variability being also due to the difficulty of reproducing the settings of the device that used an electric drill to operate the rotation of the cylinders.

The column "Kernel oil content" indicates the result of the measurement of oil content of the "kernel" fraction obtained after separation. The "Kernels optic purity" column shows the result of the image analysis performed on a sample of the kernel fraction recovered after separation. The next two columns give respectively the oil content and the optical purity of the hulls obtained after purification.

The "Losses" column shows the difference between the initial hull mass and the sum of the fractions collected. These losses are explained by the fact that some material did not fall into the receptacles placed under the cylinders due to projections and imperfect handling.

The columns proportion of "Kernels mass yield" and "hulls ass yield" give the mass balance of the separation operation. The "Initial oil content" column shows the sum of the products of the oil content of the fractions by their respective proportion. The oil content of the fractions, resulting from the purification process, was considered a better indicator of its efficiency than the optical purity criterion. For this reason, a purity rate of the fractions obtained was calculated based on an estimated value of the oil contents of the pure hulls and pure kernels using the regression between optical purity and oil content of each fraction.

Figure 4 shows this regression line along with its equation and coefficient of determination R^2 for the hulls. The oil content of 100% pure hulls predicted by this equation is 6.0%.

Table 3. Experimental results. For each experiment, results of optical purity, oil content (determined by NMR), fraction mass yields and purity indexes.

Test	Feed rate (Kg/h)	Rotational speed (RPM)	Gap between rolls (mm)	Water content (%)	Kernels oil content (% as is)	Kernels optical purity (%)	Hulls oil content (% as is)	Hulls optical purity (%)	Losses (%)	Kernel mass yield (%)	Hulls mass yield (%)	Initial oil content (% as is)	PH/RH	PH/RK	Index of combined efficacity
1	1.06	340	0.1	9.85	42.18	59.0	7.79	97.1	5.9	49.2	50.8	24.7	0.96	0.26	85.37
2	0.95	340	0.1	17.55	35.25	31.2	7.84	98.7	10.1	50.9	49.1	21.8	0.96	0.40	78.19
3	1.05	393	0.2	9.85	51.32	78.0	15.72	90.9	5.5	23.3	77.7	24.2	0.80	0.07	86.62
5	0.59	900	0.1	9.85	51.6	88.4	7.91	96.9	9.7	34.0	66.0	22.8	0.96	0.06	94.94
6	1.31	855	0.1	17.55	42.86	61.9	8.59	98.6	11.5	32.9	67.1	19.9	0.95	0.24	85.25
7	1.57	800	0.1	9.85	52.46	87.6	10.33	95.5	6.0	27.0	73.0	21.7	0.91	0.04	93.33
9	1.15	1200	0.1	9.85	48.75	90.5	8.33	96.5	7.9	35.6	64.4	22.7	0.95	0.12	91.58
10	1.81	1150	0.1	17.55	43.5	64.2	9.37	98.6	14.1	28.9	71.1	19.2	0.93	0.23	85.11
11	1.29	850	0.2	9.85	51.17	89.5	19.86	86.1	5.7	10.8	89.2	23.2	0.72	0.07	82.21
13	3.49	350	0.1	9.85	45.27	61.4	10.13	94.1	7.1	41.7	58.2	24.8	0.92	0.19	86.14
17	3.06	900	0.1	9.85	53.1	91.5	12.23	90.4	7.0	29.6	70.4	24.3	0.87	0.03	92.04
21	2.43	1200	0.1	9.85	51.56	87.6	8.02	96.8	8.1	37.3	62.7	24.3	0.96	0.06	94.79
25	1.69	1500	0.1	9.85	50.08	92.8	10.14	93.9	10.0	28.1	71.9	21.4	0.92	0.09	91.08
26	1.09	1350	0.1	17.55	40.83	55.7	7.83	98.6	14.4	34.4	65.6	19.2	0.96	0.28	83.94
29	3.99	900	0.1	9.85	49.25	75.5	9.18	94.8	9.5	40.6	59.4	25.4	0.94	0.11	91.22
33	3.62	1200	0.1	9.85	51.16	82.8	9.11	96.4	16.8	33.6	66.4	23.2	0.94	0.07	93.25
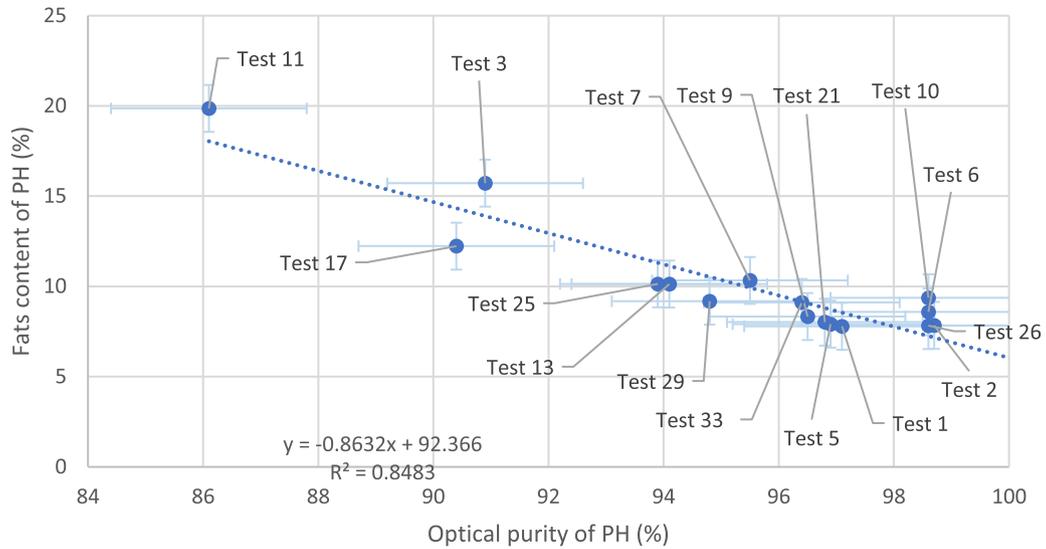
Fig. 4. Regression between optical purity of purified hulls and oil content of purified hulls. The equation is used to evaluate the oil content of 100% pure hulls.
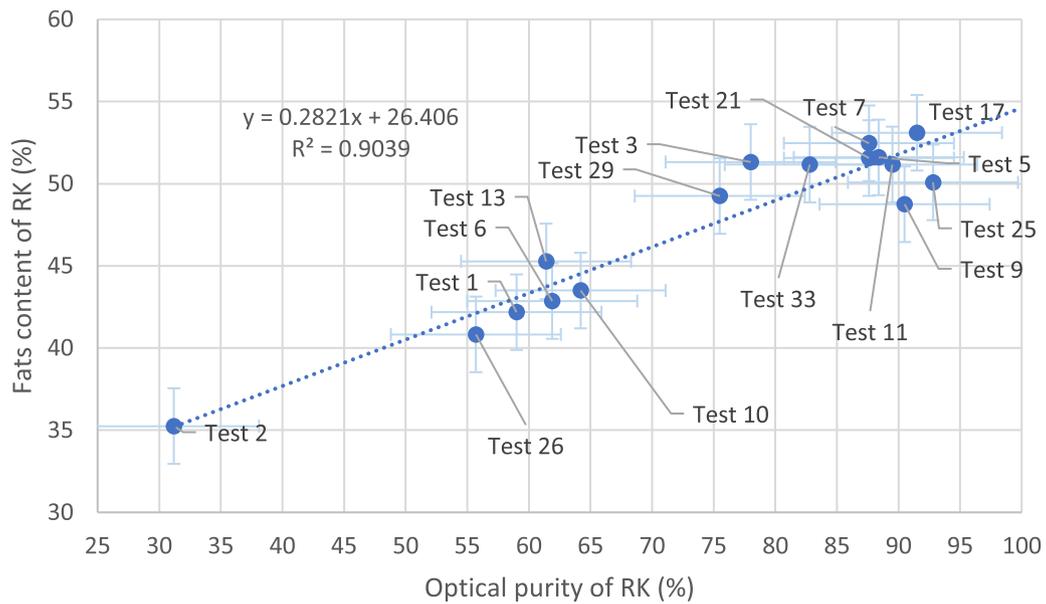
Fig. 5. Regression between optical purity of recovered kernels and oil content of recovered kernels.

In the same way, Figure 5 allowed us to estimate the oil content of pure kernels by extrapolating the regression line at 100% optical purity. The oil content of 100% purified kernels is 54.6% according to the equation obtained.

The PH/RH column shows the result of equation (1) and represents the rate of pure hulls in the recovered hulls. Similarly, the PH/RK column gives the result of equation (2) and represents the rate of pure hulls in the recovered "kernel" fraction.

$$PH/RH = 1 - (O_k - O_{RH})/(O_k - O_h), \qquad (1)$$

$$PH/RK = 1 - (O_{RK} - O_h)/(O_k - O_h), \qquad (2)$$

with O_i: oil content of component i; RH: hulls after purification; RK: kernels fraction after purification; k: pure kernels; h: pure hulls.

The index of combined efficacity was calculated by the equation (3).

$$I_e = [PH/RH + (1 - PH/RK)]/2 \times 100. \qquad (3)$$

An index of 100 would correspond to a combination of modalities giving totally pure kernels and totally pure hulls. This index is intended to allow comparison of all results on a single criterion.
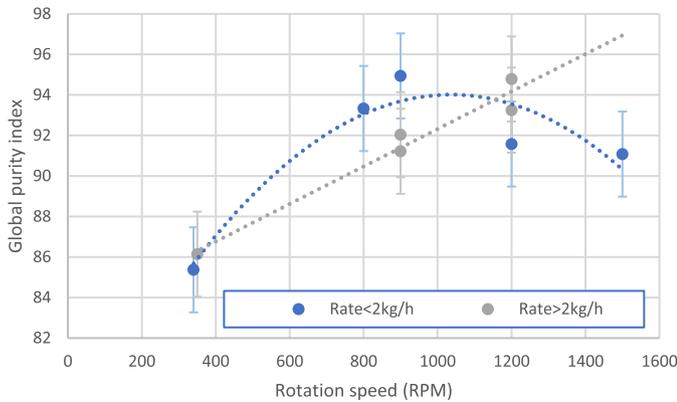
Figure 6 shows a selection of views of the fractions obtained. For trial 21, we can see an interesting compromise

Parameters	Picture of the recovered kernels (RK)	Picture of recovered hulls (RH)
Test 21 Flow rate: 2.43 kg/h Speed: 1200 rpm Gauge: 0.1 mm Water 9.8% O_{RK}: 51.6% O_{RH}: 8.0% Yield: 37/63		
Test 25 Flow rate: 1.69 kg/h Speed: 1500 rpm Gauge: 0.1 mm Water 9.8% O_{RK}: 50.1% O_{RH}: 10.1% Yield: 28/72		
Test 33 Flow rate: 3.62 kg/h Speed: 1200 rpm Gauge: 0.1 mm Water 9.8% O_{RK}: 51.1% O_{RH}: 9.1% Yield: 33/66		
Test 26 Flow rate: 1.09 kg/h Speed: 1350 rpm Gauge: 0.1 mm Water 17.5% O_{RK}: 36.9% O_{RH}: 7.8% Yield: 35/65		
Test 11 Flow rate: 1.29 kg/h Speed: 850 rpm Gauge: 0.2 mm Water: 9.8 % O_{RK}: 51.2% O_{RH}: 19.86 % Yield: 11/89		

Fig. 6. Views of the fractions obtained for a selection of trials (all the views are available as supplementary data on the journal website).

between a good purity of hulls and kernels with a yield of hulls after purification of 63%. The initial hulls were richer in kernels than the average with 24.3% oil *versus* 22.7%. The test 24 carried out with hulls having a slightly lower initial oil content (21.4%) allows to obtain a better yield of hulls at the cost of a small increase of their contamination by kernels. It is also possible that the higher rotation speed of the cylinders may have penalized the quality of the separation. Trial 33 was carried out under similar conditions to Trial 21 except that the flow rate was 50% higher. The performance was quite similar with a slightly higher hull yield due to the slight lower initial oil content. The test 26 carried out on moistened hulls shows

Fig. 7. Effect of rotation speed and feed rate on the purity of the fractions.

Fig. 8. Effect of the ratio between flow rate and rotation speed on the overall purification index.

that it is possible to achieve a near perfect purity of the hull fraction. However, this performance is paid for by a degraded quality of the kernels. In addition, humidification preferentially affects the hulls, which become heavier, making it impossible to compare yields. Trial 11 is a good example of the effect of a too wide spacing. Under these circumstances, the kernel fraction has a high purity, but the hull fraction remains very rich in kernels. At this spacing, about 65% of the kernels remained in the hull fraction.

3.1 Effect of roll spacing

Index of efficacity is mainly affected by a significant drop in hull purity, with trials 3 and 11 being mainly characterized by significant higher levels of kernels in this fraction than in all other trials. It is indeed quite understandable that a too wide spacing does not allow to correctly press the kernels on the cylinders and that a high percentage of them does not adhere when passing between the two surfaces.

For this reason, the other modalities planned at this spacing were abandoned.

3.2 Effect of hull wetting

Preliminary observations had led us to believe that wet hulls would be purer than dry hulls. Observation of the products from trial 26 in Figure 6 confirms this favorable effect.

Determinations of oil content in the hulls and optical purity also confirmed this initial visual impression. Unfortunately, this improvement translates into a reduction in the purity of the kernel fraction, both for oil content and optical purity, which degrades the overall purity index. Wet hulls yielded kernels of lower purity than dry hulls.

3.3 Effect of the rotation speed of the cylinders

Fraction purity is improved by rotational speed to some degree. It seems that this improvement is different depending on the feed rate. For flows below 2 kg/h, past an optimum at 900 rpm, it seems that the speed of rotation degrades the quality of sorting, while for flows above 2 kg/h, better results are obtained at 1200 rpm.
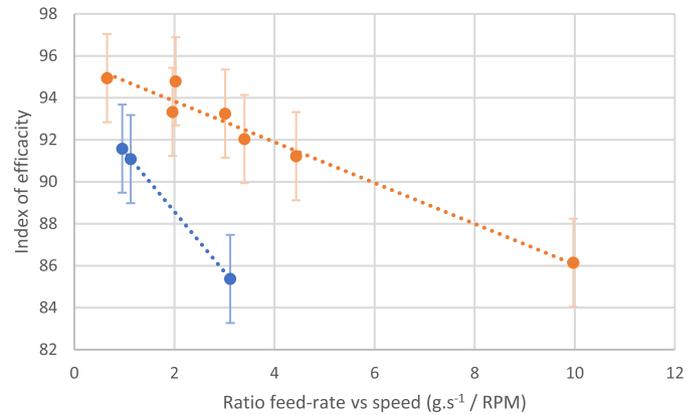
This can be seen in the Figure 7. We can consider that an optimum load of the device is necessary to obtain the desired operation. It is observed that the criterion purity of the kernels is the one that is most degraded at low speeds. It seems possible to explain it by a time of compression more important allowing a partial adhesion of the hulls. Another hypothesis would be that a certain level of centrifugal force is required to loosen the adhering hulls.

The reason why low flow rates are less well sorted at high speeds is not easy to explain. The risk of collision between particles is a priori reduced, their distribution on the working surface should not be a problem. On the other hand, the number of observations available does not allow us to be certain that the problem is not only related to a question of variability.

3.4 Effect of feed rate

The experimental set-up does not allow to highlight a significant effect of the feeding rate with a partial F probability of 0.86. The feeding system, an artisanal vibrating corridor, does not ensure a homogeneous distribution of the material on the surface of the cylinders. It can be seen in Figure 8 that there is a certain proportionality between the quality of sorting and the flow rate related to the speed of rotation (here ratio of flow rate in $g.s^{-1}$ to speed of rotation in revolutions per minute). This figure shows two distinct groups of points aligned with different slopes.

Our interpretation is that the feeding system distributed the particles over a smaller width, in the case of the blue group of points, and over a larger width, in the case of the other points. Thus, it is the surface available on the sorting plane that conditions the quality of the work. This device, intended as a proof of concept, was far from ensuring a homogeneous distribution of the particles and this appears in these results.

4 Conclusion and prospects

These preliminary trials have validated the concept. It can be concluded that it is possible to achieve a very high rate of purification (around 95%) with this system without penalizing the purity of the kernel fraction. The residual oil content that can be estimated by our NMR measurements is of 10.2%. This

figure is well below the 12% limit postulated in the introductory section of this paper.

Bell and Shires (1982), in a digestibility study, produced hulls by disk-mill followed by aspiration of the hulls and purification by sieving and obtained hulls with 10.6% oil. Kozlowska et al. (1988) observed concentrations of 14 to 19% fat in the hulls obtained from dehulling. Thakor et al. (1995) using an abrasive device for hulling followed by aspiration of the hulls obtained hulls with 18% oil. Wenlin and Fenghong (2007) using a process based on percussion of the seeds followed by separation in an air stream claim to be able to obtain a residual kernel content of less than 1% in the hull fraction. However, the best source of information appears to be the Feedipedia database, which contains a compositional table based on 32 samples indicating an average oil content of 13.2% on dry matter (11.5% at 12.5% water, Heuzé et al., 2019). The database collects analyses from industrial and experimental samples. Interestingly, the values are highly variable (7.4–24.4% on DM, standard deviation 4.5%). This variability may be partly due to the difficulty of extracting the oil present in the endosperm cells, which requires vigorous grinding to be made extractable and which not all laboratories perform (Quinsac et al., 2013).

In conclusion, compared to the literature data, our results support the best performance comparison.

The system requires a precise adjustment of the roll gap and works perfectly with hulls at natural water content. We have seen that the good functioning of the system requires a homogeneous distribution of the particles on the working surface. The feeding of the rollers requires a device which must be thought to ensure an arrival in monolayer of the particles to be separated. The process, apart from the cylinders, does not require any additional equipment. The simplicity of the principle, and the few parameters to be controlled, should allow a regular operation with few malfunctions and simple maintenance. The energy consumption and maintenance costs of this process should be low.

A search in the scientific literature and in patent databases suggests that this sorting principle is new in the field of oilseed material sorting.

The next step is to carry out pilot scale tests. For this purpose, a milling roller equipment, used for cereals milling, would be used. It would have to be modified so that the two rollers have the same rotation speed, equipped with scrapers, and differentiated guidance systems for the fractions. The quality of the steel and the surface condition is a parameter that may influence the proper functioning of the device, which is based on the adhesion of the rape kernels to the metal. This adhesion is likely to be compromised by the formation of a fat layer on the surface of the cylinders, but it seems that the passage of most hulls allows this fatty material to be sufficiently absorbed to maintain the functionality of the cylinder. Another parameter to watch is the friction effect of the scrapers on the rolls. The metal of the wipers is generally softer than that of the cylinders, however, prolonged friction can tend to polish the surfaces and make them less rough than our laboratory cylinders. A long run test will be needed to monitor the performance of the device. Another factor, that pilot scale development would need to consider, is the optimum rotational speed. The optimum would have to take into account the minimization of the process cost which implies a high capacity on the cylinders and thus a high rotation speed. The limit of the speed is the loss of separation quality that could result either from a loss of adhesion force of the kernels to the rollers, or from the increase of the centrifugal force that could eject the kernels before reaching the scraper area. The surface temperature is also likely to become limiting if the heat from the scraper friction cannot be adequately removed by transfer into the passing material.

This pilot prototype would also have to be equipped with a feeding device adapted to the handling of the hulls which are a low-density product likely to flow rather poorly.

The prospect of producing hulls with very little residual kernels would considerably improve the economic feasibility of industrial scale dehulling of rapeseed. Not only would oil losses be reduced, but the recovery of the hull fraction would be facilitated by better quality control. The depuration process allows to guarantee a constant quality with a low-fat content and consequently to find, more easily, applications in animal feed or for non-food uses. The richness in lignin of the pellicles could make them an interesting raw material for the production of biomaterials.

Supplementary Material

Table S1. Selection of patent related to rapeseed dehulling and hulls purification.
Table S2. Selection of patent related to classification B07B13 + "adherence" or "stick".

The Supplementary Material is available at http://www.ocl-journal.org/10.1051/ocl/2021046/olm.

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All patent references are given in Supplementary Material (link to the supplementary document).

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