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Rapeseed: some examples of current research
Colza : quelques exemples de recherche en France

A re-examination of the technical feasibility and economic viability of rapeseed dehulling

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Abstract – The recent success of dehulled sunflower meals on the French market encourages reconsideration of the possibility of applying dehulling techniques to rapeseed. Hulls account for 18−20% of rapeseed mass; they contain mostly fibres (72%, 78% and 99%, respectively of the seeds' NDF, ADF and ADL). Complete removal of these hulls would result in a high (43%) protein meal with enhanced added value. However, the technical feasibility of producing such a meal is impeded by the relatively high oil content of the hull fraction. This article presents a model of mass balance that takes account both of the purity of the "hull" and "kernel" fractions and comparisons of gross margins between conventional processing and dehulling-based processing. The value of dehulled rapeseed meal is assessed against both a range of market scenarios and the composition and price of a selection of alternative feeds. The gross margin differential favours dehulling only in periods where proteins are expensive and oil relatively cheap, as at present. Reducing the oil content of the hulls affects considerably the profitability of dehulling whereas modification of the protein content has only a modest impact. An important unknown is the effect of antinutritional factors on the final price of dehulled meals. Management of the glucosinolates residues through processing might decrease their noxiousness though the information on this is scant. Since this lack of knowledge is an impediment to the implementation of dehulling technology, research and development investments should start by addressing this question. Technical solutions could be developed to recover the oil contained in the hulls. Such solutions include expelling, aqueous extraction or tail-end dehulling after direct extraction of the seeds.

Keywords: Rapeseed / dehulling / proteins / oil / processing / high-protein meal / feasibility / gross-margin

Résumé – Nouveau regard sur la faisabilité économique et technique du déplliculage des graines de colza dans le contexte actuel. Le succès récent des tourteaux de tournesol décortiqués sur le marché français amène à reconsidérer la possibilité d'appliquer le procédé de dépelliculage aux graines de colza. Les pellicules de colza représentent 18−20 % de la masse des graines et contiennent principalement des fibres (respectivement 72%, 78 % et 99 % des fractions NDF, ADF et ADL des graines). L'élimination complète de ces pellicules pourrait permettre d'obtenir un tourteau à haute teneur en protéines (43 %) présentant une meilleure valeur ajoutée. À l'heure actuelle, la faisabilité technique d'un tel tourteau est compliquée par la présence d'une quantité relativement importante d'huile dans les pellicules. Cet article présente un modèle de bilan matière en tenant compte de la pureté des fractions « pellicules » et « amandes » et aboutissant à des comparaisons de marge brute entre le procédé conventionnel et celui incluant une étape de dépelliculage. La valeur du tourteau de colza dépelliculé est évaluée dans différents contextes de marché en fonction de la composition et du prix d'une sélection de matières premières. Le différentiel de marge brute n'est en faveur du dépelliculage que lorsque le prix des protéines est élevé et celui de l'huile modéré comme dans le contexte actuel. La réduction de la teneur en huile dans la fraction « pellicules » affecte fortement la rentabilité du procédé de dépelliculage tandis que la modification de la teneur en protéines a un impact plus faible. L'effet des facteurs antinutritionnels sur le prix final du tourteau dépelliculé reste difficile à appréhender. Il serait possible de moduler la nocivité des résidus de glucosinolates par le procédé mais peu d'information est disponible sur la question. Ce manque de connaissances est un obstacle au développement de la technologie, il serait donc nécessaire de commencer les investissements de recherche et développement en vue de répondre à cette question. Les solutions techniques pour récupérer l'huile contenue dans les pellicules comme par exemple le pressage, l'extraction aqueuse ou le dépelliculage après l'extraction directe des graines pourraient être développées.

Mots clés : Colza / dépelliculage / protéines / huile / tourteau à haute teneur en protéines / procédé / marge brute

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Symbols and abbreviations

ϕ: proportion of hulls in dry seeds

α: proportion of pure kernels in the processed hulls

k: proportion of pure hulls in the processed kernels

C_j^i: component concentration (g/100 g DM)

W_j^i: component concentration (g/100 g wet basis)

M_i^x: mass of fraction i (kg/100 kg of seeds wet basis)

$i = tk$: processed kernels

s: seeds

th: processed hulls

pk: pure kernels

ph: pure hulls

$\hat{s}$: estimated seed

m_s: meal from seeds

m_k: meal from kernels

O_s: oil from non-dehulled seeds

O_{tk}: oil from processed kernels

O_{m_s}: oil contained in the meal from seeds

$O_{m_{tk}}$: oil contained in the meal from kernels

j: 1 = oil, 2 = proteins, 3 = crude fibre, 4 = ashes, 5 = NDF, 6 = ADF, 7 = ADL, 8 = water, 9 = dry matter

x: n = non-dehulling, d = dehulling, p: price, pc: price corrected

ADF: acid detergent fibre

ADL: lignin

DRSM: dehulled rapeseed meal

DM: dry matter

NDF: neutral detergent fibre

RSM: rapeseed meal

SBM: soybean meal

S: coefficient

T: equivalence factor.

1 Introduction

During the period 2006−2012 consumption in France of sunflower meal grew from 710 to 1 345 kt/year. During that same period the market share of dehulled meal expanded from one third to two thirds (Le Kall, 2013). This implies that the market share of low-protein sunflower meal stagnated while that of the high-protein meal grew by a factor of 3.7. This evolution occurred against the background of substantial imports of meal from the Black Sea area and the implementation of dehulling technology in a single French oil-mill. The success of high-protein meal underlines the interest in quality improvements; it also reopens the question of the possibility of applying dehulling technology to rapeseed.

For the processing industry, the principal advantage of dehulling resides in the increased value that accompanies increases in protein concentration. For example, in May 2014, the price of one ton of non-dehulled sunflower meal was 188 €, as compared with 272 € for partially dehulled meal (La Dépêche, 4 May 2014). Considering their respective protein concentrations (28.2 and 34.8%) one ton of protein was valued at 667 € in low-protein meal whereas the same amount of protein was valued at 782 € when sold in high-protein meal. Selling on the hulls or using them as a source of energy represents an additional gain.

Dehulling technology was tested on rapeseed at an industrial scale in France in the 1980s. However, in light of oil-losses attributable to the difficult purification of the hulls fraction and the limited market interest in the dehulled meal itself, this experience was not extended to other mills. Since this time, the situation has changed considerably: vegetable proteins have become more valuable and the interest in fibres for the feed market has grown.

This study focuses on the economics of the technology and identifies the various hurdles that would have to be surmounted if highprotein rapeseed meal is to become economically viable. Our assessment of the value of the dehulled fraction has been established not from the existing information about these materials (such data that exist are obtained from the use of a specific technology with its own limitations and constraints) but rather from theoretical predicted values derived from correlations between the composition of different feedstuffs (meals, grains, by-products, *etc.*) and their market price. The mass distribution was calculated rigorously from a hypothetical repartition of the seed coats and germs in the “hull” and “kernel” fractions. The model is assessed for its sensitivity to factors such as the historical evolution in market prices, the oil content of the hulls and protein content of the meal. In the final section, we review the various hurdles that limit the technical feasibility of seed fractionation; possible solutions are suggested. Since the economic value of dehulled meals might be diminished by the presence of antinutritional factors this issue is also addressed. The concluding section presents an assessment of the pros and the cons of rapeseed dehulling. Directions for future research in particular with regard to addressing the technical hurdles to efficient dehulling, are also proposed.

2 Rapeseed composition

In Brassicaceae seeds the embryo is wrapped in tegument, a thin black coat which is mainly composed of fibre with a high proportion of lignified material (ADL). A residual endosperm adheres to the inner face of the tegument. It presents the form of a cell base with thick walls containing oil bodies and proteins bodies (Groot *et al.*, 1993).

Table 1 presents the composition of the seeds and the fractions obtained from them. Processed hulls and processed kernels are obtained through mechanical dehulling followed by purification of the fractions. These fractions are not wholly pure (kernels are contaminated by residual hulls, and *vice versa*) We therefore calculated the percentage of pure hulls in the seeds, the percentage of pure kernels in the processed hulls and the percentage of pure hulls in the processed kernels with

Table 1. Composition of rapeseed seeds, hulls, and kernels and meals.

	Oil (% DM)	Proteins (% DM)	Crude fibre (%DM)	Ashes (%DM)	NDF (%DM)	ADF (%DM)	ADL (%DM)	Dry matter content (%w/w)
Seeds (corrected values)	47.7	21.8 (20.3)	8.1	5.1	14.9	11.2	5.9	92.4
Technical kernels (corrected values)	53.3 (56.5)	24.5 (21.5)	2.7	4.7	5.27	3.3	0.3	93.4
Technical hulls	12.0	15.2	32.3	6.6	50.7	41.8	23.1	89.3
Pure kernels (calculated and corrected)	53.7 (57.0)	24.6 (21.6)	2.4	4.7	4.8	2.9	0.1	
Pure hulls (calculated)	9.1	14.8	34.2	6.7	53.7	44.3	24.6	
Theoretical seeds	48.0	20.3	8.3	5.1	13.9	10.6	4.7	
Squared differences between reals seeds and theoretical seeds (after correction)	5.2 (0.1)	0.9 (0.0)	0.1	0.1	0.9	0.3	1.6	
Hull share of the seeds component (based on theoretical seeds)	3.6%	13.7%	76.8%	24.9%	72.1%	78.0%	99.0%	
Theoretical meal from seeds	2.7	40.6	15.1	8.7	27.7	20.8	11.0	
Theoretical meal from kernels	2.0	51.4	5.7	9.9	11.1	6.9	0.6	88.7
Theoretical Meal from kernels corrected	2.0	48.4	6.1	10.6	11.9	7.4	0.7	89.0

Source: (Dauguet, *et al.*, 2013). Correction of kernel oil content corresponds to the adjustment necessary to harmonize with other composition values. Correction of protein content corresponds to an adjustment to match the average protein content of rapeseed meals.

the help of the following equations.

$$C_j^{pk} = \frac{C_j^{tk} - C_j^{ph} k}{1 - k}, \qquad (1)$$

$$C_j^{ph} = \frac{\left(C_j^{th}(1-k) - C_j^{tk}\alpha\right)}{1 - \alpha - k.}, \qquad (2)$$

$$C_j^{\hat{s}} = C_j^{pk}(1-\phi) + C_j^{ph}\phi, \qquad (3)$$

$$SS = \sum_j^7 \left(C_j^s - C_j^{\hat{s}}\right)^2. \qquad (4)$$

The values of ϕ, α and k were adjusted thanks to the solver algorithm of an Excel spreadsheet in order to minimize SS, the sum of squares (Eq. (4)), i.e., to obtain the values that give the best fit for the theoretical composition of the seeds according to equation (3).

Since there is no unique solution to this system of equations, it is necessary to set initial values for the iteration. For the hull content of the seeds, ϕ, the average value in the literature is 18% (Appelqvist *et al.*, 1972) (Kracht *et al.*, 2004), (Laisney, 1983). Values of 4% and 2% for α and k respectively were chosen in light of a visual assessment. Two constraints were introduced in the solver in order to avoid aberrant results: the value of k should be greater than or equal to 1% and the ADL value of pure kernels has to be at least equal to 0%.

In these conditions, the SS was 9.0, ϕ = 18.7%, α = 6% and k = 1%.

The adjusted value of the seeds' oil content is less satisfactory with a difference of 2.3 percentage points. This implies that the oil content of the processed kernel had been underestimated. Considering that the oil content of the seeds is consistent with average French rapeseed (CETIOM, 2014) and that the oil content of the hull fraction is equally coherent with data in the literature (Baudet, 1983) (Thakor *et al.*, 1997), we corrected the oil content of the kernel fraction from 53.3 to 56.5% in order to obtain the same mass of defatted dry matter in the hulls and kernels as in the seeds. Then, in order to avoid overestimation of the protein content of the meals, a second correction was performed. Indeed, the protein content of the seeds expressed as a proportion of dry defatted matter is higher in our seeds (41.7%) than in average French rapeseed (38.8%) (Garnon, 2011). In consequence, a new value for the seeds' protein content was introduced (20.3% of DM) and the protein content of the kernel fraction was adjusted to fit with the value corresponding to the modified seed protein content. The appropriate value was 21.5% (DM).

The compositions of theoretical meals from seeds and from kernels were calculated according to the following equations:

$$C_j^{m_s} = C_j^s \frac{\left(1 - 0.01 C_j^{m_s}\right)}{\left(1 - 0.01 C_1^s\right)} \qquad (5)$$

$$C_j^{m_k} = C_j^s \frac{\left(1 - 0.01 C_1^{m_k}\right)}{\left(1 - 0.01 C_1^{tk}\right)} \qquad (6)$$

with $j \neq 1$.

The value of the oil content ($C_1^{m_s}$) of the regular meal was taken from the results of the national survey of French rapeseed meal managed by CETIOM (CETIOM, 2014). The value of the oil content of the kernel meal ($C_1^{m_k}$) was arbitrarily set to 2%. The protein content of this theoretical meal expressed on wet basis would be 43.1% at 11% of water, a value close to the 45.6% of regular soybean meal (Sauvant *et al.*, 2004).

According to these results, one can consider that rapeseed hulls contain around 3–4% of seed oil, 13–14% of proteins 79% of crude fibre, 67.5% of NDF, 74% of ADF and 78% of lignin.

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Glucosinolates are mostly located in the germ. According to Bell and colleagues, the glucosinolates content of seeds and hulls in Tower canola are 18.2 and 4.7 µmoles/g respectively (Bell *et al.*, 1982). Depending on the dehulling yield, the glucosinolates content increases by 15−25% in the kernels. The rise in glucosinolates content in the defatted meal is difficult to predict since a significant proportion of these compounds may be degraded during the desolventization step. It was observed in a study on various dehulled rapeseed meal processed at pilot-plant scale that the ratio of the glucosinolates content in DRSM and the corresponding RSM was in the range 1.04 and 1.51 (Quinsac *et al.*, 2013)

3 Mass balance calculations

Conventional oilseed processing results in just two products: oil and meal. Usually, the gums removed from the crude oil are reincorporated into the meal and contribute thereby to its fat content. One can therefore assess the amounts of these products for 100 kg of seeds on the basis of the seeds and meals composition by the following equations:

Oil retained in the meal from non-dehulled seeds:

$$M^n_{O_{ms}} = \frac{\left(W^s_9 - W^s_1\right)}{\left(1 - 0.01.C^{m_s}_1\right)} - \left(W^s_9 - W^s_1\right) \tag{7}$$

Production of oil from non-dehulled seeds:

$$M^n_{O_s} = W^s_1 - M^n_{O_{ms}} \tag{8}$$

Production of meal from non-dehulled seeds:

$$M^n_{m_s} = \frac{\left(W^s_9 - W^s_1 + M^n_{O_{ms}}\right)}{W^{m_s}_9.0.01} \tag{9}$$

$$Ak = \frac{(1 - \varphi - \alpha)}{(1 - \alpha - k)} \tag{10}$$

$$B_k = \frac{100.Ak}{W^{tk}_9} \tag{11}$$

$$B_h = \frac{100.(1 - Ak)}{W^{th}_9} \tag{12}$$

Processed hulls:

$$M^d_{th} = \frac{100.B_h}{(B_k + B_h)} \tag{13}$$

Processed kernels:

$$M^d_{tk} = \frac{100.B_k}{(B_k + B_h)} \tag{14}$$

Oil retained in the meal from dehulled seed:

$$M^d_{O_{m_{tk}}} = \frac{\left(W^{tk}_9 - W^{tk}_9.C^{tk}_1.0.01\right)}{\left(1 - C^{mk}_1.0.01\right)} - \left(W^{tk}_9 - W^{tk}_9 C^{tk}_1.0.01\right) \tag{15}$$

Production of oil from processed kernels:

$$M^d_{O_{tk}} = W^s_1 - M^d_{O_{m_{tk}}} - M^d_{th} W^{th}_1.0.01 \tag{16}$$

Table 2. Mass balance (in kg for 100 kg of seeds).

Material	Non-dehulled (kg/100 kg of seed)	Dehulled (kg/100 kg of seed)
Production of oil	42.8	41.2
Production of meal	56.0	37.6
Lost water	1.3	1.5
Processed hulls		19.8
Total product	100.0	100.0
Processed kernels		80.2
Oil retained in the hulls		2.1
Oil retained in the meals	1.3	0.8

Production of meal from dehulled seeds:

$$M^d_{m_k} = \frac{M^d_{tk}.\frac{\left(W^{tk}_9 - W^{tk}_9.C^{tk}_1.0.01\right)}{100} + M^d_{O_{m_{tk}}}}{W^{m_k}_9.0.01} \tag{17}$$

With C^s_1, C^{tk}_1, C^{th}_1, C^{ms}_1, and C^{mk}_1 given in Table 1 in the second column and W^s_9, W^{tk}_9, W^{th}_9, W^{ms}_9 and W^{mk}_9 given in Table 1 in the ninth column.

W^i_j and C^i_j are linked by the equation: $W^i_j = 0.01.C^i_j W^i_9$. The Table 2 gives the results of the numerical application based on the corrected values from Table 1.

4 Assessing the value of the dehulled meals

The profitability of dehulling is dependent on the resulting value of the products. Since these products are not presently available on the market, modelling is the only means of assessing their likely prices. The construction of a rational model based on their feed-value is beyond the scope of this paper since we lack the required information. In the case of dehulled sunflower seeds, the market price was relatively easy to predict on the basis of their protein concentration and the market prices of other meals We have tried here to model the price of dehulled rapeseed meal, taking as a basis its theoretical composition.

We propose a multiple regression based on the composition of a selection of feedstuffs and their prices. The modelling drew on a series of 6-monthly observations from June 2008 to April 2014. The data matrix for April 2014 is presented in Table 3 (Prices, see Appendix). The composition values in the table are taken from Sauvant and colleagues (Sauvant, *et al.*, 2004). The price source is the weekly French newspaper *La Dépêche*. The quotes refer to significant markets such as Lorient for SBM, Rouen for wheat and RSM. Those selected were for the earliest delivery.

The best prediction for price is given by the following model:

$$P_{m_{tk}} = K + Oil\, W^{m_{tk}}_1 + Pr W^{m_{tk}}_2 + Ash W^{m_{tk}}_4 + NDF\, W^{m_{tk}}_5 + ADL W^{m_{tk}}_7 \tag{18}$$

The coefficients K, Pr, Ash, NDF, ADL used in equation (18) and presented in Table 4 below, were obtained through a multiple regression procedure using SAS software (9.2). At the first

Table 3. Composition (as feed) of a feeds selection, observed and predicted market values according to a multiple linear regression model (April 2014).

	Proteins	Fat	Crude fibre	NDF	ADL	Ashes	Real price (€/t)	Pred. price (€/t)
Wheat straw	3.8	1.3	37.8	70.8	6.7	6.2	42	48
Bran	15	3.3	9.1	38.5	3.2	4.9	130	176
Barley	10.1	1.8	4.6	18.4	1.1	2.2	170	186
Corn	8.1	3.8	2.2	10.7	0.5	1.5	175	166
CGF	19.3	3	7.4	34.9	1.2	3	195	200
Wheat	11	1.4	2.3	12.4	1	1.6	200	198
Alfalfa D17	15.8	2.7	26.5	41.9	7.7	10.7	213	226
Sunflower meal (28–30)	28.2	1.9	25.1	40.8	9.5	6.2	222	200
Sugar beet pulp	8.2	0.8	17.7	42.6	2.2	6.7	232	201
Sunflower meal (35)	34.8	1.4	19.6	33.3	7.3	6.8	273	294
Rapeseed meal	33.9	2.4	9.3	28.1	8.7	6.9	284	274
Peas	20.7	1	5.2	12.5	0.35	3	285	286
DDGS (wheat)	30.2	4.2	5.6	28.5	3.1	5.1	285	273
Faba bean (Vicia faba)	24.9	1.1	8.1	14.7	1.1	2.4	290	283
DDGS (corn)	24.6	3.7	7.4	34.8	2	6	293	264
Soybean meal	45.6	1.8	5.9	12.3	0.6	6.3	450	464
Dehulled RS meal	43.1	1.8	5.4	10.6	0.6	9.4		455

Table 4. Multiple regression coefficients for 13 market situations and predicted value of dehulled RSM.

	SBM (€/t)	RSM (€/t)	$P_{m_{tk}}$ (€/t)	K	Oil	Pr	Ash	NDF	ADL	R^2	P (F)
April-14	450	284	455	165.25	−10.32	5.28	17.68	−2.13	−12.30	0.955	< 0.0001
Dec-13	439	249	426	166.73	−11.04	4.45	19.68	−2.06	−14.14	0.951	< 0.0001
June-13	448	308	442	181.47	−10.21	5.56	10.52	−2.05	−7.73	0.895	0.007
Dec-12	464	306	468	220.82	−1.69	5.25	8.62	−2.31	−9.04	0.968	< 0.001
June-12	430	268	409	177.36	−4.23	4.42	12.65	−2.37	−9.01	0.904	0.0002
Dec-11	286	180	291	198.15	−9.24	1.89	8.03	−1.59	−8.42	0.836	0.0011
June-11	293	209	307	248.21	−4.22	−0.25	17.88	−2.81	−7.76	0.867	0.0131
Dec-10	331	229	329	180.27	−1.72	2.94	7.74	−1.89	−6.09	0.819	0.0037
June-10	307	182	279	95.30	−5.20	3.91	6.28	−1.24	−3.36	0.897	0.0024
Dec-09	318	170	285	88.07	−5.74	3.99	8.51	−1.27	−7.04	0.925	< 0.0001
June-09	331	165	304	102.38	−11.93	4.25	9.21	−1.18	−8.30	0.872	0.0020
Dec-08	244	145	237	113.35	−9.67	2.06	11.06	−1.20	−7.25	0.931	0.0006
June-08	373	215	352	195.85	−11.56	2.96	12.22	−2.16	−7.44	0.839	0.0105

stage, the entire composition matrix was inputted and the stepwise option employed. This method is iterative, with variables introduced or eliminated one by one according to whether their F statistic is significant at a predefined level. This analysis carried out on the different datasets did not systematically select the same variables for the model so, in a second analysis, we used the variables (oil, proteins, ashes, NDF and ADL) that had been included by the stepwise procedure in the best predicting situations. The full model was then used.

The signs on the coefficients pertaining to protein and fibre concentrations are perfectly logical. However, the negative sign for the oil and the positive sign for ashes are counter-intuitive. Since dehulled rapeseed is rich in ash, the model seems to overestimate the predicted price for this meal. It was therefore decided that the percentage ash content of the dehulled rapeseed meal (DRSM) should be replaced by the ash content of soybean meal (SBM) in order to avoid an over-optimistic assessment.

The predicted value for DRSM is strongly related to the SBM price.

$$DRSM_{\mathrm{p}} = 1.8 \times 10^{-3} SBM_{\mathrm{p}}^2 - 0.322 \times SBM_{\mathrm{p}} + 218.7. \quad (19)$$

The correlation between the predicted values of equations (18) and (19) has an R^2 coefficient of 0.97, so it is possible to use historical values of SBM as a rough predictor for the value of DRSM.

Soybean meal is the dominant protein source worldwide, accounting for 72% of vegetable proteins from oilseeds meals, legume grains and by-products of starch industry. Its value strongly influences the value of other protein materials but as shown in Figure 1, SBM and RSM prices correlation explains just 70% of the RSM value. The respective availability of these meals explains the rest of the variability (Carré *et al.*, 2014).

Because 30% of the variability in the price of RSM is not explained by the SBM price it seems relevant to take in to account this variability in the spread of meal prices. We considered the following S coefficient:

$$S = \frac{\left(SBM_p - RSM_p\right)}{\frac{\left(SBM_p + RSM_p\right)}{2}} \quad (20)$$

where SBM_p is the price of SBM and RSM_p is the price of RSM.

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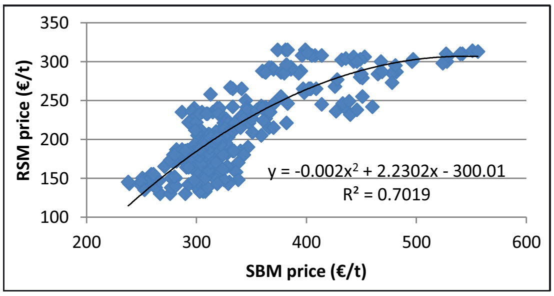

Fig. 1. Relationship between RSM prices and SMB prices, January 2008 to April 2014.

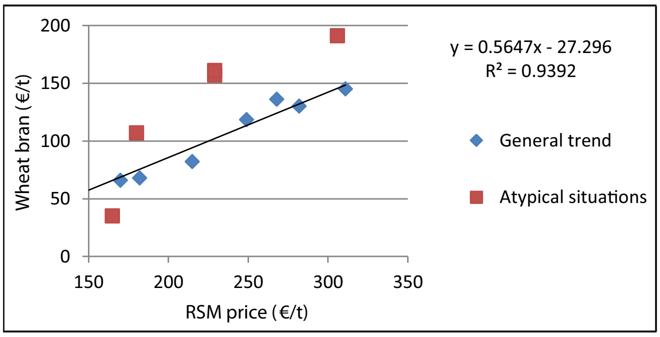

Fig. 2. Relationship between RSM price and wheat bran price.

The average S value was 0.466 during the period studied and the standard deviation was 0.135. For a third of the observations then, S was outside a range of 0.33–0.60. We introduced this additional variability into our estimate for the DRSM price by the factor T:

$$T = 1 + \frac{1}{2}(0.466 - S). \qquad (21)$$

When RSM and SBM prices are converging, the supply demand balance favours rapeseed products and hence the DRSM price should increase. In consequence, when S is lower than 0.466, T is greater than 1 and conversely, when the spread between the prices widens, the situation becomes unfavourable to DRSM and T descends below 1. The 1/2 coefficient dampens these variations in order to avoid situations in which DRSM prices are substantially higher than those of SBM. By multiplying the predicted DRSM price of equation (19) by the T factor from equation (21), we obtain a corrected value for DRSM price that takes account of this variability.

$$DRSM_{pc} = DRSM_p \times T. \qquad (22)$$

5 Prediction of the hull prices

Predicting the price of hulls is much more difficult because no other feedstuff has its profile of high oil and protein concentrations accompanied by a high proportion of lignin. These characteristics limit its possible use for animals that require fibres in their food, such as ruminants or rabbits. The oil content may nevertheless be valued by dairy cow or goat farmers Indeed, the introduction of lipids in their rations can result in higher milk production with more proteins and reduced saturated fatty acids (Brunschwig *et al.*, 2006). Methane emissions by ruminants may be reduced by adding unsaturated oils to their feed (McGinn *et al.*, 2004) although reduction by this means can according to Beauchemin, Martin and their colleagues, result the fibre fraction becoming less digestible (Beauchemin *et al.*, 2006) (Martin *et al.*, 2008). In view of the growing concern about greenhouse gases emissions from cattle, these properties could render processed rapeseed hulls an attractive source of forage, especially in intensive large production units where roughage has to be brought in from distant areas.

For this study, we decided to use the price of wheat bran as a benchmark because it has similar protein content to rapeseed hulls. Bran is, moreover, systematically cheaper than the other obvious alternative, dehydrated alfalfa; as such it is a more conservative comparator. The graph of RSM and bran prices, Figure 2, reveals a clear general trend of relative prices from which an equation for price prediction can be derived, equation (23).

Table 5. Comparison of crushing gross margins (April 2014).

Per 1 t of seeds	Regular meal (€/t of seeds)	Dehulled meal (€/t of seeds)
Seed purchase	409.0	409.0
Oil sale	315.5	304.1
Meal sale	159.0	160.4
Hulls sale		25.7
Gross margin	65.5	81.2
Oil price (€/t)	738	738
Meal (€/t)	284	427
Hulls (€/t)		130

$$Hull_p = RSM_p \times 0.57 - 27.30. \qquad (23)$$

Equation (23) has been used to predict the price of hull to an equivalence with wheat bran predicted value.

6 Gross margin comparisons

Table 5 presents a comparison between the gross margins from crushing whole meal and dehulled meal. That the comparison favours dehulling can be explained by the present structure of commodity prices: expensive proteins and relatively cheap oil. Since the second semester of 2012, the prices of oils have decreased and those of meals have increased. In order to assess the sensitivity of the economic feasibility of dehulling to such variations, we used the equivalence factor presented earlier to calculate the gross margin differential in historic contexts.

Figure 3 presents the predicted values of DRSM from equations (22) (PrDRSMc) and (19) (PrDRSMa), the gross margin comparison between DRSM and RSM using the predicted value of DRSM from equations (22) (GMc) and (19) (GMa), the price of rapeseed oil (OSR OIL) and the price of soybean meal (SBM).

This method drawing on variations in the gap between meal prices seems to give less volatile results and rarely negative profits. On the other hand, these profits are not as high

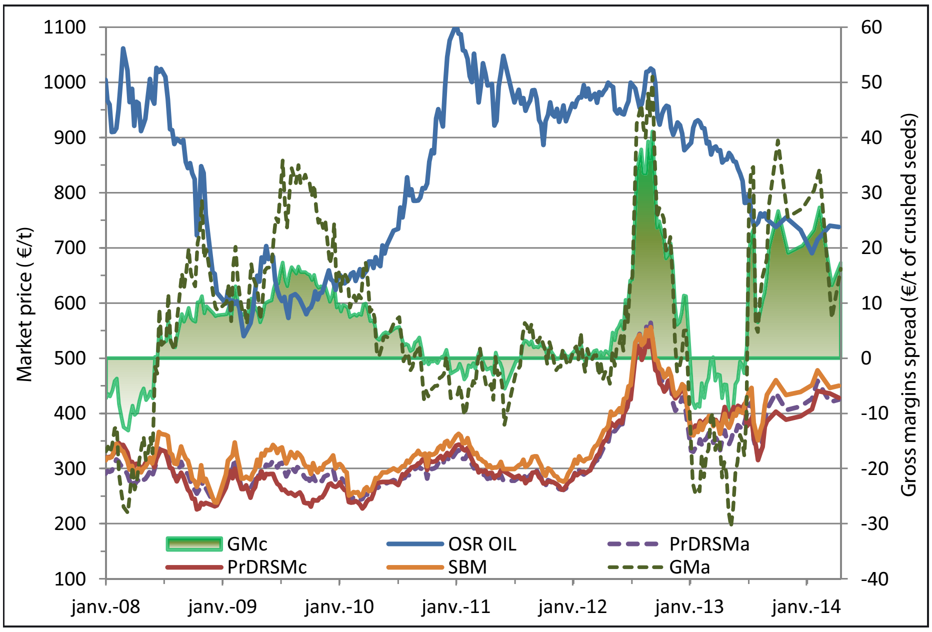

Fig. 3. Profitability of dehulling as a function of the historical variations in seed, oil and meal prices. GMc: gross margin comparison (DRSM vs RSM) using DRSM predicted value from equation (22); GMa: idem using DRSM predicted value from equation (19); OSR OIL: price of rapeseed oil; SBM: price of soybean meal; PrDRSMc: predicted value of DRSM from equation (22); PrDRSMa: predicted value of DRSM from equation (19).

Table 6. Average value of oilseeds and oilseeds products in 3 contrasted periods.

Situation	Start	End	Seeds (€/t)	OSR oil (€/t)	SBM (€/t)	RSM (€/t)	DRSMp (€/t)
1	31/01/12	26/06/12	469.7	971.9	370.1	239.7	348.6
2	18/12/12	18/06/13	462.1	879.8	385.9	298.1	392.9
3	25/06/13	18/03/14	378.4	750.2	419.7	246.6	381.3

as when the SBM price is the sole indicator of DRSM value. The predicted value for DRSM closely approaches the SBM price during the first semester of 2013 because of relatively high prices for RSM during that same period. The opposite trend occurs after June 2013 enabling a positive gross margin differential for dehulling. This observation implies that dehulling will be profitable when RSM prices are relatively low compared to SBM prices.

Particularly noteworthy is that the profitability of dehulling may become very attractive in a context of strong demand for proteins and falling oil prices. Very high oil prices, by contrast, are unfavourable because of the oil losses that occur during the fractionation of the seeds.

7 Effect of the hulls oil content in 3 different market situations

Table 6 shows the average prices for rapeseed, rapeseed oil, soybean meal, regular rapeseed meal and our predicted dehulled rapeseed meal during three periods of contrasted market situations. These periods are characterized by a decreasing price of oil, an increasing price of SBM and non-correlated values between RSM and SBM. ΔGM is the difference in gross margin with and without dehulling.

Not surprisingly, situation 3 with its lower oil price tolerates higher losses of oil during dehulling. However, in all three cases, the sensitivity of profits to these losses is strong, Figure 4; the dehulling technique has to be oil-efficient. Dehulling is never profitable when the oil content of the hull fraction exceeds 20% Surprisingly, the profitability in situation 2 with its intermediate oil price is lower than in situation 1. This is attributable to the lower improvement in the value of DRSM in situation 2 as compared to situation 1: the price of conventional RSM was expensive in comparison to of SBM value, and so the benefit of dehulling was diminished.

8 Effect of the proteins content in DRSM

The percentage of hulls left among the "processed kernels" fraction can vary. Indeed, in order to avoid too high a loss of oil it may be preferable to reduce the power applied to break the seeds and leave scraps of hull among the kernels. We therefore studied the effect of these variations on the profitability of dehulling. The DRSM prices set out in Table 6 were used to assess the economic value of partially dehulled RSM. Simple linear regressions based on equations (1)–(17) were used to predict these prices as a function of protein content. Figure 5 presents them.

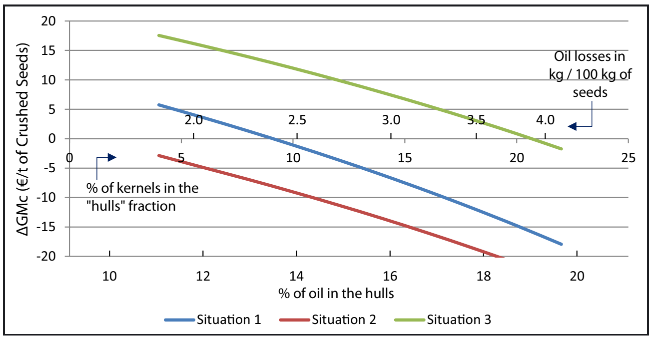

Fig. 4. Gross margin differentials in three economic scenarios and the purity of the hull fraction for DRSM with 43.1% proteins.

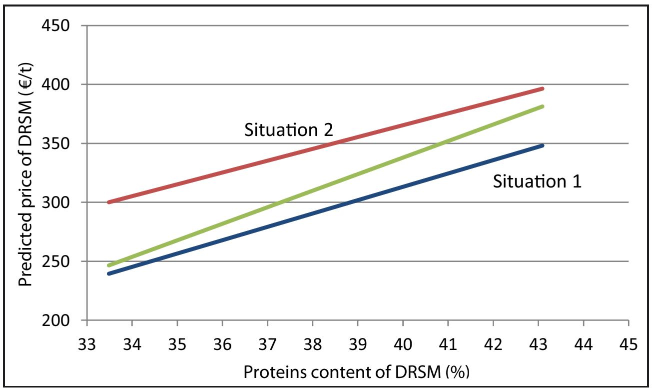

Fig. 5. Predicted prices of partially dehulled RSM according to their protein content.

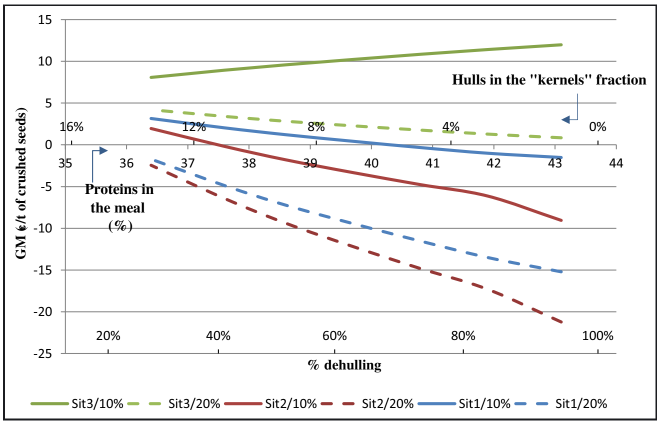

Fig. 6. Gross margin differentials under three economic scenarios with varying protein content and purity (10 or 20 % of kernels contamination) of the dehulled meal.

These modified mass balance and meal values were used to compare the gross margins from dehulling and conventional techniques. The movements in these gross margin differentials for two levels of hull purity and, as before, for three periods are presented in Figure 6. As the degree of dehulling increases, oil loss grows and the economic benefit of improving the meal's quality is positive only in situation 3 with good hull purification. In the other situations, profitability may be positive with low degrees of dehulling and become negative with high protein meals. Whilst it is apparent in Figure 5 that a slight decrease in protein concentration has in general only a moderate effect on meal value, there are thresholds in protein concentration at which meal buyers decide whether or not to purchase. In consequence, the predictions given by the model are just an indication of the potential benefit of DRSM. Considering the trade-off between protein concentration in the meal and the oil losses in the hulls, our model shows that oil losses will generally outweigh protein concentration in importance in determining the gross margin.

9 Technological hurdles

Several technological hurdles impede the development of a DRSM process: (a) poor performance of mechanically extracting kernel oil; (b) the difficulty in purifying the hull fraction; and, (c) the difficulty in preventing the concentration of antinutritional elements in the meal.

The available technologies for separating kernels from hulls require first that the seed be broken and then that the resulting fractions be separated (Rass, 2001). The first step involves impacts or controlled deformation, which generates small particles. Because of their high oil content these sticky particles are then difficult to separate efficiently from the hulls. Processed hull fractions contain about 20% of oil rather than the 12% which may be obtained under experimental conditions. As a consequence, real oil losses are not 2.1 kg per 100 kg of seeds as estimated in Table 2 but rather 4.0 kg. This figure can be reduced by employing mechanical extraction on poorly purified hulls but the quality of the oil resulting from this recovery is not very good. Kozlowska and colleagues characterized the lipids extracted from mechanically separated hulls of high and low-erucic Polish RSM varieties. They found that hull lipids contain higher acid values and lower triglycerides. Moreover, this oil had diminished oxidative stability (Kozlowska *et al.*, 1988).

To avoid these losses, it has been proposed that the teguments be removed after extraction. Sosulski and Zadernowski proposed that the meal be finely ground and the particles then dispersed in hexane in order to achieve a hydrocyclonic separation (Sosulski, *et al.*, 1981). With this technology it was possible to obtain a protein concentrated meal with 45% (DM) protein content and a hull fraction with 26% (DM) protein content. The method enabled the recovery of a small quantity of oil but the size of the low protein fraction was rather large: 34% of the initial meal. According to our calculations, meals with 1% of oil and a water content of 11.5% would have high and low protein fractions of 40.5 and 23.3%, respectively. The value of the high protein fraction evaluated by our model in situation 3 would be 345 €/t versus 420, 247, 381 €/t for SBM, RSM and our hypothetical DRSM respectively. Assessing the value of the low-protein fraction is subject to considerable uncertainty since though its oil content is low the product combines relatively high proteins (22% as feed) with a high fibre concentration (40.5, 32.9 and 17.4 % for NDF, ADF and ADL as feed). The linear regression from Figure 5 was used to propose a value for this meal which was 91 €/t (*vs.* 113 €/t for hulls that have not been deoiled). Table 7 presents a comparison of the crushing gross margins according to method proposed by Sosulski and Zadernowski.

Table 7. Comparison of gross margins applying the Sosulski and Zadernowski method (Situation 3).

Per 1 t of seeds	Regular meal (€/t of seeds)	Dehulled meal (€/t of seeds)
Seed purchase	378.0	378.0
Oil sale	320.7	326.0
Highpro meal sale	138.0	124.9
Lowpro meal sale		17.7
Gross margin	80.8	90.5
Oil price (€/t)	750	750
Highpro (€/t)	284	345
Lowpro (€/t)		91

Most of the value generated by applying Sosulski and Zadernowski's method comes from the enhanced extraction of oil resulting from the secondary contact of the ground meal with the solvent. Given that the quality of this oil could impact negatively on the refining yield and that reprocessing the meal in hexane will generate additional costs it is not clear that the improvement in gross margin will translate into an overall profit.

A simplified method in which the seeds would be ground directly in the solvent might lower the costs. However, as Sosulski and Zadernowski have noted wet milling rapeseed in hexane presents the further difficulty of the seeds' increased resistance to milling, as well as an additional burden of safety requirements.

Mustafa and colleagues have studied a simple tail-end dehulling technique in which desolventized meal has its moisture content adjusted to 16%; this meal is then disc-milled and sieved (Mustafa *et al.*, 1996). This method results in a high fibre and a low fibre fraction which account for 60 and 40% respectively of original meal. Starting with conventional meal containing 37.7% crude proteins and 13.1% crude fibre (DM basis), the low-fibre fraction contains 40.2% protein and 9.6% crude fibre; the high-fibre fraction contains 35.2% protein and 14.3% crude fibre. These compositions[1] inputted into our price prediction model at the April 2014 context, when regular meal was priced 284 €/t, give prices of 325 and 216 €/t respectively for low and high fibre meals. A gross margin comparison does not favour this method of fractionation (−13.7 €/t of seeds). This can be explained by the competition from distillers grains (DDGS) which offer relatively high protein and low lignin contents.

Another Canadian study (Clark *et al.*, 2001) using the same method of fractionation obtained slightly lower proteins enrichment performance with the low fibre fraction (+5.6% *vs.* 6.6% in the Mustafa study).

Hexane extraction of front-end separated hulls is another option. It would slightly increase the processing cost but could resolve the oil-loss issue. In theory, adding a line with an extractor and a desolventizer should not have a huge impact on the processing cost because it will use existing facilities and should not require additional manpower. If we consider a conservative cost of 20 € per ton of extracted hulls and the removal of 200 kg of hulls per ton of seeds, the additional cost would be approximately 4 € per ton of seeds. This cost is to be compared with the reduction in oil sales in Table 5 (11.4 €/t) which was calculated against a slightly lower oil price (738 *vs.* 750 €/t). The defatted hulls could be used for energy production in the same way as sunflower hulls. At 5.5 MWh/t the minimal value of this fuel would be similar to coal which is around 15 €/MWh, i.e. in the worst case 83 €/t. This decrease in value would result in a reduction in revenue from hulls sales of about 5−6 €/t of seeds but it would lead to an improvement in the protein content of the dehulled rapeseed meal. The downside of this possible solution is the high protein content of the defatted hulls which would be a pure waste per se and would cause NO_x emissions during their combustion.

Aqueous extraction of both oil and proteins could resolve this problem. In theory, aqueous extraction is unfeasible since rapeseed proteins behave as a resilient emulsifier and the result of such an extraction cannot be separated by conventional centrifugal separation. In the case of a dehulling scheme, this cream could be dehydrated and then mixed with the press cake before hexane extraction so that both the oil and proteins could be recovered. The drawback of this approach is that large amount of water must be removed from the cream and from the hulls. For example, if the fractionation results in a "kernels" fraction with 2% of residual hulls and a "hulls" fraction with 24% of kernels, 100 kg of these hulls will retain 18.6 kg of oil and 14.8 kg of proteins. So, for 100 kg of seeds, with an extraction yield of 90% for oil, proteins and other water soluble materials, we will have 19.7 kg of "hulls" from which, 7.7 kg of dry material will be extracted. This extract will constitute a cream with around 80% of water. On the other hand, the hulls could be mechanically dewatered to a hypothetical water content of 50%. Consequently, from our initial 100 kg of seeds, we would have approximately 42 kg of water to evaporate which would require 26.3 kWh. This represents about 40% of the energy contained in the residual hulls. An additional gain is the sale of 3.3 kg of oil and 2.6 kg of protein. With oil and proteins prices at 750 and 735 €/t (RSM value divided by its protein content), the gain per ton of seeds would be 44 €/t and the cost in energy consumption to dry the wet hulls 15 €/t. This assessment is rather conservative since it does not include the improvement in protein values following concentration nor does take account of the possible energy recovery during dehydration (energy contained in the vaporised water could be recovered by condensation to heat the hulls and increase their moisture content).

10 Mechanical extraction issues

Mechanical extraction constitutes a very important step in the industrial crushing process for rapeseed. Its objectives are the extraction of the main part of the oil (60–70%) and the production of cakes easily extractable by solvent. Due to their rheological properties, extracting oil from pure kernels using regular screw presses is extremely difficult. The mechanical principle of the screw presses consists in exerting a steadily rising pressure on the cake by progressively reducing its volume. Under the effect of this pressure, oil exits the cage through the

[1] The NDF and ADL values were adjusted to match the French values, oil content was considered identical and ashes set at the same level as SBM as described above.

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spaces in between the cage bars. To obtain a satisfactory yield, the pressure must be strong and the cake's porosity must be preserved. The absence of the hulls causes both a reduction of this porosity and an increase in the cake's plasticity: the cake becomes less solid and more liquid-like and as a result liquid-solid separation becomes less efficient, with more solid being expelled through the bars. This problem is known to apply to most oilseeds; in general, when using mechanical presses, it is necessary to leave a proportion of the hulls with the kernels in order to facilitate efficient separation of the oil. If a pure kernel cake is to be processed then further technological improvements will need to be made. Two options are available. The first would consist in adapting the mechanical extraction to cope with the low fibre material; the second would be more radical as it consists in skipping this step.

10.1 Adaptations to mechanical extraction

At a pilot scale, it is possible to improve the efficiency of the solid-liquid separation by decreasing the rotation speed of the press. This improvement is attributable to the liquid fraction having more time to move outward, thereby counterbalancing the cake's poor porosity. This solution cannot be carried out at industrial scale, however, because the presses' throughput would be dramatically reduced. Nevertheless, the press design could be modified to take this requirement into account notably by employing a less aggressive compression profile and reducing the thickness of the cake. As the dehulled material's oil content is proportionately higher than in whole seeds it is also necessary to adapt the capacity of the presses Twin-screw presses have been proposed to overcome the issue. These presses have co-penetrating screw flights that allow improved control of the material flow; these have been successful notably when a structured cake is at the outlet of the press and the oily material in the feeding area is too soft to push through (Isobe *et al.*, 1992). Twin-screw extruders can also be used in the same way provided that a filtering barrel is employed to facilitate oil separation. This technology is likely to be more expensive than ordinary expelling (Burghart *et al.*, 2000). Adaptation could also involve the use of hydro-thermal preparation before oil expression. By changing the temperature, residence time and drying conditions, it will be possible to modify the behaviour of the material in the press. Cooking will coagulate the proteins of oil bodies and facilitate the oil droplets' coalescence in the cells; it can also decrease the oil's viscosity. Reducing the water content of the cake can counterbalance its plasticity. An obvious limit to this is that overcooking will damage the protein. Other damage to the protein could also be the consequence of harsh conditions applied for the desolventization in order to ensure a low level of residual hexane. For this reason, the regular RSM produced in France exhibits various protein qualities that are monitored by determining the solubility index in KOH (Peyronnet *et al.*, 2011). On the other hand, it could be expected that dehulling, by removing the fibres and polyphenols which may interact, might enhance the quality of the proteins and their digestibility for monogastrics. The impact of these quality variations on the economic value of the DRSM cannot be yet assessed and our modeling does not take account of it.

10.2 Direct extraction

Since the ground material has poor porosity and so does not permit an adequate flow of solvent around the particles, this technique would require using counter-flow extraction columns instead of a percolation extractor. Successful extraction requires that several hurdles be overcome. First, because the contact time between the solvent and the solid is rather short, the particles must be reduced in size to accelerate the diffusion of the oil in the solvent. Pin mills and hammer mills are unable to function with this kind of very oily material; dry milling with flaking of very oily material is relatively satisfactory. However, flaking results in the production of a relatively wide range of particles that are not ideal for fast extraction. Wet-milling in hexane could resolve the problem but, it seems difficult to manage the safety of this technology. A further difficulty is the large difference in density between the particles and the warm hexane. The sedimentation proceeds too quickly, especially for large particles which require a longer extraction time. Increasing the upward flow of solvent is not really an option since it strongly increases the amount of miscella to evaporate at the end of the processing. A cascade of stirred tanks and centrifuge decanters would be efficient but these machines are relatively expensive and their management in explosion-proof conditions is not very attractive. Crown Iron Works Company with its model IV extractor proposes a possible solution where the material is immersed in several baths of diminishing oil concentration and where the solvent draining is carried out in thin layer.

A variant of this solution would be to use direct extraction on flaked whole seeds and undertake the fibre removal after solvent extraction. This method requires that desolventization be carried out in dry conditions in order to avoid aggregating the particles. Defatted cotyledons that would have lost the half of their mass would become crumbly while the coats would remain as large particles. The separation could be done by the usual combination of sieving and air classification.

11 Glucosinolates concentration

Although glucosinolates content in rapeseed has been notably reduced to around 15 µmol/g in double-low varieties (Labalette *et al.*, 2011), their presence remains a noticeable anti-nutritional factor (Schöne *et al.*, 1999, 2001). Their occurrence is variable in French RSM (from 0 to 20 µmol/g) since the crushing process may partly or totally degrade them and concentrate the residual content in the meal (Peyronnet *et al.*, 2011). The anti-nutritional effect of the glucosinolates is due to their breakdown products formed during the process or the ingestion-digestion *in vivo*. These compounds cannot be easily analysed and the only available information on RSM quality is the content of the residual intact glucosinolates, whose relationship with the nutritional quality is rather poor (Vigour *et al.*, 2010). The main constraint for using RSM in feeding monogastrics is the low value of metabolizable energy due to the high content of indigestible fibre and the glucosinolates, particularly for poultry. As dehulling would lower the fibre content, the glucosinolates issue should become more relevant. A better understanding of the behaviour of the glucosinolates during the crushing process to control the degradation routes and limit the formation of the most harmful compounds would contribute to the enhancement of the quality of the DRSM and would allow it to be included in monogastrics diets at higher rates than RSM.

12 Conclusions

In a context of high protein prices, the dehulling of rapeseed could help the oilseed processing sector increase its revenues. This would require that the known technical barriers be surmounted. The main issue concerns the oil losses that have a strong impact on the technology's profitability especially in periods of high oil prices. The relative decline of oil prices observed since June 2013 has eased this constraint.

The technical feasibility of mechanical purification of the hulls appears to be very uncertain. Solutions consisting in recovering the oil from the "hulls" fraction seem more accessible. Coupling aqueous extraction with mechanical extraction could have the double interest of limiting the oil losses and recovering proteins. Efficient solid-liquid separation in screw presses could limit the amount of water used; dehydrating the cream thereby obtained could enable it to be mixed into a cake for solvent extraction. Tail-end dehulling could also solve the oil losses problem but the preparation of the meal would need to be improved if efficient separation is to be effected.

The mechanical extraction (pre-press) of the dehulled material would also require improved screw-pressing if a cake compatible with existing extractors is to be produced. Adaptations of existing oil extraction methods would require improvements in our understanding of mechanical extraction and would result in new designs for these machines.

Direct extraction of the "kernels" fraction could enable the substitution of the pre-press step by the use of non-conventional extractor designs. Glucosinolates concentration could be lowered through optimization of the conditioning and crushing.

The sole certitude about forecasting market developments is uncertainty. It would therefore be otiose to make predictions about future contexts. That said, one can rely on the continuing strong demand for proteins in a world where wealth is spreading and meat consumption is on the rise. Consequently, it would be wise to reconsider rapeseed dehulling in this perspective and reset research programs towards addressing the current hurdles, notably the glucosinolates issue and its possible management during processing.

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Appendix: Price list used in the study (source: La Dépêche, June 2008-April 2014).

	June 08	Dec 08	June 09	Dec 09	June 10	Dec 10	June 11	Dec 11	June 12	Dec 12	June 13	Dec 13	April 14
Wheat straw	80	50	50	40	50	65	80	90	–	65	60	55	42
Bran	201	106	125	126	140	210	230	180	197	243	209	171	175
Barley	190	135	112	90	110	173	255	160	190	210	231	220	232
Corn	175	103	102	96	93	100	205	174	199	230	195	176	170
CGF	205	124	123	121	125	234	228	176	212	259	219	202	200
Wheat	82	65	35	66	68	161	157	107	136	191	145	119	130
Alfalfa D17	207	135	136	120	132	175	–	172	190	–	206	220	213
Sunflower meal (28–30)	195	122	132	120	126	189	213	161	193	243	204	194	195
Sugar beet pulp	210	148	162	162	155	234	238	218	240	304	252	246	285
Sunflower meal (35)	–	–	–	–	–	230	–	212	280	330	305	270	293
Rapeseed meal	260	156	210	162	–	245	–	272	260	354	350	275	290
Peas	183	100	128	115	165	175	170	135	215	247	246	185	192
DDGS (wheat)	–	–	172	160	175	210	205	181	243		–	–	285
Feveroles	215	145	165	170	182	229	209	180	268	306	308	249	284
DDGS (corn)	–	–	–	190	–	–	–	175	245	316	250	244	273
Soybean meal	373	244	331	318	307	331	293	286	430	464	448	439	450

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