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Solvent solutions: comparing extraction methods for edible oils and proteins in a changing regulatory landscape. Part 6: Impacts on meal quality☆

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Abstract – This article constitutes the sixth part of a series dedicated to the comparative analysis of extraction solvents for oilseeds. This section examines the effects of various solvent extraction methods on the quality of oilseed meals, particularly focusing on antinutritional factors and protein value. The study discusses the impact of these solvents on glucosinolates (GLS) in rapeseed meal, trypsin inhibitors in soybean meal, phytic acid and phosphorus digestibility, gossypol in cottonseed, and phenolic compounds. Alternative solvents with higher water miscibility may lead to more effective reduction of GLS in rapeseed meal due to increased moisture in the desolventizer. They also could denature trypsin inhibitors in soybeans before desolventization, but this effect is negligible due to sufficient toasting conditions in the desolventizer. The intensity of heat treatment can affect phosphorus digestibility, but this intensification often comes with undesirable effects on protein digestibility. For cottonseed, ethanol with added acids has been shown to be able to extract gossypol, while isopropanol was less effective. Phenolic compound extraction with more polar solvents has the potential to improve meal taste and appearance, but without major effect on the feed value of the proteins. Desolventization conditions significantly impact protein value, with mild cooking potentially improving digestibility, while excessive heat treatment can lead to Maillard reactions, reducing protein and the digestibility of sensitive amino acids. Non-hexane solvents have water miscibility, latent heat of vapourisation and solvent hold-up in the marc that lead to increasing the temperature, moisture and residence time required for effective desolventization likely to promote stronger reduction in protein digestibility. Further experimental data would be necessary to better assess this issue.

Kewords: Solvents / meal quality / digestibility / glucosinolates / desolventization

Résumé – Solvants d'extraction : comparaison des méthodes d'extraction pour les huiles et protéines alimentaires dans un contexte réglementaire en évolution. Partie 6 : Impacts sur la qualité des tourteaux. Cet article constitue la sixième partie d'une série consacrée à l'analyse comparative des solvants d'extraction pour les graines oléagineuses. Cette section examine les effets de diverses méthodes d'extraction par solvant sur la qualité des tourteaux oléagineux, en se concentrant particulièrement sur les facteurs antinutritionnels et la valeur protéique. L'étude discute de l'impact de ces solvants sur les glucosinolates (GLS) dans le tourteau de colza, les inhibiteurs de trypsine dans le tourteau de soja, l'acide phytique et la digestibilité du phosphore, le gossypol dans le coton, et les composés phénoliques. Les solvants alternatifs présentant une miscibilité à l'eau plus élevée peuvent conduire à une réduction plus efficace des GLS dans le tourteau de colza en raison d'une humidité accrue dans le désolvanteur. Ils pourraient également dénaturer les inhibiteurs de trypsine dans le soja avant la désolvantation, mais cet effet est négligeable en raison de conditions de toastage suffisantes pendant la désolvantation. L'intensité du traitement thermique peut affecter la digestibilité du phosphore, mais cette intensification s'accompagne souvent d'effets indésirables sur la digestibilité des protéines. Pour le coton, il a été démontré que l'éthanol avec ajout d'acides peut extraire le gossypol, tandis que l'isopropanol était moins efficace. L'extraction des composés phénoliques avec des solvants plus polaires a le potentiel d'améliorer

☆ Contribution to the Topical Issue "Extraction solvents / Solvants d'extraction".

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le goût et l'apparence du tourteau, sans effet majeur sur la valeur alimentaire des protéines. Les conditions de désolvantation ont un impact significatif sur la valeur protéique, une cuisson douce pouvant potentiellement améliorer la digestibilité, tandis qu'un traitement thermique excessif peut conduire à des réactions de Maillard, réduisant la digestibilité des protéines et des acides aminés sensibles. Les solvants non hexaniques ont une miscibilité à l'eau, une chaleur latente de vapourisation et une rétention de solvant dans le marc qui conduisent à augmenter la température, l'humidité et le temps de séjour nécessaires pour une désolvantation efficace, susceptibles de favoriser des pertes plus importantes de digestibilité des protéines. Des données expérimentales supplémentaires seraient nécessaires pour mieux évaluer cette question.

Mots-clés : Solvants / tourteaux / digestibilité / glucosinolates / désolvantation

Highlights

- Solvent selection critically influences oilseed meal quality through differential modulation of enzymatic activity (notably myrosinase) and antinutritional compound bioavailability. Polar solvents (e.g., ethanol) may extract glucosinolates and sugars, while excessive thermal desolventization due to higher latent heats of vaporization promotes Maillard reactions, reducing protein digestibility.
- Hexane-based processing is likely to maintain superior nutritional retention compared to alternative solvents due to lower thermal demands during solvent removal.

1 Introduction

The meals produced during oilseed processing are a crucial component of the global food chain, providing essential protein sources for animal feed. These proteins play a vital role in nourishing livestock, which in turn supply the animal proteins consumed by humans. Any alterations to the oilseed processing methods that could potentially compromise the quality of these proteins might have far-reaching consequences throughout the food production system. While the direct effects of solvents on proteins are important to consider, the desolventization conditions during oilseed processing are particularly critical for preserving the nutritional value of meal proteins. The temperature, duration and moisture levels during desolventization can significantly impact protein quality, digestibility, and the presence of antinutritional factors. This document examines the potential impacts of various extraction methods and solvents on meal protein quality, with a focus on how changes in processing techniques might affect the nutritional value of oilseed meals. It explores the effects on antinutritional factors such as glucosinolates, trypsin inhibitors, phytic acid, and gossypol, as well as the influence of processing conditions on protein digestibility and amino acid availability. Understanding these factors is crucial for maintaining the efficiency of animal feed production and, by extension, the entire food supply chain. As the industry considers alternative solvents and extraction methods in response to changing regulations, it is essential to evaluate how these changes might affect the quality and nutritional value of the resulting meal proteins.

2 Effect on the antinutritional factors

2.1 Glucosinolates (GLS)

Rapeseed from 00 cultivars contains less than 20 μmol/g of glucosinolates leading to the potential level of 30μMol/g in the meals. Glucosinolates are complex molecules composed of three primary components: a glucose moiety, a sulphate group and a variable side chain. These components are intricately connected through a central carbon atom that forms part of an oxime bridge. This central carbon is directly attached to the variable side chain, linked to the glucose molecule via a sulphur atom, and double-bonded to a nitrogen atom, which is further connected to the sulphate group (Glu-S-C(R)=N-O-SO_3^-). The variable side chain can be aliphatic or aromatic, leading to the classification of glucosinolates as either alkyl or indolyl, respectively. This structural diversity is responsible for the wide range of biological activities exhibited by glucosinolates. As such, glucosinolates are relatively harmless molecules but become biologically active after hydrolysis by an enzyme called myrosinase. This enzyme attacks the sulphur attached to glucose and releases this carbohydrate. A second hydrolysis then detaches the sulphate group. The oxime-derived aglycone (S-C(R)=N moiety) undergoes a variable rearrangement according to the nature of the side chain, and that breakdown product is generally a biologically active substance. (Carré, 2021). In the case of rapeseed, the main harmful glucosinolate is the progoitrin, the breakdown product of which is the 5-vinyl-1,3-oxazolidine-2-thione (5-VOT), or goitrin, a thyroid perturbator disrupting the absorption of iodine.

The impact of glucosinolates (GLS) on animals consuming rapeseed meal is largely determined by the processing methods employed. These methods can have varying effects on both the GLS and their associated enzymes. Some processes may inactivate the enzyme without altering the GLS content, while others can facilitate GLS hydrolysis, resulting in the presence of breakdown products in the meal. A final possibility is a thermal degradation of the GLS without prior hydrolysis that could leave different degradation molecules. Additionally, certain thermal treatments can induce reactions between these breakdown products and other components of the meal matrix. The specific processing approach thus plays a crucial role in determining the potential toxicity and nutritional value of the rapeseed meal for animal consumption. According to the last survey published by Terres Univia (2024), the current processing strongly reduces the GLS content in the meal, which is measured at about 6 μMol/g of dry matter (DM) in

rapeseed meals. The temperature, the duration of the exposure to the temperature, and the moisture are key factors explaining the GLS decrease. Mosenthin *et al.* (2016) observed that under constant steam injection conditions, GLS content decreased from 15 to 6 μmol/kg as toasting duration increased from 48 to 93 minutes. Concurrently, under fixed residence time conditions, GLS levels were reduced from 12 to 4 μmol/kg when steam injection intensity was elevated from moderate to high.

Considering that all the alternative solvents would lead to higher moisture in the desolventizer, there is little chance that higher GLS content could be found in the meal resulting from the use of alternative solvents. Conversely, solvents with high water miscibility can denature the myrosinase enzyme, potentially altering the degradation pathways of glucosinolates (GLS). This modification of enzymatic activity may lead to alternative breakdown mechanisms, resulting in a different profile of hydrolysis products compared to those generated through the typical myrosinase-catalysed reaction. Indeed, it is possible that the harmfulness of the breakdown products resulting from the thermal treatment of aglycone forms could be different from that of breakdown products resulting from the direct thermal degradation of the GLS. To the best of our knowledge there is no available information about this issue.

In the case of alcohols at azeotropic water concentration, we have observed a leaching effect, where a small share of the initial GLS was extracted by the solvent. In an unpublished study, we extracted 2 kg of rapeseed cake using either hexane (five extractions using 5 L of solvent each) or alcohols at their respective water azeotropic concentrations (seven extractions, same volume of solvent). The resulting glucosinolate concentrations in the extracted meals were 27 μmol/g for hexane, 22 μmol/g for ethanol (EtOH) and 20 μmol/g for IPA, The cross-flow extraction scheme maximises the removal of glucosinolates. However, under industrial conditions, where the solvent-to-solid ratio is lower, this effect is likely to be less pronounced.

2.2 Trypsin inhibitor proteins (Soybean)

Trypsin inhibitors are soybean proteins that have the capacity to bind with the protease trypsin and to block this enzyme, hence limiting the digestibility of the proteins and their absorption by animals. As proteins, these inhibitors owe this property to their three-dimensional configuration which can be modified by thermal denaturation or by disruption of the water shell by water miscible solvents. DCM with its low boiling point could lead to a shorter residence time in the desolventizer and lower temperature. In consequence, the trypsin inhibition of DCM soybean meals could be insufficiently reduced at the desolventization stage.

With water-miscible solvents, this denaturation could occur before the desolventization but due to the high miscella hold-up in the marc of these solvents, this effect is of no interest since the desolventizing/toasting condition would be largely sufficient to eliminate this activity. As for GLS in rapeseed, solvents with higher water miscibility will generate harsher temperature conditions during the toasting with no risk of modifying the antinutritional characteristics in SBM.

2.3 Phytic acid and phosphorus digestibility

Phytic acid is a derivative of inositol, a ring-shaped polyol having six carbons. Each OH group of the phytic acid is replaced by an ester bond with a phosphate (H_2PO_4). It is a form of phosphorus storage in the seeds. At neutral pH, the molecule has two or three negative charges which can readily bond with other components of the matrix (Cheryan et Rakis, 1980). The processing condition could lead to the formation of complexes with the proteins and phenolic compounds and these complexes are characterised by a lesser digestibility than the native material. In native oilseeds phytic acid is concentrated in protein body substructures called crystalloids or globoids which are visible at microscopic level as small inclusions in the proteins bodies. In this form the interaction with proteins remains limited and interactions occur mainly with mineral cations. The impact of phytates on the mineral digestibility is well documented (Serraino et al., 1985). During the processing, thermal treatment and mechanical shearing are leading to the formation of ternary complexes where divalent cations are bonding between anionic groups of proteins and phosphate. Direct interaction between phosphates and the lateral amino group are also possible. The losses in protein digestibility could be explained by the reduction of the solubility of these complexes (Albe-Slabi et al., 2024). Olukosi et al., (2017) studied the phosphorus digestibility in chicken fed rapeseed meal processed by conventional (desolventization temperature 110°C and 116°C, high direct steam rate) or mild heat treatment (desolventization temperature ∼105°C, low direct steam rate) for two rapeseed cultivars. The digestibility of the phosphorus was 30-32% for the mild treatment, 22% for the batch heated to 110°C and 13.6% for the batch heated to 116°C. On the other hand, Lee and Nyachoti (2021) found a better digestibility after heat treatment. They compared the phosphorus digestibility in pigs fed expeller press-cake of canola and soybean and a conventional rapeseed meal and according to an optional heat treatment consisting of an autoclaving at 121°C for 60 minutes. Standardised total tract digestibility was increased by ∼2.5% which remains a weak change. In experiments on rainbow trout and turbot, Burel et al. (2000) compared dehulled rapeseed meal defatted without thermal treatment and with such treatment as part of a conventional technical pathway. They observed a significant difference in phosphorus digestibility depending on the heat treatment; 26% versus 46% for trout and 49% versus 65% in turbot (low temperature vs. conventional desolventization, respectively). The authors explained that difference by the effect of the glucosinolates which were much more concentrated in the non-heated meal. Rodriguez et al. (2013) compared the phosphorus digestibility in pigs fed canola and sunflower, examining both the whole seeds and the processed meals of these oilseed crops. Their result is interesting since they observe a significant increase in phosphorus digestibility for canola meal versus seeds (46% to 58% in standardised total tract digestibility) while the reverse was measured with sunflower (52 vs 37%). The authors were not establishing relationships between glucosinolates and P digestibility; they just hypothesised a reduction in phytic P related to the processing in canola. They did not elaborate on the fact that processing was not producing the same effect in sunflower. She et al. (2017) in another experiment on pigs

measured the standardised digestibility of P in canola meal receiving a low- and high-temperature processing (temperatures not specified). The phytic acid concentrations were quite similar in both meals (2.90 vs 2.98 g/kg) and standardised digestibility remained identical. Since NDF concentrations had just 1 percentage point of difference between these meals, the heat treatment difference is likely to have been small. Pirgozliev et al. (2022) compared two rapeseed meals processed in a conventional way and in mild conditions in a chicken experiment. The profiles of inositol-phosphate (IP) were measured (IP2-6) on both meals. There was a slight difference in IP6 concentrations between the conventional and mild treatments, with values of 45.4 μMol/mL for the mild treatment and 39.8 μMol/mL for the conventional treatment. This difference was reflected in higher concentrations of lower inositol phosphates, with increases of +2.9, +0.3, +0.2, and +0.01 μMol/mL for IP5 to IP2, respectively. This change may have been induced by the higher temperature used in the conventional treatment. However, it did not result in significant differences in overall phosphorus digestibility, although small advantages in metabolisable energy and nitrogen retention were observed with the mild treatment.

In conclusion, the intensity of the heat treatment may induce some dephosphorylation in IP. However, the level of treatment required to observe a significant difference in phosphorus digestibility is likely to generate other undesirable effects on protein digestibility. The effect of processing on the complexation of phytates with proteins is not well documented, and difficult to separate from other thermal effects, including the Maillard reaction.

The extraction of phytates is hardly feasible during the solvent extraction of oil since even the most polar solvents the solubility of phytic acid is low.

2.4 Gossypol

Gossypol is a polyphenolic aldehyde found in cotton and considered toxic. It is located in specialised glands and has a reddish-yellow colour. The crude oil obtained by conventional processes contains between 0.05 and 0.5% gossypol, which is eliminated during the degumming stage of refining. The presence of gossypol in oilcake limits its use as food, but its presence in the plant reduces the need for insecticide treatments. In meal, the bound forms are not toxic or are only slightly toxic, but their binding to certain amino acids —particularly lysine —reduces the availability of these nutrients. According to current European regulations (Directive 2002/32/EC), the maximum permitted levels of free gossypol in livestock feed containing cottonseed meal are 500 ppm for cattle (excluding calves), 300 ppm for sheep and goats (excluding lambs and kids), 100 ppm for broiler poultry and calves, and 60 ppm for pigs, lambs, and kids. For laying hens, scientific recommendations advise not exceeding 30 ppm to prevent adverse effects on egg quality and reproductive performance (EFSA CONTAM Panel, 2017).

Hron et al. (1992) found that the ethanol used at high temperatures to extract cottonseed oil was not very effective in extracting gossypol, as the latter can form bonds with proteins at those temperatures. Adding phosphoric acid or citric acid to the ethanol avoids this problem. The acidified ethanol is slightly less effective than the pure solvent for extracting the oil because of its higher polarity. The acid concentrations are relatively high (0.1-0.4 M for citric acid and 0.1-0.35 M for phosphoric acid).

The same team has also proposed a method (Hron et al., 1994) in which the first wash is carried out with cold 95% ethanol to extract the gossypol. This method showed good efficiency in terms of total gossypol content (~70%) and aflatoxin (~95%). The gossypol is separated from the solvent on an adsorption column, while the aflatoxin is separated from the 'lean' miscella on a membrane and followed by adsorption. Flakes are produced by moistening the seeds to soften the glands and then drying them after flaking. The economic benefits were measured by Abraham et al. (1991) and were only demonstrated for processing batches of seeds requiring decontamination.

The use of isopropanol was first considered as a solvent to treat cotton seeds that contain gossypol. Harris et al. in 1947 proposed a process where cotton kernel flakes were extracted with 91% IPA to entrain the oil and gossypol in the miscella, which was then extracted with hexane to recover the oil and isolate gossypol. In their extensive study conducted on IPA at the Texas A&M pilot facility, Lusas et al. (1997) have considered that the best technical pathway was involving the use of expanders for transforming free gossypol into bound gossypol. In these conditions, IPA extraction does not eliminate total gossypol, and it facilitates the refining of the final oil.

Acetone has also been considered for extracting free gossypol from cottonseed; however, its use led to an objectionable 'catty' odour in the resulting meals (Hron et al., 1989). Kuk et al. (2005) have proposed to use acetone in mixture with hexane (10-25%) to improve the solvent extraction of the gossypol without impairing the meal quality but leading to the necessity to adapt the oil refining due to the resulting darker colour.

2.5 Phenolic compounds

Polyphenols and phenolic acids are not considered true antinutritional factors in the animal feed sector, but they have strong effects on the colour and the taste of the meals, some phenolic compounds causing astringency or bitterness. As already mentioned, the water addition in non-inactivated prepressed cake is likely to enhance the activity of polyphenol oxidases responsible for enzymatic browning. It is therefore likely that rapeseed and sunflower meal containing large amounts of oxidizable polyphenols would be considerably affected by this darkening. This effect has little importance for the feed value of these meals. However, this effect may not be noticeable in non-dehulled meals, which are already dark due to the presence of hulls. In contrast, this browning could significantly affect the visual quality of meals produced from dehulled seeds, where the absence of hulls typically results in a lighter appearance.

Table 2 in part 1 of this article shows the Hansen solubility parameter (HSP Ra) distances between isoflavone, kaempferol and sinapic acid, three phenolic compounds and the solvents in our comparison. Alcohols, especially in presence of water, are relatively good solvents for these substances as for most low-

molecular-weight phenolics. Condensed tannins are much less soluble. Free isoflavone is more soluble in DCM and 2-methyloxolane (2-MeOx) but in soybean, more than 90% of these flavonoids are bound to sugars and far less likely to be extracted (Genovese et al., 2005). In the case of rapeseed, EtOH extraction has been reported by Citeau et al. (2018) as removing the yellow pigments from dehulled meal. Many studies conducted at laboratory-scale have examined the extraction of phenolic compounds from meals, however studies regarding the effect of oil extraction on the fate of these compounds remain scarce.

In summary, alcohols—and to a lesser extent, other non-hexane solvents—are likely to extract more phenolic compounds during oil extraction. These substances would be removed from the oil during the processing steps of refining involving the use of water (degumming, alkaline neutralisation, and washing). Their partial removal from the meals is likely to result in a blander taste (less bitterness) and whiter aspect when the solvent has a denaturing effect on the proteins. With less miscible solvents in absence of enzyme inactivation prior to extraction, a darker colour of the meal because of enzymatic browning.

3 The effect of desolventization conditions on the proteins value

The protein digestibility is affected by the intensity of the heat treatment. Mild cooking can improve the protein digestibility by disrupting the weak interactions between protein subparts and unfolding, which enhances their accessibility to the digestive enzymes. With higher temperature and longer exposure time, the Maillard reactions induce the condensation of reducing sugars with free lateral amino groups in the proteins. These new covalent bonds have a negligible impact on digestibility when they are infrequent. However, as their number increases with prolonged exposure and higher temperatures, they progressively affect digestibility and reduce the concentration of amino acids, such as lysine, which are involved in these bonds. The literature on this topic is vast, and an exhaustive citation of all relevant studies would be beyond the scope of this paper. One interesting study on the issue was made at the Wageningen University by Salazar-Villanea et al. (2016). They carried out extensive in-vitro characterizations of rapeseed meal processed with a range of growing toasting time (0 to 120 min at temperatures of ~110°C). Several parameters were modified by the heat treatment: the protein dispersibility index (PDI) measured at neutral pH decreased non-linearly with a large drop during the beginning, then more progressively and only a little at end of the treatment. On the contrary, the nitrogen solubility index (NSI) measured at alkaline pH decreased more linearly going from 80% to 43% after 120 min. The treatment was also visible on the denaturation enthalpy of the proteins which dropped from 2.23 J/g of protein to 0.74 J/g at the end. Another marker of the heat treatment was the neutral detergent fibre (NDF). It is a usual measure of the total fibre content of the feedstuff which has been designed to assess the content in pectin, hemicellulose, cellulose and lignin. This parameter evolved from 27.4% to 36.5%. This increase is the result of a loss in protein solubility in the neutral detergent, and it reflects the losses in digestibility. The glucosinolate content is significantly affected by the treatment, decreasing from 28 to 2 μmol/g. The degradation kinetics differ between indolyl and alkenyl GLS. After 20 minutes of treatment, the indolyl GLS concentration was reduced by half, while the alkenyl GLS decreased by only 19%. On the side of amino acids, a linear decrease of lysine was observed from 6.3% to 4.85% of the crude proteins and for available lysine from 6.2 % to 3.86 % of the CP. All these effects can be found in other studies on processing and are proportional to the intensity of the treatment. The consequence on the feed value of the meal is also well documented and can be related to both the loss of digestibility of the proteins and the loss of limiting amino acids. Pastuszewska et al. (1998) with a similar range of rapeseed meal observed a better biological value in rats fed with meal receiving a short time heating versus crude meal because of the reduction in GLS harmfulness, but when protein solubility dropped to 43%, the growth decreased by 37%. Grala et al. (1994) studied the feed value of rapeseed meals made in an industrial oil-mill by varying the toasting temperature. Oil mill 1 provided meals toasted at 90°C, 95°C and 100°C, while oil mill 2 supplied meal toasted at 120°C. Lysine content was affected by the temperature in meals from the first mill (5.20, 4.8 and 4.33 % of amino acids). Decreases in available lysine negatively affected feed intake, body weight gain, and feed utilization in pigs. However, equal feed values were observed in two meals derived from oil-mills using significantly different toasting temperatures (90°C vs. 120°C). This unexpected similarity can be attributed to other processing parameters, such as residence time and moisture content in the DT. Kasprzak et al., 2017 have also compared the digestibility of rapeseed meal prepared according to two levels of heat treatment on broilers. The difference in KOH protein solubility in the two treatments was relatively weak (49 vs 43% for the cultivar PR46W21, desolventization 105°C vs. 110°C; and 45 vs 36% for DK Cabernet, desolventization 105 vs. 116°C). Nevertheless, the standardised crude protein digestibility was significantly reduced (83 vs 79% and 80 vs 75%, respectively), as in a larger extent for lysine (80 vs 72% and 77 vs. 66%). In another experiment made with rapeseed processed with a range of residence time going from 48 to 93 min, Eklund et al. (2015), measured a reduction in standardised ileal digestibility of CP from 65 to 60% and from 64 to 54 % for the lysine in pigs with increased residence times.

From these studies made with meals processed in conditions similar to those of the industry, it can be clearly established that the intensity of the heat treatments applied to rapeseed is detrimental to its nutritional quality when KOH protein solubility is decreased below 50-60%. Soybean is also affected by the same phenomenon as attested by multiple studies (Chang et al., 1987; Araba and Dale, 1990; Parsons et al., 1992)

The solvent hold-up capacity, its enthalpy of vapourisation, water content, and boiling point affect the amount of heat required to evaporate the solvent contained in the marc. To transfer this energy to the meal, the heating surface in the desolventizer will have to be increased proportionally to the change in heat requirement. For example, with EtOH, the heat requirement at DT level is three times that of hexane. That means that the DT heating surface will have to grow in the same proportion. This could be achieved by increasing the

number of trays, i.e. the height of the device and the surface of each tray. Growing the surfaces of the trays leads to difficulties because it is difficult to build a perfectly flat surface on large diameters. Another aspect is the linear speed of the sweeping arms which cannot exceed 1m/s to avoid the risk of generating sparks in presence of foreign material. Doubling the surface of the trays would reduce the frequency of agitator blade passes. As a result, the efficiency of the heat exchange will be reduced and the contact time of the material on the heating surface will be increased generating heat damages for the particles in contact with the hot surface. To avoid these limitations, another possibility resides in extending the residence time by increasing the amount of material on the trays. This solution is cheaper than extending the heating surfaces and is likely to be the preferred one. It is therefore likely that the residence time would increase at the detriment of the protein digestibility.

Switching solvent will have a significant impact on the heat treatment applied to the meals and will increase the extent of protein degradation to the proteins. The protein content of these meals is their main point of interest, and a reduction of meal digestibility would lead to a loss in its economic value. The variation in meal value is likely to reflect the total DT heat (see Table 2, line "D" of the fourth article in this series dedicated to extraction solvents). EtOH and IPA meals would be those with the largest impacts. Considering the strategic importance of the protein supply of the European farms, if alcohols were to be used as extraction solvent, processing methods must be revised to overcome this issue by adding a mechanical dewatering step as proposed by Hron et al. (1984) or Lusas et al. (1997).

4 Conclusion

The choice of solvent for oilseed extraction has a limited direct impact on antinutritional factors in the resulting meal. Instead, the most significant factors affecting meal quality are the water kinetics during extraction and, more importantly, the desolventization process—particularly the temperature and duration of heat treatment. The desolventization conditions play a crucial role in determining the final quality of the meal proteins. Mild heat treatment can improve protein digestibility by unfolding protein structures, making them more accessible to digestive enzymes. However, prolonged exposure to high temperatures can lead to Maillard reactions, potentially reducing protein digestibility and amino acid availability, especially lysine. For antinutritional factors:

- Glucosinolates (GLS) in rapeseed meals are primarily affected by temperature, duration of exposure, and moisture during processing. Alternative solvents with higher water miscibility may lead to harsher temperature conditions during toasting, potentially further reducing GLS content.
- Trypsin inhibitors in soybean meals are likely to be sufficiently denatured during desolventization, regardless of the solvent used, due to the high temperatures involved.
- Phytic acid and phosphorus digestibility may be influenced by heat treatment, but the effects are complex and can vary depending on the oilseed type and processing conditions.
- Gossypol in cottonseed meals can be affected by solvent choice, with some alternative solvents showing potential for improved extraction.
- Phenolic compounds may be more readily extracted by alcohols and other non-hexane solvents, potentially altering meal colour and taste but with minor impact on the feed value.

It is challenging to provide precise predictions about the consequences of switching solvents due to the scarcity of experimental data under real desolventization conditions. This highlights the need for further research in industrial settings to fully understand the impacts of alternative solvents on meal quality. For alcohol-based and possibly other non-hexane solvents, implementing a mechanical pre-desolventization step could be highly beneficial in maintaining meal quality. However, additional research is required to optimise this process and evaluate their effectiveness across different oilseed types and processing conditions. As the industry considers alternative solvents in response to changing regulations, it is crucial to conduct comprehensive studies that examine not only oil extraction efficiency but also the effects on meal quality, including protein digestibility, antinutritional factors, and overall nutritional value. This research will be essential in ensuring that any changes in extraction methods do not compromise the critical role of oilseed meals in the animal feed industry and, consequently, the global food supply chain.

Conflicts of interest

The authors have no conflicts of interest to disclose.

Authors contribution statement

Patrick Carré: conceptualization, administration, original draft, review and editing. **Chandra Dev Borah**: validation, review and editing. **Thomas Piofczyk**: conceptualization, administration, validation, review and editing. **Sara Hadjiali**: validation, review & editing.

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