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Nutritional quality of proteins from major oilseeds – a review☆

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Abstract – Driven by the ongoing dietary transition in Western countries, numerous research studies focus on new sustainable plant-based sources. Oilseeds, known for their high lipid and protein content, represent a promising option. This review focuses on the protein quality of oilseeds and their potential to meet population wide nutritional needs. Although the nutritional value of the protein of oilseeds is generally lower than that of animal proteins, due to deficiencies in certain indispensable amino acids (particularly lysine) and reduced digestibility, several strategies can enhance their value. Combining oilseeds with legumes to achieve complementary amino acid profiles, processing techniques such as dehulling and oil extraction, as well as bioprocesses (fermentation/germination), all contribute to improved protein quality. Moreover, oilseeds provide bioactive peptides and polyunsaturated fatty acids which often exhibit anti-inflammatory and/or pro-anabolic effects. In conclusion, oilseeds are valuable sources of both protein and lipids, and current dietary guidelines support increased consumption of these seeds among the general population.

Keywords: Oilseed / plant-based protein / protein quality / digestibility

Résumé – Qualité nutritionnelle des protéines des principaux oléagineux : revue. Motivé par la transition alimentaire actuelle des pays occidentaux, de nombreux travaux de recherche se concentrent sur de nouvelles sources végétales durables. Les oléo protéagineux, graines caractérisées par leur forte teneur en lipides et en protéines, constituent une source alimentaire végétale prometteuse. Cette revue s'intéresse à la qualité des protéines d'oléo protéagineux ainsi qu'à leur capacité à répondre aux besoins nutritionnels de la population. Bien que la qualité des protéines d'oléo-protéagineux est souvent inférieure à celle des protéines animales, en raison de leur déficience en certains acides aminés indispensables (particulièrement la lysine) et de leur digestibilité, plusieurs procédés permettent leur amélioration. La complémentarité des profils en acides aminés avec les légumineuses, les procédés de transformation comme le décorticage et le déshuilage ainsi que les bioprocédés (fermentation/ germination) améliorent la qualité protéique des graines. De plus, les oléo protéagineux permettent l'apport de peptides bioactifs et d'acides gras polyinsaturés ayant des effets anti-inflammatoires et/ou pro-anabolisants. En conclusion, les oléo protéagineux représentent de bonnes sources de protéines et lipides et les recommandations préconisent une augmentation de leur consommation dans la population globale.

Mots-clés : Oléo-protéagineux / protéine végétale / qualité protéique / digestibilité

Highlights

- Oilseeds are valuable sources of lipids and proteins, particularly in the context of dietary transitions in Western countries.
- Protein quality can be improved by blending oilseeds with complementary protein sources to achieve a balanced indispensable amino acid (IAA) profile, as well as through processing techniques such as dehulling and oil extraction, and bioprocesses like fermentation and germination.

☆ Contribution to the Topical Issue: "Diversity of Plant Proteins extracted from Oil & Protein Crop / Diversité des protéines végétales issues des oléoprotéagineux".

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1 Introduction

Many Western countries are currently undergoing a dietary transition driven by environmental, societal, economic, and public health concerns (FFAS, 2019). Dietary transition refers to population-wide changes in food production and consumption patterns. Western food systems are predominantly based on animal-source protein (70% *versus* 30% plant-source protein) (Gueugneau, 2023). The consumption of animal-source protein in these proportions is the focus of much debate (Guéguen *et al.*, 2016), and the need to shift towards healthier and more sustainable diets is driving interest in plant-based food sources. As a result, extensive research has been conducted into plant-based alternatives to animal-protein products (FFAS, 2019). The main plant protein sources are cereals, legumes, and oilseeds that play a central role in dietary transition by helping to diversify dietary protein sources (Estève-Saillard, 2016). Oilseeds in particular offer numerous benefits, both in terms of agronomics and nutritional value.

Oilseeds are defined as a plant cultivated primarily for the high lipid content of their seeds, such as *Helianthus annuus* (sunflower) and *Brassica napus* (rapeseed) that are the two main oilseed species farmed in Europe (Terres Univia, 2025a). In the 1970s, the term canola was registered for rapeseed varieties with low erucic acid and glucosinolates. In Europe, it's often called double-zero or double-low rapeseed. The terms are then frequently used interchangeably in the literature. The term rapeseed will be used throughout this review as its focus is on proteins (Bourdon, 1989). Some oilseeds also have a high protein content, such as *Glycine max* (soybeans) and *Arachis hypogaea* (peanut). Although there is no strict universally-accepted threshold, the generally-accepted criteria for classification as an oil–protein seed is at least 15% fat and at least 15% protein in the whole seed (Kotecka-Majchrzak *et al.*, 2020) (Tab. 1). These values reflect a balance between a high oil content, characteristic of oilseeds, and a high proportion of protein. Worldwide production of oil-protein seeds between February 2024 and February 2025 was 420.76 million tons for soybeans, 85.31 million tons for rapeseed, 51.12 million tons for sunflower seed, and 50.39 million tons for peanut (USDA, 2024).

Oilseed crops are mainly cultivated worldwide for their oil, but the oil extraction process generates large quantities of co-products such as press cakes, which may have potential nutritional value, due to their high protein content (Terres Univia, 2019). One ton of sunflower seed produces 540 kg of seed cake and 440 kg of oi (Terres Univia, 2025b), and 1 ton of rapeseed produces 560 kg of seed cake and 420 kg of oil (Terres Univia, 2025c). These co-products are used mainly for animal feed, and rarely for human consumption. However, more studies are focusing on ways to valorize these co-product cakes for human consumption in order to improve the sustainability of food practices and diversify sources of protein for human nutrition (Arrutia *et al.*, 2020).

Current research into promising new protein sources is investigating a number of oilseed species, *e.g.*, *Camelina sativa* or 'camelina' (Juodka *et al.*, 2022). Oilseed cultivation also offers particular benefits. Oilseed crops address significant agronomic challenges by providing food resources for insects and contributing to entomophilous pollination (Terres Inovia, 2023). The cultivation of oilseeds, particularly legumes, also has environmental advantages linked to their capacity for biological nitrogen fixation which reduces the need for nitrogen fertilizers (Calles *et al.*, 2016).

Oilseeds are also important sources of lipids. The major oilseeds contain between 18% and 50% lipids, with a high content of polyunsaturated fatty acids (PUFAs) (Orsavova *et al.*, 2015). Oilseeds provide omega-6 fatty acids in the form of linoleic acid (LA) as well as omega-3 fatty acids, mainly in the form of α-linolenic acid (ALA) (Tab. 2). These fatty acids are considered essential because they cannot be synthesized by the body and so must be supplied through diet. Furthermore, ALA is a precursor of the conditionally essential fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), two long-chain PUFAs known to have anti-inflammatory effects (Pinel *et al.*, 2014). However, the ALA conversion rates to EPA (7%–21%) and DHA (only 0.01–1%) are low (Saini *et al.*, 2021), which makes it important to consume enough ALA-rich oil to meet the body's EPA and DHA needs. In healthy adults, lipid requirements represent about 35%–40% of total energy intake (Anses, 2021). For LA, the minimum physiological requirement in adults is 2% of total energy intake, *i.e.*, 4.4 g per day for a daily intake of 2,000 kcal. For ALA, the minimum physiological requirement is 0.8% of total energy intake, *i.e.*, 1.8 g per day for a daily intake of 2,000 kcal (Anses, 2021). Specific populations, such as growing children, pregnant women, or older adults, have specific needs for PUFAs to support neuronal development, cardiovascular health, and the preservation of cognitive functions (Troesch *et al.*, 2020).

The aim of this review is to assess the nutritional quality of oilseed-source proteins and how their consumption can meet the needs of healthy adults as well as specific populations (children, pregnant women, and older adults). The study of oilseeds can be approached from multiple perspectives due to the nutritional, technological and industrial challenges they raise. This review primarily addresses the nutritional aspect, while also considering sustainability.

2 Oilseeds and protein quality

2.1 Protein content of oilseeds

A diet that meets protein and indispensable amino acid (IAA) requirements is crucial to maintaining body protein store, and health (Joint WHO/FAO/UNU Expert Consultation, 2007). The protein content of major oilseeds ranges from 20% to 40% protein in the native-state seed (Tab. 2). Removing oil from the product concentrates the nutrients present in the non-lipid component of the seed, thus increasing the protein content of its co-products (Terres Univia, 2025a). Oilseed meal, derived from de-oiled press cakes, for example, typically contain 30% to 50% protein (Tab. 3). However, although the quantitative protein content of food is important for covering nutritional needs, it is essential to also consider the quality of the proteins consumed.

2.2. Protein quality of oilseeds

The quality of a protein is mainly based on its IAAs content and its digestibility.

Table 1. Lipid and protein content of the whole seed of the main oilseeds.

Oilseeds	Soybean	Peanut	Sunflower	Rapessed
Lipid content	18–20%	45–50%	40–50%	40–45%
Protein content	35–40%	25%	15–20%	20%
Sources	(Morin and Pagès-Xatart-Parès, 2012; FAO, 2003; INRA/CIRAD/AFZ, 2021)			

Constituents are expressed as percent of seed wet weight.

Table 2. Lipid composition of the main oilseeds.

Oilseeds	Soybean	Peanut	Sunflower	Rapeseed
Lipid content	18–20%	45–50%	40–50%	40–45%
Omega-3 pufa Content*	1.2–2%	0–0.1%	0–0.1%	8–10%
Omega-6 pufa Content**	8–12%	15–30%	25–30%	15–30%
Sources	(Morin and Pagès-Xatart-Parès, 2012; FAO, 2003; INRA/CIRAD/AFZ, 2021)			

Constituents are expressed as percent of seed wet weight.
* The values given represent the aggregate total of all omega-3 PUFA species.
** The values given represent the aggregate total of all omega-6 PUFA species.

Table 3. Protein content of major oilseeds in native seeds and their meals.

Oilseeds	Soybean	Peanut	Sunflower	Rapeseed
Seed: protein content	35–40%	25%	15–20%	20%
Cake: protein content	45–50%	45–50%	35–40%	30–35%
sources	(FAO, 2003; INRA/CIRAD/AFZ, 2021)			

Constituents are expressed as percent of seed wet weight.

2.2.1 Amino acid profile

Most plant-based protein are deficient in certain indispensable amino acids (IAAs) and are therefore considered incomplete compared to the reference protein established by FAO (FAO, 2013). Deficiency in any IAAs prevents overall nutritional needs from being met, as the remaining amino acids cannot be fully utilized for protein synthesis. They will therefore be deaminated and oxidized, then irreversibly eliminated. Limiting AAs could, therefore, significantly affect protein synthesis. In Tujioka *et al.* 2011, showed in rats that fractional and absolute protein synthesis rates in body tissues decreased with a decline in the quality of dietary amino acids (AA). The IAAs profile of a protein is evaluated by a chemical score calculated as:

Chemical score = Indispensable amino acid content (mg/g protein) / Indispensable amino acid content in the reference protein (mg/g protein)

The calculation is performed for each IAA, and the lowest value is used to determine the chemical score of the protein. If chemical score is less than 1, the protein is considered incomplete or deficient in one or more IAAs (WHO/FAO/UNU, 2007). The chemical scores of proteins from the main oilseeds generally vary between 0.5 and 1.

An unbalanced profile of indispensable amino acids (IAAs) is also common in most oilseed proteins, with many oilseeds being deficient in lysine, a strictly essential IAA. This is, for example, the case with rapeseed and sunflower (Tab. 4). Lysine plays a critical role in numerous biological processes, serving as a site for post-translational modifications such as acetylation, methylation, ubiquitination, and SUMOylation. These modifications occur on lysine residues of histone and non-histone proteins and are central to DNA damage repair (Chatterjee *et al.*, 2012). Moreover, Laleg *et al.* also reported that rats fed a lysine-deficient wheat semolina diet, had lower muscle mass, particularly in the plantaris and soleus muscles, compared to rats fed an iso-nitrogenous casein (animal-based) diet (Laleg *et al.*, 2019).

Other oilseeds, often also classified as legumes, may be deficient in sulfur-AAs (methionine and cysteine), peanuts are a notable example. Soybean, however, is one of the few oilseeds that has no AA deficiencies (FFAS, 2019).

2.2.2 Digestibility

The second major factor of protein quality is protein digestibility. Digestibility refers to the ability of a protein to be hydrolyzed into AAs and short peptides and then absorbed in the intestinal tract. Chewing and breaking food into smaller pieces increases surface area for enzyme action of the oral phase, particularly α-amylase and the proteolytic enzymes of subsequent digestion phases. In the gastric phase which involves pepsin, the first enzyme breakdown of protein happens. Finally, it ends in the intestinal phase, during which

Table 4. Chemical scores of proteins from major oilseeds.

Oilseeds	Soybean	Peanut	Sunflower	Rapeseed	Casein
Chemical score	1	0.55	0.39	0.75–0.98	1.19
Limiting amino acids	Nil	Methionine Cysteine	Lysine	Lysine	Nil
Sources	(INRA/CIRAD/AFZ, 2021; FAO and WHO, 1991)	(INRA/CIRAD/AFZ, 2021; FAO and WHO, 1991)	(FAO and WHO, 1991	(Bracher, 2019; INRA/CIRAD/AFZ, 2021; FAO and WHO, 1991)	(FAO and WHO, 1991)

Table 5. True nitrogen digestibility in humans for proteins from the major oilseeds compared to casein.

Oilseeds	Soybean (Concentrate)	Peanut (Meal)	Sunflower (Isolate)	Rapeseed (Concentrate)	Casein
Protein digestibility	95%	94%	94%	95%	99%
Sources	(FAO and WHO, 1991)	(Deglaire and Moughan, 2012; FAO and WHO, 1991)	(FAO and WHO, 1991)	(FAO and WHO, 1991)	(FAO and WHO, 1991)

pancreatic proteases (trypsin, chymotrypsin, elastase, and carboxypeptidase) break peptide bonds and release small peptides and free AAs. These degradation products (AAs and small peptides) are then absorbed, while any unabsorbed proteins and peptides transit into the colon where they are either used by the microbiota or excreted (Marques de Sousa, 2022).

In the human body, proteins from oilseeds, and plant-source proteins in general, have a much lower digestibility than animal-source proteins (Guéguen *et al.*, 2016). Animal-source proteins, such as casein, have between 90% and 100% digestibility, whereas the digestibility of plant-source proteins ranges from 35% to 100% (FFAS, 2019). Table 5 reports fecal digestibility values in humans for the major oilseeds.

The heterogeneity in oilseed protein digestibility can be explained by the diversity of plant raw materials, the protein package, and processing methods. Plant raw materials can be distinguished into three types: flours, concentrates, and isolates (Guéguen *et al.*, 2016). Flours generally contain 10% to 30% net protein and are obtained by grinding whole seeds. However, due to their high oil content, there are few if any oilseeds used in the form of flours. Concentrates typically have between 50% and 60% net protein content, and are produced through chemical and/or thermal processes, such as seed de-oiling (Séré *et al.*, 2022). Isolates, which are extracted through precipitation, alkaline extraction or ultrafiltration, usually have more than 75% protein content and have higher protein digestibility than both concentrates and flours (Séré *et al.*, 2022). Protein digestibility can be measured *via* several methods that use very different models. It is possible to assess digestibility *in vitro* using static (Brodkorb *et al.*, 2019) and dynamic models, or *in vivo* using animal models, such as ileum-cannulated mini-pigs or rodents (FAO and WHO, 1991). Finally, fecal or ileal digestibility can be assessed in humans. Given the invasive nature of ileal AA digestibility measurements, a protein isotopic labeling technique was developed to non-invasively assess protein digestibility by measuring the isotopic enrichment in plasma (Guillin *et al.*, 2024). Heterogeneity in digestibility is thus explained by the different assessment models used.

2.2.3 Protein quality evaluation

The two protein quality criteria, *i.e.*, IAA profile and digestibility, are not correlated. For example, sunflower protein has a good digestibility index (94%) but a low chemical score (0.39) due to its lysine deficiency (FAO and WHO, 1991). This is why scores have been developed to assess overall protein quality taking into account these two criteria.

Until 2013, the recommended index for evaluating the quality of dietary proteins was the protein digestibility-corrected AA score (PDCAAS). The PDCAAS is obtained using the formula: *PDCAAS = Chemical Score* × Digestibility of the protein*

**Chemical Score reflects the composition of a protein source in IAAs relative to the nutritional requirement for these AAs (Tessier et al., 2021).*

In 2013, the FAO recommended using digestible indispensable AA score (DIAAS) to address some of the limitations of the PDCAAS index. In particular, it proposed using the digestibility of individual AAs rather than the protein. DIAAS takes into account the ileal digestibility of each AA to eliminate endogenous nitrogen loss. DIAAS is calculated using the formula (FAO, 2013):

DIAAS = Chemical Score × True ileal digestibility of the amino acid*

**Chemical Score reflects the composition of a protein source in IAAs relative to the nutritional requirement for these amino AAs (Tessier et al., 2021).*

It has been shown that digestibility can vary significantly between AAs (Gaudichon, 2002; Rutherfurd, 2015). Unlike protein digestibility, which can be assessed on the basis of fecal nitrogen losses, AA digestibility has to be measured at ileal level, which involves methodological constraints. Unlike

Table 6. Protein quality of major oilseeds based on PDCAAS index and DIAAS index, compared to casein.

Oilseeds	Soybean (Concentrate)	Peanut (Meal)	Sunflower (Isolate)	Rapeseed (Concentrate)	Casein
Pdcaas	0.90–1	0.52	0.37	0.93	1
Diaas	0.80–0.90		0.45–0.50	0.70	1.45
Sources	(FAO and WHO, 1991; Mathai *et al.*, 2017)	(FAO and WHO, 1991)	(FAO and WHO, 1991; Ertl *et al.*, 2016)	(FAO and WHO, 1991; Ertl *et al.*, 2016)	(FAO and WHO, 1991; Guillin *et al.*, 2022)

Table 7. Comparative analysis of plant-based proteins sources: cereals, legumes and oilseeds.

	Cereals	Legums	Oilseesds
Protein content	7–15%	20–40%	20–40%
Limiting amino-acids	Lysine	Methionine, Cysteine	Lysine – Methionine, Cysteine
Digestibility	80–90%	80–95%	85–95%
Functional properties	Elasticity, water holding	Gelling, water/oil holding	Emulsification, foaming, gelling, water/oil holding
Sources	(Avelar et al., 2024; FAO and WHO, 1991)	(FAO and WHO, 1991; Keskin *et al.*, 2022)	(FAO and WHO, 1991; Singh *et al.*, 2022; Zhang *et al.*, 2023)

Constituents are expressed as percent of seed wet weight.

PDCAAS, DIAAS is not truncated at 1. Therefore, in the absence of a limiting AA, can reflect a protein's ability to compensate for deficiencies in other protein sources. PDCAAS values for the main oilseeds ranges from 0.5 to 1, while DIAAS values of the most limiting AA range from 0.45 to 0.9 (Tab. 6). Soybeans rank among the highest plant-based proteins in terms of PDCAAS and DIAAS, with scores ranging from 0.9–1 and 0.8–0.9, respectively. These high values reflect soybean's balanced indispensable amino acid (IAA) profile, which has no limiting amino acids, combined with its excellent digestibility. Similarly, rapeseed has a high chemical score and good digestibility, giving it PCAAS and DIAAS values of 0.93 and 0.7 respectively. In contrast, peanut and sunflower proteins have lower scores due their IAAs deficiencies. For peanuts, the PDCAAS is 0.52 while for sunflower, the PDCAAS and DIAAS values are 0.37 and 0.45–0.5 respectively.

2.3 Oilseeds and protein requirements

Recommended protein intakes vary depending on age, health status, and level of physical activity. In healthy adults, the nutritional recommendations in Europe for protein are about 0.83 g per kg body weight per day, which equates to approximately 10% to 20% of total energy intake (Anses, 2016).

However, there are specific populations that have specific protein intake needs. For children aged up to 3 years old, for example is recommended to provide 0.94–2.60 g/kg/day protein (Afssa, 2007), and for elite athletes 1.3–1.5 g/kg/day for strength sports and 1.2–1.4 for endurance sports (Afssa, 2007).

The recommended intake for older adults who develop anabolic resistance is 1 to 1.2 g protein/kg body weight per day together with regular physical activity to maintain skeletal muscle mass (Bauer *et al.*, 2013).

The French National Nutrition and Health Program currently recommends an intake of at least 2 portions of about 60 g (pre-cooked weight) of legumes per week and a small handful (about 30g) of nuts per day (PNNS, 2024). If we consider that oilseeds and legumes have a protein content of 20% or more, this guideline would provide at least 15% of the recommended weekly protein intake for a healthy adult weighing 75 kg. However, as stated previously, quality of protein intake must also be considered.

2.4 Oilseeds among plant-based protein sources

Within the broader landscape of plant-based proteins, oilseeds proteins occupy an intermediate position between those derived from cereals and legumes (Tab. 7). Nutritionally, protein content of many oilseeds is generally higher than that of cereals, but slightly lower than that of legumes. Their AAs profile is often limited by relatively low levels of sulfur-containing AAs (methionine, cysteine) or lysine, whereas legumes are mainly restricted by sulfur-containing AAs and cereals by lysine. In terms of digestibility, oilseed proteins exhibit values slightly higher than those of cereals and comparable to those of legume (FAO and WHO, 1991). Finally, oilseed proteins have many promising functional properties such as emulsification, foaming, gelling, or water/oil holding (Singh *et al.*, 2022; Zhang *et al.*, 2023). Cereal proteins are known for their elastic properties (Avelar *et al.*, 2024), while legume proteins are characterized by a high gelling capacity and the ability to hold water and oil (Keskin *et al.*, 2022).

3 Modulate protein quality of oilseeds

Other determinants of dietary proteins can shape the metabolic fate of their amino acids (AA) once absorbed. Thus, protein package also called the food matrix, food processing (Zahir *et al.*, 2018), blending with other protein sources (Berrazaga *et al.*, 2020), and response to gut conditions are all parameters that can modify the physicochemical properties of

Table 8. Major antinutritional factors in major oilseeds.

Oilseeds	Soybean		Peanut		Sunflower	Rapeseed	
Antinutritional factors	Tannin	1.9 mg/g	Tannin	8.9mg/g	No known significant factors	Glucosinolate	5–20 μmoles/g
	Trypsin inhibitor	1.2 mg/g	Trypsin inhibitor	5.6 mg/g			
	Protease inhibitor	1.2 mg/g	Phytic acid	2.6 mg/g			
	Phytate	1.2 mg/g					
Sources	(Adeyemo and Onilude, 2013; Samtiya *et al.*, 2020)		(Samtiya *et al.*, 2020)		(Borredon *et al.*, 2011)	(Evrard, 2005)	

proteins and ultimately their digestion, absorption, and bioavailability for peripheral tissues such as skeletal muscle (Boirie *et al.*, 1997).

3.1 Protein package

The food matrix of the proteins, referred to here as 'protein package', also plays a major role in protein quality. The protein package is defined as the set of components that accompany a protein source in a food. It may include lipids, fiber, vitamins, minerals, and other bioactive compounds, which could all affect protein digestibility. Lipids, polysaccharides, and fiber play a complex and still poorly understood role in protein digestibility and digestion rate, which they can either reduce or enhance (Grundy *et al.*, 2016; Ding *et al.*, 2022). Dietary fiber is well known to have positive health effects, but it can also interact with digestive enzymes and/or substrates in ways that limit nutrient bioavailability and digestibility. Dietary fiber may reduce enzyme–substrate interactions by increasing the viscosity of the digesta or by directly binding to enzymes and substrates (Grundy *et al.*, 2016). Numerous components of the protein package are consequently classified as antinutritional factors (ANFs) as they interfere with the digestion of oilseed proteins (Tab. 8). Examples of ANFs include protease inhibitors such as trypsin or amylase inhibitors, which hinder the activity of digestive enzymes involved in protein breakdown, and other molecules such as tannins and saponins that bind to nutrients, complexing their structure and reducing their digestibility (Samtiya *et al.*, 2020). The presence of ANFs slows the digestion rate, which negatively impacts digestibility (Gilani *et al.*, 2012). Li *et al.* investigated the ileal digestibility of soybean meal in pigs before and after autoclaving the meal to reduce the activity of ANFs. Trypsin inhibitor activity was 3 g/kg in the autoclaved soybean meal *versus* 13 g/kg in the non-autoclaved meal. The autoclaved soybean meal also had 50% higher ileal digestibility than the non-autoclaved sample (Li *et al.*, 1998).

Furthermore, plant and animal proteins are also significantly different in terms of structural organization. The structure of the proteins influences the accessibility of cleavage sites for digestive enzymes. Plant-based proteins are often encapsulated in rigid cell walls and contain more beta sheets than animal proteins, which makes them less amenable to hydrolysis and decreases their digestibility (Marques de Sousa, 2022). Carbonaro *et al.* used infrared reflectance spectroscopy to study the secondary structure of legume proteins, particularly soybean, and concluded that the beta-sheet structures of legume proteins have negative effects on *in vitro* digestibility (Carbonaro *et al.*, 2012).

Processing methods (cooking, dehulling, fermentation, etc.) also have significant effects on protein digestibility.

3.2 Strategies to improve protein quality of oilseeds

3.2.1 Protein blends

One strategy to improve protein quality is to rebalance the IAA profile. Oilseeds, often deficient in lysine, can be combined with other protein sources that have complementary IAA profiles. For example, oilseeds can be blended with legumes such as pea, soybean or lentil, which are rich in lysine and low in sulfur-containing AAs (methionine, cysteine) and therefore provide complementary (Berrazaga *et al.*, 2020). It has been shown that intake of a complementary plant protein mixture with a balanced IAA profile stimulates muscle protein synthesis rates after exercise, in a manner equivalent to whey protein (VAN DER Heijden *et al.*, 2024). Similarly, Berrazaga *et al.* showed that the intake of wheat–legumes pasta formulated with a balanced IAA profile led to a similar protein synthesis rate in muscle to a casein diet (Berrazaga *et al.*, 2020). In summary, most oilseeds are naturally deficient in lysine but can be combined with legumes to deliver a balanced IAA profile and thereby support optimal protein synthesis.

3.2.2 Processing methods

The low natural digestibility of proteins in native oilseeds can be improved through various processing methods tailored to each type of seed. For legumes, simple culinary processes like soaking or cooking have been shown to improve protein digestibility. Soaking allows the seed to hydrate, which partially inactivates certain ANFs such as protease inhibitors. Cooking deactivates thermosensitive ANFs and alters the structure of proteins in a way that makes them more accessible to digestive enzymes. El Suhaibani *et al.* in 2020, studied raw goat pea seeds (*Securigera securidaca L.)* and found that their phytate and tannin contents decreased from 4.32% ± 0.38 and 7.10% ± 0.063, respectively, before cooking to 1.47% ± 0.021 and 4.51% ± 0.077, after cooking for 20 min. After soaking in water for 6h at 25 °C, tannin content decreased to 4.50% ± 0.028. Furthermore, AA analysis revealed that isoleucine, leucine, phenylalanine, and histidine concentrations increased after soaking (EL-Suhaibani *et al.*, 2020). Thermal treatments also modify protein structure and thus affect protein digestibility. Carbonaro *et al.* observed a loss of the beta structure of legume proteins after autoclaving, which increased protein availability (Carbonaro *et al.*, 2012). However, these culinary processes are not really suited to oilseeds such as sunflower or rapeseed which are consumed in a different form to legumes and are mainly processed by dehulling or oil extraction. Dehulling oilseeds has the potential to improve the protein content of the oil cakes. For example, dehulled sunflower cake contains 37% protein *versus* 27% in non-dehulled seeds (Terres Univia, 2025a). Similarly, after oil extraction, the resulting cakes have a higher protein concentration than the initial whole seeds (INRA/CIRAD/AFZ, 2021). However, oilseed oil extraction has a large environmental footprint, particularly because it demands high energy input and uses chemical solvents such as hexane that can contaminate the local environment. The continued depletion of non-renewable resources and increasing consumer demand for environmentally friendly products have spurred an increasing number of studies investigating alternative strategies to replace hexane and other petrochemical-derived solvents. Bio-based solvents (or 'green solvents') obtained from plants through biorefinery industries designed to maximize the use of all plant material represent a more sustainable alternative solution (Fine *et al.*, 2013).

New sustainability-driven strategies are emerging to improve protein quality and functionality. One such approach is dry fractionation, which is an alternative to wet processing. Dry fractionation combines seed milling and dry separation. This method is more resource efficient (low use of water and energy), reduces the use of chemicals and significantly limits the loss of micronutrients during processing compared to wet methods (Schutyser *et al.*, 2025). Wockenfuss *et al.* (2023) demonstrated that air classification combined with triboelectric separation improves the protein enrichment of defatted rapeseed press cake. Another strategy is enzymatic hydrolysis, which involves using proteolytic enzymes to break down high molecular weight into peptides or AAs. This approach enhances protein digestibility by making the resulting peptides and AAs more accessible to digestive enzymes (Opazo-Navarrete *et al.*, 2025). Beaudart *et al.* (2021) demonstrated that enzymatic hydrolysis of rapeseed significantly improved both seed digestibility and functional properties.

Bioprocesses such as fermentation and germination ultimately modify food texture and flavor while also improving nutritional profile. Fermentation and germination have been shown to significantly improve protein digestibility. Germination, characterized by the resumption of metabolic activity in the seed, leads to changes in protein structure and breaks down ANFs. Alonso *et al.* showed that a 24 h germination treatment improved the *in vitro* digestibility of faba and kidney bean proteins compared to the native seed. This improvement is attributed to a significant reduction in ANFs (phytic acid, tannins, and polyphenols), which are known to form complexes with nutrients and reduce protein digestibility (Alonso *et al.*, 2000), compared to the native-state seed. Similarly, El Suhaibani *et al.* observed a significant reduction in phytate and tannin levels after germinating goat pea seeds *(Securigera securidaca L.)* for 48 h at 25 °C.

Fermentation, by bacteria and yeasts, can degrade ANFs, particularly phytic acid. Yan *et al.* showed that compared to a non-fermented control diet, diets containing fermented soybean flour significantly increased the apparent ileal digestibility of proteins and AAs in pigs. They demonstrated that fermentation changed the nutritional composition of soybeans, increasing their crude protein and AA content and decreasing their ANF content such as glycinin and trypsin inhibitors (Yan *et al.*, 2022). Sousa *et al.* highlighted that fermentation of rapeseed and sunflower cakes led to an increase in their bioactive properties, particularly by enhancing their antioxidant capacity (Sousa *et al.*, 2023). Yasar *et al.* (2018) showed that 48 h of fermentation with *Bacillus Subtilis ATCC PTA-6737* reduced the phytic acid content of sunflower meal by approximately 40%. Increasingly, research is focusing on precision fermentation, which aims to produce food ingredients in a cost effective and sustainable manner using abundant and low-cost substrates. This is achieved through precise genetic modifications that rewire metabolic pathways in microorganisms. Precision fermentation improves the overall quality of food products, notably by enhancing flavor and increasing the production of vitamins and antioxidants. It is particularly being explored for soy proteins to impart meat like flavors (Hilgendorf *et al.*, 2024).

Nevertheless, few studies have focused on the impact of bioprocessing on the quality of oilseeds protein. Results on legumes indicate that bioprocessing reduces major ANFs and could therefore offer a promising route for enhancing the nutritional value and utilization of oilseeds in human diets.

3.3 Lipid–protein interactions

Dietary lipids are known to have interactions with proteins when these two nutrients are consumed during a meal and/or are present in one or more foods. Research is increasingly investigating lipid–protein interactions in order to understand their role in shaping overall protein metabolism processes, and oilseeds, which are characterized by high lipid and protein contents, are a major focus of these interactions. Interactions between lipids and proteins are numerous, have multiple impacts, and occur at different stages of metabolism.

3.3.1 Digestion and absorption

Lipids ingested simultaneously with proteins, as it is the case when consuming oilseeds, can affect the physiological processes of digestion and absorption. However, the effects of lipids on protein digestibility remains complex to unravel and still not fully understood.

Lipids can modulate enzymatic activities in the gastrointestinal tract. The presence of lipids can hinder access to the protein cleavage sites of digestive enzymes (proteases). If proteases have restricted access to proteins, then they will undergo less degradation and thus be less absorbed (Zahir *et al.*, 2018). However, the effects of lipids on protein digestibility greatly depend on the structure of the proteins and lipids involved. Oilseed proteins, acting as emulsifying agents, combined with unsaturated fatty acids present in the seeds, promote fluidity and stable emulsion formation. Studies, primarily based on animal sources (pork and chicken protein), have shown that lipid–protein emulsion prevents protein aggregation and gives digestive enzymes easier access to the proteins dispersed in the emulsion, which should promote protein digestibility (Zhou *et al.*, 2019; Ding *et al.*, 2022).

Table 9. Examples of bioactive peptides identified in major oilseeds (Zhang *et al.*, 2023).

Oilseeds	Soybean	Peanut	Sunflower	Rapeseed
Bioactive peptide	LVQGS, II, ID, IFY, LFY LYY, and NWGPLV; LPYPR ; ILL, LLL and VHVV	TPA, LPS, SP	FVNPQAGS	VPHLLVATFGVLLVLNGCLAR and GQLLVVPQGFAVVK; IPK, LP, VPHL and IPNQT
Properties	ACE-inhibitory; Hypocholesterolemic; Antilipidemic	Antioxidant	ACE-inhibitory	Antimicrobial; Hypoglycemic
Sources	(Kodera and Nio, 2006; Rho *et al.*, 2009; Shimakage *et al.*, 2012; Tsou *et al.*, 2013; Yoshikawa *et al.*, 2000)	(Ji *et al.*, 2014)	(Megías *et al.*, 2009)	(Duan *et al.*, 2021; You *et al.*, 2022)

However, Ding *et al.* (2022) concluded that the emulsifying properties of proteins varied depending on the type of protein, and that for soy proteins, increasing the fat content did not improve protein digestibility, unlike for pork and chicken proteins. To our knowledge, no studies have examined the impact on protein digestibility of the emulsion of proteins and lipids from oilseeds.

However, these interactions are also largely modulated by the food processing methods employed. For example, heat treatment causes lipid oxidation, leading to the formation of reactive oxygen species (ROS). ROS cause oxidative damage to proteins and lead to protein aggregation, which has a negative effect on protein digestibility (Chen *et al.*, 2022). Ding *et al.* showed that digestibility can be affected by protein type and fat content, although soy protein showed no change in digestibility following an increase in fat content (Ding *et al.*, 2022).

3.3.2 Protein metabolism

Oilseeds are naturally rich in PUFAs. When the seed is consumed whole, as can be the case for soybeans, sunflower seeds, and peanuts, it provides an intake of α-linolenic acid (ALA) which is a precursor of omega-3 fatty acids such as EPA and DHA. A large number of studies have found evidence that these fatty acids protect pancreatic beta cells, which produce insulin, and reduce hepatic lipogenesis and skeletal muscle lipotoxicity. Several of these effects may be linked to the anti-inflammatory properties of EPA and DHA (Pinel *et al.*, 2014). The anti-inflammatory properties of PUFAs can also be explained by their impact on gut microbiota. A clinical study involving 22 healthy middle-aged subjects showed that administration of 4g per day of EPA and DHA led to a decrease in some bacteria, such as *Coprococcus* and *Faecalibacterium*, and an increase in more beneficial bacteria such as *Bifidobacterium*, *Oscillospira*, *Roseburia*, *Lachnospira*, and *Lactobacillus*. These results suggest that omega-3 PUFAs could promote the growth of beneficial bacteria with anti-inflammatory potential (Watson *et al.*, 2018).

Such anti-inflammatory mechanisms can influence protein synthesis pathways. Pro-inflammatory signals can inhibit protein synthesis pathways by activating catabolic pathways. By reducing inflammation, omega-3 PUFAs help restore a more pro-anabolic environment, enabling better activation of the PI3K/Akt/mTOR pathway, which plays a central role in protein synthesis (Saxton and Sabatini, 2017).

Dietary omega-3 PUFAs also induce membrane remodeling, which affects cellular signaling. After incorporating PUFAs, cellular membranes become more flexible and protein transport across the lipid bilayer membrane is facilitated, which positively impacts protein metabolism (Ma *et al.*, 2004). Many studies have used fish oil as the primary source of PUFAs, but few studies have focused on the effects of plant-source PUFAs. It would be valuable to investigate the impact of plant sources of PUFAs, and particularly oilseeds, on lipid composition and membrane properties.

3.4 New criteria for determining protein quality?

The adequacy of current criteria used to assess protein quality is in question because they primarily rely on protein digestibility and chemical score. While these factors are important, they do not fully capture the complexity of protein functionality (FAO, 2013). The quality of a given protein depends on its composition, structure, and protein package, but it is also specific to the population consuming it, as well as their physio pathological state.

Another potentially important criterion to consider is the speed/rate of protein absorption by the intestine. Proteins can be digested at different rates, hence the principle of ‘slow’ and ‘fast’ proteins (Boirie *et al.*, 1997). The rate of protein digestion and AA absorption from the intestine has a major effect on whole-body protein anabolism. ‘Slow’ proteins will induce a low but prolonged plateau of moderate amino-acidemia, whereas ‘fast’ proteins will lead to a sharp but transient increase in aminoacidemia. For example, in anabolic resistance settings, it is more effective to favor a short hyperaminoacidemia by eating ‘fast’ proteins in order to overcome the high anabolic threshold and enable muscle anabolism. Oilseed proteins, such as the proteins in soybean, have a modest digestion rate. Soy proteins form small particles that are quickly emptied from the stomach and can enter the small intestine, whereas casein forms larger particles and therefore slows the rate of gastric emptying (Wang *et al.*, 2021).

The ability of a protein to generate bioactive peptides with beneficial effects is also another candidate criterion for protein quality. Han *et al.* identified several bioactive peptides in various oilseeds (soybean, rapeseed, sunflower, sesame) that have antioxidant, antihypertensive, immunomodulatory and antidiabetic properties (Han *et al.*, 2021). Studies have found that numerous biopeptides from major oilseeds have an ACE-inhibitory activity that is evidence of antihypertensive, antioxidant, hypoglycemic (DPP-IV inhibitory), hypocholesterolemic, antilipidemic and antimicrobial properties (Tab. 9) (Zhang *et al.*, 2023).

In recent years there has been an increasing interest in the protein content of biologically active AAs. These biologically-active or functional AAs are defined as AAs that participate in and regulate key metabolic pathways (Wu, 2013). Research has identified leucine and arginine as anabolic AAs involved in stimulation and activation of protein synthesis pathways (Salles *et al.*, 2024). Leucine is more abundant in animal-source proteins than plant proteins, whereas arginine is typically found in relatively high quantities in plant-source proteins, such as oilseed. Oilseeds such as rapeseed and sunflower have relatively leucine-rich and arginine-rich AA profiles: rapeseed contains 7.1% Leu and 5.8% Arg, while sunflower contains 6.7% Leu and 7% Arg (Zhang *et al.*, 2023).

4 Conclusion

Oilseeds are emerging as promising plant-based food sources to support a dietary transition toward more sustainable eating patterns. Oilseeds are rich in lipids, particularly PUFAs such as ALA, which is a precursor of EPA and DHA that are known to have anti-inflammatory effects. In addition to their lipid profile, major oilseeds contain substantial protein levels from 20% to 40% in native state, making them good candidates for covering daily protein requirements. However, like most plant-based proteins, oilseeds proteins are generally considered lower in quality compared with animal-source protein. This is due to imbalanced profiles of IAAs often characterized by deficiencies in lysine or sulfur-containing AAs, as well as lower digestibility than animal-source proteins. However, it is possible to enhance the quality of these plant proteins *via* various techniques and processes, such as blending sources to restore a balanced profile or applying bioprocesses such as fermentation or germination. Oilseed proteins also offer further advantages, such as the composition of the protein matrix, content of bioactive AAs, and ability to generate bioactive peptides. Finally, the composition of oilseeds promotes interactions between lipids and proteins which, although complex and not yet fully understood, can have positive effects on protein digestion, absorption, and metabolism.

Conflicts of interest

The authors have no conflict of interest to declare.

Author contribution statement

Catherine Bompart: Conceptualization, Writing Original Draft, Marine Gueugneau : Conceptualization, Writing Review, Stéphane Walrand: Conceptualization, Writing Review.

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