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Oats as a source of nutritious alternative protein

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ABSTRACT

The common oat (*Avena sativa*) is a widely-grown cereal grain that has recently garnered attention as a potential source of innovative and alternative foods to replace animal protein. This review article considers the many characteristics of oat-based foods, focusing on oat protein quality and the nutritional effects of oat protein consumption. We first summarize the role of oats as a sustainable alternative protein source before considering dry and wet separation technologies for the enrichment or isolation of oat protein. We then discuss oat protein, including technological properties such as solubility, foaming, emulsification, gelling, and fibrillation capacity, which predict its applicability in diverse liquid and solid foods. We emphasize the potential of oats as a plant-based protein source for the design of innovative dairy and meat alternatives. The review also discusses oat protein quality, particularly its protein digestibility-corrected amino acid score compared to other plant-based protein sources, and insights related to the functionalization oat protein for improved performance. Finally, we consider the ability of oat protein to enable a dietary shift, including knowledge gaps and avenues for future research. This review consolidates existing knowledge on oats and oat protein, providing a comprehensive understanding of technological functionality, applicability in diverse food categories, nutritional potential, protein quality, and associated health benefits.

1. Oat as a sustainable alternative protein source

Global oat production between 2011 and 2021 remained at a steady 21–25 million tons, although this accounts for less than 1 % of total cereal grain yields (FAO, 2023). The biggest oat producers are the Russian Federation and Canada followed by Australia, Spain, the United Kingdom, Brazil, and Finland. Most oats are used as animal feed. For example, only 20 % of the Finnish oat harvest is consumed by humans. However, food usage is increasing, particularly with sales of innovative oat-based products designed as dairy and meat alternatives.

Oats have unique properties compared to other major grains, including higher protein levels than many other cereals (up to 20 % protein), a balanced amino acid composition with up to 36 % essential amino acids, and the absence of gluten and allergens (Boukid, 2021). Oats therefore provide an alternative source of protein to replace conventional dairy and meat products. Oat protein is rich in sparingly-soluble globulins, making it suitable for the preparation of extruded meat alternatives. In addition to protein, oat also contains lipids, vitamins, antioxidants, and soluble dietary fiber (mixed-linked β-glucans) that help to reduce cholesterol levels in the blood.

Oats can grow in diverse environmental conditions and on a variety of soil types, including acidic soils. This robustness is likely to make oats more important in the future, as the changing climate makes cereal agriculture more challenging. However, the quality of harvested oat grains is sensitive to weather conditions, and they are easily infected by mycotoxin-producing fungi in wet weather. Improved agricultural practices and new oat varieties that resist fungal contamination are needed to ensure that high-quality oats are available in the future.

Traditional oat ingredients include oat flour, flakes and bran, which are used in breakfast cereals, bakery products and porridges. Many novel oat ingredients based on soluble dietary fiber (mixed-linked β-glucans) or protein have been described more recently, and are mainly used in beverages, snacks, and meat alternatives.

This review article discusses protein separation technologies for the production of oat protein concentrates and isolates and considers the quality and functional attributes of oat proteins, as well as functionalization strategies and applications in traditional and novel foods (Fig. 1).

2. Separation technologies for oat protein

Oat grain is harvested with the non-edible hulls intact. This hard outer shell is then removed to reveal the seeds (groats), which are

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typically heated with steam to inactivate endogenous lipases. Therefore, most data concerning the separation of oat protein involves dehulled and steamed starting material. There are also reports in which oat flakes or bran are used as the raw material. The protein quality differs between oat tissues: the seed germ is richer in lysine and threonine, whereas the bran and endosperm fractions are richer in glutamic acid (Peterson, 2011). This allows the modification of protein quality by selecting different oat tissues for protein separation. Differences in the functionality of oat protein ingredients produced by different methods generally reflect the relative proportions of protein classes that differ in solubility, the degree of protein denaturation, and the content of non-protein components. High-moisture wet extrusion methods typically benefit from a high protein content and low protein solubility, whereas beverage applications benefit from minimal protein denaturation and high solubility.

2.1. Dry separation methods

Oat groats typically contain 14–20 % protein, which is a higher protein content than corn, rice or barley. Different milling products contain different amount of oat protein (Peterson, 2011): the protein content is lowest in the inner groats, comprising the starchy endosperm (10 % protein), and highest in the germ (44 % protein) and outer groats (19 % protein). Oat endosperm flour and oat bran can be separated by sieving based on the different particle sizes, and the common milling product (oat bran) contains 20–30 % more protein than products from whole oat groats, such as oat flakes or wholegrain oat flour.

Air classification is a dry separation method based on differences in particle size, shape and density. This can separate coarse and fine particles, also enabling the partial separation of components such as starch, protein and dietary fiber. Air classification has been used to separate starchy material from the oat bran fraction, which also concentrates the protein in the bran. The process yields an oat bran concentrate with up to 32 % dietary fiber and 21 % protein. After defatting with hexane, fractionation by air classification can produce fractions with slightly more than 30 % protein, but starch removal does not improve the protein content much further (Wu and Doehlert, 2002). Higher protein concentrations can be achieved by separating the protein bodies from the dietary fiber. Due to the high oil content of oats, this separation is difficult without a prior lipid removal step. Sibakov et al. (2011) have described a fractionation process consisting of lipid removal by supercritical CO_2 extraction, followed by two consecutive milling and air classification steps. This process yielded a fraction containing 73 % protein with a 5 % mass yield and a 22 % protein yield.

Another dry separation technology is tribo-electrostatic separation, in which particles are separated based on their tribo-charging properties. In this technique, protein-rich particles acquire a positive charge and carbohydrate-rich particles acquire a weak negative charge or no charge at all. Only a few studies have described this approach in oats, and only moderately successful protein separation was achieved (Konakbayeva et al., 2022). The most recent innovation is extrusion-aided dry separation, a single-step separation process where oat flour can be separated in to protein-rich and starch-rich fractions (Nikinmaa et al., 2022). The protein content of the protein-rich fraction was 73–79 % with a protein yield of 71–73 %. The protein-rich fraction was similar to texturized vegetable protein in its functional properties and applicability (Fig. 1c).

2.2. Wet extraction methods

The wet extraction of plant proteins relies on protein solubility in the extraction medium. Oat protein is more soluble in water under alkaline rather than neutral conditions. Typically, oats are heated to avoid the formation of off-flavors by endogenous enzymes, but this also affects the solubility of oat proteins. Runyon et al. (2015) reported that heat treatment reduced oat protein solubility to 36 % during alkaline extraction compared to 75 % in the absence of heat treatment.

The extraction of oat proteins under alkaline conditions (pH 9–11) is often followed by salt-induced isoelectric precipitation at pH 4–5 to concentrate the extract, and then a desalting step before drying (Wang et al., 2022). The oat protein isolate obtained by such processes typically has a protein content of 67–87 %. Ultrafiltration has also been used to concentrate proteins extracted under alkaline conditions. Immonen et al. (2021b) studied extraction under mildly alkaline conditions followed by ultrafiltration/diafiltration to obtain an oat protein concentrate that maintained oat protein functionality, resulting in a protein content of 45 % in the spray-dried product.

Enzymatic treatment during wet extraction can improve the functionality, yield or purity of the oat protein concentrate. Enzymes that break down starch and cell wall components are often used for this purpose. For example, oat grain treated with a mixture of β-glucanases before alkaline extraction increased the protein yield from 15 % to 56 % (Liu et al., 2008). Enzymatic deamidation has also been combined with oat protein extraction to improve protein solubility (Immonen et al., 2021b).

Strong alkaline conditions may alter the functionality of oat proteins by inducing crosslinking, racemization, peptide chain fragmentation, thiol oxidation and β-elimination reactions. As an alternative, plant proteins can be extracted in a saline buffer, for example 0.5–1.0 M NaCl or $CaCl_2$. However, a comparison of alkaline (pH 9.5) and saline (0.5 M $CaCl_2$) extraction conditions showed that alkaline extraction achieved a protein yield of 67 % compared to 25 % in the saline buffer (Yung Ma, 1983).

Deep eutectic solvent extraction has also been applied to oat protein

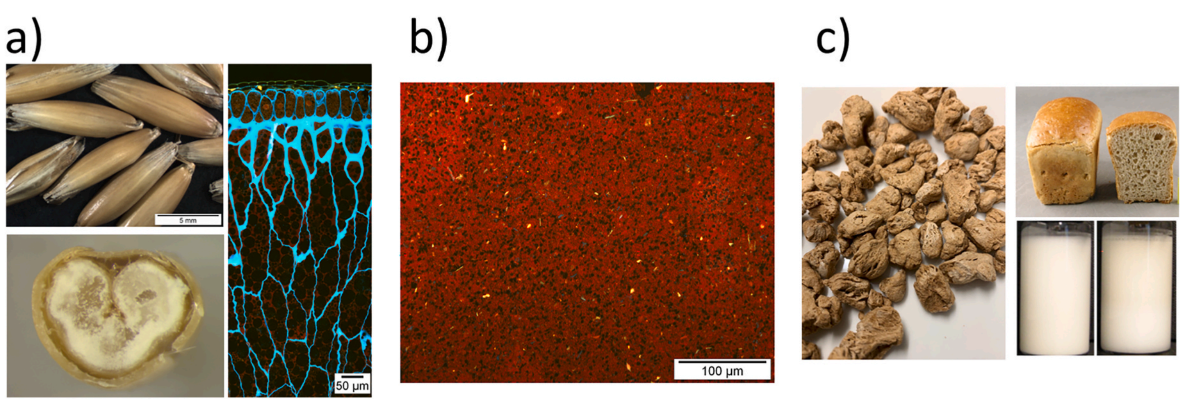

Fig. 1. Oats, oat protein and food applications. a) Oat grains and cross-sectional images, with β-glucan in blue and protein in red. b) Microscopic image of oat protein concentrate obtained by dry fractionation. c) Appearance of texturized oat protein, high-protein oat bread, and oat-based milk substitute. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Yue et al., 2022). These eutectic mixtures of hydrogen bond donors and acceptors are considered safe and sustainable as solvents and the extraction process is simple. Even so, there is still a need to evaluate food safety aspects to rule out any potential toxicity of solvent residues.

3. Properties of oat protein

Unlike wheat, barley and rye, 70–80 % of total oat protein belongs to the salt-soluble fraction (globulins) whereas the alcohol-soluble prolamins (known as avenins in oat) form a minor component (4–14 %). Oat globulins contain higher levels of basic amino acids (lysine, histidine and arginine) than avenins, whereas avenins are richer in sulfur-containing amino acids as well as glutamic acid, glutamine and proline (Peterson, 2011). However, avenins have a lower proline content than wheat, barley and rye prolamins (Shewry, 1999). Water-soluble albumins account for 9–20 % of total oat protein and are rich in lysine. Glutelins are not considered major oat storage proteins (Peterson, 2011).

The heat-tolerance of oat protein is largely determined by the globulins, which have a thermal denaturation temperature of 110 °C. This is 10–20 °C higher than soy glycinin and sunflower helianthinin, and may reflect differences in secondary and tertiary structure, charge distribution and surface hydrophobicity (Mäkinen et al., 2017). Industrial heat treatment reduces the solubility of oat protein from 75 % to 36 %, and this is probably due to the denaturation of albumins and avenins (Runyon et al., 2015).

Native oat protein has low solubility in water compared to other plant proteins, and particularly in comparison to pea protein. Native oat protein also has lower water-holding, emulsion and stability values than pea protein, but equal or higher values for oil-holding capacity and foaming properties (Tang et al., 2023). The solubility of oat protein is significantly dependent on the pH, ionic strength, and ionic species of the buffer, with particularly low solubility at neutral or slightly acidic pH. This is the main factor limiting the utilization of oat protein in foods because the foaming and emulsifying properties of oat protein isolates are also low in the pH range 4–7 (Ma, 1984). The solubility of oat protein isolates reaches a peak of 40–50 % in extremely dilute buffers (Li and Xiong, 2021).

The functionality and applicability of oat protein can be improved and widened by modification treatments (Mäkinen et al., 2017). Hydrolysis and amino acid modification alters the net charge and hydrophilicity of protein in oat protein isolates. For example, the acylation of nucleophilic groups has been shown to improve the solubility, emulsification and fat-binding capacity of oat protein isolates (Ma, 1984). In contrast, succinylation introduces more negatively charged groups and increases electrostatic repulsion, thus reducing solubility and emulsion coalescence (Ma, 1984; Mirmoghtadaie et al., 2009). The solubility, colloidal stability, emulsification and foaming properties of oat protein can be improved by deamidation, which converts the amides of glutamine and asparagine residues into negatively charged carboxyl groups and causes conformational changes (Mirmoghtadaie et al., 2009; Nivala et al., 2017). The limited hydrolysis of oat protein using proteases or peptidases has been reported to increase its solubility, water-holding capacity, antioxidant potential, and metal-chelating activity, and its ability to form emulsions, foams and gels (Brückner-Gühmann et al., 2021; Zheng et al., 2020). The emulsification of oat protein isolates is also improved by glycation, conjugation with dextran (Zhang et al., 2015), and the reduction of disulfide bonds (Li and Xiong, 2023).

4. Applicability of oat protein in novel food concepts

4.1. Cereal foods as carriers for oat protein

A dietary shift to plant-based foods requires alternative proteins to have similar or even better technical, sensory, and nutritional properties than their animal counterparts. Although oat protein has a neutral taste and is easily digestible, its limited solubility hinders applications in high-protein food matrices. Cereal foods such as bread, pasta, flakes and puffs are typical carriers for oats and oat protein (Table 1, Fig. 1c). But the absence of gluten (which confers viscoelastic properties) and the high levels of β-glucan pose challenges in the development of products fully based on oats or oat protein. Furthermore, incorporating protein into bread can affect the quality of the crumb structure. Some studies have used oat protein concentrates or isolates as part of a wheat-based formulation in bread, with varying outcomes. For example, adding 3–6 % oat protein concentrate (52 % protein, 28 % fat) to wheat bread increased loaf volume, but the addition of >5 % oat protein isolate reduced loaf volume and increased hardness and chewiness (Pastuszka et al., 2012). Sourdough fermentation with oat protein concentrate improved the crumb texture and delayed starch retrogradation in gluten-free oat breads with claims that >20 % of total energy is derived from protein (Rekola, 2015). Crosslinking enzymes can be used to enhance the strength and viscoelastic properties of oat protein networks, which can improve crumb structure and loaf volume. However, more research is needed because the treatment of oat flour (9 % protein content) with laccase increased the loaf volume and reduced crumb hardness and chewiness in one study (Renzetti et al., 2010) but increased crumb hardness in another (Flander et al., 2011).

Gluten-free pasta with claims of high protein levels and a balanced amino acid profile was produced by the dry fractionation of oat followed by the recombination of the starch-rich fraction (9 % protein, 78 % starch, 10 % dietary fiber) and protein-rich fraction (42 % protein, 45 % starch, 6 % dietary fiber) along with a faba protein concentrate (68 % protein, 1 % starch, 12 % dietary fiber) also produced by dry fractionation (Duta et al., 2019). The addition of protein concentrates increased the hardness and chewiness of the product while reducing the predicted glycemic index.

Single-screw or twin-screw extrusion are often used to produce cereal-based foods, including snacks, pasta and breakfast cereals. Pasta is generally extruded at 50–70 °C whereas breakfast cereals and snacks require much higher temperatures (110–150 °C). In the latter case, partial protein denaturation occurs in oat extrudates (13–17 % protein) causing a loss of solubility, functionality and oxidative stability, but also inhibiting expansion thus increasing hardness (Sibakov et al., 2015). Paste extrusion or 3D printing is an emerging technology that provides structural and compositional flexibility in food design. Pastes prepared from oat protein concentrate (48 % protein, 37 % starch, 7 % dietary fiber) demonstrated elastic properties and fine particle sizes suitable for printing, thus achieving a printing quality comparable to pastes prepared from starch and skimmed milk powder (Lille et al., 2018).

4.2. Oat protein-based dairy and meat alternatives

The popularity of plant-based dairy and meat alternatives is growing, with analogs of milk, yogurt and butter all gaining traction alongside meat replacements. Table 1 provides a summary of dairy and meat alternatives containing oats that are already on the market. Due to limited protein solubility and colloidal stability, the commercial plant milk analogs often have a lower protein content (1 %) than cows' milk (3.5 %). The neutral taste of oat protein makes it an excellent candidate for dairy analogs. Researchers have explored the possibility of increasing the protein content of these products by improving the solubility of oat protein (Nieto-Nieto et al., 2014). Oat proteins can form gels when heated, but only at high concentrations, and they do not create structures when acidified, such as during the gradual pH decline that occurs during fermentation (Brückner-Gühmann et al., 2019). In contrast, starch gels form easily when a pre-heating step is introduced before fermentation, and the declining pH then leads to the formation of embedded oat protein clusters. The stability of fermented oat-based yogurt alternatives therefore relies primarily on the starch gel rather than an oat protein gel (Brückner-Gühmann et al., 2019). Oat protein-polysaccharide interactions involving inulin, carrageenan and

Table 1
Products on the market that contain oat proteins.

Product category	Oat ingredients (%)[a]	Other ingredients	Nutritional content (g/100g)	References
Oat cereals	Wholegrain oat flour (71–93 %)	Starches, sugars/natural sweeteners, fibers, emulsifiers, salt, acidity regulators	Energy 1577–1641 kJ Protein 11–13 g Fat 5–7 g (saturated 1 g) Carbohydrates 58–71 g Fiber 8–15 g	https://www.fazeraito.com/ https://www.elovena.com/en https://www.quakeroats.com/ https://www.nestle-cereals.com
Oat bread with 100 % of cereal ingredients oats	Oat bran, oat flour, oat flakes (53–64 %)	Water, yeast/sour culture, plant oil, thickeners, sugar, fiber, salt, preservatives	Energy 927–1065 kJ Protein 8–11 g Fat 4–5 g (saturated 0.8–0.9 g) Carbohydrates 28–39 g Fiber 5–11 g	https://leipomosalonen.fi/ https://www.vaasan.fi/en/ https://www.lidl.fi/ https://www.fazer.com/
Oat pasta	Oat flour (30 %) or oat flour and oat fibre (30 %)	Wheat flour, water	Energy 1475–1534 kJ Protein 10–13 g Fat 4–5 g (saturated 0.7–0.9 g) Carbohydrates 61–70 g Fiber 4–8 g	https://www.myllynparas.fi/ https://www.torino.fi/ https://www.pasta.lt/en/ https://www.organicnationeg.com/
Oat-based milk substitute	Oats (8–10 %)	Water, plant oil, starch, stabilizers, acidity regulators, emulsifiers, thickeners, salt	Energy 150–209 kJ Protein 0.3–1.3 g Fat 0.9–2 g (saturated 0.1–0.2g) Carbohydrates 6–9 g Fiber 0.8–1.5 g	https://www.oatly.com/ https://www.alpro.com/ https://www.fazeraito.com/ https://www.valio.com/ https://planti.fi/
Oat-based cream substitute	Oats (8–10 %)	Water, plant oil, starch, stabilizers, acidity regulators, emulsifiers, thickeners, salt	Energy 600–723 kJ Protein 0.9–1 g Fat 13–15 g (saturated 1–2 g) Carbohydrates 6–9 g Fiber 0.8 g (*one product*)	https://www.fazeraito.com/ https://www.oatly.com/ https://planti.fi/ https://www.elovena.com/en
Oat-based yoghurt substitute	Oats (6–8 %), oat flour (8 %) or oat milk	Water, starch, plant oils, thickeners, other plant proteins, calcium, salt, sugar, acidity regulators, stabilizers, preservatives, cultures, vitamins	Energy 219–366 kJ Protein 0.9–2 g Fat 0.6–3 g (saturated 0.1–3 g) Carbohydrates 9–12 g Fiber *not mentioned*	https://www.valio.com/ https://www.oatly.com/ https://www.fazeraito.com/ https://planti.fi/
Oat-based cream cheese	Oats (9 %) or oat bran (3 %) or oat milk	Water, plant oils, starch, other plant proteins, salt, stabilizers, sugar, acidity regulators, vitamins, preservatives	Energy 773–996 kJ Protein 1–3 g Fat 14–21 g (saturated 8–18 g) Carbohydrates 2–14 g Fiber 0.8–2 g	https://www.oatly.com/ https://en.mokaurameijeri.fi/ https://ilo.fi/en/home/ https://www.philadelphia.co.uk/
Oat milk ice cream	Oat milk (4 %, *one product*)	Sugar, plant oils, sugar, thickeners, other plant proteins, salt, stabilizers, emulsifiers, acidity regulators	Energy 692–887 kJ Protein 0.5–2 g Fat 6–13 g (saturated 6–10 g) Carbohydrates 25–31 g Fiber 0.9–3 g	https://www.oatly.com/ https://www.breyers.com/us/en https://sodeliciousdairyfree.com/ https://planetoat.com/ https://www.pingviini.fi/

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Table 1 (*continued*)

Product category	Oat ingredients (%)[a]	Other ingredients	Nutritional content (g/100g)	References
Oat chocolate	Oat flour (15 %) or oat powder (22 %)	Sugar, cocoa butter and mass, emulsifiers, salt	Energy 2273–2344 kJ Protein 4–5 g Fat 33–37 g (saturated 19–21 g) Carbohydrates 52–58 g Fiber 5 g (*one product*)	https://www.fazer.com/ https://hipchocolate.com/
Oat-based meat analogs	Oats (15 %) or oats as flour, bran and protein (20 %)	Water, other plant proteins, plant oil, sugar, salt	Energy 613–813 kJ Protein 17–27 g Fat 3–5 g (saturated 0.5–0.7 g) Carbohydrates 7–10 g Fiber 7 g	https://www.valio.com/ https://harkis.fi/en/

[a] Typical share of oats in the product if known.

dextrin can also improve gelling properties by forming phase-separated networks at neutral pH (Nieto et al., 2016).

High-moisture extrusion processing is a more recent innovation than dry or puffing extrusion and involves high temperatures and extensive shearing, where the water content can vary from 50 % to 70 % depending on the properties of the powder mix. The long cooling die at the extruder exit enables protein fiber elongation and orientation to form meat-like structures. The pre-treatment of oat protein concentrate (40 % protein) with trans-glutaminase and heat enhanced the fibrillation of oat protein, and anisotropic structures resembling meat were formed (Pöri et al., 2022). Blends of pea protein isolate and oat okara (the pulp remaining after the production of oat milk) have also been processed by high-moisture extrusion, and fibrous protein structures similar to meat were obtained at temperatures >150 °C (Immonen et al., 2021a).

There have been no systematic studies focusing on the improvement of oat protein functionality and it is important not to underestimate the effect of protein extraction (dry or wet) and the degree of purity on the functional properties and applicability of oat proteins. There is an urgent need for multifunctional, minimally processed and affordable protein sources, where oat protein can help to close the protein gap.

5. The potential of oat protein to promote a dietary shift

As discussed above, the positive nutritional qualities of oat protein include its balanced amino acid composition, high content of essential amino acids, suitability for gluten-free diets, and low allergenicity, although the overall protein quality is inferior to soybean and pea. The amino acid score is 0.66–0.75 for oat, which is slightly lower than that of soy but much higher than that of wheat (Nosworthy et al., 2023). Oat protein has beneficial effects on physical performance and recovery, and several bioactive peptides derived from oat proteins have been shown to influence biological functions (Boukid, 2021).

The quality of a protein depends not only on the amino acid content but also its digestibility. Oat is classified in the *no quality claim* category, with a digestible indispensable amino acid score (DIAAS) < 75 based on the reference pattern for 0.5–3 year olds, the limiting amino acid being lysine. The DIAAS of oat protein is higher than that of wheat, rice, corn, hemp or fava bean but lower than that of rapeseed, lupin, pea, canola, soy or potato, and that of animal proteins such as whey, egg, pork or casein. The protein digestibility corrected amino acid score (PDCAAS) in raw (69) and cooked (60) oat samples is generally lower than that of soy (raw 59–75, cooked 73) but higher than that of wheat (raw 40–42, cooked 39–40) (Nosworthy et al., 2023). Cooking reduces the DIAAS and PDCAAS of oats, indicating that thermal treatment changes the accessibility of amino acids. Kiln roasting and stirring roasting have also been shown to reduce the amino acid scores of oat proteins. However, heat treatment may improve protein digestibility by denaturation, increasing the exposure of otherwise hidden peptide bonds to digestive enzymes.

The processing of plant-based ingredients may increase or decrease protein digestibility by changing the interactions between proteins and other components, such as carbohydrates, dietary fibers and anti-nutritional factors in the food matrix (Lappi et al., 2022). For example, *in vitro* protein digestibility was significantly reduced when a wheat biscuit was enriched with oat bran fiber or lentil, and when pea protein isolates were enriched with β-glucan. The PDCAAS of oat protein concentrate (60) and cooked oat protein concentrate (57) were found to be higher than that of oat flour (51) (Sánchez-Velázquez et al., 2021). The digestibility of oat protein isolate *in vitro* is high, and is increased further by ultrasound pre-treatment. However, little information is available about protein digestibility in foods containing oat protein. *In vitro* protein digestibility after incubation for 2 h was 25 % for oat milk compared to 25 % for almond milk, 22 % for hemp milk, 21 % for soy milk, and 26 % for cows' milk (Lappi et al., 2022).

The global demand for animal products has increased due to changes in dietary patterns, higher incomes, and population growth (Szenderák et al., 2022). More than two-thirds of consumers identify as omnivores and the rest as vegetarian, vegan or pescetarian. However, flexitarian diets (based mainly on plants but occasionally incorporating meat) are becoming more prevalent and will contribute to a shift in dietary preferences, which are influenced by social, cultural, environmental, and traditional factors as well as income. In Europe, the consumption of meat is declining and many European consumers are planning to adopt a flexitarian lifestyle. The main barriers preventing the transition to more plant-based foods in Europe are price, lack of information, and lack of choice when eating out, whereas in the USA the main barriers are taste and price.

Protein intake (g/capita/d) in Europe is 102.7 g, of which 58.3 g comes from animal sources and 44.4 g from plants (Poutanen et al., 2022). Cereals account for most plant-based proteins consumed in Europe (~70 %) and globally. Consumer acceptance of mild-flavored oat protein is high compared to other plant-based proteins such as soy and pea (Boukid, 2021). However, the global protein intake of oat protein is only 0.1 g/capita/d, rising to 0.8 g/capita/d in Nordic countries (Poutanen et al., 2022).

The average consumption of meat, eggs and seafood is 117 g/capita/d and the consumption of milk, yoghurt and cheese is 97 g/capita/d, although there is significant regional variation (Miller et al., 2022). The *Planetary Health Diet* provides guidelines to achieve an optimal diet for human health and environmental sustainability. The *Eat Lancet* report suggests that the *Planetary Health Diet* (for an intake of 2500 kcal/d) should include 232 g/d of whole grains and that the consumption of meat, fish and eggs should be reduced to 84 g/d and that of dairy foods (whole milk or derivatives) to 250 g/d. However, there is some debate on the optimal proportion of animal-based foods, and whether this should increase to ensure the adequate intake of vitamin B12, calcium, iron and zinc. A shift toward plant-based diets would mean a drastic increase in whole grain consumption at the expense of animal-derived foods. Recent studies have estimated the possibilities that some animal protein can be replaced with cereal proteins and specifically oat protein (Mogensen et al., 2020; Poutanen et al., 2022). In Europe, 20 % (11.6 g) of the current animal protein intake of 58 g/capita/d could be replaced with cereal proteins and other plant-based proteins. In practice, this change could be achieved by consuming a large portion of oat porridge, 400–500 mL of an oat-based yoghurt or milk analog, or 29 g of an oat-based meat alternative. Mogensen et al. (2020) focused on the use of foods containing oat protein concentrate as replacements for traditional food products (wheat bread, pasta and yoghurt) and calculated that it would be possible to remove all beef and 45 % of pork from the diet and still maintain the same protein level of 57 g/capita/d as in the original Danish diet by replacing all the traditional food products with foods containing oat protein concentrate. Alternatively, it would be possible to reduce the intake of beef from 26 to 16 g by replacing only 15 % of the traditional food products with oat protein equivalents. This emphasizes the role that foods containing oat protein could play in the transition from animal-based to plant-based diets.

6. Future outlook

We need to find sustainable sources of protein while significantly cutting down on our consumption of meat and dairy products. Plant-based foods are an essential component of our diet, providing a source of protein and dietary fiber. Oats are among the most prominent global cereals but oat grain is used mainly for animal feed rather than food. However, oats could provide a reliable protein source for humans reflecting its high nutritional value, versatility, and low environmental impact compared to some other plant-based protein sources such as wheat, soy and rice.

Notably, the fervor surrounding plant-based alternatives to animal foods has shown some recent signs of decline. The initial hype, driven by concerns about health, sustainability, and animal welfare, has given way to a more nuanced perspective. One reason for this is the still relatively high price of innovative plant-based foods (e.g., dairy and meat substitutes) compared to traditional animal counterparts. For example, 1 L of oat milk in Europe costs €2.25 compared to €0.89 for cows' milk. Meat alternatives containing oats cost on average €17/kg in Europe compared to €8–10/kg for minced beef. There are also sensory differences between animal-derived foods and their plant analogs, and a realization that not all plant-based alternatives are created equal. Oats differ from other plant protein sources in their neutral taste and proven nutritional benefits. However, we cannot ignore the fact that some plant-based alternatives consist of highly processed, refined ingredients and may contain additives that raise health concerns. To rekindle the enthusiasm for plant-based foods, these issues must be addressed. Future research and development should aim to improve the nutritional profile and taste of plant-based products by decoupling bioprocessing technologies such as germination and fermentation with minimal processing technologies (e.g. dry separation, milling, pulsed electric fields and high-pressure). As consumer awareness of the environmental and health benefits of oat proteins continues to grow, the ability of oats to meet the increasing demand for plant-based protein alternatives is likely to become even more significant.

It is evident that, for the diversification of foods, oats alone are not enough to provide a direct replacement for all animal proteins. The recent EIT Food policy brief focusing on alternative proteins states that protein sources should be diversified to include various sources in the diet (EIT Food, 2023). However, oats can deliver both protein and dietary fiber (especially mixed-linked β-glucans) and phytochemicals to achieve more balanced nutrition than animal products. To optimize the amino acid composition, oat protein could be combined with protein from legumes to make combination meat analogs, some of which have already emerged in the market.

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Ulla Holopainen-Mantila: Conceptualization, Writing – original draft. **Saara Vanhatalo:** Conceptualization, Writing – original draft. **Pekka Lehtinen:** Writing – original draft. **Nesli Sozer:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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