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# Oat Milk By-Product: A Review of Nutrition, Processing and Applications of Oat Pulp

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**ABSTRACT**

Oat milk production is increasing due to consumer demand for nutritious dairy alternatives. Oat pulp is an insoluble residue and the main by-product of oat milk production. Approximately 0.2–0.45 kg of oat pulp is generated from every 1 kg of oat milk, and an estimated 228 kilotons is produced annually on a global scale, which is projected to increase to 500 kilotons by 2030. Oat pulp is rich in protein, dietary fibre, β-glucan, lipids, and bioactive compounds, but rapidly degrades due to microbial activity, and this byproduct is currently discarded to landfills with an associated negative impact on the environment. To promote the valorisation of oat pulp, it is important to understand the nutritional profile, oat milk processing, and its current applications. This review outlines and discusses oat milk production, nutrition, functionality, and food applications of oat pulp, and then proposes research trends for the valorisation of oat pulp, including fractionation into protein, dietary fibre, starch, and bioactive-rich fractions with potential use for various purposes. Cost-effective utilization of oat pulp and similar by-products is vital in tackling both environmental issues and the escalating need for sustainable food production.

**KEYWORDS**
Oat milk by-products; waste valorisation; bioactive compounds; food processing; food applications

## Introduction

About a third of global food production is lost or wasted,[1] amounting to an estimated 2.5 billion tons in 2021.[2] Food loss and waste account for a significant 8–10% of global greenhouse gas emissions,[1] and represents a loss of nutrients that could help nurture a growing population.[3] Valorisation of food waste is an emerging solution to tackle this issue while enhancing the food system to become more economically and environmentally sustainable.[4,5] The approach of valorisation aligns with the circular economy model, which proposes to utilize by-products as raw materials for various industrial purposes and mitigates reliance on new resources. Food waste can be categorized into eight groups, including waste from the fruit and vegetable industry, cereal and grain processing, oil crop processing, brewery, and winery industry, root and tuber processing, marine industry, meat industry, and dairy industry.[6] Generally, food waste generated from animal food production is less than that generated from plant food production.[7] Due to the dietary shift towards plant-based diets, it is expected that even more waste will be generated from plant food production.[8,9] Notably, wastes from fruit and vegetable processing, vegetable oil extraction, and plant-based beverage production contain high-value components such as colorants, proteins, and enzymes.[6,10–12]

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One of the popular products in plant-based diets is dairy alternative beverages, commonly referred to as plant-based milk. The rising demand for plant-based milk is closely tied to its nutritional benefits, including a low level of saturated fat and rich concentration of health-promoting compounds such as phenolics, antioxidants, and essential fatty acids.[13,14] In addition, the dietary shift towards plant-based diets, such as flexitarian or vegan, has further contributed to the rise of plant-based milk consumption in developed countries. In the US, there was a 600% increase in veganism from 2014 to 2017.[15] Similarly, the UK and Canada reported 1.2% and 2.3% of their populations identifying as vegans, respectively.[15] This global dietary shift is also reflected in the plant-based milk market, which experienced significant growth, reaching $27.3 billion in 2022, and it is projected to rise to $44.8 billion in 2027, with a compound annual growth rate (CAGR) of 10.4% from 2022 to 2027.[16] Australia also mirrors this trend, with a steady increase in plant-based milk consumption and a corresponding decline in dairy milk consumption. According to the Australian Bureau of Statistics, between 2019 and 2021, each Australian consumed about 125 mL of dairy milk alternatives every week and the increased rate of plant-based milk is matched by the fall of dairy milk, which is approximately 30 mL per week.[17] Despite the evident popularity of plant-based milk, it is crucial to address the environmental impacts of these milk alternatives, particularly concerning their unresolved waste management.

Almonds, soybeans, and oats are the three most prominent raw materials for producing plant-based milk in the European Union, the United States of America, the United Kingdom, and Australia.[18–21] Almond milk and soy milk have long dominated the plant-based milk market compared to oat milk. Almonds have been a commercially and nutritionally important nut-like seed since 1950, with the US, particularly California, leading in production and exportation.[22] Soy milk, on the other hand, has been consumed in China for 2,000 years and addresses nutritional deficiencies, such as calcium, especially in regions with insufficient dairy milk supply.[23] Oats, although a dietary staple in Europe, rank only sixth among major cereal grains globally, with just 10% of the global oat crop used for human consumption.[24] Oat milk was first introduced by the company Oatly about three decades ago, based on research performed at Lund University.[19,25] Consumer preference for plant-based milk in the West is for alternatives made from cereals, nuts, and seeds like almonds, oats, or peas.[23] Especially, in the U.S. oat milk exhibits the fastest growth rate at 350% and has become the second most popular plant-based milk, capturing 17% of the market with a total value of $424 million.[26] This trend can be attributed to the health-promoting effects, including therapeutic effects in hypercholesterolemia and as an anticancer agent, owing to its elevated dietary fibre, functional proteins, essential fatty acids, and unique phytochemicals like avenanthramides.[27–29]

Plant-based milk is generally produced by wet milling the grains, filtering, and pasteurization of the liquid portion. The solid residue left after filtering, often called press cake or pulp, is a by-product and is commonly used for low-value applications like animal feed, composting, biogas generation, or landfill disposal.[8,30–32] The global market for oat milk is valued at nearly $3 billion,[33,34] and for oat milk production, approximately 0.2–0.4 kg of oat pulp is generated per kilogram of oat milk.[38–41] Based on an average $5 sale price per 64 oz (1.9 L) of oat milk, this translates to an annual production of around 228 kilotons of oat pulp, with projections estimating this figure will reach 500 kilotons by 2030. The proximate composition of oat milk and its pulp varies depending on oat cultivars, forms, and processing methods. Oat pulp is characterized by a high moisture of around 60% and nutritive material. Some macronutrient levels in oat pulp were reported (on a dry weight basis, dwb) as follows 25.71–52.10% protein, 7.79–14.28% lipids, 12.30–27.49% carbohydrates, 27.32% starch, 22.97% insoluble fibre, 3.19% soluble fibre, and 7% β-glucan.[38–41] It should be noted that untreated oat pulp is susceptible to microbial spoilage due to its high concentration of nutrients and moisture content.[42] Information on the valorisation of oat pulp in the literature is limited, likely due to the relatively recent emergence of oat milk as an important plant-based milk, and possibly challenges associated with microbial spoilage.

This review aims to provide insight into the potential valorisation of oat pulp by reviewing the status of oat milk manufacturing processes, highlighting the nutrient and bioactive compositions of oats and their functional properties, post-processing treatments for oat pulp, and reporting applications of oat pulp in food products.

## Oat milk production and generation of oat pulp

Oat milk is generated through a series of controlled mechanical and enzymatic processes.[43] As illustrated in Fig. 1, the production begins with soaking dried oats in water for up to 8 hours, followed by wet milling at a ratio of 1:2.7 (weight/weight), alongside enzymatic treatment to form a slurry.[35,44] This slurry is then filtered to obtain the oat extract, separating it from the insoluble residual, referred to as oat pulp.[37,45] To resemble the nutritional qualities of dairy milk, the oat extract is fortified with vitamins and minerals, while additives such as stabilizers, sweeteners, and flavourings are introduced to enhance its sensory properties.[37,45] Homogenization is then applied to improve the stability of the final product, as oat milk behaves as a complex oil-in-water emulsion. In oat milk, fat globules are dispersed in water and loosely stabilized by oat particles, while insoluble particles, such as undissolved proteins and dietary fibre, contribute to the suspensions.[46,47] These particles can cause creaming, aggregation, and sedimentation which may compromise the stability of the emulsion over time.[46,48,49] Before packaging for sale as oat milk, the oat extract undergoes heat treatments like pasteurization or sterilization to extend shelf life, allowing it to be stored at either refrigerated or room temperature.[37,45]

The quality of oat milk depends on the enzymes used during production.[37] For example, amylases are utilized to overcome high starch content in oats (50–60%), which gelatinizes between 44.7–73.7°C.[45, 50] The action of α- and β-amylases facilitate the conversion of starch into dextrins, maltose, and maltotriose, helping maintain the liquid consistency of oat milk while naturally increasing its sweetness without added sugars.[45,50] Deswal et al.[35] identified the optimal α-amylase concentration and liquefaction time was 2.1% (dwb) and 49 minutes, respectively. Enzymes like glucoamylase (0.5 mL/100 g oats) and β-glucanase (0.05 mL/100 g oats) can further enhance the acceptability and phenolic content of oat milk.[37,51] Proteins also play crucial roles in modifying the texture, mouthfeel, and flavors of food products.[52] Protein-modifying enzymes such as papain, flavoured protease, and biological protease have been applied to improve oat protein functionalities.[49] For instance, the major storage protein in oats is globulin, which exhibits poor solubility in water but is soluble in saline solutions. This insolubility is attributed to its predominantly hexameric form, which also causes a high denaturation temperature at 112°C.[53,54] Therefore,

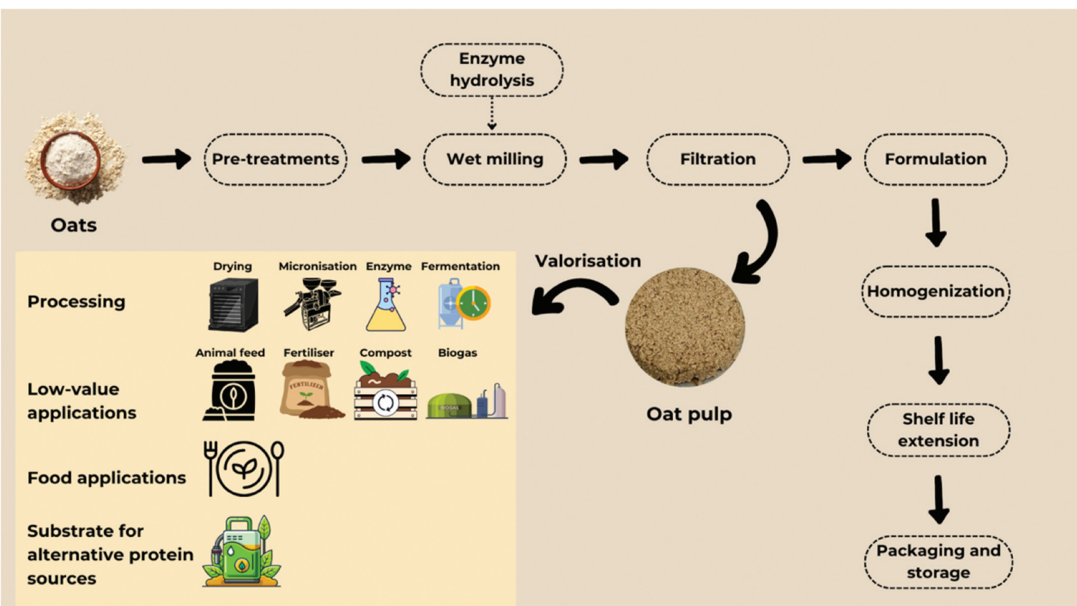


**Figure 1.** The process of oat milk production and valorisation techniques of oat pulp.

proteases in combination with heat treatment can dissociate globulins into smaller polypeptides and amino acids, alleviating the aggregation problem and increasing the solubility and digestibility of oat protein.[49,54,55] Additionally, phytases can reduce antinutritive compounds such as phytates in oats, increasing the bioavailability of key micronutrients like zinc, calcium, and iron.[56]

Oat milk, like other plant-based milk, is susceptible to microbial growth due to its nutrient-rich content. To extend its shelf life, various heat treatments such as pasteurization, sterilization, and ultra-high temperature (UHT) processing are commonly used.[57] Pasteurization is often performed at 100°C, sterilization at 121°C, and UHT between 135–150°C.[23] However, intensive thermal treatments may degrade the quality of plant-based milk, which already has inferior quality compared to bovine milk, potentially leading to nutrient deficiencies in regular consumers.[57] Hence, innovative non-thermal shelf life extending technologies have been proposed to mitigate the negative effects of thermal treatments. For instance, the use of UV technology offers lower energy input than thermal pasteurization, and preserves food colour and flavours with minimal impact on nutrients.[58] A recent study demonstrated the effectiveness of UV-C assisted thermal process in inactivating *E. coli* K-12 in oat milk and even improving the characteristics of an oat-based yogurt product.[58] Other techniques such as high-pressure processing, high-pressure homogenization, and pulsed electric fields have also shown promise in extending the shelf life of plant-based milk by inhibiting pathogen growth.[57] Poliseli-Scopel et al.[59] have shown that combining ultra-high-pressure homogenization with mild heat treatment (300 MPa and 75°C) in soy milk has resulted in commercially sterile products of better quality than those produced by pasteurization or UHT, while also improving physical.[59] Li et al.[60] demonstrated the effectiveness of pulse electric field treatment on soy milk, completely inactivating *E. coli, S. aureus*, and soybean lipoxygenase without compromising quality. These innovative methods have yet to be thoroughly explored for oat milk, presenting opportunities for future research to enhance its quality and shelf life.

The production of oat milk inevitably generates oat pulp, a byproduct that is increasing at a concerning rate, despite the perception that plant-based milk production is more environmentally sustainable compared to dairy milk.[36] Research on oat pulp remains limited, particularly regarding its composition and effective waste management strategies, as the estimated 228 kilotons of oat pulp produced annually is a relatively small portion of the 190 million tons of food byproducts produced annually [1]. However, managing this byproduct has become a significant challenge, and with the projected strong growth of oat milk production in the coming years, we estimate that 500 kilotons of oat pulp will be produced annually by 2030. The disposal of such a significant quantity of oat pulp poses both environmental and economic concerns. Its high moisture content and biodegradable nature make oat pulp a favourable medium for the growth of pathogenic microorganisms, which can contribute to the spread of transmissible diseases.[61] Moreover, like many food industry byproducts, oat pulp is often subjected to landfilling or incineration, contributing to greenhouse gas emissions, freshwater and air pollution, and soil degradation.[61,62] Even with other preferable immediate waste management options like composting and anaerobic digestion still generate a considerable amount of greenhouse gases, unpleasant odour, time consuming, and impair the quality of soil in vicinity.[63] Given these environmental risks, there is an urgent need for further research into the characteristics of oat pulp to develop sustainable valorisation pathways that focus on daily use and high-value applications which could significantly reduce the environmental impact of oat pulp while unlocking economic potential. The valorisation of oat pulp could play a critical role in transitioning toward more sustainable and circular production practices within the plant-based milk industry.

## Nutritional composition of oat products

### *Macronutrients*

The compositions of oats, oat milk, and oat pulp vary significantly, each offering distinct nutritional profiles as shown in Table 1. The major constituent in oats is carbohydrates, representing 63.7% on average, mainly comprised of starch, dietary fibre, and minor levels of sugars and oligosaccharides.[24,65] Oats exhibit a relatively high dietary fibre content ranging from 11.00–19.67%, with soluble fibre content (58%) higher than insoluble fibre (42%).[49,65] Within the dietary fibre present in oats, β-glucan with a concentration between 3.90% and 7.50%[49,67] stands out as a significant component due to its health-promoting effects, such as associated with reducing LDL (low-density lipoprotein) and total cholesterol levels.[72,73] β-glucan is also beneficial for patients with type-2 diabetes due to the effect of increasing solution viscosity, leading to delayed gastric emptying time, increased satiety, and reduced food intake.[74] Several prior studies have found that the consumption of foods rich in β-glucan (with at least 3 g/day of β-glucan), such as oat muesli bars, oat bread, or oat milk can result in decreased serum cholesterol and LDL cholesterol, and glucose and insulin response.[75–77] Moreover, high molecular weight β-glucan can improve the gut microbiota in patients with mild hypercholesterolemia, reducing cardiovascular risk markers.[78] However, it can be challenging for consumers to achieve the recommended β-glucan level with commercial products, as this information is not always readily available on nutritional panels and may vary across products with different formulations and processing methods.[79] Oats contain a substantial content of protein, varying between 12.4 and 24.5%, making them the highest among the major cereal grains.[65] Furthermore, oat protein possesses a well-balanced amino acid composition, making its quality as good as soy protein, which is considered to be nutritionally equivalent to meat, milk, and egg protein.[80] Oat protein also has a high biological value (74.5–79.36%) and highly digestible (90.3–94.2%).[67] Oats possess a relatively low lipid content but are high among the major cereal grains.[24,65] The total content of oil in oats ranges from 2.20–15.00%, with an average of 8%.[81] The lipid profile of oat is well balanced between monounsaturated fatty acids (37%) and polyunsaturated fatty acids (42%), and a low concentration of saturated fatty acids (20%). The primary fatty acids in oats are 20% palmitic (C16:0), 35% oleic (C18:1), and 40% linoleic (C18:2).[71,82,83] Polar lipids in oats have been utilized in the baking industry with positive effects in improving bread volume and prolonging softness.[84,85] Moreover, oats contain a high level of lecithin, a wide range of sterols, and lipophilic antioxidants with various benefits and applications.[14,86,87] Additionally, oat lecithin is considered a safe food additive to be used for all ages.[86]

Similarly to fresh oats, oat pulp also exhibits high carbohydrate and dietary fibre content, approximately ranging from 12.30 to 27.49% and 15.80 to 37.14%, respectively. However, the dietary fibre in oat pulp consists mainly of insoluble fibre, approximately 22.97%, with a minor level of soluble dietary

**Table 1.** Nutritional composition of oats, oat milk, and oat pulp.

| Nutrients | Fresh oats | Oat milk (regular) | Oat pulp |
|---|---|---|---|
| Moisture content | 6.50–12.98% | 88.02–90.60% | 54.30–65.00% |
| Carbohydrates | 31.55–74.82% | 6.60–25.00 g/100 mL | 12.30–27.49% |
| Dietary fibre | 0.21–19.67% | 0.80–3.00 g/100 mL | 15.80–37.14% |
| Protein | 7.40–24.50% | 1.00–4.00 g/100 mL | 25.71–52.10% |
| Lipids | 2.20–15.00% | 1.50–6.00 g/100 mL | 7.79–14.28% |
| Vitamin A | 0.86 mg/g | 0.667–180 μg/100 mL | N/A |
| Vitamin D | 0 | 0.30–5.10 μg/100 mL | N/A |
| Vitamin E | 0.45–1.23 mg/100 g | N/A | N/A |
| Thiamine (B1) | 0.002–0.763 mg/100 g | N/A | N/A |
| Riboflavin (B2) | 0.001–0.139 mg/100 g | 0.5 mg/100 mL | N/A |
| Niacin (B3) | 3.00–8.00 mg/100 g | N/A | N/A |
| Pyridoxine (B6) | 0.119 mg/100 g | N/A | N/A |
| Folate (B9) | 56.0–60.0 μg/100 g | 2.00–2.50 μg/100 mL | N/A |
| Calcium | 42.10–127.0 mg/100 g | 100 mg/100 mL | N/A |
| Iron | 3.86–6.32 mg/100 g | 0.60–1.00 mg/100 mL | N/A |
| Phosphorus | 162.8–502.0 mg/100 g | 40.0–100.0 mg/100 mL | N/A |
| Potassium | 214.6–575.0 mg/100 g | 40.0–400.0 mg/100 mL | N/A |
| Magnesium | 62.4–171.4 mg/100 g | N/A | N/A |

values are obtained from various sources and expressed on a dry weight basis (dwb) except for oat milk.[38,39,41,64–71].

fibre at approximately 3.19% (dwb).[40] Oat pulp also has a high protein content varying between 25.49 and 32.42%, which can reach 52.10%, with the presence of all essential amino acids.[40] The lipid content in oat pulp is relatively low, ranging from 2.80% to 6.44%. As a result, oat pulp retains a considerable amount of nutrients contributing to important physicochemical properties for various applications.

Oat milk, despite being a nutritious beverage, has compositions different from oats and oat pulp. The concentrations of carbohydrates and dietary fibre in oat milk are significantly lower due to the removal of the solid fraction, oat pulp, during the manufacturing process (Table 1). Protein content in oat milk is also low, potentially removed along with oat pulp, as the majority of protein is attached to the insoluble fibre portion. Oat milk, like other plant-based milk, is formulated to mimic bovine milk in terms of sensory and nutritional qualities. Thus, additional nutrients and stabilizers may be added, which might not be present in or higher than natural oats.

## Micronutrients and bioactive compounds

In terms of micronutrients, oats are rich in phosphorus and potassium, with moderate levels of zinc, iron, manganese, and magnesium, but very low calcium.[65] Oats possess most of the vitamins except for vitamins D, C, and $B_{12}$.[65] The primary vitamin in oats is vitamin E, with major forms α-tocotrienol and α-tocopherol.[88] Although the presence of B vitamins in oats is not as significant compared to other common cereals, oats still contain small quantities of several important B vitamins, particularly B1, B2, B3, B6, and B9.[89–91] The total sterols in oats range from 30-70 mg/100 g, with the most abundant sterols being β-sitosterols, followed by $\Delta^5$-avenasterol, campesterol, and stigmasterol.[92] It was ascertained that oat avenasterols can stabilize and reduce oxidation of edible oils such as cottonseed or soybean oil even at frying temperatures.[93] Oats also contain tocols, including α-tocotrienol (43%) and α-tocopherol (18%), which have shown health benefits, such as lowering cholesterol and possessing anti-inflammatory properties.[88,94] Furthermore, oats contain a unique group of antioxidants known as avenanthramides (AVAs), along with phenolic compounds, and flavonoids.[95]

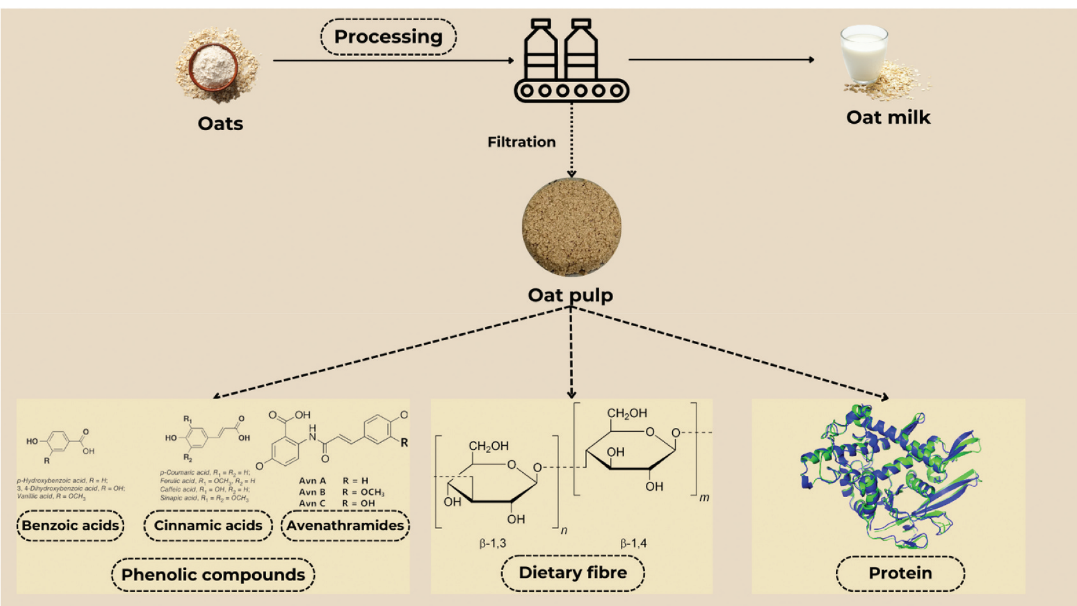


**Figure 2.** Bioactive compounds in oat pulp.

AVAs in oats exhibit high antioxidant activity, surpassing other phenolic compounds like vanillin and caffeic acid by 10 to 30 times.[96] Furthermore, preliminary research suggests that AVAs may exhibit anti-inflammatory and antiatherogenic properties.[97] Specifically, they have been shown to inhibit monocyte adhesion to human aortic endothelial cells and are presumed to hinder the release of pro-inflammatory compounds such as cytokines and chemokines, thereby contributing to the overall reduction of inflammation and potential protection against cardiovascular diseases.[97] Additionally, AVAs are believed to play a role in regulating blood pressure by promoting the production of nitric oxide, which leads to the dilation of blood vessels.[98] Due to a wide range of polyphenols with potent antioxidant activity, oat flour has been added to different kinds of foods such as fats (lard, tallow), mayonnaise, chips, and nuts, to protect against oxidation.[81] Oat phenolic compounds are mainly derived from hydroxybenzoic and hydroxycinnamic acids, with major compounds like ferulic, protocatechuic, vanillic, gallic, p-coumaric, caffeic, and sinapic acids.[95,99,100] A previous study has shown that 40 g of oat-based commercial products provide significant amounts of total phenolics (up to 25.1 mg) and avenanthramides (up to 2 mg).[95] It should be noted that information on micronutrients and bioactive compounds of oat pulp is still scarce. Therefore, future studies are recommended to characterize in more detail the composition of oat pulp.

## *Nutritional limitations and concerns in oat-derived products*

While oat milk provides numerous health benefits, it also presents specific nutritional challenges. It is notably lower in essential nutrients such as protein, calcium, magnesium, and vitamin D compared to bovine milk, primarily due to the inherent composition of oats and the nutrient loss that occurs during processing.[23,101,102] Consequently, substituting oat milk for bovine milk entirely can result in various deficiency-related health issues, particularly among vulnerable populations, such as children and the elderly. Legally, manufacturers are required to clearly label their oat milk products, indicating that they are unsuitable as a complete milk replacement for children under the ages of 2 and 5, especially if their protein and fat content falls below that of bovine milk.[102] To address these nutritional gaps, oat milk, along with other plant-based milk, is commonly fortified and enriched with additional protein and micronutrients to better align with the nutritional profile of bovine milk.[23,101,103]

Another important consideration is the presence of antinutrients in oats, which can hinder the absorption of essential nutrients.[90] Phytic acid, abundant in oats, limits the bioavailability of minerals such as zinc, iron, calcium, copper, and magnesium in the human gut.[79] Additionally, it can bind to proteins and starches, further impeding their bioavailability.[90] Fortunately, most phytic acid is concentrated in oat bran, and since many oat milk products are not made from whole oats, the bran is typically removed to improve sensory quality.[104] If any phytic acid remains, the inclusion of phytase can further decrease its concentration.[103] Additionally, processing steps such as fermentation, soaking, and heat treatment also contribute to the reduction of phytic acid content in oats.[48]

Oats have been officially recognized as gluten-free by the European Commission Regulation (EC) No. 41/2009, making them suitable for individuals with celiac disease.[105] However, despite this recognition, earlier studies raised concerns about the suitability of oats for celiac patients, recommending their exclusion from gluten-free diets due to the risk of allergen exposure from cross-contamination, which can occur during cultivation in the same fields, processing in shared facilities, or transportation alongside soy, barley, or other allergenic nuts.[106] Nevertheless, subsequent research has shown that oats can be safely incorporated into the diets of both children and adults with celiac disease.[105,107] Thus, individuals with celiac disease should be aware of these considerations, read labels carefully, and consult with dietitians or doctors Fig. 2.

## Processing and applications of oat pulp

### *Processing*

Oat pulp is an affordable, nutrient-rich source of bioactive compounds that can be transformed into a functional powder ingredient, reintroduced into the food chain, and applied in other industries to support a circular economy and sustainable production. Each processing method significantly impacts the physicochemical properties of oat pulp, so evaluating the suitability of each approach requires analysing its advantages, drawbacks, and limitations. An overview of the oat pulp valorisation process is provided in Fig. 3 below and discussed in this section.

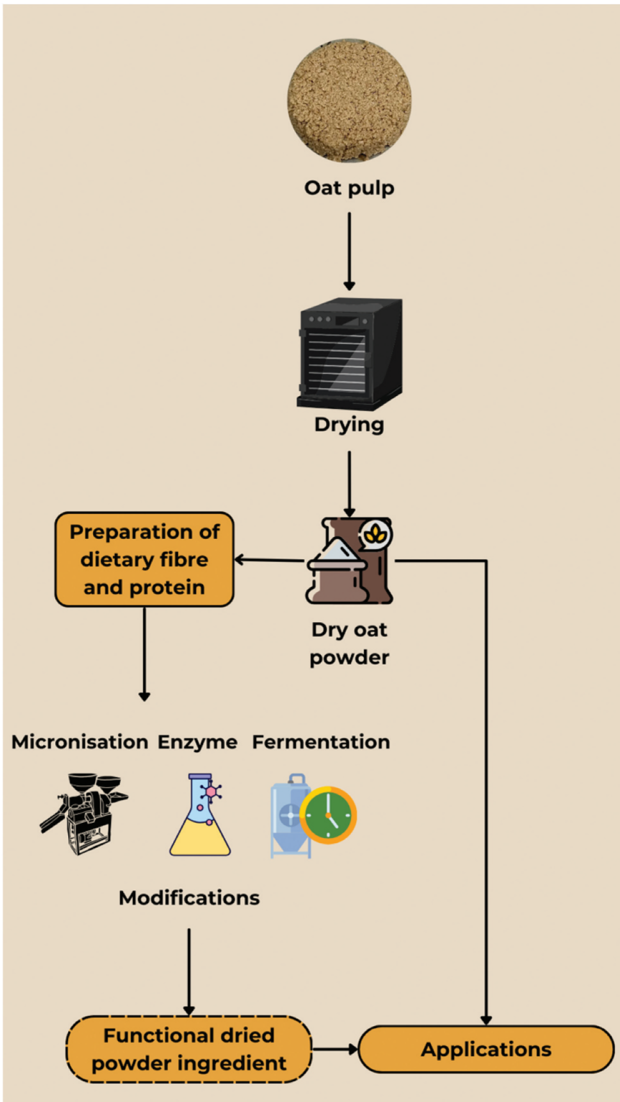


**Figure 3.** Overall valorisation pathway of oat pulp.

## Drying

Drying is a necessary step in waste management and valorisation strategies to convert a food byproduct into a powdered ingredient. This process is versatile to be used as pre-treatment, during, or post-treatment with the main objective is to extend shelf life by effectively lowering the water activity and moisture content of food byproducts to below 0.6 and approximately 10%, respectively, which inhibits the activity of spoilage enzymes and microbial growth.[63,108,109] Moreover, drying reduces the mass and volume of food byproducts, improving storage, transportation, and handling.[108] This is especially important for highly perishable materials like oat pulp, which contains about 61% moisture.[38] Reducing its mass and volume not only lowers the frequency of pulp collection from food businesses but also decreases greenhouse gas emissions linked to transport and decomposition.[63] Although information on drying oat pulp is still limited, insights from drying other food byproducts, such as soy okara and fruit pomaces, can provide valuable guidance. When drying food byproducts it is commonly to use hot air drying, vacuum drying, or freeze drying, which can be used alone or in combination with others.[110]

While the beneficial effects of drying on moisture content and water activity are well-known, energy consumption needs to be considered when comparing different drying methods for food byproducts, as drying can be energy-intensive and account for up to 25% of production costs.[63,108] For instance, Davy et al.[111] compared the performance of hot air drying and freeze drying on soy okara, demonstrating that hot air drying reduced drying time and energy consumption while better preserving bioactive compounds such as soysaponin, daidzin, and genistin. Similarly, Araujo et al.[112] demonstrated that microwave drying reduced energy usage compared to hot air drying for apple and ginger pomace, though the higher equipment costs of methods may limit their industrial application.

For any drying method, the temperature or the energy required to remove moisture must be carefully optimized due to its strong correlation with drying time, moisture removal rate, and its influence on both the physical and chemical properties of the sample. Research has shown that drying should be as rapid as possible to prevent the degradation of nutrients, flavour, texture, and colour.[113] Higher drying temperatures, such as above 80°C, significantly reduce drying time by accelerating moisture removal, which in turn reduces energy consumption.[111,114,115] This approach has been found to maintain phenolic compounds and antioxidant capacity more effectively in food byproducts such as coffee pulp and soy okara by minimizing thermal degradation and oxidation, owing to the shorter drying time and reduced oxygen exposure.[111,114] However, for other byproducts like orange and blueberry pomaces, lower temperatures are more favourable for preserving phenolic compounds.[116,117] Temperature also has a critical impact on the dietary fibre and protein content of oats. Studies suggest that the ideal drying temperature for oats ranges between 80°C and 120°C to ensure efficient drying while preserving protein concentration and minimizing excessive denaturation.[118] Drying at high temperatures may lead to a reduction in the concentration of β-glucan in oats, as thermal degradation and depolymerization can break it down into smaller molecular fragments, altering its structure and concentration, which may affect its functional properties.[118]

Drying techniques are another crucial factor influencing the physical and chemical properties of a sample. Oven drying, such as hot air drying, is widely employed to effectively remove moisture from many plant food byproducts due to its cost-effectiveness, ease of operation, and capability to achieve low moisture content and water activity.[110] For example, drying soy okara at 110°C for 140 minutes by hot air drying is better than freeze drying in terms of retaining phenolic compounds, soyasaponins, and antioxidant capacity.[111] Vacuum drying has the same principle as hot air drying but is conducted under reduced pressure to lower the boiling point of water and reduce the exposure to oxygen during drying.[110] This might help decrease the drying time and oxidation process; however, in some cases, vacuum drying takes more time than hot air drying due to moisture in the drying chamber is removed more rapidly by a fan in the hot air drying system.[119] Recently, microwave-assisted drying has emerged as a more energy-efficient alternative for drying food byproducts, significantly reducing drying time while still preserving more bioactive compounds compared to hot air drying.[120] When applied to soy okara, papaya peel, and pulp, microwave-assisted drying considerably reduces drying time while maintaining higher levels of bioactive compounds than those achieved with traditional hot air drying.[121,122] Research has also shown that microwave-assisted drying not only modifies the structural properties of dietary fibre of soy okara and oats but also increases their soluble dietary fibre content.[123–125] It is suggested that adequate thermal energy can increase soluble dietary fibre content and solubility by partly breaking down glycosidic bonds in polysaccharides and reducing their molecular weight.[124,126,127] Moreover, microwave-assisted drying enhances the ability of oat soluble dietary fibre to absorb glucose, cholesterol, and sodium cholate.[125] Furthermore, heat treatments such as hot air drying and microwave drying can inactivate lipases and improve lipid stability in oat bran without compromising β-glucan and lipid content or the sensory quality of oats.[128,129] Despite the advantages associated with microwave-assisted drying, its application at an industrial scale can be challenging due to the high cost of equipment and the need for large processing capacities. Thus, microwave drying is often combined with other drying techniques to leverage the benefits of both methods.[120]

Studies have also investigated non-thermal drying techniques to address the challenges associated with thermal drying, particularly in preserving thermally labile compounds, colour, shape, and flavour. However, these techniques are often not feasible for processing food byproducts due to cost ineffectiveness and limitations in large-scale applications. They are typically reserved for highly specific purposes, particularly for high-value products or the preservation of valuable compounds.[120] Non-thermal drying techniques include freeze drying and supercritical CO2 ($SCO_2$) drying; however, to date, there have been no documented instances of food waste being dried using $SCO_2$. Alternatively, high-pressure pasteurization (HPP) has been applied to various plant-based milk byproducts, including oat pulp.[38,130] HPP effectively reduces the microbial load in oat pulp while modifying protein structure and increasing soluble fibre content, thereby modifying its physical properties. Although HPP offers advantages such as short processing times and energy savings, it requires significant capital investment compared to conventional thermal drying methods and may not be suitable for high-speed production lines.[38] Consequently, comprehensive studies on drying methods and conditions for oat pulp are essential. These studies should prioritize cost-effectiveness while ensuring the preservation of nutritional quality and enhancing functionality to extend shelf life and improve usability.

### *Preparation of oat protein*

Oat pulp is rich in protein, presenting a promising source for obtaining protein-enriched fractions suitable for use as a functional food ingredient. The process of extraction and modification of protein from oat pulp is summarised in Fig. 4. Plant-based proteins offer diverse techno-functional properties, such as foaming, emulsifying, and gelling formation, making them suitable for different applications such as food fortification, nutraceuticals, or natural ingredients in cosmetic products.[131] These enriched protein fractions can be categorized into three groups based on their protein content: protein flours (<65% protein), protein concentrates (65–90% protein), and protein isolates (above 90% proteins).[131–134] However, these terminologies may sometimes be misleading, since certain plant protein products, such as those isolated from oats or legumes, might not attain the specified 65% or 90% protein content but are still classified as protein concentrates or isolates due to manufacturing process.[133,135] It is noteworthy that, before protein isolation or extraction from oats, a defatting step is recommended to enhance protein yield and purity.[136–138]

Traditional methods for extracting protein from oats and other plant-based sources involve heating and the use of chemicals, often utilizing organic solvents and alkaline solutions.[139,140] While increased temperatures can enhance extraction efficiency due to the positive correlation between temperature and mass transfer rates, excessive heat can lead to the degradation of target compounds through enzymatic or chemical reactions.[141,142] Commonly used organic solvents, such as hexane, ethanol, and isopropanol, are employed in extracting protein from various

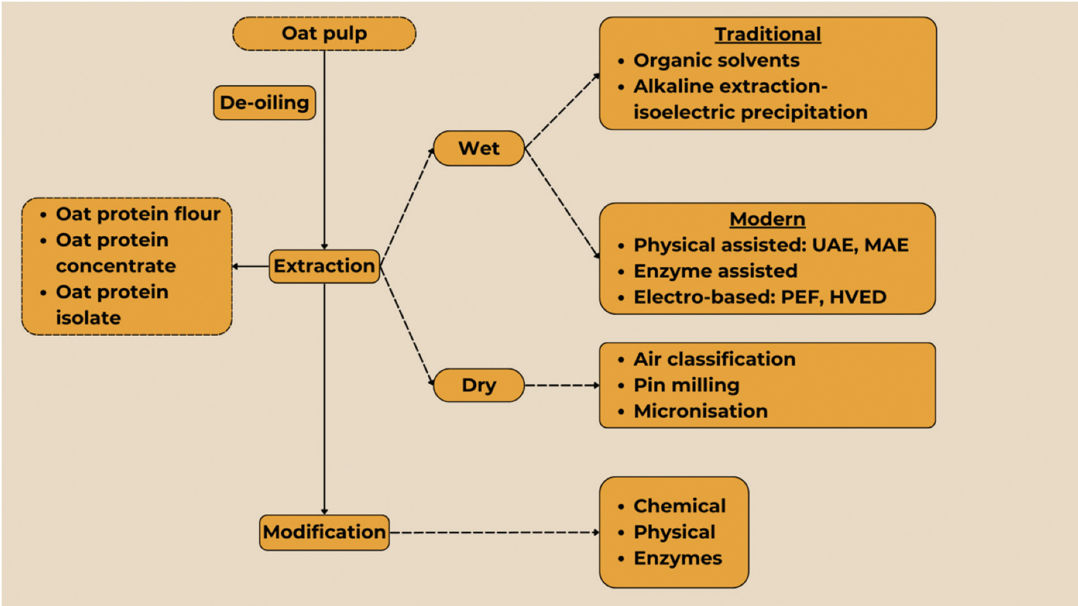


**Figure 4.** Extraction and modification of oat protein. UAE: ultrasound-assisted extraction; MAE: microwave-assisted extraction; PEF: pulsed electric field; HVED: high voltage electric discharge.

materials like rice bran and alfalfa leaves, with protein yields ranging from 8.9% to 20.4%.[143,144] However, organic solvent use can also co-extract high amounts of oil, thereby reducing the protein purity achieved through the extraction process.[142] Furthermore, protein recovery remains limited when using organic solvents alone for certain materials, particularly those with major storage proteins other than prolamins. For instance, oats, whose primary storage protein is globulin, show lower protein solubility in alcohol-based solvents.[142] To increase protein yield, organic solvents are often combined with water or alkaline solutions, achieving yields as high as 90%, depending on the solvent composition and the material being processed.[145,146] Nonetheless, organic solvents, particularly alcohol-based ones, can adversely affect protein conformation and structure, thereby diminishing functionalities such as oil-water interaction and potentially impacting the health benefits of the protein.[136,147] Alkaline extraction, widely preferred for oat protein extraction, promotes conditions favourable for producing protein fractions with higher purity, yielding products with protein content in the range of 65%–90%.[136,137] However, highly alkaline conditions may compromise protein functionality.[138,139] Moreover, traditional extraction methods are time and energy intensive, and often require hazardous chemicals and large amounts of water, raising significant environmental concerns.[148]

In recent years, a range of emerging extraction technologies using enzymes, ultrasound, microwave, pulsed electric field, and high voltage electrical discharge have been developed to enhance extraction efficiency, improve economic viability, and minimize environmental impact when recovering functional proteins from various plant materials.[149] Ultrasound-assisted extraction (UAE), although has not been reported for oat pulp protein extraction, represents a promising advancement in protein extraction techniques. This innovative method has demonstrated potential for effectively extracting protein from various plant sources, providing higher purity, improving yield, and enhancing protein functionalities compared to conventional methods. UAE operates by generating high-energy sound waves to induce cavitation bubbles, which upon expansion and collapse, create shockwaves that disrupt nearby cells and tissue, and facilitate the mass transfer of target compounds across cell walls or membranes into the extraction medium.[131] For instance, UAE (30°C, 90W, 25 kHz) was applied to extract protein from watermelon seeds with water as solvent yielding a 13% increase in protein extraction compared to conventional aqueous agitation extraction.[150] UAE also required 20% less water volume and reduced the extraction time from 120 minutes to only 9 minutes.[150] Additionally, proteins extracted using UAE exhibited improved functional properties, including better foaming capacity, gelation capability, and water- and oil-holding capacity.[150] Future studies should focus on establishing optimal extraction conditions and considering the potential application of this technique for the extraction of protein from oat pulp.

Microwave-assisted extraction (MAE) presents another promising option for extracting protein from the oat pulp, although this technique has yet to be employed in this specific context. MAE has demonstrated positive results in obtaining higher protein yields from various plant sources. For example, exposing six soybean cultivars to microwaves at 2450 hz for 10 minutes at 80°C resulted in protein yield improvement of up to 50% compared to the conventional water bath method.[151] The increased protein yield observed with MAE is due to a heating mechanism occurring within cells, caused by friction generated by polar molecules oscillating in a rapid alternating electric field, thereby disrupting cell structure. In contrast, conventional methods primarily deliver heat energy directly to the cell surface, which then conducts into the cell body.[151] Moreover, microwave processing can lead to non-thermal effects, such as the breaking of hydrogen bonds, further enhancing protein extraction.[131]

Electric field-based methods, such as pulsed electric field (PEF) and high voltage electric discharge (HVED), are recommended for more challenging plant materials, like seeds, press cakes, and cereal brans.[152,153] PEF uses high voltage, short duration pulses to electroporate cells, creating temporary or permanent pores and hence increasing the extraction efficiency. On the other hand, HVED applies high energy electric pulses to a liquid medium, producing a plasma channel that causes substantial cellular disruption through electrochemical reactions, shockwaves, cavitation, and light emission.[152,154,155] In a study by Sarkis et al.,[153] protein and phenolics extraction efficiencies of sesame press cake after being treated with HVED and PEF were examined. Both electric field technologies exhibited superior extraction efficiencies compared to conventional methods, with advantages including reduced reliance on organic solvents, lower temperature processing, and shorter extraction times. However, their impacts differ; after 1 ms of exposure to 42 kJ/kg, the phenolics concentration was 5 times higher for PEF but 24 times higher for HVED compared to the non-treated sample. Similarly, the protein obtained from the HVED sample was about 10 times higher than PEF treated sample at the same energy input (42 kJ/kg) and exposure time (1 ms). While there are no reports on the application of PEF and HVED for oat pulp protein extraction, it is recommended to apply and compare these techniques in future studies for isolating protein from oat pulp.

Enzymes have a dual role in improving both the efficiency of oat protein extraction and the functionalities of these proteins. Carbohydrases, for instance, can break down cell walls, releasing more proteins and other bioactive compounds.[156,157] A study by Prosekov et al.[139] found that defatted oat bran treated with amyloglucosidase (EC 3.2.1.3) yielded a protein concentrate with 20% higher protein content than non-treated oat bran. Additionally, the treated oat bran demonstrated improved solubility, water retention, and foaming capacity. Proteomic and peptidomic study conducted by Aiello et al.[40] observed that treating oat press cake with various enzymes, including amylase, cellulase, and proteases led to modifications in the protein matrix, resulting in the release of new proteins and low molecular weight peptides. These newly identified proteins include avenins, avena alpha amylase trypsin inhibitors, and those that contribute to oat grain softness vromindolines, and tryptophanin.[40] The introduction of these enzymes also induced protein unfolding, indicated by the reduction of α-helices and increase of β-helix in the oat protein structure.[40] These changes were linked to the increase in sulfhydryl (SH-) groups. Consequently, the antioxidant activity and functional properties of the proteins improve, as more functional groups within the proteins became less hindered due to the unfolding structure.[40] This was further evidenced by the FRAP antioxidant activities of the treated oat press cake, which were up to 40% more potent than the untreated sample.[40] The presence of low molecular weight peptides and certain amino acids such as valine, phenylalanine, tyrosine, and lysine also contributed to the higher antioxidant activity of the enzyme-treated oat press cakes.[40,158] Despite the significant improvements offered by the enzymes in oats and other plant-based protein extraction and production, there are some drawbacks to consider. These include the high cost of enzymes, difficulties in industrial scale-up, complex interactions with other bioactive compounds resulting in low enzyme activity, and challenges in enzyme inactivation.[159] It is important to balance the advantages of enzyme-assisted processes with these potential limitations when considering their implementation in the food industry and other applications.

Dry fractionation methods like air classification can be utilized to prepare oat protein concentrate.[140] The process involves milling the oats and then applying air classification on the fine fraction to obtain the protein fraction with approximately 40% protein.[160] These methods offer advantages such as lower energy input and retention of more nutrients in the protein-enriched fraction since they do not require solvent dilution or removal after processing. However, materials rich in lipids can pose challenges as they are adhesive and poorly dispersed in the air, leading to low separation efficiency and yield.[140] To address this issue, plant-based materials with high lipid content are commonly defatted before processing using organic solvents such as hexane or 70% ethanol.[140] An alternative to solvent defatting is to use supercritical carbon dioxide (SC-$CO_2$), which has shown promising results in defatting oats, leading to improvements in protein yield and functionalities.[160–162] Studies have shown that oats treated with SC-$CO_2$ were able to yield a protein concentrate containing 73% protein with improved foaming and emulsifying properties.[160,162]

## *Preparation of oat dietary fibre*

Dietary fibre is an essential part of the human diet, consisting of non-digestible polysaccharides with more than 10 monomers.[163] High dietary fibre intake has been associated with a reduced risk of chronic diseases.[163] Soluble dietary fibre is commonly found in fruits and vegetables, whereas insoluble dietary fibre is more abundant in cereals and whole grain products.[164] However, it is important to note that the amounts of soluble and insoluble dietary fibre can vary within high-fibre foods.[164] The different types of dietary fibre offer distinct health benefits through their fermentation by gut microbiota in the gastrointestinal tract. Insoluble dietary fibre adds bulk to the waste, prevents constipation and haemorrhoids, and is mostly unable to be utilized by gut microbiota.[165,166] In contrast, soluble fibre has better functional and physiochemical properties, as they are rapidly fermented by the gut microbiota, leading to the formation of short-chain fatty acids which reduces the risk of gastrointestinal diseases such as irritable bowel syndrome, functional constipation, and colorectal cancer.[167–169]

Oat pulp comprises a dominant fraction of insoluble dietary fibre (23%) alongside a smaller portion of soluble dietary fibre (3.2%) and shares a composition similar to other plant-based food byproducts such as orange and lemon pomace and soy okara.[40,170,171] Oats are noteworthy for their substantial β-glucan content, which is recognized for its cholesterol-lowering effect so a valuable source of β-glucan due to their availability and cost-effectiveness.[72,74] Research has focused on isolating β-glucan from oat pulp, employing techniques like ultrafiltration to extract β-glucan effectively from the other constituents of the pulp.[41] Methods for isolating β-glucan and modifying the dietary fibre of oat pulp are illustrated in Fig. 5. For example, Patsioura et al.[41] optimized conditions for recovering β-glucan from oat pulp by using a polysulfone membrane with a crossflow module, maintaining the transmembrane pressure below 2 bar, and keeping a β-glucan concentration below 600 mg/L. Polysulfone emerged as the most suitable membrane due to its ability to prevent β-glucan from adhering to the membrane surface and causing operational issues. This membrane demonstrated favourable retention, flux, permeability, and resistance to membrane fouling.[41] Further enhancement was achieved by coupling the polysulfone membrane with a crossflow module, instead of a dead-end cell, leading to an improved retention of β-glucan and greater fouling resistance without compromising the permeate flux.[41] This configuration proved effective in treating industrial oat pulp with a β-glucan concentration under 600 mg/L.[41] It is crucial to note that maintaining the transmembrane

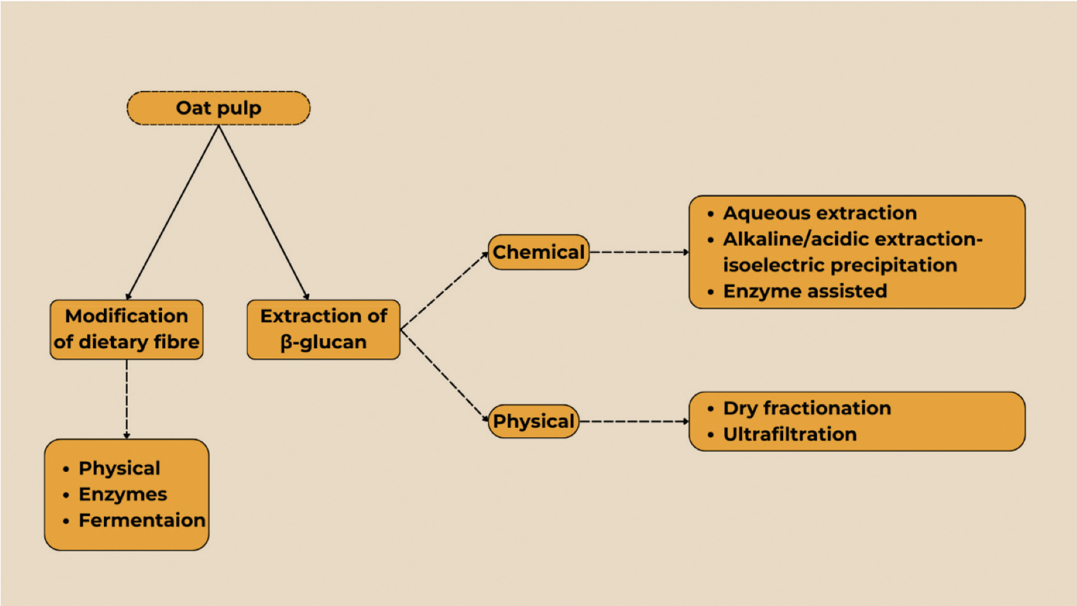


Figure 5. Isolation of β-glucan and modifications of dietary fibre of oat pulp.

pressure below 2 bar is critical to avoid membrane damage. While this process offers advantages, it does present limitations in completely isolating β-glucan from macromolecules like protein. However, this could potentially be advantageous, as both proteins and β-glucan are valuable compounds with potential health benefits. Another non-chemical method for separating oat β-glucan from other components in oat pulp is dry fractionation, which involves milling and air classification to yield β-glucan-enriched powder with concentrations of 20–25%.[172,173] Sibakov et al.[172] enhanced conventional dry fractionation with novel electrostatic separation, obtaining a β-glucan-enriched fraction containing 48.4% β-glucan. These physical, solvent-free techniques are environmentally friendly and have low energy consumption, producing a higher molecular weight β-glucan due to the reduced impact of harsh chemicals compared to wet extraction methods. Highly concentrated β-glucan fractions of up to 90% can be obtained through aqueous or alkaline extraction.[174,175] However, the high viscosity of β-glucan, even at low concentrations, complicates filtration in these wet extraction techniques, requiring large volumes of extracting solvent and high energy inputs for mixing and drying.[172] Furthermore, the use of high pH solutions or elevated extraction temperatures can degrade β-glucan, reducing its molecular weight and consequently its viscosity and biological activities.[176] The combination of enzymes such as α-amylase and protease can alleviate these effects and improve β-glucan extraction outcomes; however, the cost of these enzymes must be considered for large-scale applications.[177]

Recent studies have focused on improving the functional properties of dietary fibre derived from plant-based food by-products. This is primarily due to the presence of a high level of insoluble dietary fibre, containing hemicellulose and cellulose, which is poorly dispersed in water and forms insoluble polysaccharide-protein complexes, which can adversely affect the desired properties of the dietary fibre.[124,178] Moreover, there is a focus on increasing soluble fibre content in these plant-based sources, especially for applications in the food industry such as enhancing the texture, stability, and nutritional value of food products.[124] Dietary fibre from plant-based food byproducts is highly valuable since they are natural, which not only is preferred by consumers over synthetic sources but also aligns with the growing demand for more sustainable and eco-friendly products.[166] The modification of dietary fibre from plant-based sources can be achieved through various methods, including physical and biological approaches, either individually or in combination.[124] Physical methods involve high temperature, high pressure, and high-speed impact to reform the structure and composition of dietary fibre. For instance, dynamic high-pressure microfluidization (DHPM), is a method that combines high-speed impact, high-pressure shear, and cavitation effects to modify dietary fibre. DHPM leads to various physical effects, such as instantaneous pressure, particle size reduction, reduced agglomeration, and increased porosity.[179] Wang et al.[180] demonstrated the effects of DHPM on rice bran under the optimal pressure of 150 MPa, resulting in increased soluble fibre content, and improved adsorption capacity of cholesterol and toxic element Pb(II). DHPM also improved the functionalities of insoluble fibre, including oil, water-holding capacity, cation exchange capacity, and total negative charge.[180] Chen et al.[181] reported similar positive effects when applying DHPM with the pressure of 120MPa on oat insoluble fibre. The particle size of oat insoluble fibre was significantly reduced from 111.13 μm to 74.36 μm, with better solubility, water-, and oil-holding capacity. While DHPM is a promising pre-treatment for dietary fibre modification in biomass, it does require sophisticated equipment and has a tendency for micropores to clog with large particles.[124]

The level of soluble dietary fibre and functionalities in plant byproducts can be improved by physical ultrafine grinding, also known as micronisation. This process involves using equipment such as planetary ball mills, hammer mills or super micron mills.[178,182] Micronisation expands the potential applications of dietary fibres as functional ingredients or for the development of fibre-rich functional foods. It effectively overcomes challenges related to the texture and sensory quality of foods, which may be adversely affected by the direct addition of dietary fibres, particularly in products like yoghurts.[183] Moreover, micronisation results in powdered materials with improved dispersion, adsorption, solubility, and a better nutritional absorption rate.[184] A significant decrease in particle size also allows for alterations in the ratio between insoluble and soluble fibre.[184] Xue et al.[185] ground oat bran to a particle size range of 5–30 μm, enabling the creation of fibre-rich soft cheese with enhanced acceptability when incorporated at 1%. The process effectively increased the soluble fibre content while decreasing the insoluble fibre. Another study on soy okara, using a 5 mm planetary ball mill with a rotation of 750rpm, reported a significant reduction in particle size from 161 to 15 μm, with 43% of insoluble fibre being converted into soluble fibre.[186] Moreover, the micronisation process increased flavonoids content and converted daidzin and genistin into their more bioavailable aglycone forms.[186] Micronisation of oat byproducts, such as husk and bran, is a valuable valorisation method, as evidenced in the studies by Dziki et al.[182,187] The resulting superfine oat bran and husk were almost undetectable on the tongue, and the mixture of these byproducts (60–70% husk, 30–40% bran) produced a fibre-rich powder with a synergistic effect and enhanced antioxidant activity,[182] suggesting potential use as a value-added or supplement ingredient. However, controlling particle size is crucial, as excessively fine particles (below 550 μm) can negatively impact hydration properties.[188] In addition to physical methods, biological modifications using enzymes and microorganisms offers a way to enhance the functionality and nutritional value of dietary fibre derived from plant byproducts. Commercially available enzymes like cellulase, xylanase, and viscozyme L, as well as microorganisms such as *Trichoderma viride*, *Trichoderma harzianum*, *Bacillus natto*, and *Monascus anka*, have been widely studied and utilized in the food industry to improve the digestibility and beneficial properties of dietary fibre. Cellulase is a multi-component enzyme system with a synergistic effect mainly comprised of β-glucanase and β-glucosidase that can degrade cellulose.[124] The use of this enzyme in modifying dietary fibre has shown promising results. Wang et al.[189] treated ginger insoluble residue with cellulase, leading to modified insoluble fibre with a less rigid structure, highly porous, and higher solubility due to less hindrance of hydrophilic and hydrophobic functional groups. This modification resulted in an improved water retention and oil binding capacity. Similar effects were observed when coconut press cake was treated with cellulase, which led to a higher cation exchange capacity (CEC), potentially reducing fat absorption in the body.[190] The modified insoluble fibre with high CEC interferes with the emulsification process, forming complexes with lipids and micelles, making them less accessible to digestive enzymes and bile acids.[191] Moreover, when cellulase (15 U/g) was combined with xylanase (30 U/g) and applied to potato pulp at 50°C with pH 4.8 for 2.5 hours, a modified potato soluble dietary fibre with better physicochemical and functional properties than commercially available products was produced.[192] This suggests that modified insoluble fibre can serve as a value-added ingredient with health-promoting effects for incorporation into daily foods and improvement of their stability. In another study, the use of viscozyme L was used by Zhang et al.[193] to modify the insoluble fibre of soy okara. After modifications, soy okara insoluble dietary fibre exhibited improved water-, oil-holding capacity, and swelling capacity indicating the presence of soluble dietary fibre properties. Moreover, the modified insoluble fibre demonstrated increased absorption capacities of glucose, and cholesterol, and better cation exchange capacity. It should be noted that enzymatic modifications are generally more expensive than physical methods; however, the later methods require large operation space and harsh operating conditions. In contrast, enzymatic modifications for dietary fibre are highly specific, efficient, require less working space, and offer mild processing conditions to yield better appearance and purity products. Combining enzymes such as cellulase with physical methods such as hydrostatic pressure can create a synergistic effect and further improve the functionalities of dietary fibre.[194] For example, the combination process only required 200 MPa pressure for 15 minutes, yet it is sufficient to break down apple soluble dietary fibre into lower molecular weight soluble polysaccharides while improving hydration and emulsion properties.[194]

Fermentation with bacteria, yeast, and fungi has a long history in the food industry, used to produce beverages, bread, sauces, and dairy products.[195] When applied to plant byproducts, fermentation can decompose complex dietary fibre structures through enzyme secretion, enriching final products with health-promoting metabolites.[195]

### *Bacterial fermentation*

Bacterial genera such as *Bacillus* are often used in food fermentation to enhance the functional properties of dietary fibre. For instance, *Bacillus natto* can increase the solubility of millet bran, and improve its antioxidant content and activity.[196] These modifications contribute to better water-holding and oil-holding capacities, along with improved thermal stability.[196] Bacterial fermentations typically require an acidic environment (pH ~ 5) and a relatively long inoculation period, often exceeding 40 hours and sometimes extending to 7 days,[197–199] suggesting this mode of modifications needs more optimization to be able to apply on an industrial scale.

### *Fungal fermentation*

Fungal species from the genera *Trichoderma* and *Monascus* are effective in modifying dietary fibre in plant byproducts.[200] For example, fermenting tea residues with *Trichoderma viride* increased the soluble fibre content by eight times, while also enhancing its capacity to absorb toxic elements like Pb, Cd, and Cu.[198] Similarly, *Monascus anka* fermentation of soy okara resulted in an improvement in soluble dietary fibre, as well as enhanced water- and oil-holding capacities and swelling ability.[197]

### *Solid-state fermentation*

Solid-state fermentation offers an innovative approach to utilizing oat pulp as a substrate for valuable product generation in the food industry. Similarly to soy okara and other dietary fibre residues, oat pulp can undergo biotransformation through this process to produce enzymes, bioenergy, organic acids, and pharmaceuticals.[201] In contrast to traditional submerged fermentation methods, solid-state fermentation involves the growth of microorganisms like bacteria, yeasts, and fungi on solid, moist substrates under controlled conditions with low water input.[201] Various oat-based materials, such as oat bran and oat flour, have been successfully fermented using *Saccharomyces cerevisiae* (baker's yeast) and various lactic acid bacteria species, resulting in favorable outcomes. For instance, Calinoiu et al.[202] demonstrated that oat bran is a suitable substrate for solid-state fermentation of baker's yeast. After 4 days of fermentation, the viable cell count of *S. cerevisiae* reached $3.8 \times 10^8$ CFU/g, in stark contrast to the no-growth control sample.[202] Additionally, the highest total phenolic content was observed after 4 days (0.45 ± 0.02 mg GAE/g dwb), marking an 83% increase compared to the control sample.[202] The fermentation process can break down cell walls, releasing bioactive compounds.[203] Depending on the microorganism used, the fermentation process can lead to the production of specific enzymes, such as glucoside hydrolase, cellulase, esterases, and β-glucosidases, thereby converting bound phenolic compounds into their free forms. This enhances factors such as bioavailability, reactivity, and antioxidant activity.[204,205] Furthermore, the solid-state fermentation process significantly increased the content of individual antioxidant compounds, including ferulic, p-coumaric, caffeic acids, avenanthramide, and dihydroxybenzoic acids.[202] The elevated antioxidant content directly correlated to improved antioxidant activity, as evidenced by a 42.22% increase in DPPH inhibition ability after 4 days of fermentation.[202] This approach is not only economically feasible but also has the potential for industrial scaling, given the abundance of oat pulp and *Saccharomyces cerevisiae*, which is classified as a Generally Recognized As Safe (GRAS) food ingredient.

## Applications of oat pulp

A large amount of oat pulp generated from oat milk production is traditionally considered as waste and often disposed of in landfills. However, companies operating in the oat milk market and the broader food waste management are increasingly adopting sustainable practices to repurpose oat pulp, thereby reducing environmental impact.[68,206] While the feasibility of directly incorporating oat pulp into human consumption remains an area requiring further exploration, current practices predominantly involve utilizing oat pulp as animal feed, soil improvement, and renewable energy generation. Various applications of oat pulp are outlined in Table 2.

**Table 2.** Valorisation of oat pulp for different purposes.

| Applications | Description | References |
|---|---|---|
| Renewable energy, composting, and soil improver | Oat pulp is incorporated with organic materials within a biodigester, facilitating its natural decomposition. This process yields compost, thereby enhancing soil quality. Concurrently, biogas is generated, contributing to sustainable electricity production. | [207] |
| Animal feed | Oat pulp presents a highly nutritious alternative for animal feed, serving as a viable substitute for conventional feed crops. This method is the second most sustainable method for repurposing food by-products, as per prevailing food waste models in both the US and EU. | [31,206] |
| Functional food products | Oat pulp has been applied in the production of high dietary fibre bread, gluten-free cookies, and biscuits, highlighted by their low GI, elevated fibre and protein content, and inherent antioxidant properties. | [39,208,209] |
| Oat protein for dairy alternative | Oat protein extracted from oat pulp, or the oat pulp itself can serve as a key ingredient in the formulation of functional yoghurt products or dairy free fermented products with high fibre content and favourable sensory quality. | [210–212] |
| Oat pulp for synbiotic foods | Oat pulp can undergo fermentation with lactic acid bacteria, including strains from *Lactobacilli* and *Bifidobacteria* genera, resulting in the production of synbiotic foods. | [213,214] |
| Oat protein for plant-based meat analogue | Oat protein is emerging as a promising alternative to soy and wheat proteins in plant-based meat analogues. When combined with other plant-based proteins like hemp and peas, it not only diversifies the product range but also enhances the nutritional profile. Additionally, oat protein offers allergen-free benefits and provides desirable textural properties, making it an appealing choice in developing meat alternatives. | [215–218] |
| Oat pulp as protein hydrolysate for cell culture media | Utilized fermentation and extract derived from fermented oat pulp for culturing fungi, microalgae, or animal tissue cells offer a cost-effective alternative to conventional serum cell culture media. | [219–222] |

### *Oat pulp as a functional food ingredient*

Oat pulp represents a versatile and valuable functional food ingredient, especially for applications targeting health-conscious consumers. A straightforward method for upcycling oat pulp involves drying, milling, and sieving before incorporating it into various food products. Due to its high dietary fibre and β-glucan content, oat pulp can not only enhance the nutritional profile of everyday foods but also help meet daily dietary fibre requirements. Oat pulp has been incorporated into wheat bread to increase the dietary fibre content.[39] Foods with high β-glucan can have significantly lower glycaemic index (GI) values. For example, white bread with added β-glucan has a GI value 32–37% lower than traditional white bread.[76] A study by Jenkins et al.[223] observed that breakfast products containing elevated β-glucan like oat bran cereals had a significantly lower GI value than traditional options such as white bread. Each gram of added β-glucan was found to reduce the GI value by 4.0 units, without affecting the palatability of the foods.[223] β-glucan prevents the rise of the GI value through two mechanisms. Firstly, it can form highly viscous solutions in the digestive tract, which slows down the emptying rate in the stomach and delays the digestion of starch, leading to a gradual and more stable release of glucose.[28] Secondly, β-glucan resists digestion in the upper gastrointestinal tract, remaining intact until it reaches the colon, where it serves as a prebiotic for gut bacteria, stimulating the production of short-chain fatty acids. Additionally, oat starch can be isolated from oat pulp which has high viscosity, adhesion, and surface coating properties that are highly sought after in the food industry. It serves multiple purposes, including thickening, gelling, stabilizing, bulking, fat replacement, and texturizing in various food formulations.[224,225] Oat starch offers unique advantages, such as improving bread quality. The inclusion of oat starch in bread formulations resulted in bread with yellow-tinted crumb, improved elasticity, and resistance to shear forces during tearing, even after overnight storage.[226] In addition to its use in bread, oat pulp has been successfully incorporated into functional biscuits, particularly when combined with chickpeas to boost protein content and enhance sensory appeal.[208] These biscuits exhibit excellent water-holding capacity, high fibre content, and the absence of a gluten network, which simplifies dough processing compared to wheat-based biscuits.[208] Furthermore, biscuits made with oat pulp have reduced starch levels due to α-amylase activity during oat milk production, resulting in a low-calorie product.[208] While oat pulp offers many nutritional advantages, it is essential to balance its inclusion to maintain sensory quality, as excessive amounts of plant-based byproducts can impact consumer acceptance.[227] In bread formulations, for example, oat pulp inclusion levels around 10–15% have been identified as optimal for achieving both high nutritional value and desirable texture, colour, and specific volume.[39]

### *Oat pulp as a substrate for fermented and synbiotic food*

Oat pulp demonstrates a viable option as a substrate in the fermented dairy product like yoghurt. With its high levels of components such as protein and starch possessing gelling abilities, oat pulp becomes an appealing addition to yoghurt formulations, contributing to their nutritional and sensory characteristics. While the adjustment to the flavour and aroma of yoghurt can be made by different means such as adding flavours or fruits, modification of yoghurt texture can only be achieved by the production process itself.[210] Consumer preferences lean towards yoghurt with a creamy texture, smooth mouthfeel, robust gel strength, and minimal syneresis.[210] Synthetic stabilizers such as gelatine and modified starch can be used to improve yoghurt texture, but their acceptance among consumers is limited. Oat protein concentrate can be obtained from oat pulp similar to soy protein concentrate derived from soy okara,[228] and emerges as a sustainable ingredient suitable for both dairy and non-dairy products. Its inclusion not only delivers health benefits by providing dietary fibre, protein, and other bioactive compounds but also serves as a valuable component in yoghurt-like formulations. Incorporating oat protein concentrate into dairy yoghurt showcases favourable compatibility with milk protein, facilitated by the presence of starch content.[210] Brückner-Gühmann et al.[210] found that yoghurt enriched with oat protein concentrate exhibited faster acidification and gel formation compared to both skim milk powder-enriched yoghurt and yoghurt enriched with oat protein isolate. Additionally, oat protein concentrate also supported the growth of lactic acid bacteria to levels similar to those observed in skim milk powder-enriched yoghurt. However, the solubility of oat protein concentrate remained lower than that of skim milk powder due to the incompatibility between oat protein and milk protein arising from differences in solubility, molecular weight, and conformation of oat globulin and milk casein micelles.[210] This incompatibility was partially mitigated by the presence of the remaining starch fraction which gelatinized during the heating process, binding water and increasing viscosity.[210] The gelatinization of starch reduced water availability for the whole system, causing milk protein in the water phase to become more concentrated, resulting in a denser structure and heightened level of elasticity.[210] Moreover, the starch within the oat protein concentrate contributed to enhanced water-holding capacity, thereby improving gel stability and reducing syneresis in yoghurt. Studies have indicated that the addition of polysaccharides such as starch, dextrin, and inulin can enhance heat-induced gel strength and stability.[211,229,230] Meanwhile, oat protein isolate, despite its higher protein concentration, lacks starch and exhibits poor compatibility with milk protein due to low solubility at pH 4 (the pH of yoghurt), and pH 7 (the pH of most dairy milk).[210] This suggests that oat pulp, in its fresh state, could be directly employed for a high dietary fibre yoghurt production, bypassing the dehydration step, and reducing energy consumption. By leveraging the complementary effects of components like starch, dietary fibre, and protein, oat pulp can be used to produce fermented probiotic beverages or yoghurt-like products, enhancing their quality. Through fermentation with *Lactobacillus delbrueckii subsp. bulgaricus* and *Streptococcus thermophilus*, oat protein concentrate yields a product characterized by a yoghurt-like texture and mildly sour, lactic fermented flavour.[212] The presence of starch (44.7%) in the oat protein concentrate contributes to strengthening the structure of this soft gel-like liquid product through the gelatinization process.[212] Furthermore, the substantial content of starch can be enzymatically degraded by amylases, providing an inherent carbohydrate source that supports the growth of fermenting bacteria. Importantly, the fermentation process has minimal impact on both essential and non-essential amino acids.[212] A similar approach has been observed with fresh soy okara, resulting in the creation of okara yoghurt, probiotic and synbiotic foods with high protein, fibre content, and large viable probiotic colonies ($\geq 10^7$ CFU/ml), all accompanied by favourable sensory qualities.[231,232]

Oat pulp possesses high levels of β-glucan and dietary fibre, providing the opportunity for producing synbiotic foods containing both prebiotic dietary fibre and probiotic lactic acid bacteria. A study by Zhang et al.[213] exemplified this concept by conducting solid-state fermentation of whole oats with lactic acid bacteria. Certain genera of lactic acid bacteria, including *Lactobacilli* and *Bifidobacteria*, are known for their health benefits, such as reducing lactose intolerance, cholesterol levels, and cancer risk, and enhancing the immune system.[233] Throughout the fermentation process, oats maintained acidic pH values and served as a suitable substrate for supporting the growth of *L. plantarum* TK9 and *B. animalis* subsp. *Lactis* V9. The viable cell count increased significantly, reaching $2.85 \times 10^9$ CFU/g after 28 hours and $3.17 \times 10^8$ CFU/g after 40 hours of fermentation, respectively. The fermentation yielded 506.67 mg and 383.33 mg of lactic acid per 100 g from *L. plantarum* TK9 and *B. animalis* subsp. *Lactis* V9 fermentation, respectively.[233] While the fermentation process led to a slight reduction in the levels of soluble dietary fibre and β-glucan,[213,214,233–235] indicating that these bacteria utilize these components as an energy source for growth, there was a significant increase in free amino nitrogen.[213] This suggests that lactic acid bacteria effectively hydrolyse and decompose oat protein into smaller peptides and amino acids, making them more bioavailable and potentially offering enhanced health benefits, particularly those with a molecular weight of less than 6 kDa.[213,235] This effect was evident in the decrease of 22.93% – 26.08% in peptides with molecular weights exceeding 10 kDa and the increase of 4.44% – 5.96% in peptides with molecular weights less than 6 kDa.[213]

## Oat pulp for plant-based meat analogue

Plant proteins offer a promising solution to address environmental and religious concerns related to meat production by enabling the creation of plant-based meat analogues (PBMAs). The global PBMA market has seen substantial growth, with its value increasing from USD 1.6 billion in 2019 to an anticipated USD 3.5 billion by 2026, reflecting a CAGR of 12%.[236] Extrusion technology is the primary method for producing PBMAs (Fig. 6), as it transforms plant proteins into fibrous structures

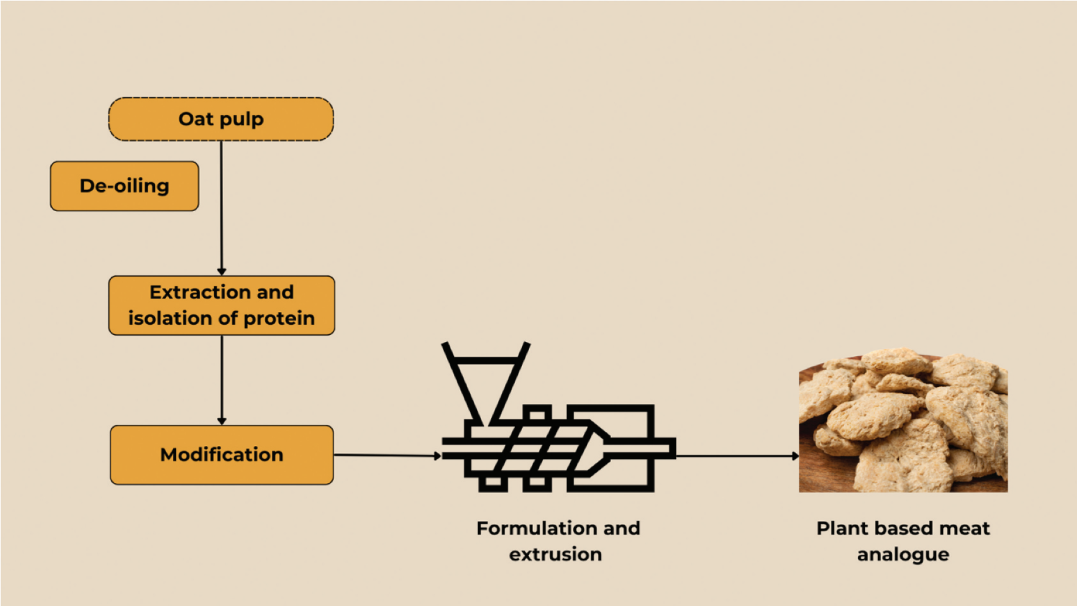


**Figure 6.** Integration of oat pulp in plant-based meat analogues.

that closely resemble meat.[215,237,238] During extrusion, proteins denature, leading to conformational changes and protein aggregation. The extrusion process causes protein molecules to unfold and cross-link, forming dense protein bonds that yield the fibrous texture crucial for PBMAs.[237] Most PBMAs rely on protein flours, isolates, or concentrates from soy and wheat due to their high protein content, availability, and functional properties.[239] However, issues related to cultivation, GMOs, and allergies have shifted interest towards alternative plant-based proteins, such as oats, hemp, and peas, as substitutes for soy and wheat in PBMA production.[240] Benefits of incorporating oat-based ingredients in PBMAs are summarised in Table 3. Oat pulp, and protein and dietary fibre fractions from oats have been explored for use in PBMAs.[215,237] Assessments of PBMAs consider not only sensory attributes but also nutritional quality, particularly the amino acid profile and digestibility of proteins. Oats offer a balanced amino acid composition, though they are limited by lysine content and have an amino acid score ranging from 0.66 to 0.75.[243] The digestible indispensable amino acid score (DIAAS) of oat protein is below 75, based on the reference pattern for children aged 0.5–3 years.[243] This score is higher than that of wheat, rice, corn, hemp, and faba bean proteins but lower than that of rapeseed, lupin, pea, canola, soy, or potato proteins, and animal proteins like egg and pork.[243] Different forms of oat protein show varying protein digestibility-corrected amino acid scores (PDCAAS), with oat flour having the lowest protein content and a PDCAAS of 51, which is lower than the PDCAAS of oat protein concentrate at 61.[244] Using oat protein alone to produce PBMAs via extrusion is challenging, as its quality is insufficient for achieving a meat-like texture independently. The protein concentration in oat pulp is relatively low, ranging between 25.71% and 52.10%, much lower than that found in soy okara.[227] The essential amino acid content of oat protein is approximately 21%, which is below the WHO/FAO/UNU amino acid requirements and does not fully meet the nutritional objectives for PBMAs to match animal protein quality.[245] Other plant-based proteins, such as hemp, wheat, and lupin, also contain various essential amino acids but fall short of meeting adult amino acid requirements. For example, oats and hemp are limited by lysine, while legumes generally lack sulphur-containing amino acids.[245] Each plant protein source exhibits unique water and oil-holding capacities, which correlate with other functional properties like emulsification and gelling, contributing to the texture, succulence, and juiciness of PBMAs.[246] However, it can be difficult to compare the properties of oat protein directly with other plant proteins due to differences in isolation processes and conditions of manufacturing such as pH and temperature.[247] Consequently, using only one source of plant-based protein is not ideal for developing PBMAs. Instead, combining oat protein with other plant proteins compensates for their individual limitations in amino acid profile, protein quality, and sensory characteristics, resulting in a product that appeals to a broader consumer base. Including oat-based ingredients in PBMAs provides health benefits and textural improvements due to the presence of dietary fibre and β-glucan, which contribute to improved texture, bowel health, satiety, and fullness.[246] For instance, combining an oat β-glucan-enriched fraction (containing 28% β-glucan and 23% protein) with faba bean protein (65% protein) for PBMA production via low-moisture extrusion has shown that each ingredient complements the other, improving the amino acid composition and increasing the DIAAS of the final product from 72.2 (using the β-glucan fraction alone) or 76.1 (using faba bean protein concentrate) to 90.2 in the blend.[218] PBMAs from this oat-faba bean mixture demonstrated excellent textural and sensory quality, with sufficient β-glucan per serving (over 1 g) to meet the European Food Safety Authority's health claim requirements for LDL cholesterol reduction.[218] The compatibility of oat-based ingredients with other plant proteins is further supported by a recent study from Zahari et al.,[215] which explored the combination of oat pulp with hemp protein concentrate for high-moisture meat analogues. This meat analogue exhibited consistent layered structures, distinct fibrillar patterns, and brown colour, which contribute to their visual appeal and overall quality.[215] These analogues exhibited consistent layered structures, distinct fibrillar patterns, and brown coloration, enhancing their visual appeal and quality.[215] The substantial dietary fibre and β-glucan content enhance nutritional quality and contribute to the thickening and reducing cooking losses in meat analogues, attributed to high water-holding capacity and the ability to stabilize oil-water emulsions.[215] Other plant-based proteins, like pea protein, are also combined with oat protein to create PBMAs with a fibrous, meat-like texture.[216,217,241] The synergy between pea and oat proteins enhances the amino acid profile and protein content of extruded pea-oat analogues.[217] Both proteins contain antinutrients, such as trypsin inhibitors and phytic acid, but the extrusion process reduces these antinutrients, increasing the bioavailability of proteins and starch.[217] The proportion of oat-based materials in meat analogues is crucial, especially considering their contribution of carbohydrates such as dietary fibres and β-glucan, which could potentially affect product characteristics. Research indicates that the optimal oat material ratio falls within the range of 30–50% when utilizing oat fibre concentrate.[241] While oat dietary fibre and β-glucan offer beneficial water-holding capacity, an excessive concentration may lead to a denser meat structure, hindering water movement through capillary vessels.[241] Ramos Diaz et al.[241] found that meat analogues with lower fibre content (30–50%) exhibited substantial void areas in the meat structure, while those with elevated oat fibre content (above 70%) could reduce the void thickness in the meat analogue and disrupt the fibrous structure, which adversely impacts the mechanical strength of the meat analogue, particularly under conditions of low moisture extrusion. Similar findings were observed in the study by De Angelis et al.,[216] where oat-pea meat analogue (30% oat protein – 70% dry fractionated pea protein concentrate) displayed comparable effects during low moisture extrusion. Therefore, combining high-protein plant sources with oat-based ingredients holds promise for diversifying PBMAs in the market, improving nutritional and sensory properties, and expanding their appeal to consumers.

### *Oat pulp as a fermentation substrate for the production of microbial protein and cell cultivation*

Alternative protein sources, such as fungi, microalgae, and animal cells cultivated through cellular agriculture, are gaining significant attention as sustainable options to address the environmental impact of conventional animal protein production and consumption. Fermentation is one of the techniques for cultivating these proteins, which can be performed either through submerged fermentation (SMF) or solid-state fermentation (SSF). SDF, while advantageous in terms of lower water and

**Table 3.** Benefits of incorporating oat-based ingredients in plant-based meat analogues (PBMAs).

| Ingredients | Benefits | References |
|---|---|---|
| Oat protein – dry fractionated pea protein | Dry-fractionated pea protein has a lower oil absorption capacity than oat protein, although oat protein has a lower protein content. Combining the two resulted in a PBMA with good sensory quality and a protein content of 55 g/100 g dry weight basis (dwb).<br>Pea protein often carries an undesirable flavour, but adding 30% oat protein reduced the odour and improved the overall sensory quality of the PBMA. | [216] |
| Oat protein concentrate – pea protein concentrate/isolate | Adding oat protein increased the water and oil absorption capacities, out-performing formulations with pea protein extrudate alone.<br>The texture of oat-pea protein PBMAs matches the strength of a chicken sample. | [134] |
| Oat fiber concentrate – pea protein isolate | Oat fiber concentrate can be added up to 50% of the oat-pea PBMA formulation while maintaining a fibrous, meat-like structure.<br>The dietary fiber content of oat-pea PBMAs is significantly increased with the addition of oat fibre concentrate. | [241] |
| Oat protein concentrate – pea protein isolate | The combination of oat protein (up to 70%) and pea protein at optimal extrusion conditions produced PBMAs with a mild flavour and good nutritional quality, presenting a promising alternative to soy and wheat protein. | [242] |
| Oat fibre fraction – faba bean protein | PBMAs formulated with oat fibre fraction and faba bean protein demonstrated improved nutritional, sensory, and physicochemical properties compared to each ingredient alone.<br>The inclusion of oat fibre fraction provided sufficient β-glucan (1 g per serving) for PBMAs to carry a health claim related to reducing LDL cholesterol. | [218] |
| Oat pulp and hempseed protein concentrate | Utilizing two food byproducts enabled the production of PBMAs with high dietary fibre content, uniform layering, firm texture, and a fibrous structure through high-moisture extrusion. | [215] |

energy use, presents challenges in scalability, making it more suitable for small-scale production.[248] SMF, on the other hand, requires greater water and energy input but is preferred in industrial contexts due to its scalability, adaptability to various reactor designs, and capacity to produce higher concentrations of bioactive compounds compared to SSF.[249] Despite these advancements, the market availability of alternative proteins remains limited, largely due to the high costs of growth media required for their cultivation.[250–252] Substrates derived from oats could offer a cost-effective solution for this challenge. Important considerations for using such substrates include their non-toxic nature, affordability, ability to support rapid cell growth, and consistent availability for repeated cultivation cycles without long-term adverse effects.[253] Although oat-based materials have shown promise as nutritious ingredients, their application as growth media for alternative proteins is still underexplored. In comparison, other plant-based byproducts, such as soy okara and cereal processing residues, have been successfully utilized in cultivation media for these microorganisms, which showcase the potential for oat-based substrates to support the production of alternative proteins.

### *Fungi cultivation*

Filamentous fungi offer a promising alternative to animal protein, providing a nutritious, affordable, and more sustainable protein source compared to conventional meat.[254,255] Fungal biomass is a complete protein source that is highly digestible and rich in bioactive compounds, micronutrients, and dietary fibre.[256] Specifically, mycoprotein, derived from fungal biomass, mimics the structure of meat while being nutrient-dense.[256] Various species from the Ascomycota (e.g., *Aspergillus oryzae*, *Fusarium venenatum*, *Monascus purpureus*, *Neurospora intermedia*) and Zygomycota (e.g., *Rhizopus oryzae*) families are widely used in the food industry.[1] Fungal biomass or mycoprotein is produced by culturing filamentous fungi in controlled fermentation, where oxygen and carbohydrates, mainly glucose, are converted into protein-rich biomass.[252] Currently, *Fusarium venenatum* is the most widely known mycoprotein, produced in submerged fermentation (SMF) systems, with Quorn™

being its prominent brand.[252] However, the production relies on highly refined glucose syrup as the primary carbon source, supplemented with ammonium and biotin, which contributes to high production costs and limits sustainability.[252] A key advantage of mycoprotein is its adaptability, as filamentous fungi can grow on various substrates by secreting enzymes like amylase, invertase, and protease, which help break down diverse nutrients.[252,256,257] However, not all substrates that support mycoprotein growth are suitable for human consumption, making careful substrate selection crucial. Although *Fusarium venenatum* has traditionally been used for mycoprotein production, *A. oryzae* and other fungi species are gaining attention due to its high protein yield and versatility. *A. oryzae* has demonstrated the ability to produce mycoprotein from fermentation with pea processing by-products, achieving a yield of 0.26 g/g, surpassing other species such as *F. venenatum*, *Monascus purpureus*, *N. intermedia*, and *R. oryzae*.[257] Traditionally used in fermenting soy-based foods like soy sauce and miso paste, *A. oryzae* has also been cultured with soy byproducts like soy okara and soy whey to produce protein-rich biomass.[252] These byproducts support *A. oryzae* growth, yielding varying levels of biomass and protein concentration depending on the fermentation conditions.[252] The form of soy-based ingredients and incubation methods significantly affect fungal biomass and protein production. Static incubation with soy okara yields better biomass quantity, as agitation may cause the biomass to entangle with the substrate, and the protein tends to accumulate in the liquid.[252] In contrast, incubation with soy whey benefits from agitation, which helps distinguish the biomass and the protein accumulated within the fungal biomass.[252] Oat-based ingredients like oat flour and oatmeal have also been used to produce fungal biomass for nutrient-rich food applications, with *A. oryzae* and *Trichoderma viride* showing promising results. In submerged fermentation with oatmeal medium supplemented with potato peptone, *T. viride* showed significant growth, with spore counts increasing from $4.20 \times 10^4$ spores/ml to $3.52 \times 10^6$ spores/ml after 120 hours.[251] The biomass protein content ranged from 30% to 40%, correlating with biomass concentration.[251] Similar to soy okara, fungal biomass separation from the solid oat substrate is challenging due to the tight attachment of fungal hyphae.[251] A study by Rousta et al.[256] have explored using oat flour as a substrate for *A. oryzae* fermentation to produce edible fungal biomass, capable of supplying up to 42% of the protein requirement per 100 g dry biomass for a 70 kg adult. Oat flour, with its high surface area from milling, improves nutrient accessibility for fungi.[256] After fermentation, the fungal biomass showed a significant increase in total amino acid content (110%), with lysine and threonine levels increasing by 3.4 and 2.6 times, respectively.[256] Dietary fibre and lipid content also increased, particularly polyunsaturated fatty acids like linoleic acid, oleic acid, and palmitic acid.[256] Additionally, fermentation enhanced micronutrient content, including vitamins E and D2, and minerals, underscoring the potential of oat pulp as a cost-effective substrate for mycoprotein production in the food industry.[256]

### Microalgae cultivation

Microalgae contain up to 70% protein, including all 20 essential amino acids required for human nutrition.[258,259] They can be cultivated with minimal land and water use compared to convention. Notably, some marine microalgae can be grown without the need for freshwater, making them a highly sustainable protein source.[258,259] The primary methods for cultivating microalgae are heterotrophic (non-photosynthetic) and autotrophic (phototrophic) cultivation.[260] However, the addition of organic ingredients to the cultivation process increases production costs, which can discourage consumption, particularly given the unappealing taste of microalgae. Using plant-based byproducts to develop culture media for promoting the growth of heterotrophic microalgae presents a practical solution, especially in environments where land is scarce. This approach is also cost-effective, as operational expenses for heterotrophic cultivation account for 78% of total costs, mainly due to the high price of substrate media.[260] Currently, the cost for heterotrophic cultivation is approximately \$4.00 per kg, comparable to autotrophic production costs.[260] However, costs could potentially be reduced by 75% by selecting suitable, abundant, and cost-effective substrates that enable high biomass conversion rates.[260] Heterotrophic microalgae cultivation offers several advantages, including faster growth, higher cell densities, and more efficient biomass production compared to autotrophic methods, with growth rates potentially increasing up to 10 times.[261] Unlike autotrophic microalgae, which are limited by sunlight availability, heterotrophic cultures can grow rapidly, reaching high cell densities (exceeding 75 g/L) by utilizing organic compounds as nutrients.[261] Recent studies have revealed that heterotrophic microalgae cultures can also produce pigments such as carotenoids, lutein, and phycocyanin, which were previously thought to be exclusive to autotrophic conditions.[262,263] Moreover, heterotrophic cultures can generate proteins and micronutrients that are unavailable with autotrophic strains.[264,265] In a study by Kim et al.,[266] soy okara underwent solid-state fermentation with food-grade filamentous fungi, resulting in a nutrient-rich medium that supported the growth of *Phaeodactylum tricornutum*, a marine microalga high in omega-3 fatty acids, particularly eicosapentaenoic acid (EPA). The fermented okara medium showed significantly higher carbohydrate, nitrogen, and phosphorus content, leading to double the biomass production compared to conventional media (0.52 g/L vs. 0.25 g/L) after 7 days. An important finding was that an undiluted medium, with excessive levels of nitrogen and phosphorous, inhibited *P. tricornutum* growth.[219] Similar observations were made in other studies where excessive nutrient concentration hindered cell growth due to substrate inhibition, a phenomenon that renders overly beneficial compounds cytotoxic to cells.[222,260,267] The study by Kim et al.[266] also reported a five-fold increase in fucoxanthin, a carotenoid with health benefits related to anti-obesity, anticancer, and antidiabetic properties, from 0.24 mg/L to 1.17 mg/L. Furthermore, the composition differences between the fermented okara medium and conventional media influenced the types of fatty acids found in the microalgae cells. Microalgae grown in the fermented okara medium exhibited an increase in beneficial fatty acids such as EPA and other polyunsaturated fatty acids, while those grown in conventional media had higher levels of saturated and monounsaturated fatty acids. This highlights the potential of oat pulp as a comparable byproduct to soy okara for the sustainable and cost-effective production of microalgae.

### *Animal cell cultivation*

Cultured meat is derived from the cell culture of animal-derived cells, and aims to closely mimic the composition, flavour, and texture of animal meat. The initial introduction of a cultured meat burger patty in 2013 marked a significant milestone, albeit at a high cost due to various technology barriers. Over time, some barriers have been overcome, yet cultured meat affordability lags behind that of other alternatives such as plant-based meat analogue.[268] The main obstacles lie in the high production costs, primarily stemming from the expenses related to the growth substrate media. Moreover, these challenges are compounded by factors such as technical intricacies, nutritional concerns, regulatory considerations, and consumer acceptance issues.[269] The predominant medium to support the growth of animal muscle tissue cells traditionally relies on fetal bovine serum (FBS), which raises ethical concerns and introduces batch-to-batch variations in quality due to its harvesting process.[270] Additionally, FBS supply might diminish as cultured meat becomes mainstream.[271] Thus, finding serum-free, animal-free alternatives becomes imperative. Existing serum-free media like Essential 8™ and Fibroblast Growth Medium™ are more prevalent in biopharmaceutical production and medical research. While these growth media can be used in cultured meat production by sustaining the proliferation of primary bovine myoblast cells for up to 6 days, the efficiency is lower than that produced by 20% FBS or 10% horse serum medium.[270] Moreover, their inclusion of costly growth factors restricts their practicality for cultured meat production.[270] Thus, to maximize the profitability of cultured meat production, opting for more complex components and less defined growth media proves to be a pragmatic approach.

Fermentation or hydrolysis of plant-based milk byproducts like oat pulp or soy okara can form plant peptones that are composed of various nitrogen sources such as amino acids and peptides, as well as carbohydrates and phosphate that support the proliferation and differentiation of animal tissue cells.[270,272] A critical aspect of growth media is its specificity to certain cell types, ensuring that it can effectively support their growth. Most cultured animal cell lines cannot efficiently utilize complex nutrients. Instead, they rely on glucose, glutamine, specific amino acids, and fatty acids.[270] The efficacy of less refined, complex growth media hinges on the ability of animal cell lines to tolerate and utilize sugars beyond glucose and complex nitrogen sources.[270] While there are challenges, pursuing this strategy holds significant promise for bringing cultured meat production closer to a wider consumer base. Recent research has shown that hydrolysates or peptones derived from plant proteins and plant milk byproducts can be employed to create animal-free and serum-free culture media for various cell types, including animal cell cultivation.[220,250,272] In a study by George et al.,[272] plant peptones sourced from wheat and cotton, were successfully utilized to improve the health and quality of bovine embryos cultured in vitro. When compared to bovine serum albumin (BSA), both wheat and cotton peptones, added to the culture medium at concentrations of 0.56 mg/mL and 0.18 mg/mL respectively, demonstrated similar embryo development and hatching rates as achieved with 4 mg/mL BSA. Furthermore, embryos cultivated with plant peptones exhibited comparable resistance to freezing and were capable of successful elongation after transfer. In another study by Teng et al.,[220] soy okara was fermented with *Rhizopus oligosporus*, and the resulting extracts were explored as a potential alternative to fetal bovine serum (FBS) in cell culture media. The study focused on investigating the effectiveness of different protein fractions from fermented okara extracts, categorized by molecular weight (50 kDa, 10 kDa, and 3 kDa), when applied to human cell cultures, namely HepG2 and HEK293, as well as C2C12 and immortalized porcine myoblast (IPM) cultures, with the intended for cultured meat application. The results indicated that fractionation by molecular weight improved the quality of the okara extracts, resulting in enhanced cell viability for both HepG2 and HEK293 cell lines compared to unfractionated extracts. This suggests the presence of inhibitory or antinutrient compounds in soybeans, potentially exceeding 50 kDa in molecular weight. However, selectively filtering the protein fraction could remove both inhibitory and beneficial compounds. Certain proteins found in animal serum which are crucial for various cultures have their molecular weight near or exceed 100 kDa, including albumin, fibronectin, and antibodies.[220] Notably, different fractions exhibited varying effectiveness, with 50 kDa and 10 kDa extracts performing well for HEK293 cells, while 10 kDa and 3 kDa extracts were more effective for HepG2 cells. The optimal concentrations of fermented okara extract for supplementing HEK293 and HepG2 cells were found to be 1.0 mg/mL and 2.0 mg/mL, respectively. Lower concentrations of okara extract (1–2 mg/mL) also yielded improved cell viability, suggesting the important effect of substrate inhibition phenomena. The study further utilized MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assays to assess cell viability and growth, revealing that the 50 kDa fraction effectively replaced serum in supporting the growth of HEK293 and HepG2 cells. This fraction achieved a relative growth efficiency (RGE) of 70%, compared to the traditional use of FBS (RGE of 100%). While C2C12 cells are commonly utilized to study muscle cell growth under lab conditions, their findings might not perfectly align with cultured meat production realities, given that these cells are derived from mice.[220] Conversely, IPM cells offer a more relevant context, as they come from pigs, which are more similar to the cells used in cultured meat production.[127] This choice ensures results that are likely to be more applicable to practical cultured meat production scenarios. To explore the efficacy of fermented okara extract in cultured meat production, the study incorporated fermented okara extract (1.0 mg/mL) into reduced-serum media (2.5% and 5% FBS). In C2C12 cells, cultures with 5.0% serum containing various fermented okara extracts, whether fermented for 24 or 72 hours, exhibited better results than media with only 2.5% serum. Nevertheless, 2.5% serum media still showed more viable cells than serum-supplemented media across most fermented okara protein fractions. Among cultures with 5.0% serum, the 50 kDa fraction from the 24-hour fermented okara extract yielded the best results after 72 hours, with exponential growth observed between 48 and 72 hours. For IPM cultures, differences emerged between those supplemented with 24-hour and 72-hour fermented okara extracts. The outcomes suggested that 72-hour fermented okara extracts contained compounds that promoted higher proliferation and viability, consistent with results obtained from C2C12 cultures. This implies that 72-hour fermented okara extracts can serve as a partial substitute for serum. However, refining the extract composition is necessary before effectively integrating the into cultured meat production practices.

## Challenges and future considerations

One of the primary challenges in oat pulp utilisation is the need to enhance its safety and sensory properties, particularly taste and texture, to improve consumer acceptance. The direct incorporation of oat pulp into food products may not always be feasible due to these limitations. Another challenge lies in the optimisation of processing methods, such as drying and modification, to retain its nutritional value while improving its techno-functional properties. The scaling up of these processes in an economically viable manner also remains a challenge, as the production of oat milk, and consequently, oat pulp increases to meet the growing demand for plant-based dairy alternatives.

Future studies are recommended to overcome technical barriers and unlock the potential of oat pulp to support healthy and sustainable diets:

- In-depth characterization of the macronutrients, micronutrients, bioactives, and microbiome of fresh oat pulp generated from different oat milk production sites, and their changes over time at local ambient conditions.
- Study the impact of different drying conditions and techniques on nutritional composition, taste, and texture to identify the most food-compatible and cost-effective conditions for dry fresh oat pulp.
- Investigate fractionation technologies for the preparation of protein, dietary fibre, and bioactive compounds or enriched fractions from oat pulp, also evaluating techno-functional properties and techno-economic feasibility.
- Investigate fermentation of oat pulp or enriched fractions to produce nutritionally improved food ingredients, synbiotic and fermentation derived protein products.
- Prototype food applications of oat pulp, enriched fractions, and isolated components to validate nutritional claims and showcase the potential value of oat pulp in food products.

## Conclusion

Oat pulp holds significant promise as a sustainable and versatile ingredient in food production. Its rich content of dietary fibre, protein, micronutrients, and bioactive compounds presents numerous opportunities for enhancing the nutritional quality of various food products. However, the full potential of oat pulp remains largely untapped, with its composition and benefits yet to be thoroughly characterised. While the direct use of oat pulp as a food ingredient offers clear nutritional advantages, challenges related to its safety, taste, and texture must be addressed to improve consumer acceptance. Processing methods, such as drying, modification, and fermentation, are essential for enhancing shelf life, and texture, and making oat pulp a more valuable resource across a wider range of applications.

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