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Faba bean and oat as ingredients in fermented plant-based foods: opportunities and challenges

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ABSTRACT

The food production system contributes approximately 37 % of global greenhouse gas emissions, with animal-based food generates twice as many emissions as plant-based food. To address this issue and feed a growing population, a shift towards a plant-based diet is recommended. There is an urgent need for the development of more plant-based foods alternatives with high nutritional and sensory qualities. In Sweden, Faba bean and Oat are being increasingly explored as efficient protein crops that can be grow in Swedish climate. This review provides updated insights into the use of faba bean and oat in plant-based food products, including their nutritional profile and anti-nutrients, the functional properties including protein, starch, fibre and lipids. Despite the increasing use of faba bean in plant-based meats and dairy analogues, concerns remain regarding their sensory and anti-nutritional aspects. However, a mixture of faba bean with cereal has shown promising results with desirable attributes.

1. Introduction

The release of greenhouse gases, which is the main cause of the current climate change, is largely attributed to human activities. The food system is a major contributor, accounting for 21–37 % of emissions (Crippa et al., 2021; Gibbs & Cappuccio, 2022). Food and Agriculture Organization (FAO, 2022) has reported that the global agri-food system is responsible for 16 billion tons of carbon dioxide equivalent (Gt CO_2eq) emissions, primarily from farm gate, land-use, and pre- and post-production processes. Notably, the production of animal-based food generates approximately twice as many greenhouse gases as plant-based food (Xu et al., 2021).

Adopting a plant-based diet that aligns with the United Nations' Sustainable Development Goals (SDG) offers a promising solution to the challenge of feeding a projected global population of 10 billion people by 2050. Thus, European countries should prioritize local food systems to promote food self-sufficiency and sustainable production (Crippa et al., 2021; Gibbs & Cappuccio, 2022).

Plant-based diet offer substantial environmental advantages, including a 76 % reduction in land usage, a 49 % decline in total global greenhouse gas emissions, and a 49 % decrease in eutrophication compared to animal-based diets (Crippa et al., 2021; Gibbs & Cappuccio, 2022). Additionally, some clinical trials have reported that healthy plant-based food might reduce the risk of development of obesity, chronic diseases, and promote overall health (Shabir et al., 2023)

Traditional plant-based protein foods such as soybean-based products including tofu, tempeh, and seitan, have been available for decades, and in recent years have gained popularity in western countries (Ahnan-Winarno et al., 2021). Tempeh, a fermented soy-based food, is attractive because of its affordability, ease of preparation, and health benefits (Ahnan-Winarno et al., 2021). Tempeh is a traditional food from Indonesia; its main ingredient is soybean fermented with *Rhizopus* spp. Numerous attempts have been made to replace soybeans with other types of protein sources such as lentils, lupine, corn, and barley (Aaslyng & Højer, 2021).

In Northern Europe, soybeans cannot be harvested due to a cooler climate, which prevents them from fully maturing and producing a usable yield; therefore, Sweden and majority of European countries, mainly rely on imported soybean (Debaeke et al., 2022). Faba bean (*Vicia faba* L.) is an attractive alternative to replace soybean in plant-based food production as it can be cultivated in Europe and is recognized for its high content of protein, dietary fibre and health-promoting bioactives components (Dhull et al., 2022). Moreover, faba bean might contribute to crop diversification and biological

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nitrogen fixation. The most recent report by Statistics Sweden (2022) estimated a total production of faba bean of 79,600 ton. The majority of this is used for animal feed. It was also estimated that its climate impact is relatively low compared to other beans, with approximately 0.18 GHG (kg CO_2e) (Tidåker et al., 2021). Despite its nutritional potential, faba bean application in food industry is limited due to anti-nutritional and sensory factors. Legumes including faba bean, are deficient in certain essential components, especially sulfur-containing amino acids (methionine and cysteine) and tryptophan. These deficiencies can be addressed by incorporating cereals, which are naturally low in lysine but contain high methionine and cysteine levels, into the final faba bean products and improve sensory aspects (Murphy et al., 2023).

Oat is an important food crop in Sweden and the Nordic countries. According to Lantmännen Harvest forecast (2024) (Lantmännen, 2024), approximately 630,000 tonnes of total weight of oat are harvested in Sweden every year. Oat have excellent nutritional profile with a high protein content, unique lipid composition, starch, dietary fibre, vitamins and minerals. Furthermore, oat and by-products are rich in a variety of other health-promoting bioactive compounds such as β-glucan, avenanthramides and polyphenolic compounds. Some of those compounds have been extensively studied for their health benefits, including reducing the risk of developing type 2 diabetes and heart disease. However, the availability of nutrients in oat is also hindered by the presence of anti-nutritional factors as phytic acid, avenin, and polyphenols. Phytic acid chelates essential minerals, reducing their bioavailability, while polyphenols can bind to proteins and digestive enzymes, decreasing protein digestibility. Although avenin is primarily a storage protein, it may contribute to reduced protein availability in some cases due to its rigid cell structure and interactions (Z. Yang et al., 2023).

This review aims to provide updated insights into the use of faba bean and oat in plant-based food products, their nutritional profile, anti-nutrients, and the functional properties of faba bean and oat fractions including protein, starch, fibre and lipids.

2. Nutritional composition and functional properties of faba bean

2.1. Proteins

Faba bean (*Vicia faba* L.) genotypes display considerable variation in seed size. Typically, var. *minor* produces small seeds, var. *major* is known for large seeds, while var. *equina* exhibits seeds of intermediate size (Punia et al., 2019). Same as seed size the Faba bean protein content highly varies due to genetic diversity among the species and environmental conditions. Labba, Frøkiær and Sandberg (2021) reported a range of protein content from 26 % to 33 % in 15 faba bean varieties cultivated in Sweden. Globulins are the major protein storage in faba bean, serving as a nitrogen source after seed germination (Rahate et al., 2021). The legumin-like (11S) and vicilin-like (7S) subunits of globulins in faba bean have been the research focus due to their technological properties. Similar to other legumes, faba bean is limited in sulphur-containing amino acids and tryptophan but is rich in lysine and leucine (Labba, Frøkiær and Sandberg, 2021).

Faba bean protein has better thermal stability than soybean protein at ionic strength of 0.5, which makes it a promising functional ingredient for foods that undergo intense thermal treatment. This characteristic is due to the high thermal denaturation midpoint temperature of the 11S and 7S globulins in faba bean compare those in soybean (Rahate et al., 2021). Since many food applications run within a pH range of 5–7 and frequently include the use of NaCl, it is critical to understand protein gels performance within these conditions since the isoelectric point of faba bean proteins falls within the 5.0–5.5 range (Langton et al., 2020). The wet extraction of protein from faba bean is an attractive option for food applications because it eliminates the glucosides vicine and convicine, which cause favism (Langton et al., 2020; Rahate et al., 2021).

The solubility of the faba bean protein is relatively low, due to the large formation of aggregates during the protein extraction. However, high-pressure homogenization, alkaline extraction, isoelectric precipitation or enzymatic hydrolysis might improve efficiency of protein extraction (Langton et al., 2020; Rahate et al., 2021). High-pressure homogenization enhances solubility and foaming but not emulsifying properties. Enzymatic hydrolysis boosts faba bean protein solubility and foaming capacity, but emulsifying properties remain unaffected. However, the foaming capacity still lags behind that of pea and lentil proteins (Rahate et al., 2021).pH strongly affects protein solubility by altering the net surface charge, which is influenced by both amino acid composition and structural conformation. The highest solubility of faba bean protein is observed at pH values between 8 and 9, and at pH 2. Faba bean globulins are rich in acidic (glutamic and aspartic acid) and basic (lysine, arginine, histidine) amino acids, which contain ionizable side chains sensitive to pH changes. At the isoelectric point (around pH 4.5–5.0), the positive and negative charges are balanced, reducing electrostatic repulsion and promoting aggregation, resulting in low solubility. At alkaline (pH 8–9) or acidic (pH 2) conditions, ionization increases the net surface charge, enhancing repulsion and improving solubility. In addition, pH shifts can disrupt the tertiary and quaternary structures of legumin and vicilin, partially unfolding the proteins and exposing hydrophilic regions, which further contributes to improved solubility (Arogundade et al., 2006; Punia et al., 2019).

Physical, chemical, and enzymatic protein modification including acid precipitations, alkaline dissolutions and extraction, filtration, heating, drying, lyophilisation, homogenization, alkalise hydrolysis, use of microbial transgluminase might improve the emulsifying properties of faba bean proteins (Murphy et al., 2023). Such modifications alter the structure of the protein and its surface characteristics, increasing its flexibility and ability to unfold at the oil–water interface. These changes expose more hydrophobic groups that enhance adsorption to oil droplets and promote stronger intermolecular interactions, resulting in a more stable and cohesive interfacial film, improving the emulsion (Karaca et al., 2011).

2.2. Carbohydrates

Faba bean is a rich source of carbohydrates, including starch, dietary fibres and non-digestible oligosaccharides. Estimated carbohydrates content as 57–60 %, from which 37.0–51.5 % is starch and 7.3–13.1 % dietary fibre (Lampi et al., 2020; Nilsson et al., 2023).

Overall, the faba bean starch granules can be described as oval, round, elliptical, and irregular in shape, with some cavities on their surfaces, strong and weak birefringence patterns (Punia et al., 2019). The characteristics referring to birefringence indicate a weaker pattern and disorganized amylopectin double helices, making the granules fragile and affecting starch techno-functional characteristics (Nilsson et al., 2022; Punia et al., 2019).

Solubility of faba bean starches was 9.9 % at 90 °C, which is low due to the granules' integration and strong binding forces. X-ray diffraction analysis of the crystalline structure of faba bean starch granules showed a high relative crystallinity range between 20.2 % to 21.9 % (Dhull et al., 2022; Punia et al., 2019).

The enthalpy of gelatinisation for faba bean starch was at the lower end of the spectrum compared to tapioca and maize starches. Faba bean starch has high amylose content which increases the gelatinisation temperatures, and higher content than wheat starch. Thus, it could be predicted that food application with faba bean starch will gelatinise at higher temperature compared with wheat starch, both during and after heating (Nilsson et al., 2022).

In faba beans, starch accounts for approximately 37.0–51.5 % of the dry weight. Within this fraction, around 47 % is resistant starch, 35 % is slow-digestible starch, and 15 % is rapidly digestible starch. Thus, faba bean starch decrease the rate of glucose release into the bloodstream, leading to a lower glycaemic index (Nilsson et al., 2022; Punia et al., 2019). Large variations in dietary fibre content of faba bean were reported; according to Labba et al. (2021), the content ranged from 11.4 to 16.6 %, whereas Dhull et al. (2022) reported the range from 15 % to 30 %. In Swedish faba bean varieties, dietary fibres for soluble fraction ranged from 0.6 to 1.1 %, and insoluble fraction from 10.7 to 16.0 %, the majority of the fibre is hemicellulose, followed by cellulose and lignin (Punia et al., 2019). Faba bean also contains high levels of non-digestible oligosaccharides of the raffinose family. Stachyose is a tetrasaccharide composed of two galactose units, one glucose, and one fructose, while verbascose is a pentasaccharide containing three galactose units, one glucose, and one fructose. These oligosaccharides are not digested in the human small intestine due to the lack of the α-galactosidase enzyme and are instead fermented by gut bacteria in the colon, producing gases that cause flatulence. The content of oligosaccharides in faba bean in Sweden varies among different cultivars, with raffinose ranging from 1.1 to 3.9 g/kg, stachyose from 4.4 to 13.7 g/kg, and verbascose from 8 to 15 g/kg (Labba, Frøkiær and Sandberg, 2021; Dhull et al., 2022).

2.3. Lipids

Fat content in faba bean depends on the cultivar and varies from 2.3 to 3.9 %. Polyunsaturated fatty acids (PUFA) constitute 49–56 % of total lipids in bean seed flour. The major unsaturated fatty acids in faba bean are linoleic acid (53 g/100 g lipid) and oleic acid (25 g/100 g lipid) and the major saturated fatty acids – palmitic (15 g/100 g lipid) and stearic (4 g/100 g lipid) (Goldstein & Reifen, 2022; Yoshida et al., 2008). Oat polar lipids, which include phospholipids, glycolipids, and sphingolipids, represent a significant portion of oat lipids and may contribute to the health benefits of oats. Emerging evidence suggests these lipids influence gut hormone release, slow gastric emptying, and potentially improve metabolic markers such as plasma lipids and appetite regulation. However, further studies are needed to clarify their specific effects on cardio-metabolic health (Hossain et al., 2021).

2.4. Vitamins and minerals

Faba bean is a good source of some vitamins and minerals. Maturity stage, industrial processing and cultivar determine mineral uptake and accumulation affecting the levels of vitamins and minerals. Faba bean is particularly known to be rich in folate with a good stability. Stability is likely due the high antioxidant capacity, which might protect folate from oxidation during in vitro digestion (Hefni et al., 2015). Faba beans contain several minerals including sodium, potassium, calcium, copper, zinc, iron, manganese, magnesium, phosphorus, and sulphur. Faba bean have higher levels of iron and calcium compared to other legumes (Labba, Frøkiær and Sandberg, 2021). Faba beans are rich in B-group vitamins specially in folate (vitamin B_9), thiamine (B_1), riboflavin (B_2), niacin (B_3) and limited amount of Vitamin C, but these are sensitive to soaking and cooking. Alkaline soaking and prolonged cooking increase vitamin losses due to leaching. Autoclaving preserves B vitamins better than regular cooking (Dhull et al., 2022; Revilla, 2015).

According to Labba et al. (2021), iron and zinc levels in 15 faba bean cultivars vary from 1.8 to 21.3 mg/100 g and 0.9 to 5.2 mg/100 g, respectively. In recent years, research has been carried out to increase the bioavailability of iron and zinc by elimination of phytic acid or polyphenols, which interfere with the mineral absorption.

2.5. Bioactive compounds

Faba bean is a good source of various bioactive compounds with health-promoting properties, such phenolic compounds, mainly glycosylated derivatives of flavonoids and phenolic acids. Over 100 phenolic compounds have been identified and characterized (Abu-Reidah et al., 2017; Loizzo et al., 2020). Šibul et al. (2016) reported higher antioxidant activity in faba bean extracts compared with soybean, common bean, chickpea, white lupin and grass pea (Šibul et al., 2016).

2.6. Anti-nutrients

Despite its high protein content, dietary fiber, and environmental sustainability, the use of Faba bean in food and feed is limited by the presence of anti-nutritional factors. These include pyrimidine glycosides (vicine and convicine), phytic acid, tannins, saponins, and trypsin inhibitors, which can impair nutrient absorption, reduce protein digestibility, and in some cases, vicine and convicine pose health risks to susceptible individuals. While these compounds serve protective roles in the plant, such as anti-microbial defense during germination, their thermostability challenges food safety and processing. Moreover, several anti-nutrients are directly associated with off-flavours and bitterness, notably vicine, convicine, saponins, and tannins, which reduce faba bean food and ingredients sensory acceptability. Understanding their occurrence, biochemical pathways, and mitigation strategies is essential to realizing the full nutritional and economic potential of faba bean as a sustainable protein source (Rahate et al., 2021; Tuccillo et al., 2025).

2.6.1. Vicine and convicine

The presence of vicine and convicine is one of the major factors restricting larger consumption of faba bean. High intake of vicine and convicine might lead to favism in sensitive individuals with a deficiency in glucose-6-phosphate dehydrogenase, causing a severe form of haemolytic anaemia that could affect to more than 400 million people worldwide (Dhull et al., 2022; Multari et al., 2015). The glycosides vicine and convicine are metabolised to the aglycones divicine and isouramil, which are the primary factors linked to favism (Multari et al., 2015).

2.6.2. Phytic acid

Myo-inositol 1,2,3,4,5,6-hexakisphosphate (IP6), known as phytic acid, is the primary storage of phosphorus in plant seeds. Phytic acid forms stable complexes with mineral ions, specifically zinc, iron, and calcium, making them unavailable for intestinal uptake (Pujol et al., 2023). In Swedish cultivars, phytic acid levels ranged from 112 to 1281 mg/100 g (Labba et al., 2021). No significant difference in phytic acid content was found between conventional and organic farms, with a mean value of 1.0 ± 0.2 g/100 g (Zehring et al., 2022).

Anti-nutritional properties of phytic acid has been a topic of extensive discussion. According to Bloot et al. (2021), excessive consumption of phytic acid might lead to the reduced availability of nutrients. Currently, phytic acid is recognized by the Food and Drug Administration (FDA) as a nutraceutical and is included in the list of Generally Recognized as Safe (GRAS) (Pujol et al., 2023; Zehring et al., 2022). In vitro and in vivo studies have demonstrated the anti-cancer activity of phytic acid, as well as its beneficial effects in cardio metabolic diseases, due to its potent antioxidant and anti-inflammatory action. Because of its ability to bind with iron, forming an inactive chelate, phytic acid exhibits pronounced antioxidant activity, capable of preventing the formation of hydroxyl radical (Pujol et al., 2023). However, clinical trials show that high phytic acid intake in children and the elderly can reduce mineral absorption, risking deficiencies in calcium, iron, and zinc, which are vital for growth and bone health (Pujol et al., 2023).

2.6.3. Saponins

Saponins consist of a steroidal or triterpene moiety, linked to a mono- or oligosaccharide moiety (Multari et al., 2015). In faba bean, the saponin content varies from 20 to 110 μg/g (Labba, Frøkiær and Sandberg, 2021). The presence of saponins in food has been linked to a myriad of unfavourable effects, including diminished sensory appeal due to heightened bitterness and astringency, impaired nutrient bioavailability, reduced trypsin and chymotrypsin activity enzymatic inhibition, and erythrocyte hemolysis (Sharan et al., 2021).

2.6.4. Tannins

Condensed tannins, polymeric compounds made of flavan-3-ols units, are the main type found in faba beans. These tannins are mostly concentrated in the hulls and have astringent properties that can reduce protein digestibility and impair iron absorption, leading to a reduced quality of protein in foods and a possible impairment in the absorption of dietary iron (Fekadu Gemede, 2014). Faba bean in Europe typically contain approximately 8–9 % condensed tannins, with the most abundant form being condensed tannins (Oomah et al., 2011).

2.6.5. Lectins

Generally, beans contain the high amounts of lectins, those are carbohydrate-binding proteins. In low doses, they can reduce the bioavailability of polysaccharides and minerals, bind to complex another carbohydrates, and cause erythrocytes to agglutinate, potentially interfering with nutrient absorption (Multari et al., 2015). However, studies have shown that some lectins can also act as antioxidants, slow down digestion, and prevent spikes in blood sugar and insulin levels (Lopez et al., 2002). There is currently limited knowledge on the amount of active lectins in the human diet and their long-term health effects. The lectin content in the Swedish cultivars of faba bean ranged from 0.8 to 3.2 hemagglutinin units (HU) per milligram (Labba et al., 2021).

2.6.6. Protease inhibitors

Protease inhibitors (PIs) are peptides that could have harmful effects on proteolytic enzymes in human and animal. The most prevalent forms of PIs found in legumes are the Bowman-Birk inhibitors and Kunitz trypsin, which are involved in various proteolytic processes, including signal initiation, transmission, and cellular apoptosis (Saha et al., 2022). The PIs are associated with blood coagulation, the damaging effect on different hormone pathways and inflammatory processes (Saha et al., 2022).

Walter et al. (2023) reported values for the trypsin inhibitor activity in faba bean from 50 German farms from 36.4 to 46.0 trypsin inhibition units (TIU) /mg; with an average value of 42.6 TIU/mg. The content of trypsin inhibitor activity was partly associated with low tannin content. Relatively low content of trypsin inhibitor activity has been reported in 15 cultivars of faba bean in Sweden, from 1.2 to 23.1 TIU/mg (Labba et al., 2021). Those values are lower than in soya bean (46 TIU/mg) (Shi et al., 2017).

3. Nutritional composition and functional properties of oat

Oat breeding often focuses on forage yield, pest resistance, and stress tolerance rather than grain quality. As a result, the nutrient composition of harvested oats is strongly influenced by environmental factors like temperature, rainfall, and soil conditions. Seasonal variations affect plant metabolism, causing differences in grain yield and nutritional content even within the same genotype (Martinez et al., 2010). On average, for three Swedish variaties, 100 *g* of oat contain ~51–68 % carbohydrates, ~11–18 % protein, 10 % fibre, and ~4.–7 % lipids and 4–10 % moisture content (Norlander et al., 2024), the variation was due not only to oat variety but also to the kilning process.

3.1. Proteins

The protein content of oat groats ranges from 13 to 20 %. Oat globulins constitute a significant proportion of the total protein content of the grain, comprising 75–80 %, while prolamins, specifically avenins 10–15 %. In contrast to wheat, the oat genome lacks α- and ω-gliadin genes and exhibits similarity with γ-gliadins, low molecular weight glutenins (Ainsworth & Soon, 2023). The analysis of genes encoding avenin in oat by Kamal et al. (2022) has revealed the presence of inactive genes and pseudogenes in a proportion comparable to that of wheat γ-gliadins. Thirty-six distinct 11S globulins, five globulin-1 proteins, and two 7S globulins were identified in that study. Kamal et al. (2022) concluded that a lower proportion of avenin proteins contain immune-reactive regions associated with coeliac disease compared to the high prevalence observed in wheat or barley. This low incidence of immunogenic proteins in oat, along with other factors such as the infrequent occurrence of detected T cell epitopes, provides support for the incorporation of oat into gluten-free diets.

The amino acid composition of oat proteins varies significantly among different protein fractions, oat varieties and extraction methods. Globulins contain the highest amounts of essential amino acids such as phenylalanine, threonine, histidine, and valine, as well as non-essential amino acids such as arginine. In contrast to prolamins and glutelins, albumin and globulin are considered high-quality proteins. Oat contain higher amounts of lysine and threonine compared to other cereals (Klose & Arendt, 2012).

Oat protein solubility is low, which is a limiting factor for applications within the pH range of 4 to 7. This is because oat globulins contain glutamine-rich regions located at the surface of the globulin, which are exposed to the solvent, rendering oat globulins less hydrophilic than other globulins. Furthermore, the heat treatment as kilning process applied to inactive enzymes and prevent rancidity, which usually follows the dehulling process, has a negative impact on oat protein solubility. It has been hypothesized that the loss in solubility is related to protein denaturation and preferential aggregation of albumin and prolamin fractions, whereas globulin proteins are less sensitive to heat treatment (Spaen & Silva, 2021).

In terms of the techno-functional properties of oat protein isolate foaming and emulsifying are the most relevant properties that make it suitable application in food industry. The stability of foams increased from 69 % to 80 % when the pH changed from 4.5 to 10.5 (Mel & Malalgoda, 2022). Although oat protein isolates demonstrated a foaming capacity similar to that of lupin protein isolates, they display two-fold higher foam stability. Owing to the unfolding of oat globulins resulting in a transition from β-sheet to a random coil conformation and the formation of insoluble aggregates between pH 3.0 and 7.0, oat protein isolates exhibit limited emulsifying ability at pH 5. This limitation restricts the application of oat protein isolates in emulsion and foam systems. In contrast, native oat proteins can create strong gels only under alkaline pH levels and with a heating phase (110–120 °C). Under acidic and neutral pH, the formed gels are weak with poor water holding capacity. Partial hydrolysis by flavourzyme and trypsin can enhance the oat protein gel properties (Brückner-Gühmann et al., 2019).

Various methods have been employed to enhance the functional properties of oat proteins. Deamination and succinylation have been used to improve oat protein solubility (Mirmoghtadaie et al., 2009), and enzymatic treatments with trypsin, alkalise, and transglutaminase have been used to increase the emulsification factor and protein solubility.

Rawal et al. (2023) demonstrated the potential of producing plant-based beverages with mild chemical treatment using plant-based Pickering emulsion. Defatting oat flours before extraction can also improve the profile of the oat protein isolates or concentrates. CO_2-supercritical defatting pre-treatment significantly improved functionality, aromatic profile, purity, solubility, and emulsifying properties of oat protein. This treatment has also been successfully applied in oat oil extraction (Yue et al., 2021).

3.2. Carbohydrates

Starch is the most abundant source of carbohydrate in oat, ranging from 50 % to 65 %, from which approximately 40 % is slowly digestible, and 29 % is resistant starch. Oat contain a high proportion of amylose, 25–29.4 %, which is larger than in rice and contributes to a slower digestion rate. Raw oat starch consists of the A-type polymorph, which has a relatively low crystallinity of approximately 23 %, making it more susceptible to enzymatic hydrolysis (Rasane et al., 2015). There is a relationship between the degree of branching of amylopectin and the digestion rate, as shorter chains are associated with higher digestion rates (Li et al., 2011).

β-Glucans is one of the soluble dietary fibre fractions found in the endosperm cell walls and aleurone of grains, and their concentration on a dry basis ranges from 1.7 % to 5.7 %. β-glucans are widely studied due to their health benefits (El Khoury et al., 2012). In 2002, the US Food and Drug Administration (FDA) approved health claims for β-glucan stating that consumption of 0.75 g/serving or 3 g could reduce the risk of cardiovascular diseases. Similarly, EFSA approved a claim that 3 g of oat β-glucan per day helps reduce blood cholesterol levels, potentially lowering heart disease risk (Jenkins et al., 2002). The mechanism behind it is based on oat β-glucans ability to increase chyme viscosity and delay the rate at which the stomach empties. As the digesta travels to the intestine, the high viscosity of β-glucans could interfere with the transfer of released glucose to enterocytes, resulting in a steadier glycaemic response (Paudel et al., 2021). The undigested part of β-glucans undergoes fermentation by the microbiota, which releases short-chain fatty acids such as butyric acid, propionic acid, and acetic acid. The health benefits of β-glucans led to their industrial-scale extraction for obtaining valuable ingredients with multiple applications. However, the high molecular weight and viscosity of the native molecule make it challenging to use β-glucans in their natural form. Therefore, modification of the β-glucans, which affects their primary structure and spatial conformation, is used. Various techniques, such as physical treatments (e.g., freezing or kilning), chemical treatments, mechanical treatments, enzymatic treatments, irradiation, extrusion-cooking, can be used to modify β-glucans (El Khoury et al., 2012; Paudel et al., 2021).

3.3. Lipids

Oat have higher lipid content compared to other cereal (3–11 % DM). The composition of fatty acids varies depending on the cultivar, but in general, the major fatty acids are 16:0 (palmitic acid), 18:1 (oleic acid), 18:2 (linoleic acid), and a small amount of 18:3 α-linolenic acid (Paudel et al., 2021). (Hui et al., 2019) meta-analysis revealed that oat bran was the most effective intervention for reducing total cholesterol (TC) and LDL cholesterol (LDL-C), followed by oat. In contrast, barley, brown rice, wheat, and wheat bran showed no significant improvements in blood lipids. These findings suggest that increasing oat-based whole grains may be beneficial for lipid control.

In the industrial processing, lipids are reduced to improve the milling process and ensure the stability and adequate shelf life. The lipid reduction is necessary for extraction of β-glucan, but optimisation of defatting is still needed (Li et al., 2021).

Lipids have a direct effect on the functional properties of the oat flours and starch behaviour. Li et al. (2021) observed the negative correlation between lipid contents and gel strength and increase in peak viscosity and pasting time. The oil and starch content were negatively correlated.

3.4. Vitamins and minerals

One of the most important vitamins in oat are tocols, or vitamin E, with high antioxidative activities. Tocols encompass tocopherols and tocotrienols, which exist in several forms: α, β, γ, and δ. Total tocopherol (T) and tocotrienol (T3) content (αT, αT3, βT, βT3, γT3) in 7 Swedish oat cultivars varied from 14.1 to 22.6 mg/kg of dry matter (Bryngelsson et al., 2002). Oat also contains folates, calcium, zinc, iron, selenium, copper, and manganese (Rasane et al., 2015).

3.5. Bioactive compounds

Avenanthramides (AVAs) are soluble phenolic compounds with strong antioxidant properties, specific to oats and unique among cereal grain (Woolman & Liu, 2022). These compounds are bioavailable, have anti-inflammatory, anti-atherogenic, and antioxidant properties (Thomas et al., 2018). The highest content of AVAs was found in the whole grain, and processing has only limited effect on AVAs levels (Pridal et al., 2018). The AVA content in different products, such as oat grains and flour, rolled oat, breakfast cereals, oat bread, biscuits, pasta and others, from the Jönköping region of Sweden and Boston, Massachusetts, varied from 2 to 82 μg/g (Pridal et al., 2018). Oat bran concentrate had the highest levels of both phenolic acids and AVAs (Soycan et al., 2019). The highest levels of bioactive compounds are in native oat or hulled grains, but they are not consumed by humans in this form, instead dehulled (Tang et al., 2023).

Antioxidative properties of bioactive compounds are influenced by heating, pH, and interactions within the food matrix. Fermentation, germination, ultrafine grinding, and enzymatic methods have enhanced total phenolic content and antioxidant capacity (Choi et al., 2023).

3.6. Anti-nutrients

Phytate is one of the most abundant anti-nutrients in oat. Oat contains high phytate levels, 5.9 g/kg DM (L'Hocine et al., 2023) while, Swedish faba bean cultivars exhibit significantly higher levels, ranging from 112 to 1281 g/kg (Labba et al., 2021), although the endogenous phytase activity in oat is lower than in other cereals. The levels of oxalate and tannins in oat grains ranged from 28.2 to 71.4 and from 38.8 to 51.5 g/kg DM, respectively (Alemayehu et al., 2021). Generally, oxalate levels in oat is comparable to these in wheat. The levels of anti-nutrients significantly differed among the oat varieties.

4. Combination of faba bean and oat to improve taste and nutritional quality

The presence of anti-nutrients and the unpalatable off-flavours of faba bean limit it wider use in food industry. Additionally, neither faba bean nor oat has a complete amino acids composition, amino acid analysis (e.g., HPLC) is performed and compared to reference standards as FAO/WHO to identify limiting amino acids. Faba beans, as a grain legume, are limited in sulfur-containing amino acids such as methionine and cysteine, as well as tryptophan, whereas cereal grains like oats are low in lysine but high in sulfur-containing amino acids. This complementary amino acid profile makes the pairing of legumes and cereals ideal for balanced plant-based nutrition (Labba et al., 2021). An efficient way to achieve desirable sensory properties and complete protein is to combine faba bean and oat in the same food product, ex. tempeh-like products (Rahmawati et al., 2021). This part is focused on possibilities to develop fermented products as tempeh-like using a combination of faba bean and oat with improved nutritional value, taste and textural properties.

5. Tempeh production

Traditionally, tempeh is produced from dehulled and cooked soybeans. CODEX Alimentarius CXS 313R-2013 defined tempeh or tempe as a compact white cake-form with soybean, using a solid-state fermentation with *Rhizopus* spp. The product is usually compact, nutty, meaty and mushroom-like flavour. The moisture content maximum 65 % w/w, protein minimum of 15 % w/w and lipid 7 % w/w min. Tempeh is a widely accepted and sustainable source of protein with health benefits and affordable price (Ahnan-Winarno et al., 2021). The major steps in tempeh preparation are presented in Fig. 1. The fermentation process with *Rhizopus oligosporus* can decrease the content of antinutrients, allergens, it might elevate the content of macro and micronutrients as vitamin B_{12} and bioactive compounds (Wolkers – Rooijackers et al., 2018). However, the presence of B_{12} in tempeh might be due to opportunistic non-pathogenic of *Klebsiella pneumonia* (Ahnan-Winarno et al., 2021). Nevertheless, a food-grade vitamin B_{12} producer is *Propionibacterium freudenreichii,* which in the presence of *Rhizopus oryzae* increased vitamin B_{12} content in lupin-based tempeh-like product up to

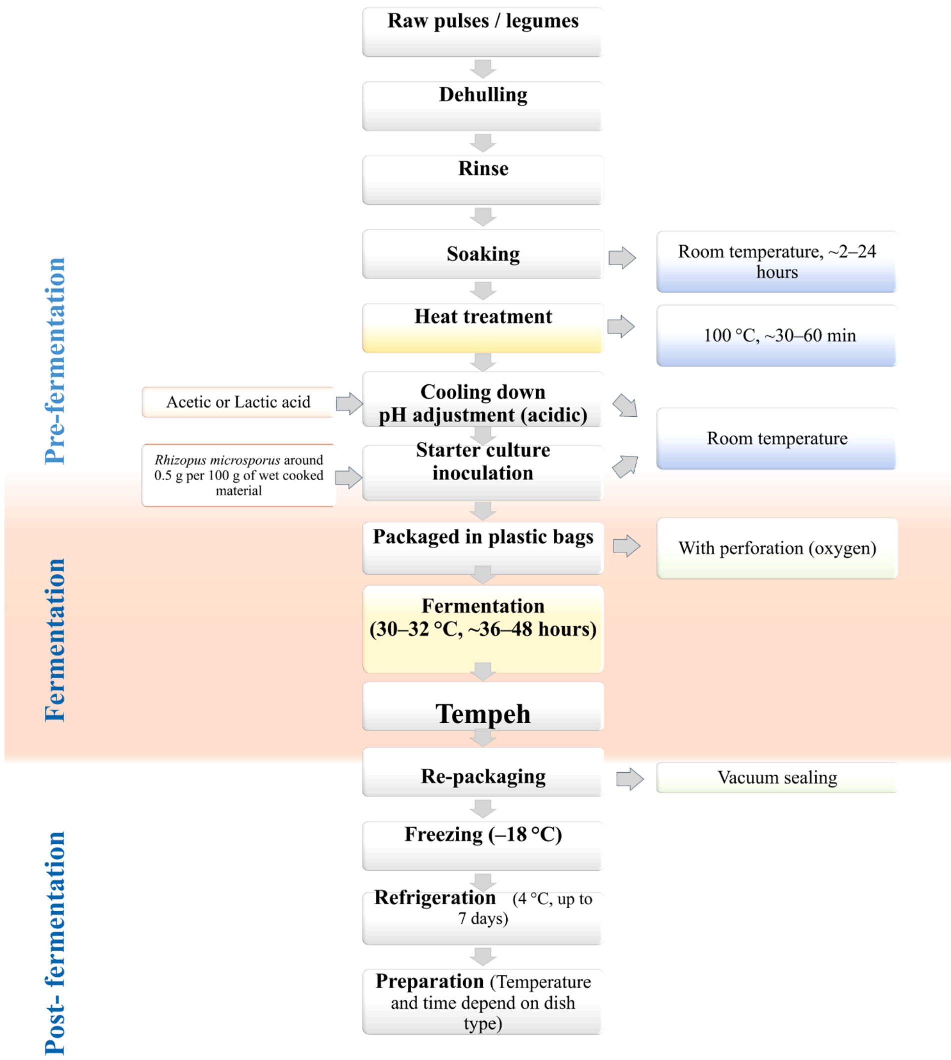

Fig. 1. Tempeh-like fermentation flow chart production adaption from ((Fernandez Castaneda et al., 2024) adaptable for pulses and/or grains.

0.97 μg/100 *g* (Wolkers – Rooijackers et al., 2018).

Even though traditional tempeh is based on soya bean, several attempt were made to use other raw material for tempeh production. Erkan et al. (2020) investigated the physico-chemical and sensory properties of tempeh from different legumes, including soybean, chickpea, lentils, and faba bean, using *R. oligosporus.* The process in general involved soaking of the legumes in tap water, boiling, and dehulling, then the solid-state fermentation was performed with *R. oligosporus,* and the pH was adjusted with vinegar. The mixture was then placed in plastic bags with perforations, fermented at 30–34 °C. Oat has been also used for tempeh-like food as high content of γ-amino-butyric acid (GABA), however the solid and chewy texture was compromised due to the oat rheological properties (Cai et al., 2014). Moreover in vitro digestion study by Alminger et al. (2012), found that fermented oat tempeh had faster starch digestion and higher glucose response compared to fermented barley, and those in vitro results closely matching human trial data.

Nassar, Mubarak and El-Beltagy (2008) used faba bean, lupine, chickpea, peas and their mixture for tempeh production. The process involved dehulling and ground intro grits, the acidification was done by adding 1 % of lactic acid (85 % concentration), and incubation period was for 48 h at 37 °C. Berghofer et al. (1998) used a combination of faba bean, soybean and oat for tempeh production. Instead of boiling the beans, they applied steaming for 20 min at 121 °C and the fermentation was completed in 24 h. Noticeable, the processing varied depending on lab or industrial scale.

5.1. Starter culture

The most common starter culture for tempeh is *R. oligosporus* (Aaslyng & Højer, 2021). With a diverse metabolic process and the ability to produce various enzymes, *Rhizopus* fungi are well-known for thriving on decomposing plant matter. These fungi have been used for centuries in Southeast Asia to make fermented foods and beverages and have significant applications in enzyme manufacturing. *Rhizopus* fungi also produce ethanol, lactic, and fumaric acids; their cell mass finds use in the food and feed industries. *Rhizopus* fungi's multifaceted applications make them crucial in various sectors (Gautheron et al., 2024).

The structure of *Rhizopus* is composed of a wall skeleton consisting of polymers such as glucosamine and N-acetylglucosamine. Chitosan, which is the deacetylated form of glucosamine, is the major component of the wall and is responsible for maintaining the shape and integrity of the membrane. Metabolically, *Rhizopus* routes sugars through pyruvate, central to carbohydrate catabolism, producing lactic acid or ethanol under oxygen-limited conditions, and acetyl-CoA for the tricarboxylic acid cycle with sufficient oxygen. *R. Oligosporus* also metabolizes proteins, producing proteases exemplified by its use in tempeh production (Gautheron et al., 2024).

Polanowska et al. (2020) investigated the effect of 3 different strains of *R. Oligosporus* in faba bean fermentation for 6 days, demonstrated that

R. oligosporus fermentation significantly enhanced the nutritional value of faba bean by increasing γ-linolenic acid, GABA, and producing beneficial sterols like stigmasterol and campesterol. Strain ATCC 22,959 showed the greatest impact, leading to significant changes in fatty acid, sterol, protein, and amino acid content. These results underscore the importance of selecting appropriate strains and raw materials for tempeh production to create nutritionally enriched products. Nassar, Mubarak and El-Beltagy (2008) also demonstrated that *R. oligosporus* fermentation significantly enhanced the nutritional profile of faba bean, increasing protein and fiber while reducing fat, carbohydrates, and anti-nutritional sugars like raffinose and stachyose did proximate analysis including moisture, crude fat, ash, total protein, reducing sugar and starch.

5.2. Effects of consuming tempeh on human health

Tempeh has garnered attention for its potential health benefits across various physiological domains. Research indicates that tempeh serves as a good source of calcium, which is vital for bone health. The fermentation process enhances mineral bioavailability, potentially supporting bone density and reducing the risk of osteoporosis (Haron et al., 2010). In addition to its mineral content, tempeh is rich in soy isoflavones, phytoestrogens that may mimic estrogen in the body (Khosravi & Razavi, 2021). Regular consumption of soy products like tempeh has been associated with alleviating menopausal symptoms and supporting bone health in postmenopausal women (Cassidy et al., 2006).

The isoflavones present in tempeh exhibit antioxidant properties that may help mitigate oxidative stress, a key contributor to aging and cancer development. Some research suggests that tempeh-derived bioactive peptides may have antihypertensive effects. Moreover, its high antioxidant content contributes to neuroprotection by reducing oxidative stress and enhancing microglial cell function (Chang et al., 2009; Xiao et al., 2016). Overall, tempeh presents a multifaceted profile of health benefits, substantiated by various studies. Its nutritional composition and bioactive compounds contribute to its potential in promoting bone health, metabolic balance, cognitive function, and cardiovascular well-being (Handajani et al., 2020 Kiers et al., 2002).

While the health benefits of tempeh are well-documented, clinical trials, in vivo and in vitro studies have largely focused on soybean-based tempeh, leaving alternative formulations underexplored. The fermentation of other legumes and cereals presents a promising opportunity for expanding tempeh functional properties. Combining legumes with whole grains for tempeh production could enhance its dietary fiber content and amino acid composition, as well as the reduction of anti-nutritional factors due to fermentation, and improve sensory properties. Tempeh formulations could offer a milder flavour and softer texture, potentially improving consumer acceptance. Given the rising interest in plant-based functional foods, further clinical research is necessary to fully understand the health effects of legume and cereal-based tempeh, particularly in relation to gut microbiota, metabolism impact and long-term disease prevention.

6. Fermented food applications: faba bean and oat

Faba bean ingredients in food applications require post-production processes such as physical, chemical, enzymatic, or fermentative operations (combination). The use of protein concentrates and isolates remains unclear due to limitations in sensory and anti-nutritional aspects. Some examples of the application of faba bean flour and its fraction is in plant-based meat substitute (Sharan et al., 2021).

Processing techniques applied worldwide, including soaking, grinding, cooking, and sprouting, with aim to reduce antinutritional compounds. Particularly, soaking reduces the boiling time required, and in combination with boiling, further decreases phytic acid, trypsin inhibitor, and some of the flatulent oligosaccharides responsible for abdominal pain and discomfort (Arsov et al., 2024). However, bioprocessing, particularly fermentation, offers a promising approach to improve the nutritional, functional and sensory qualities of plant products made from faba beans and oats, while reducing antinutrient levels (Rahate et al., 2021). A schematic view of the possible changes and differences between non-microbial and microbial methods for antinutrient reduction is shown in Fig. 2.

Various microorganisms, including yeast, filamentous fungi, and lactic acid bacteria, have been investigated for these purposes. Fermentation of faba beans by *Lactobacillus plantarum* significantly reduced antinutritional factors like vicine, convicine, trypsin inhibitors, and tannins, while enhancing protein digestibility and amino acid content (Coda, Melama, Giuseppe, et al., 2015; Pulkkinen et al., 2019; Verni, Coda, et al., 2019).

Fermented faba bean flour showed improved functional properties resulting in softer textures and reduced viscosity, making it suitable for baked goods (Sozer et al., 2019). Overall, fermentation positively impacts the nutritional profile and functional characteristics of faba beans.

Fermentation has been shown to increase polyphenol availability and antioxidant activity in oats by degrading cell walls (Yang et al., 2023). However, selecting appropriate probiotic strains for fermenting faba beans and oats remains complex due to their distinct properties. Optimizing fermentation conditions is crucial to prevent undesirable attributes like bitterness or off-flavours, making it a key area for future research (Stone et al., 2024; Yang et al., 2023). Table 1 provides a summary of studies examining the effects of fermentation primarily on faba bean and oat-based products separately due to the limited research in developing product that combine both raw materials. Results demonstrate that fermentation can substantially improve protein digestibility and amino acid profiles of faba bean and while reducing anti-nutrients as phytic acid present in both faba bean and oat-based products, as well as contribute to enhancing their sensory characteristics.

Faba beans, traditionally used in developing countries primarily through boiling and stewing, are now gaining wider food applications globally due to increased awareness of their nutritional and environmental benefits. Faba bean products have shown promise as a partial substitute for wheat and as a gluten-free option, with shorter cooking times compared to other legumes (Jakubczyk et al., 2019). Additionally, fermentation has been shown to improve protein digestibility and enhance sensory properties. Faba bean protein isolates possess functional properties comparable to those of animal and other plant proteins, including good solubility, emulsifying capacity, and oil-holding ability (Karaca et al., 2011; Tuccillo et al., 2022). These characteristics make them suitable for use in protein drinks, baked goods, meat analogues, and emulsified products such as mayonnaise. Fermentation remains one of the most effective techniques to address major challenges related to flavour and digestibility. Although food development using faba bean-oat mixes is still limited, this combination holds potential as a complementary match in future product formulations.

7. Conclusion

Faba beans are a rich source of protein and lysine but are deficient in sulfur-containing amino acids such as methionine and cysteine. Oats, recognized for their low allergenicity, also lack lysine. Combining these crops yields a complementary protein profile, while fermentation may further enhance amino acid composition.

In the Nordic region, both crops contribute to sustainable agriculture. Faba beans, as nitrogen-fixing legumes, reduce reliance on synthetic fertilizers, while oats, well adapted to cool climates, and require minimal agricultural inputs. Their cultivation supports efforts to lower the environmental impact of food production.

Despite the increasing incorporation of faba beans into plant-based products, challenges persist regarding sensory attributes and anti-nutritional compounds. Blending with oats presents a promising strategy to improve nutritional quality and sensory appeal. Future research

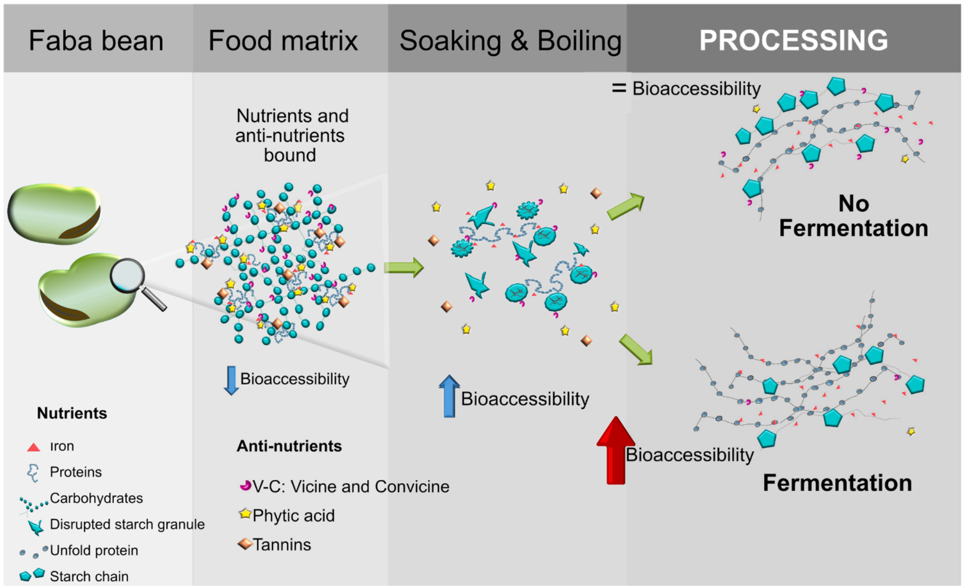

Fig. 2. Schematic view of the changes in faba bean due to processing (without fermentation) and bioprocessing (with fermentation), showing a significant increase in the bioaccessibility of protein, amino acids, and minerals due to the breakdown of complex compounds and the release of free amino acids, alongside a reduction of anti-nutritional factors.

Table 1
Solid-state fermentation application on faba bean and oat and in combination, example of different microbial fermentation and main impact in the nutritional and technological quality for food.

Raw materials	Food product	Microorganism	Key findings	References
Faba bean				
Faba bean	Tempeh	*R. oligosporus*	Improved nutritional aspects and increasedbγ-aminobutyric acid, decrease of vicine and convicine	(Polanowska et al., 2020)
Faba bean soaked and grounded	Suggest in bread, pasta or snacks	L. *plantarum 299v*	Increase amount of peptides and novel peptides discovered.	(Jakubczyk et al., 2019)
Faba bean grounded	Suggest in tempeh	*R. oligosporus*	Solid-state bioconversion system to increase l-DOPA and increase in β-glucosidase	(Randhir et al., 2004)
Faba bean flour	Suggest in bakery	L. *plantarum* VTT E-133,328	Reduction of vicine, convicine and galacto-oligosaccharide	(Coda, Melama, Rizzello, et al., 2015)
Faba bean flour	Suggest in bakery, beverages, high protein formulas	*Aspergillus oryzae and Rhizopus oligosporus (separately)*	Increase of protein content but decrease on solubility Pre-fermentation of faba bean flour improved high-protein and sensory	(Gautheron et al., 2024; Muñoz-Pina et al., 2024)
Faba bean	Crashed and grounded	Combination of 13 single LAB strains	Reduction of anti-nutrients vicine and convicine, presence of vitamin B_{12}	(Kahala et al., 2024)
Faba bean	Suggest in protein-rich snacks for children and adolescents	*Pleurotus ostreatus*	Increase protein content and essential amino acids	(Montemurro et al., 2021)
Faba bean		Mix of LAB with *Propionibacterium freudenreichii* P18	Reduction of vicine, convicine and galacto-oligosaccharide, production of B_{12}	(Berghofer et al., 1998)
Oats				
Whole-grain oat	Solid-state fermented foodstuff	L. *plantarum B1–6* and *R. oryzae.*	Higher degree of hydrolysis, increase of smaller peptides	(Wu et al., 2018)
Oat bran milled	Up-scaling of by-products	*S. cerevisiae*	Increase of total phenolic content	(Călinoiu et al., 2019)
Dehulled oat, oat flour, protein oat	Tempeh	*R. oligosporus*	Antioxidant ABTS+ activity increase	(Eklund-Jonsson et al., 2006; Green et al., 2024)
		R. oryzae	Improve essential amino acid, dietary fibre.	(Cai et al., 2014; Rousta et al., 2022)
Faba bean and Oats				
Faba bean-oat mixture (ratio 70:30 w/w)	Overnight-oat style	Mix of *Levilactobacillus brevis, Pediococcus pentosaceus, Limosilactobacillus fermentum*	Reduction of vicine, convicine and galacto-oligosaccharide while enhancing of sensory profile by trained pannelist	(Kahala et al., 2023)

should prioritize the utilization of whole beans and grains to minimize processing energy, thereby advancing sustainable food systems, particularly in the Nordic context.

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Ethical statement – studies in humans and animals

Not applicable.

CRediT authorship contribution statement

Laura Alejandra Fernandez Castaneda: Writing – original draft, Visualization, Investigation, Conceptualization. **Maud Langton:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Galia Zamaratskaia:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of competing interest

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

Data availability

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

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