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Production and importance of cereal grain proteins

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Abstract. Many cereal products consumed by Poles every day contain cereal grains. Grain is identified mainly as a raw material providing energy in the form of starch, which dominates its composition. However, cereal products in the daily diet also provide a significant portion of protein. They are often overlooked and downplayed. Cereal protein, as it is of plant origin, is considered a protein of lower biological quality because of deficient exogenous amino acids (mainly lysine), but it contains a number of important amino acids. Nowadays an increasing number of people pay attention to adequate protein consumption, especially people practising sports, due to the number of functions that protein performs and the amino acids it is composed of. The role of plant protein will increase in the future, due to the growing human population. The problem of suboptimal proportion of amino acids can be solved by properly conducted breeding focused on protein quality. People with gluten intolerance or who want to exclude this protein from their diet can also benefit from protein from non-bread cereals and pseudocereals. Therefore, more and more products with increased protein content are created on the basis of cereal grains, and with an appropriate balance of amino acids. It is possible to obtain high-protein products with a very good amino acid composition from additional raw materials. The aim of this review is to analyse the scientific literature on the quantity and quality of cereal grain protein and its production and nutritional importance for humans and animals.

Keywords: protein, biological value of protein, vegetable protein, cereal protein, high-protein products.

INTRODUCTION

Protein is a dietary element that performs a number of important functions and metabolic processes in the body. It participates in the formation of cells, enzymes, some hormones and other structures of the human body. Its adequate quantity in the diet is a key element of a proper nutrition. Protein is present in many foods of both plant and animal origin. However, plant protein is considered less valuable in terms of its amino acid profile, because it does not contain all the essential amino acids in the right proportion. Egg protein is considered to be the model protein with the best amino acid profile and ratio. It has a high biological value because it resembles human body proteins. However, plant protein should not be marginalised, and it is now of particular importance in a vegan diet, where all animal protein sources are eliminated. Among plant protein sources, the most commonly used are legumes, now known as pulses. Products made from soya beans, beans, chickpeas or lentils are an integral part of the diet of vegetarians and vegans. However, it is worth noting that they also contain many anti-nutritive substances. Cereals, on the other hand, provide both a significant proportion of energy from the starch stored in the grains, but also protein. The protein content of grains is affected by a number of factors, the main ones being species, cultivar, nitrogen fertilisation and weather conditions. The protein content determines the technological and nutritional quality of the grain. The most important factor of protein quality is its amino acid composition. Many cereal products are consumed daily by Poles. Grain is mainly identified as a raw material providing energy in the form of starch, which predominates in its composition. However, cereal products also provide a significant proportion of protein in the daily diet. This is often overlooked and underestimated. Cereal protein is considered to be of low biological quality due to its plant origin, however, apart from the deficient essential amino acids (mainly lysine), it contains a number of important amino acids. An increasing number of people pay attention to adequate protein intake, particularly those involved in sport, but protein is equally important for all health-conscious people. Therefore, an increasing number of products with higher protein content are being developed based on cereal grains. High-protein cereal products with a very good amino acid composition can be obtained owing to addition of raw materials. Among plant sources of protein in the human diet, protein from cereals is second only to legumes. The world's most widely grown three cereals: maize, rice and wheat, provide 42% of the total protein in the diet of people in developing countries (Kropff, Morell, 2019). Globally, wheat provides about 16.3 g of protein per person per day, the highest among cereals, indicating the very high importance of this cereal in meeting people's protein needs (Shewry, 2024). In the global protein production in 2018, among the plant proteins in the human diet, grains of different cereal species contributed the most (~22 g protein/person/day), while legumes contributed less (~2 g protein/person/day) (Adhikari et al., 2022). From the data cited, it appears that the role of protein from cereal grains in meeting the needs of humans and animals for this element in the diet, is underestimated. It has been therefore recognised that cereal protein has a major and multifaceted role in human nutrition both directly, and indirectly when is converted into animal protein in products, such as meat and eggs, due to its high feed value. Copa-Cogeca (2019) drew the European Commission's attention to the importance of cereal crops in protein production in Europe. The argument that the representatives of this organisation highlighted was the importance of cereals in the overall protein production in the European Union, 37 million tonnes of protein or 84% of the total plant protein comes from cereal crops (Copa-Cogeca, 2019). Globally, cereals produce 50% of total protein, legumes 5%, and animals including fish just over 20% (Kowieska et al., 2010). Such significant protein production from cereals, despite its much lower content in grain relative to legumes, is due to significant grain yield. The higher grain yield compensates the lower protein content, which translates into a higher protein yield per hectare of crop. Depending on the cereal species and cropping intensity, this ranges from 0.23 t ha^{-1} (for rye) to 0.58 t ha^{-1} of protein for wheat. However, the cost of producing 1 kg of protein from cereals, such as wheat and maize is twice as high as for soya and other legumes (Boczar, 2018). Among cereals, only oats shows a lower price of produced protein compared to soybean (Safdar et al., 2023). The negative environmental aspect of cereal protein relative to legumes is the higher carbon footprint. Production of 100 g of cereal protein releases 2.7 kg CO_2-equivalents of emissions, compared to 0.84 kg CO_2-eq. in case of legumes (Poutanen et al., 2022).

The aim of the work is to make a preliminary estimate of protein production from cereal grains in Poland and to highlight its importance in human and animal nutrition based on statistical data and scientific literature.

SOURCES AND MATERIALS

This review article uses the latest scientific papers on the protein content of grains of different cereal species, protein quality and its biological value, and the importance of protein in human nutrition and the importance of feed protein. In order to identify as many publications as possible and include as many studies as possible, a search engine for scientific papers of Web of Science (http://apps.webofknowledge.com) and Google Scholar was used. The search used criteria for keywords related to the topics such as grain protein, importance of grain protein, amino acid profile, protein content, nutritional value of protein, plant protein, feed protein, protein production. Scientific literature was selected by the main criterion of topics related to cereal protein, as well as the experiments being conducted under field conditions, not in greenhouses or pots, and being published in a reputable scientific journal of open access. Both Polish and world scientific literature was used. In general, 60 items of literature most corresponding to the above indicated criteria were used.

For the estimation of protein production, data on the area of the crop and average yield for individual cereal species published for 2022 in the data of the Central Statistical Office in Poland were used. Polish literature on grain protein content was relied on the main point of reference because the goal was to make this estimate of protein yield for Poland. The most recent scientific papers with extreme values of protein in grain of individual cereals (lowest and highest protein content) were used. These ranges are shown in Table 1 and Figures 1 and 2.

ESTIMATED CEREAL PROTEIN PRODUCTION IN POLAND IN 2022

58% of total protein produced from cereals in the European Union is used for animal feed and the remainder 42% in human nutrition (Copa-Cogeca, 2019). The overlooked role of cereal grains in this regard should consequently also be recognised. Cereal protein production needs to be increased.. One incentive would be to reward higher protein

Table 1. Estimation of protein production from cereal grains based on Central Statistical Office (CSO)data and calculation of protein content according to quoted authors.

Grain species	Form	Crops surface in 2022 according to CSO 2023 [thous. ha]	Average yield according to CSO 2023 [t ha^{-1}]	Protein content [%]		Protein yield [kg ha^{-1}]#	Range of total protein yield [million t]##
1	2	3	4	5		6	7
Wheat	winter	2315	5.3	10.5–13.8	Oleksy et al., 2008	556.5–731.4	1.3–1.7
	spring	203		13.5–14.1	Woźniak, Makarski, 2013	715.5–747.3	0.2
Triticale	winter	1169	4.5	14.3 –16.1	Jaśkiewicz, 2014	643.5–724.5	0.8–0.9
	spring	63		11.6	Knapowski et al., 2010	522.0	0.3
Grain maize		1196	7.1	9.1–12.7	Podkówka et al., 2015	646.1–901.7	0.8–1.1
Barley	winter	308	4.4	11.1–12.1	Chrzanowska-Drożdż, Kaczmarek, 2007	488.4–534.4	0.2
	spring	332		10.8–12.0	Noworolnik, Leszczyńska, 2018	475.2–528.0	0.2
Oats	In Poland only spring varieties are cultivated	466	3.3	7.4–16.2	Leszczyńska 2021	244.2–534.00	0.1–0.2
Rye	In Poland only winter varieties are cultivated	662	3.6	8.8–10.5	Noworolnik, 2009 Buksa et al., 2012	316.8–378.00	0.2–0.3

Self calculations based on yield and average protein content according to the authors.
Own calculations based on area and protein yield per ha from column 6.

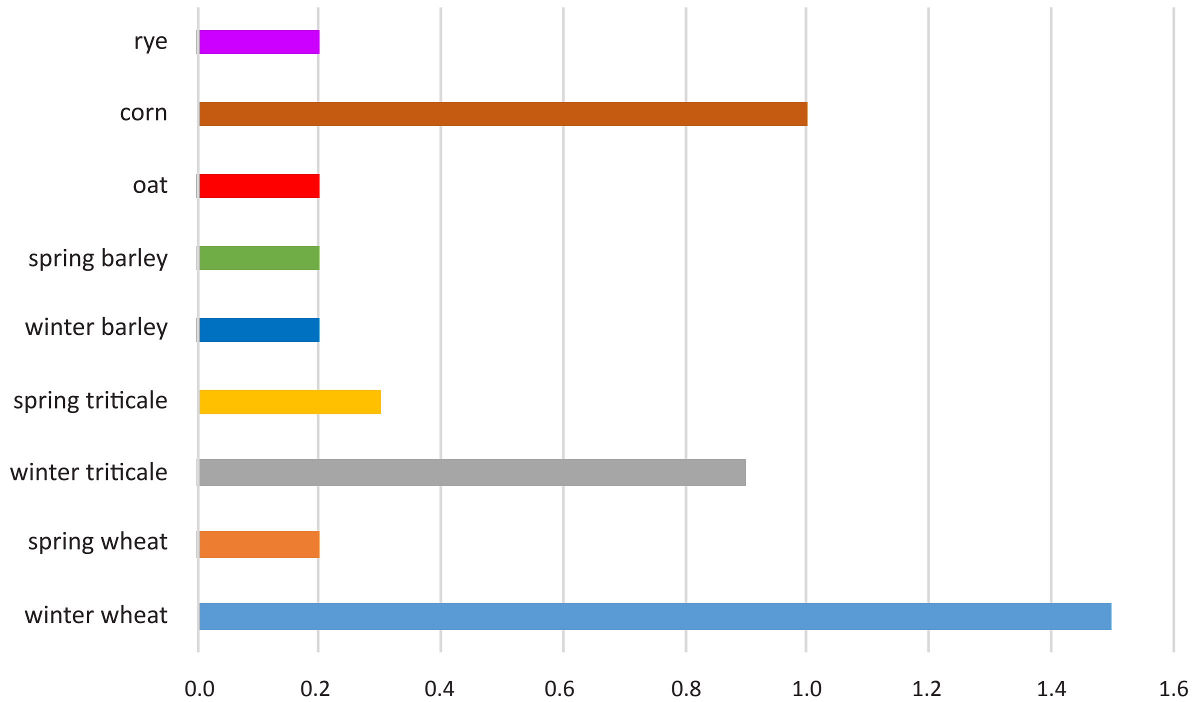

Figure 1. Protein production from individual cereals and their forms (spring or winter) in Poland in 2022. The values indicated are the average calculated from the maximum and minimum values in Table 1 (column 7).

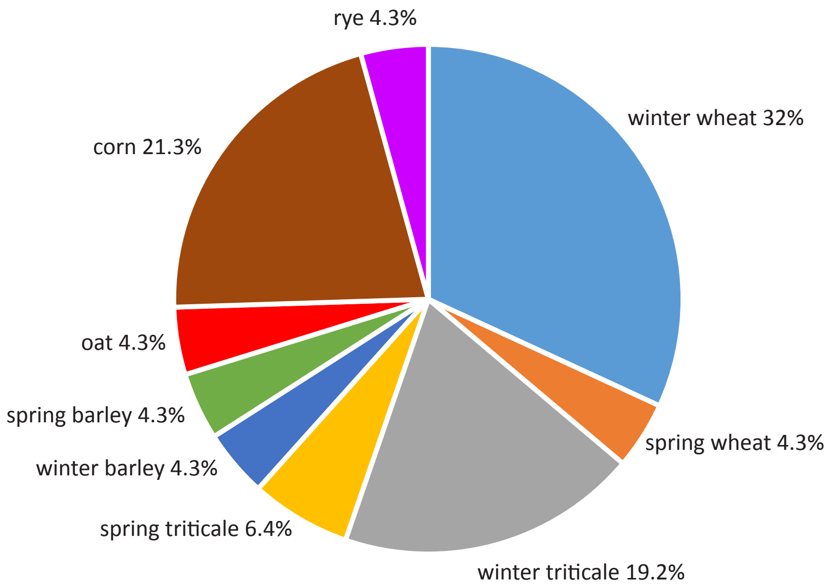

Figure 2. Percentage share of individual species and forms (spring or winter) of cereals in total cereal protein produced in Poland in 2022 (values calculated on the basis of data from Figure 1).

content in grain through price premiums when cereals are purchased. This would be justified as increasing protein content requires more intensive agrotechnology, especially the use of a higher and divided nitrogen rate, which significantly increases production costs. The current lack of premiums does not encourage farmers in Poland to use available methods to effectively increase protein content. Protein content and grain yield affect protein yield. The protein content of grain is a trait that depends on many factors, therefore it is very difficult to accurately estimate the annual protein production from cereal grain in Poland. The calculations made indicate that between 4.1–5.1 million tonnes of protein could have been produced from cereal grain in Poland last year 2022 (range of minimum and maximum values from Table 1 – this is a very general estimate, used in the article for comparative purposes only.). Among cereals grown in Poland, winter wheat, maize and winter triticale have the largest share in protein production. The cultivation of these three cereals yields a total of 3.4 mln tonnes of protein (value from the sum of Figure 1) – which translates into 72.5% of total protein production from cereal grain (value from the sum of Figure 2). Taking into account both forms of cereal (spring and winter), the value of protein production from wheat rises to 1.7 (36.3% – total value from Figure 2) and from triticale to 1.2 million tonnes (25.6%), with maize the three cereal species in total producing 3.9 million tonnes of protein (83.2%). The vast majority of this protein is consumed by animals as feed. However, in the form of cereal products (bread, flakes, groats, etc.) it is consumed by humans.

FACTORS AFFECTING THE PROTEIN CONTENT OF GRAIN

The protein content of the grain is influenced by many factors, but the level of nitrogen fertilisation is considered to be the main one. The supply of an adequate amount of this element as a substrate for amino acid production ultimately influences the protein content of the grain as well. In addition to the amount of nitrogen supplied to the cereal crop, the form of the nitrogen is important in order for its conversion to protein to take place efficiently. According to Leite et al. (2021), nitrate fertilisation increased the protein content of maize grain to a greater extent (11.6%) compared to the urea or ammonium form. Different cereal cultivars have varied efficiency of utilisation of this element and, therefore, their grain may have diversified protein content. As a result, as for example in triticale, cultivars with a higher protein content in the grain can be distinguished (Jaśkiewicz, 2017a). The average protein content of triticale is in the range of 14–16% (Jaśkiewicz, 2017a), with research showing that cultivars with a protein content of even more than 20% are possible (Elangovan et al., 2011). Among fodder cereals, the highest protein in grain is found in triticale of winter cultivars, which contains about 2.7–4.5 p.p. more of this component than grain of spring cultivars. An inverse relationship applies to wheat, whose spring forms contain 13.5–14% protein (Woźniak, Makarski, 2013) and winter forms 10.5–13.8% (Oleksy et al., 2008). In barley of spring and winter forms, the protein level is in a similar range and amounts to 10.1–12%

protein (Noworolnik, Leszczyńska, 2018, Chrzanowska-Drożdż, Kaczmarek, 2007). Oat grain contains 11.5% protein in hulled cultivars, while naked cultivars contain 14.4% of this component (Biel et al., 2020). In maize, depending on the cultivar, grain protein levels range from 9.1 to 12.7% (Podkówka et al., 2015). Rye has the lowest proportion of protein in the grain of all cereals, with a content of 8.8–10.5% (Noworolnik, 2009; Buksa et al., 2012). The protein content of cereal grains should be developed through a combination of properly managed agrotechnology, especially nitrogen fertilisation, together with modern quality breeding. The identification of molecular markers within genes affecting grain protein content can effectively support and accelerate breeding progress for this trait (Kartseva et al., 2023; Safdar et al., 2023). The progress of cereal breeding for increased grain protein content is of utmost importance. Wheat in particular, as a cereal of strategic global importance in human nutrition, should be improved in terms of protein content, thus improving the supply of this important element in the human diet. Modern research techniques are able to identify the genetic basis of increased protein content and use it in cereal improvement for this trait. Alomari et al. (2023) showed that wheat contains a significant number of genes affecting the protein content of the grain, which modify the value of this trait from -0.50 to +0.54% and can be used to improve protein content. Starczewski et al. (2010) found an increase in the protein content of wheat when it was grown in a mixture of winter cereals with triticale.

Protein content in cereal grain is also influenced by a number of other agrotechnical factors. One of them is the forecrop. Results obtained by Ingver (2020) showed that the yield and protein content of spring wheat increased significantly after all the leguminous forecrops, even after the annual species of crimson clover and Alexandria clover. Legume forecrops, through established nitrogen-rich post-harvest residues and its subsequent mineralization, provide cereals with nitrogen that cause their better yield. Instead, in the case of cereal crops growing one after another, maintaining the appropriate amount of nitrogen in the soil, requires the use of mineral nitrogen fertilizers (Guinet et al., 2020).

Weather conditions during the growing season are also important for the protein content in grain. They are particularly important during the grain filling phase, when drought stress can affect nitrogen transformations and its content in grain (De Santis et al., 2021). Drought stress combined with a high dose of nitrogen fertilization may negatively affect the protein content, therefore in drought conditions lower doses of nitrogen mineral fertilizers are more beneficial (Barati, Ghadiri, 2016). Short-term drought has a lesser effect on grain protein content than drought lasting the entire growing season (Wan et al., 2022).

BIOLOGICAL VALUE

The total protein content determines human nutritional value and feed value of grains, but their amino acid profile is also important. The grains of the different cereal species are characterised by different contents of this component, as well as by the biological value of the protein. Protein molecules are made up of combinations of twenty amino acids, which are used as a substrate for the body's protein synthesis.. The biological value of a protein is expressed by the content of the individual essential amino acids in the protein and their ratio. One of the most important amino acids limiting the utilisation of cereal protein, is lysine. Cereal protein is relatively poor in this amino acid, but its content in protein varies. Studies in barley have shown that genes encoding key enzymes required for lysine biosynthesis in plants, dihydrodipicolinate synthase (DHPS) and the catabolic enzyme, bifunctional lysine-ketoglutarate reductase/saccharopine dehydrogenase, are responsible for increased lysine accumulation in grain (Decouard et al., 2022). Also in triticale, cultivar is a factor that modifies the amino acid profile of the protein. Jaśkiewicz and Szczepanek (2018) found a correlative relationship between triticale cultivar and protein amino acid profile. However, some traits may be negatively correlated with each other. A higher protein content in the grain may result in a lower nutritional value. A study by Biel and Maciorowski (2012) showed that a cultivar with a lower protein content had a higher content of essential amino acids. Many studies show that through targeted breeding of cereals, it is possible to achieve an increase in both protein content and amount of essential amino acids. Particularly important in breeding programmes is the use of genes influencing increased lysine and methionine content (Shewry, 2007). This effect has been achieved in the case of naked oats. The grain proteins of naked oat cultivars contain more lysine, methionine and tryptophan compared to the hulled cultivars (Biel et al., 2020; Shabolkina et al., 2024). In a study by Shabolkina et al., (2024), the naked oat cultivars Bekas and Baget contained more essential amino acids (74.6 and 73.0% of FAO/WHO recommended standards, respectively) compared to the hulled cultivar Konkur (69.4%).

The agro-technology used and weather conditions are also of great importance. Variable weather conditions from year to year affect the protein profile, including the content of exogenous and endogenous amino acids. Weather conditions affect the plants' utilisation of nitrogen from the soil, which is used for protein synthesis. A lack of rainfall significantly decreases the uptake of this nutrient which reduces the amount of protein, but also affects its amino acid profile (Singh et al., 2012). Differences in the biological value of winter wheat protein from different years were shown by Kowieska et al. (2010). The same winter wheat cultivar (Rywalka) exhibited differences in protein quality, expressed by the essential amino acid index (EAAI – Index), which showed a difference of 12.1 (95.6 in 2008 vs. 83.5 in 2007). The use of appropriate cultivation technology also has a significant effect on the biological quality of the protein. The intensive technology associated with the application of a higher amount of nitrogen increases the content of both exogenous and endogenous amino acids and especially lysine in the amino acid profile compared to integrated cultivation (Sułek et al., 2023). In contrast to intensive agriculture, organic farming does not significantly affect the amino acid profile of cereal protein (Bobko et al., 2009).

CEREAL PROTEIN IN THE HUMAN DIET

Cereal grains are the basic raw material from which many of the products consumed by people every day are produced. Cereal products are considered a source of starch and fibre, but they also provide some protein. However, it lacks some essential amino acids, which disrupts the amino acid interactions and reduces the use of other amino acids for protein synthesis by the body (Del Moral et al., 2007; Jiang et al., 2014; Chernova et al., 2021; Besaliev et al., 2021). Due to the significant share of cereal products in the diet of people, especially vegetarians and vegans, it is reasonable to conduct research to identify the possibility of increasing the protein content of wheat grain and improving its biological value by selecting a production technology suitable for a given species/cultivar (Jiang et al., 2014; Hamany-Djande et al., 2020). According to a study by Laskowski et al. (2019), cereal products provide about 23% of the protein consumed by Poles. Among the cereal products consumed, bread (bread, rolls) is the largest contributor to the total protein supply from cereal products. The amount of dietary protein consumed by Poles with cereal products is similar to its percentage in Western Europe. Even in highly developed countries like the UK, cereals are an important source of protein, with total cereals and bread providing 24% and 9% of total protein intake by adults respectively (Beverley et al., 2020). A group of people who pay particular attention to balancing their diet in terms of protein are sports people, particularly bodybuilders. For them, a high dietary protein supply is important, but so is its quality. The role of protein in the diet of athletes is to speed up the muscle regeneration process and achieve exercise supercompensation. For this reason, they have an increased need for protein with a high proportion of essential amino acids in the diet. The insufficient amino-acid composition is supplemented with branched-chain amino acids (BCAAs), which play an important role in muscle protein synthesis. Research shows that as many as 52% of trainees consume a high-protein diet (Panasiewicz, Grochowicz, 2016). A properly selected diet with a proportionally increased share of plant protein (within a wide range of total protein) has a beneficial effect on improving health, as well as slowing age-related loss of muscle mass especially in elderly people (Achrem-Achremowicz, 2023). Taking into account the general trend in increasing protein intake by people interested in protein-rich diet, plant raw materials and cereal grains in particular, are used to produce protein concentrates and isolates dedicated to amateur and professional athletes (Kostrakiewicz-Gierałt, 2024). All cereal products, despite their diverse protein content, contain too little lysine compared to our body's requirement for this amino acid. This is particularly true for refined products (e.g. light bread) compared to wholegrain products (e.g. dark bread). At the same time, wholegrain products, due to their increased fibre content, are characterised by poorer protein digestibility. Fibre is an essential ingredient for the proper functioning of the digestive tract. A comparison of the biological value of the protein of the basic four cereals shows that oats has the best amino acid composition, followed by rye, barley and wheat. The lower nutritional value of the protein contained in cereal products can be compensated by combining cereal products with dairy products and eggs in meals. They are rich in lysine and are very good at compensating for its deficiency. Combining these products promotes more efficient protein utilisation and increased nutritional value (McKevith, 2004). A good source of lysine are buckwheat nuts, which contain a significant amount of this amino acid in the protein – the same or even slightly higher than in the reference protein (Pisulewska et al., 2001). In addition, the modern trend of research related to high-quality food also includes obtaining high-quality cereal products with adequate nutritional value of protein on the basis of cereal products only. Cereal flakes, especially the very popular oat flakes in Poland, can be such a food. Cereal flakes made from triticale, durum wheat and barley, which contain 13.46, 11.92 and 11.67% protein, respectively, can also be valuable in terms of protein content (Galal et al., 2024). Bread, as a frequently consumed food product, is particularly predisposed to expand its range with products characterised by increased protein content. Increased protein content in bread can be achieved by the addition of a protein isolate from wheat (glutens) or maize (zeins), which does not impair its sensory and organoleptic properties, but increases its nutritional value (Hoehnel et al., 2019). However, as indicated by the study of Cervantes-Pahm et al. (2014), maize or sorghum protein has a lower protein digestibility compared to the protein of other cereals, hence such diet requires more supplementation. Thus, despite the increased protein content, it may not be fully utilised by the body. Another way of enriching bread with protein is the addition of flour from legumes, e.g. from lupins can increase the protein content of baked bread by up to almost three times – from 12.3% in wheat bread to 34.6% in wheat bread with the addition of lupin flour (Piasecka-Jóźwiak et al., 2018). Obtaining a higher content of this important element in bread is possible through the use of a number of additives, such as protein isolates and the addition of raw materials with a higher protein content, e.g. legumes. High-protein breads or other cereal products are also prepared by a large number of people themselves. In recipes, however, the most common component that increases the protein content or also imparts a flavour is a protein supplement. A Polish research team has shown that high-protein pasta can be obtained with the use of wheat grain-based products (wheat germ, bran and wheat germ protein isolate). In particular, the use of a protein isolate in the recipe makes it possible to obtain a high-protein product within the meaning of EU law, but, importantly from the point of view of biological quality, the product has an amino acid composition in line with the FAO standard (Teterycz et al., 2023). Protein isolates from cereals, especially wheat, are gaining popularity among people who are trying to achieve a protein intake of 2–2.5 g kg^{-1} body weight. They are used as a cheaper source of concentrated protein than the most popular casein protein. The advantage of wheat protein isolates is that they can increase the concentration of protein in home-prepared products, such as oatmeal, pancakes, biscuits or protein bars made from cereal flour. Oat grain can also be used as a raw material for protein concentrates, which can then be used to manufacture products. When discussing the importance of cereal proteins, mention should also be made of the special role of certain antioxidant cereal protein hydrolysates. They have the ability to neutralise free oxygen radicals. Proteins isolated from the wild forms of oats, *Avena sterilis* and *Avena maroccana*, are particularly active in terms of antioxidant activity relative to cultivated oat cultivars (Karaś et al., 2013). Proteins with antioxidant activity are also contained in pseudo-cereal grains, such as quinoa and buckwheat (Worobiej et al., 2016ab). Enriching the diet with pseudo-cereals or combining them in foods together with proteins from traditional cereals, promotes more favorable amino acid ratios in the food (Joye, 2019). The results of the study by Han et al (2019) on true ileal digestibility (TID) in different cereals (brown rice, polished rice, buckwheat, oats, millet millet, foxtail millet, tartary buckwheat, adlay and whole wheat) showed that whole grain wheat and tartary buckwheat had the highest digestibility. This indicates that it is worth combining these two species in human food products.

The increasing number of people with gluten intolerance means that society has a greater knowledge of celiac disease, as well as knowledge about gluten itself and products containing it (Piec, Janczar-Smuga, 2022; Wojciechowska et al., 2023). Research conducted by Croall et al. (2019) indicates that social attitudes towards gluten, resulting from the growing number of people with intolerance to this wheat protein, contribute to a significant increase in the number of people falsely convinced that they are allergic to it and an increasing number of people choose a gluten-free diet not for health reasons but as a way of life to be generally healthy ("Lifestylers"). The number of such people who exclude gluten-containing products from their diet is about 11% of all people using a gluten-free diet (Araya et al., 2020). This may indicate a certain trend among consumers. However, as Rybicka (2023) notes, the use of gluten-free diet products may lead to a lower intake of important micronutrients compared to products based on popular gluten cereals.

IMPORTANCE OF CEREAL PROTEIN IN THE FEED INDUSTRY

Cereal species grown in Poland are mainly for feed purposes (Klepacki, Slavkova, 2016). Annually, about 61% of cereal production is used for the production of animal feed mixtures (Jaśkiewicz, Sułek, 2017). Globally, the proportions are different. Of the total global grain production, 35% is used for feed and 41% is consumed by humans (Poutanen et al., 2022). The much higher consumption of cereal grain for feed purposes in Poland is due to the a very high population of poultry, but also pigs for which feed production requires a significant share of cereals in formulations. Cereals used for feed preparation can provide more than half of the total protein in feed (Dzwonkowski, Bodyl, 2014). The other half of the protein requirement is met from high-protein raw materials, the standard being post-extraction soybean meal imported to Poland from South American countries and the USA. There is therefore a deficit of feed protein, which, following the import ban, could further exacerbate the problem for the feed industry and the animal production sector. Increasing the protein content of grain could significantly reduce the cost of animal feed and support the profitability and competitiveness of animal production in Poland – especially pigs and poultry (Florek, Czerwińska-Kayzer, 2022). Triticale has the greatest potential for use as a feed grain. This can be seen in the correlation of triticale production volumes in regions with high animal density and intensive livestock production (Jaśkiewicz, 2017b). It exceeds rye with its higher protein content and its higher yield per area, as well as its lower content of anti-nutrients. The lower protein content in rye grain is not the only negative aspect compared to other cereals. Rye grain also contains inhibitors of trypsin, an important enzyme that is responsible for protein digestion. By inhibiting the action of trypsin, they reduce the digestion and assimilation of protein by the body. As shown in a study by Sułek et al. (2024), the concentration of trypsin inhibitors in rye grain is influenced by cultivar, nitrogen fertilisation and weather conditions during the growing season. According to the cited authors, the highest amount of trypsin inhibitors was in the growing season characterised by high rainfall. In addition to the total protein content, which is an important discriminator of feed value, its amino acid profile is also important. One of the most important amino acids limiting the utilisation of cereal protein is lysine. Its content is relatively low in cereal protein, making it necessary to supplement cereal-based feed with other protein raw materials (mainly post-extraction soybean meal), as well as a synthetic form of this amino acid – L-lysine. Among cereals, barley has the highest content of this important amino acid. Triticale protein contains significantly less lysine, and wheat contains almost twice as much. The amino acid profile of protein in cereals is determined by genetic factors. Jaśkiewicz and Szczepanek (2018) found a correlation between triticale cultivar and protein amino acid profile. The applied agrotechnology and weather conditions are also of great importance. Variable weather conditions from year to year have an impact on the protein profile, including the content of exogenous and endogenous amino acids.

ANTINUTRITIONAL SUBSTANCES

Antinutritional substances may directly or indirectly determine distribution use, both in human and animal nutrition. Antinutritional substances are compounds naturally occurring in plants that can limit or prevent the utilisation of nutrients or have a harmful effect on the human body. Cereal grains contain small amounts of antinutritional substances, but they do not pose a serious risk. Protease inhibitors (trypsin and chymotrypsin) and tannins have an adverse effect on protein digestion. Trypsin inhibitors are mainly found in rye and triticale. Tannins are mainly found in wheat, and in smaller amounts in grains of other cereals (Sikorska et al., 2022). Significant proportion of rye grain is used in the feeding of various animal species, mainly pigs and poultry (Brzozowski et al., 2023). However, a limitation to its wider use is its content of antinutritional substances, which have a negative impact on animal health and development by hindering the action of proteolytic enzymes. These include alkylresorcinols, water-soluble pentosans and trypsin inhibitors. However, due to the varietal variation associated with the content of these substances, the grain of some modern rye varieties may have a higher feed value (Schwarz et al., 2014). Rye grain of hybrid varieties can be used in poultry nutrition in a higher proportion than population varieties (Milczarek et al., 2020; Janiszewski et al., 2021; Grabiński et al., 2021). Alkylresorcinols are a group of phenolic lipids. Most of these compounds are located in the central parts of the fruit and seed coat. The highest content of these compounds is found in rye grain (360–2180 mg kg^{-1}), with smaller amounts present in triticale grain (294–1145 mg kg^{-1}) and wheat (268–943 mg kg^{-1}) (Ciurescu et al., 2022). Literature data indicate that alkylresorcinols interact with other compounds present in grain to reduce animal weight gain (Ismagilov et al., 2020). Feeding animals cereal grain from which alkylresorcinols have been extracted increases production effects (Skrzypek et al., 2007).

Non-starch polysaccharides (NSP), especially water-soluble pentosans, also exhibit antinutritional effects. Compared to other cereals, rye grain contains the highest amount of these compounds (Dynkowska, 2019). The high water-binding capacity of NSP and the resulting swelling hinders the penetration of the digestive content by enzymes that hydrolyse starch, proteins and fats. These compounds swell in the digestive tract causing reduced feed intake, poorer utilisation of the nutrients and energy contained in the feed, and ultimately lower body weight (Boros, 2015). The only method to neutralise their antinutritional effect is to add xylanase enzymes to the feed (Lagaert et al., 2014).

Among poultry, geese are less sensitive to the antinutritional effects of pentosans and alkylresorcinols, for which hybrid rye grain has comparable nutritional value to oats (Lexhaller et al., 2019). In older animals, the antinutritional effect is no longer as strong and can even have a positive effect on health by acting prebiotically. Trypsin inhibitors have the strongest anti-nutritional effect on both young and adult animals. They inhibit proteolytic enzymes produced by the pancreas forcing it to work more intensively and causing weight increase (Katoch, 2022). The negative effect of trypsin inhibitors also manifests itself in poorer utilisation of protein and amino acids from the digestive contents. Higher trypsin inhibitor activities are found in rye grain than in grain of other cereal types (wheat and triticale). These compounds are found in both endosperm and embryos. Their activity is associated with low molecular weight cereal proteins, which include albumin and globulins (Piasecka-Kwiatkowska, Warchlewski, 2000a). The adverse effects of inhibitors on the animal body are mainly due to a reduction in the activity of digestive enzymes and a decrease in digestibility and also in the utilisation of nutrients, especially protein, leading to a reduction in animal weight gain (Piasecka-Kwiatkowska, Warchlewski, 2000b).

SUMMARY

Protein from cereals has so far been underestimated in the human diet. Both in Poland and worldwide, it accounts for a significant proportion of total dietary protein intake. Its role will be even greater in the future, due to the growing population. In view of this, action is needed to maximise the protein content of grain and the yield of protein from cereal crops. The problem with cereal proteins is the sub-optimal proportions of amino acids, which do not correspond to the proportions humans should consume to promote growth and a healthy metabolism. Hence, it is also important to promote research into the use of genetic methods to improve the amino acid composition of cereals and to improve agrotechnology. In addition, the food industry should develop grain-based products that take into account the amino acid balance, using both cereal grain as a source of protein, but also pseudo-cereals in their formulations to supplement deficient amino acids. New cereal-based products with higher protein content and a better balanced formulation are sure to have a wide appeal as they help to meet human daily protein requirements. People with gluten intolerance or who want to limit or eliminate gluten from their diet should use gluten-free cereals and pseudocereals, rather than completely give up cereal products. Cereal protein is also important in meeting the demand for feed protein, and an increase in its production is also desirable due to increasing farm animal populations (in Poland especially poultry) and the need to feed livestock in the future.

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