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


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Review

Triticale: A General Overview of Its Use in Poultry Production

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Abstract: Triticale, a hybrid of wheat and rye, is one of the most promising grain crops. In terms of productivity, the level of metabolizable energy, and the composition of essential amino acids, triticale surpasses rye and is not inferior to wheat. It is resistant to the most dangerous diseases and pests. In terms of nutritional value, triticale can compete with wheat, corn, sorghum, and barley. The presence, however, of antinutrients in triticale such as non-starch polysaccharides, alkylresorcinols, and trypsin inhibitors significantly reduces the biological value of this crop. In the global practice of compound feed production, there are many methods and technologies for processing grain raw materials to increase their nutritional value. Enzymatic treatment and extrusion technologies are worthy of special attention. The high content of triticale in the compound feed of poultry breeder flocks should be used effectively, taking into account the characteristics of triticale varieties and climatic conditions. An optimal triticale level in feed (15% for layer and broiler chicks) may improve body weight gain and reduce feed costs when raising replacement young stock. Layer breeder flocks fed a 20% triticale-based diet may have increased egg production, high viability, and flock uniformity. Producing triticale–soy and triticale–sunflower extrudates and supplementing the diet of poultry flocks with essential amino acids represent promising avenues for maximizing the benefits of triticale. Innovative methods of achieving this goal should be further developed and put into practice, particularly given the expansion of triticale’s cultivation areas.

Keywords: triticale; poultry farming; feeds; chickens; amino acids; antinutrients; enzymatic treatment; extrudates



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1. Introduction

Poultry producers consistently face the challenges of increasing flock productivity and reducing production costs. Additional issues to be kept in mind include disease control (with a minimum use of antibiotics) for both animals and food crops, animal welfare, and environmental concerns. Balanced feeding plays one of the most crucial roles in poultry production. It needs to meet all the needs of the bird in accordance with age and productivity, providing a diet consisting of the required content of basic nutrients, energy, and biologically active substances including, proteins, amino acids, and carbohydrates [1–15]. Moreover, in order to expand the fodder base in the worldwide poultry industry, the sustained expansion of the harvesting area of cereal crops that are more resistant to climate change is essential [16–18].

Cereals are the main component of poultry feed. Conventionally, corn and wheat are most widely used for this purpose. Barley is utilized to a lesser extent, with rye and

oats in smaller quantities. In recent years, the share of traditional cereals in compound feed for poultry has lowered in developed countries from 69–70% to 40–50%. This is due to both secondary ingredients of industrial processing and non-traditional feeds [16,19]. Alongside these conventional components, new cereal crops have appeared in poultry diets [20–23], such as sorghum and triticale (\times *Triticosecale* Wittmack) (Figure 1). The latter is a promising crop and, with its rational use, can be a valuable compound feed ingredient and successfully partially replace the cereal crops traditionally used [17,23–31]. This becomes especially important in connection with the growing share of cereals that will be used for the production of biofuels, i.e., ethanol, biodiesel, and solid fuel pellets (e.g., [32–35]). The purpose of this review is to consider the nutritional, economic, and environmental benefits (as well as the drawbacks) of the rye–wheat hybrid triticale in poultry production.

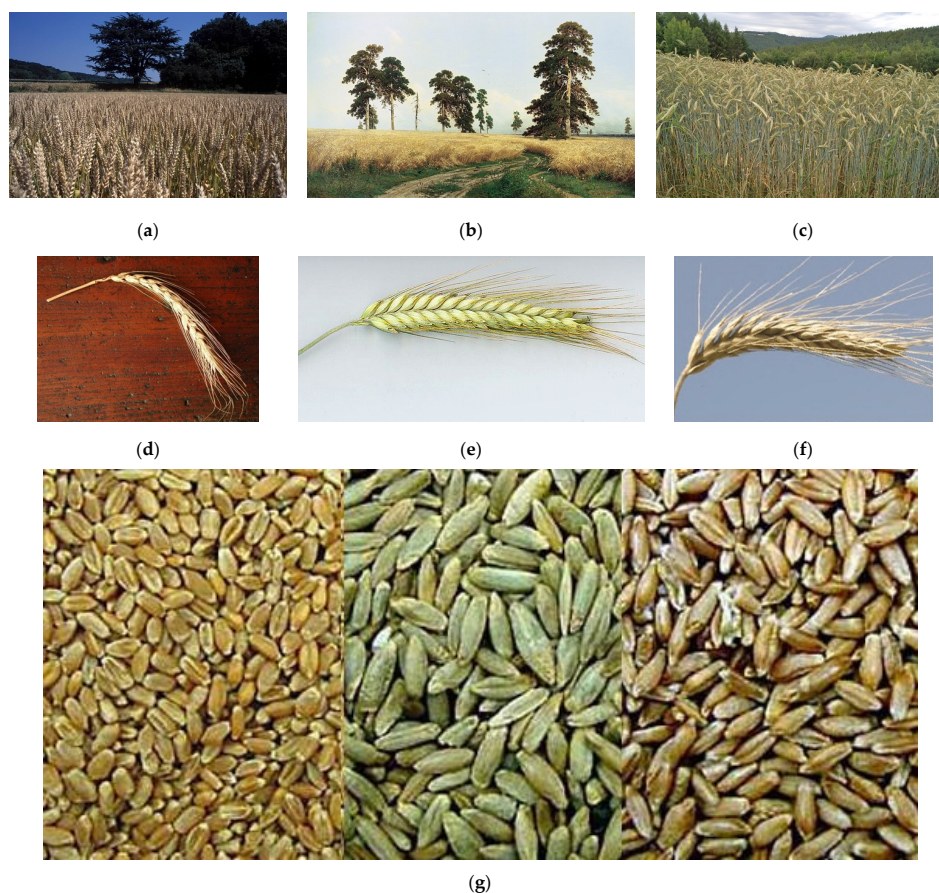


Figure 1. Phenotypes of wheat (*Triticum aestivum*; left), rye (*Secale cereale*; middle), and their hybrid, triticale (right): (a–c) cultivation fields; (d–f) single ears; and (g) seeds. Image sources: (a) [https://commons.wikimedia.org/wiki/File:Parcelle_De_bl%C3%A9_REGAIN_\(Yvelynes\)_CL_Weber_\(23787338000\).jpg](https://commons.wikimedia.org/wiki/File:Parcelle_De_bl%C3%A9_REGAIN_(Yvelynes)_CL_Weber_(23787338000).jpg), CC-BY-2.0 (accessed on 10 February 2024); (b) <https://commons.wikimedia.org/wiki/File:Rozh.jpg>, Ivan Shishkin (1878), CC-PD-Mark (accessed on 10 February 2024); (c) <https://commons.wikimedia.org/wiki/File:Triticalefeld.jpg>, CC-BY-SA-3.0 (accessed on 10 February 2024); (d) https://commons.wikimedia.org/wiki/File:Fumento_Tenero_Rieti.jpg, CC-BY-3.0 (accessed on 10 February 2024); (e) [https://commons.wikimedia.org/wiki/File:Secale_cereale_\(Roggen\)-2008b.jpg](https://commons.wikimedia.org/wiki/File:Secale_cereale_(Roggen)-2008b.jpg), CC-BY-SA-3.0,2.5,2.0,1.0 (accessed on 10 February 2024); (f) https://commons.wikimedia.org/wiki/File:LPCC-623-Espiga_de_triticale.jpg, CC-BY-SA-3.0 (accessed on 10 February 2024); and (g) https://commons.wikimedia.org/wiki/File:Wheat,_rye,_triticale_montage.jpg, PD USDA (accessed on 10 February 2024).

2. Triticale: Description, Significance, and Distribution

Triticale was first generated by crossing wheat (*Triticum*) with rye (*Secale*), and it belongs to the group of amphiploids [36] (Figures 1 and 2). By combining the chromosomal complements of two different botanical genera, wheat and rye, humans have managed, for the first time in the history of agriculture, to synthesize a new agricultural crop, which, according to experts, will become one of the leading grain crops in the near future [24,25,27,28,30,37]. Indeed, triticale is rapidly becoming a popular choice for poultry feed because of several desirable characteristics.

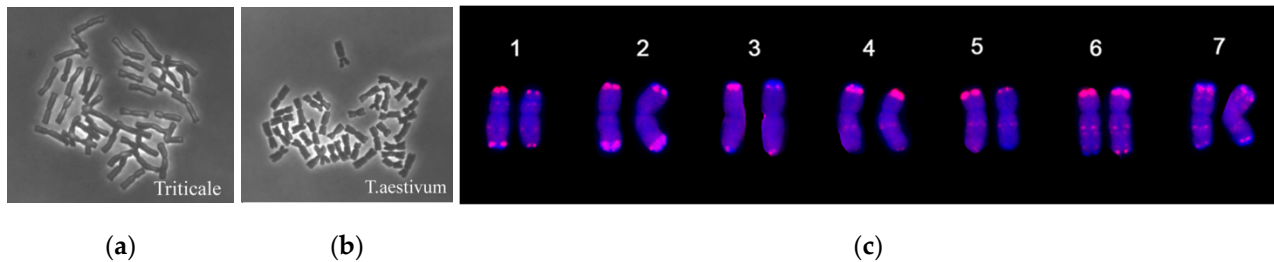


Figure 2. Karyotypes of triticale (a) and its parents, wheat (*Triticum aestivum*; (b)) and rye (*Secale cereale*; (c)). The fifth rye chromosome (5R) contains candidate genetic loci associated with important tolerance traits in triticale [38,39]. Image sources: (a) https://commons.wikimedia.org/wiki/File:Karyotype_of_Triticale.png, CC-BY-2.0 (accessed on 10 February 2024); (b) [https://commons.wikimedia.org/wiki/File:Karyotype_of_wheat_\(Triticum_aestivum\).png](https://commons.wikimedia.org/wiki/File:Karyotype_of_wheat_(Triticum_aestivum).png), CC-BY-2.0 (accessed on 10 February 2024); and (c) [https://commons.wikimedia.org/wiki/File:Karyotype_of_Austrian_rye_\(Secale_cereale\).png](https://commons.wikimedia.org/wiki/File:Karyotype_of_Austrian_rye_(Secale_cereale).png), CC-BY-2.5 (accessed on 10 February 2024).

Triticale can adapt easily to a range of diverse growing conditions, and it is, thus, a reliable crop for poultry feeding in a range of situations. The studies of Nielsen et al. [40] and Faccini et al. [41] highlighted the ability of triticale to tolerate multiple climatic conditions and soil types. This ability to adapt means that triticale can be available and affordable in many marketplaces, protecting it from price fluctuations. Triticale attracts special attention due to the fact that it is grown in many agricultural areas of the world. Its introduction and cultivation are one of the most promising agricultural growth sectors associated with the expansion of the use of non-traditional feed components for poultry. It has become widespread in the countries in Eurasia but less so in North and South America, Africa, and other regions (Figure 3). This new sector of agriculture is also driven by climate change, particularly on the Eurasian continent where large areas of land have become more amenable for growing grain crops. Triticale is able to surpass both of its parent forms in terms of important indicators such as yield and nutritional value [42–45]. Triticale, like all cereals, is richest in carbohydrates and also contains proteins, fats, mineral components, and biologically active compounds [42–44,46,47].

Triticale is resistant to many phytopathogenic diseases characteristic of cereals [48], e.g., fusaria [49–53]. Among fungal pathogens, wheat stem rust, caused by *Puccinia graminis* f.sp. *tritici* (Pgt), appears to be one of the most serious for cereal crops. However, a new synthetic tetraploid triticale obtained by crossing rye (*Secale cereale*) with einkorn wheat (*Triticum monococcum* spp. *monococcum*), a carrier of the stem rust resistance gene *Sr35*, has been described [54]. According to several observations [51–53], the amount of tetraploid triticale grain with internal infection did not exceed 30%, while, for wheat, this indicator reached 90%. Triticale is also not affected by powdery mildew, yellow rust, nor brown rust [27,54–59]. According to triticale producers [60–69], its spring varieties provide an environmentally friendly stable grain yield due to immunity and tolerance to disease. They are grown without the use of fungicides and are able to compete with annual weeds. This eliminates the need to use herbicides on crops [50,70–76]. In terms of resistance to adverse soil, climatic conditions, and the most dangerous diseases, triticale is not inferior to rye and surpasses wheat [39,48,50,77–80]. Another great advan-

tage of triticale is its significant potential for frost and winter tolerance, ensuring sufficient overwintering [27,38,39,48,54,62,66,69,81–83]. Recent triticale genome-wide studies revealed quantitative trait loci and candidate genes associated with abiotic (freezing) and biotic (pink snow mold) stress tolerance that are located on chromosomes such as 2B (descendent from wheat) and 5R (inherited from rye; Figure 2c) [38,39]. Spring triticale is a very promising crop for ensuring the stable production of food and technical and fodder grain in different climatic zones [60,63,64,67,70,72,74,75,84,85]. This is especially important for difficult weather conditions that, on average, once every four years, lead to the death of large areas of winter grain crops [37,61,65,68,86,87]. Reseeding these areas with fresh grain crops makes it possible to maintain grain balance.

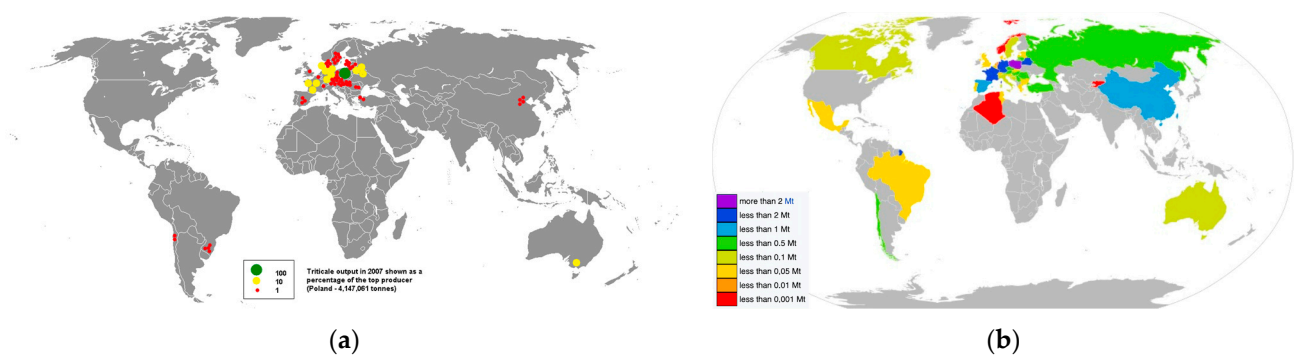


Figure 3. Global distribution of triticale output by producers in 2007 (a) and 2018 (b). (a) As a percentage of the top producer (Poland, 4.15 Mt); (b) triticale producers by production quantity (in Mt). Image sources: (a) <https://commons.wikimedia.org/wiki/File:2007triticale.png>, PD-user (accessed on 10 February 2024); (b) https://commons.wikimedia.org/wiki/File:Top_Triticale_producers_2018.svg, CC-BY-SA-4.0 (accessed on 10 February 2024).

According to FAO data (as quoted in [19]), the harvesting area of triticale in the world in 2017 was 5.6 million hectares. The majority of it was in Poland (1.2 million ha), Russia (600 thousand ha), Germany (404 thousand ha), France (331 thousand ha), Belarus (500 thousand ha), and Ukraine (200 thousand ha) [41,63,67] (Figure 4). This area’s growth continues (Figure 3), and it can be predicted that, in the coming years, triticale will occupy one of the top places among cereal crops.

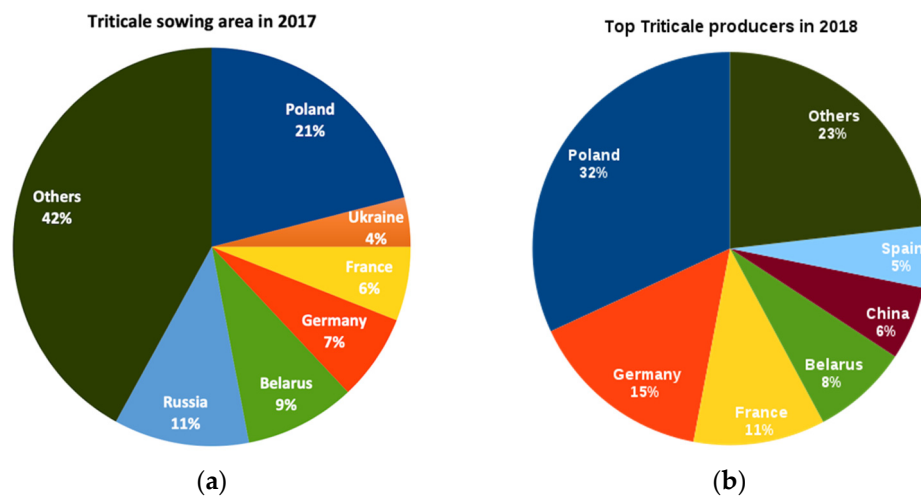


Figure 4. Percentages of the world’s triticale sowing area (a) and production (b) by top countries. Image sources: (a) authors’ own design; and (b) https://commons.wikimedia.org/wiki/File:Top_Triticale_producers_2018.svg, CC-BY-SA-4.0 (accessed on 10 February 2024).

The yield of triticale varies from 3.05 t/ha to 7.2 t/ha in different fields, depending on the fertilizer and mineral background [37,70,72,74,75,86,87]. In many places, triticale significantly surpasses wheat and rye in terms of grain yield, protein content, and its harvest per hectare [61,65,68]. Triticale, barley, and rye grains contain more crude protein and a better amino acid profile than corn, including a higher content of lysine, methionine, threonine, and tryptophan [48,88,89].

3. The Nutritional Value of Triticale

One of the key advantages of triticale as a feed for commercial chickens is its superior nutritional value compared to other crops. It has considerable potential to improve the nutritional value of diets fed to broiler and layer chickens [19,90–92]. Triticale has a balanced profile of protein, carbohydrates, and dietary fiber and is, thereby, well suited to fulfil the daily dietary requirements of commercial flocks [42–44,46,47]. The relatively high protein content in triticale helps to promote optimal growth, while the carbohydrates contained therein provide a crucial energy source [88].

3.1. Metabolizable Energy, Crude Protein, Starch, and Fiber Content

A distinctive feature of triticale is its relatively high crude protein content and metabolizable energy value (13.5–13.7 MJ/kg) [88]. With respect to the metabolizable energy level, triticale surpasses rye and is not inferior to wheat [19,26,28,29,31]. Its crude protein content, depending on the variety and agro-ecological growing conditions, ranges from 8 to 16%. In terms of crude protein content, triticale grain surpasses not only rye, oats, and barley but often wheat as well. In modern newly created varieties of triticale, however, this indicator, due to increased starch content, has slightly lowered values and does not exceed the level of wheat [93]. Depending on the year of cultivation, the crude protein content in different varieties of spring triticale varies within approximately the same limits (12–13%), being similar to that of wheat. In winter triticale varieties, compared to spring triticale, the crude protein content is 2–3% lower (i.e., 10–11%). In some samples of winter triticale grown with a minimal use of fertilizers, the crude protein content ranges from 7 to 8% and is similar to rye [19,26,28,29,31].

The main component of triticale grain, like other cereals, is starch [94], accounting for $\frac{3}{4}$ of the grain's weight [95]. It is known from the literature [19,94] that grain density declines with a rise in protein content and, conversely, rises via an increase in starch content. The relative content of starch in triticale is lower and that of protein is higher than those of rye and wheat [94,96,97]. Unlike wheat and rye, triticale starch is characterized by a low amylase content (23.7%). In terms of density (at 30 °C), triticale starch exceeds rye starch (1.4465 vs. 1.4209) but is slightly less than the starch of soft wheat (1.4832) [98]. Moreover, the overall digestibility of triticale (79.8%) is higher than that of oats (79.4%) and barley (75.0%), with, specifically, a protein digestibility (92%) exceeding that of wheat (90%) and rye (84%) [77,79,80].

Gluten from the flour of this crop is of a high quality, and it is, thus, often used to prepare varietal mixtures with low-quality wheat flour. From the flour of modern triticale varieties, the food industry has also begun to bake high-quality bread, biscuits, and other confectionery products [48,84,85,99–101].

In triticale, the total dietary fiber content ranges between 13 and 16% [98]. The major components of dietary fiber are arabinoxylan (average 6.8%), fructan (average 2.3%), cellulose (average 2.1%), Klason lignin (average 1.6%), and β -glucan (average 0.7%) [98]. Overall, cellulose has a rather small proportion in triticale [19]. The dietary fiber profile and molecular weight distribution of the extractable dietary fiber components in triticale grains are considerably closer to those of wheat than rye [102]. Both cultivar and location have an impact on the content of total dietary fiber and its components [98]. For instance, cellulose, in one of the studies [19], occupied an average of 2.7% (from 2.4 to 3.3%), with the differences between winter and spring triticale varieties being insignificant.

3.2. Amino Acid Composition

The nutritional value of protein depends on amino acid composition and, specifically, the balance of essential amino acids [42,103,104]. The triticale grain, as well as other grain crops, contains the most important and indispensable amino acid, lysine [105]. Therefore, its content in triticale can serve as one of the indicators of the overall protein quality of this grain. In this respect, the triticale grain has an increased lysine content (1.56 g/kg), i.e., almost 1.4 times more than that of wheat and twice as much as corn [9,106,107]. In terms of the lysine content (about 3% of the total protein amount), triticale can surpass wheat (by 16–20%) [108,109]. Indeed, the content of lysine in improved lines of triticale was originally close to that of high-lysine corn [110]. In comparison to wheat, the triticale grain also contains more free essential amino acids such as valine, leucine, and others [103,111].

3.3. Antioxidants and Minerals

Triticale grain has a relatively high content of B-group vitamins as well as antioxidants, including vitamin E and phenolic acids. In particular, triticale contains water-soluble vitamins B₁ (0.4 mg/kg dry matter (DM)), B₂ (0.1 mg/kg DM), B₃ (1.4 mg/kg DM), B₅ (1.3 mg/kg DM), B₆ (0.1 mg/kg DM), and B₉ (73.0 µg/kg DM). Out of the fat-soluble vitamins, only vitamin E is present (about 0.9 mg/kg DM) [6,10,14,112–115]. A high ash content is also characteristic of triticale grains [99], and the main mineral substances in triticale are phosphorus and potassium.

4. Triticale Content in Feed

The effectiveness of triticale as a fodder crop depends on the level of input, variety, and application conditions [20,44,116–119]. Triticale is included in the compound feed for livestock [17] including cattle, pigs, sheep [3,120–122], and, specific to this review, poultry [24–31,123]. It partially replaces wheat, corn, and sometimes legumes; however, there are varying opinions in the data regarding the ratio of triticale to use, ranging usually from 15 to 60% [26,28,29,31,47,124,125] (Table 1).

Table 1. Selected poultry feeding trials using triticale.

| Triticale Content in Feed | Type of Poultry | Effect | References |
|-------------------------------------|----------------------------------|---|------------------|
| 15% | layer breeders (chicks) | Increased feed conversion, improved viability | [24,25,27,28,30] |
| 20% | layer breeders (adults) | Increased egg production (by 2.5%), egg yield (by 4.6%), egg hatchability (by 2.4%) | [24,25,27,28,30] |
| 40% (triticale–sunflower extrudate) | layer breeders (adults) | Increased egg production (by 3–5%) | [126] |
| 50% (triticale–soy extrudate) | layer breeders (adults) | Increased egg hatchability (by 1.86–2.11%) | [126] |
| 20 to 69% | broiler chickens | No negative effect on growth and development compared to corn | [127] |
| 70% corn replaced with triticale | laying hens | Did not impair performance | [128] |
| 40% corn replaced with triticale | broiler chickens | Did not reduce growth rate | [129] |
| 50% corn replaced with triticale | broiler chickens | Did not reduce growth rate | [130] |
| 50 or 70% | laying hens (White Leghorn) | Decreased egg performance, increased feed consumption | [131] |
| 15% | broiler chickens | Optimal content of triticale in the diet | [132] |
| 35% (triticale–sunflower extrudate) | replacement chicks (laying hens) | Reduced feed consumption per 1 kg body weight gain (by 2.4 and 5.4% in the first and second months of rearing), improved flock uniformity (by 0.6%) | [122,133] |

According to the studies of Pettersson [129] and Charalambous et al. [130], the replacement of 40% and 50% of corn with triticale grains did not reduce broiler growth intensity and feed efficiency. Indeed, only the complete replacement of corn lowered chicken performance indicators. It has been determined [90–92,132] that the optimal triticale content in the diet of broilers was around 15%, suggesting that a further increase in the proportion of triticale could lead to a reduction in body weight and a rise in feed costs.

Brzóška [128] stated that 70% of corn in the diet of laying hens can be replaced with triticale without a deterioration in performance. At the same time, according to Leeson and Summers [131], when 50% or 70% of triticale was included in the compound feed of White Leghorn laying hens (regardless of the diet structure), egg production decreased and feed consumption increased. Significant differences between breeds of laying hens in terms of body weight gain, hen feed consumption, egg weight, and cholesterol content in the eggs were found when they were fed wheat, triticale, and rye [134]. The identification of the optimal triticale level in the diet of poultry, however, requires further research. Significant discrepancies in the results of various studies regarding optimal triticale levels can be related to both the methodology of conducting experiments and the characteristics of triticale varieties grown under different conditions and in different countries [93]. For instance, Landfried [116] established that the proportional replacement of 60% of wheat with triticale had no negative effect on poultry performance. When isoprotein rations were included due to wheat replacement, however, performance significantly deteriorated.

For poultry breeder flocks, a high triticale content in compound feed should be utilized, with consideration for variety characteristics and climate [24,25,27,28,30,135,136]. For example, optimal triticale levels in compound feed (up to 15%) contributed to increased body weight gain, reduced feed costs, and a normal viability when rearing layer breeder pullets. Adult layer breeder chickens fed up to 20% of triticale presented an increase in their egg laying (by 1.5–2%), high viability (96.7–100%), and flock uniformity [19]. Male breeder turkeys fed triticale (8.5%) had improved tenderness and shear value of cooked breast meat in contrast to meat from birds fed diets consisting of corn–soy or triticale–soy [137].

5. Levels of Limiting Amino Acids in Triticale-Based Diets

For the efficient utilization of feed, diets should be used that are balanced in terms of both the amount and the ratio of amino acids. A bird cannot store amino acids, so it should receive them continually and in the right amount; excessively consumed amino acids are deaminated [138–140]. The degree of assimilation of amino acids from specific feeds has a great influence on the efficiency of feed consumption by poultry. Accordingly, the higher the degree of assimilation, the more accessible amino acids are from a particular feed. There is, thus, a direct relationship between the quality of amino acid exposure, productivity, and the health of poultry [141,142].

When using triticale, the balancing of compound feed by amino acids, vitamins, and minerals is also crucial [28,143–145]. There are few data in the literature, however, regarding limiting amino acids when using triticale-based rations, and the data obtained in various experiments on this issue are also quite contradictory. Some authors [42,146,147] reported that an increased lysine supplementation in diets high in triticale directly improved the live weight of piglets, while methionine inhibited their growth. Shimada and Cline [148] noted that the first limiting amino acid in triticale diets for rats is lysine, and the second is threonine. Similar results were obtained in pigs [105,146], and a positive effect of elevating the methionine level when using triticale was also not found. Herein, the opposite results were obtained in broilers: when adding lysine to compound feed with a high triticale content, the body weight of broilers did not increase, while the addition of methionine improved growth [43,47,149]. At the same time, the increased lysine level in compound feed with triticale led to a greater performance of chickens and egg weight. Such a discrepancy in the results can probably be related to certain peculiarities of triticale, e.g., varieties and agro-climatic conditions of cultivation [16,18], as well as the type of diet in which triticale was included.

Thus, there is a need for further research on the optimal level of limiting amino acids in triticale-based rations for specific regions and varieties regionalized in them, taking into account the prevailing types of diets (corn–soybean, wheat–sunflower, etc.). In this regard, not only methionine and lysine deserve attention but also threonine, which can be the second limiting amino acid in compound feed with triticale [19,105].

6. Methods of Leveling Antinutrients in Triticale-Based Feed for Poultry

6.1. Enzymatic Treatment

Despite its many advantages as a food crop, triticale contains many antinutritional substances, such as non-starch polysaccharides (NPS), alkylresorcinols, and trypsin inhibitors that can reduce its biological value significantly [19,48,150]. The presence of these substances impedes its more widespread use in poultry feeding; however, with the help of recent technological innovations, the impact of these antinutritional factors can be overcome or at least mitigated [46].

One of the promising methods capable of breaking down NPS in triticale is the application of enzyme preparations [151,152]. The main negative effect of NPS in triticale is related to its ability to elevate the viscosity of chyme. This, in turn, depends on NPS polymer structure. Splitting such polysaccharides into smaller fragments should, in theory, prevent the creation of a mesh structure and jelly-like chyme, significantly reducing the antinutritive properties. The effect of additives such as enzyme preparations [153] is difficult to estimate when using components in compound feed that are difficult to hydrolyze (barley, rye, millet, sorghum, triticale, peas, sunflower, rapeseed, flax, etc.), since their use in a large amount has a detrimental effect on feed assimilation and poultry performance [154–158].

Enzymes, unlike hormones and biostimulants, are not added to act on the bird's body directly but on the components of compound feed in the gastrointestinal tract [19,159,160]. For example, cellulases catalyze the hydrolysis of the cellulose macromolecules in feed to dextrins and glucose, whereas proteases such as trypsin catalyze the hydrolysis of proteins to amino acids [161,162]. To increase the digestibility and availability of nutrients in compound feed with reduced consuming ability (barley–wheat), therefore, it is recommended to introduce enzyme preparations containing a complex of amylolytic, pectolytic, cellulolytic, and proteolytic enzymes [163,164].

In poultry farming, feed enzyme preparations are widely used [155,157,158] and also contain accompanying organic and mineral substances. These include the remains of the nutrient medium of microorganisms, various fillers and stabilizers, preservatives, and products of the vital activity of microorganisms (amino acids, vitamins, organic acids, etc.). However, the main components of enzyme additives are hydrolytic enzymes (cellulases, xylanases, β -glucanase, α -amylases, proteases, pectinases, phytase, etc.) that play an important role in the assimilation of feed nutrients [97,156,165–168] and are mainly extracted by microbial synthesis using fungi and bacteria.

In numerous studies, it has been established that the inclusion of enzyme preparations with xylanase activity in compound feed based on wheat, rye, and triticale contributed to the better development of chickens and better digestion of dry matter, protein, fat [167–171], and crude fiber [163]. According to García et al. [172], the use of enzyme preparations with xylanase and β -glucanase activity in compound feed with barley contributed to a reduction in chyme viscosity, increased nutrient assimilation and the average daily gains, and cut feed costs. Herewith, some authors found a positive effect on the average daily body weight gain of chickens but did not note an improvement in feed conversion. Moreover, the use of enzyme preparations did not give positive results in a number of investigations. For instance, Brenes et al. [156] did not find a positive effect of enzymes on the productivity of chickens when using wheat and rye.

In a number of studies, it was established that xylanase was effective only when using coarsely ground wheat or whole wheat [156,165,166]. That is, there was an increase in the body weight of chickens by 21% when the enzyme preparation was included in the diet with 7% rye, but this increase was only 11% when the chickens were fed with

a limited fodder amount. In addition, the variety and growing conditions of cereals are of a significant importance. In particular, according to Partridge [173], the application of enzyme preparations in rations with some wheat varieties was much more effective than for other varieties. Under the influence of the enzyme preparation, there was an elevation in the body weight of chickens from 2 to 41% depending on the barley variety.

According to Pettersson and Åman [174], when using triticale with a low, medium, and high content of pentosans (5, 6, and 7%, respectively) in broiler feed, the effect of the enzyme preparation was practically absent at a low content of pentosans. The highest effect was observed when there was a greater content of pentosans. In addition, enzymes that break down NPS [152] can have a different structure depending on their origin (from bacteria or microscopic fungi of specific species and strains) and the effect of their use depends on this. Moreover, depending on their origin, enzymes cleave NPS in different ways and, as a result, can even elevate the viscosity of a solution, i.e., increase the negative effect of NPS [165,175].

The high content of carbohydrate fractions in feed, which are difficult to hydrolyze, reduces the efficiency of the use of nutrients in feed mixtures. When using compound feed with high levels of triticale containing antinutritional substances, treatment of the feed with the appropriate amount of enzyme preparations is paramount [159,160]. The main biological activity of enzyme preparations in this context can be summarized as follows [19]:

- They destroy the walls of plant cells, increasing the availability of starch, protein, and fat, which are included in their composition, for the action of enzymes of the gastrointestinal tract;
- They increase the digestibility of nutrients and improve their absorption in the small intestine [169];
- They eliminate the negative effect of antinutritional factors that affect the absorption and use of nutrients [46];
- They improve the microbiological environment of the intestines by reducing viscosity and increasing the level of monosaccharides [166].

Thus, the recognition of antinutrients in triticale, including NPS, alkylresorcinols, and trypsin inhibitors, necessitates a careful analysis of the crop's nutritional characteristics. This acknowledgment helps to create a fair assessment of how triticale should be used in poultry feeding.

Another promising way to increase the fodder value of cereals and, in particular, triticale is the use of various processing techniques [176]. For instance, Preston et al. [177] found that pelleting wheat-based feed improved chicken performance, with hot pelleting having a higher chyme viscosity compared to cold pelleting. Venäläinen et al. [178] noted the improvement in the fodder qualities of barley after passing it through rollers. According to Perttilä et al. [114], barley ensiling increased the metabolizable energy and digestibility of dry matter for broilers more effectively compared to passing it through rollers. Barley expansion contributed to a decline in chyme viscosity and an improvement in body weight gain and feed conversion, not only in comparison with native but also with micronized barley.

6.2. Extrusion Treatment

Extrusion is one of the most effective and affordable technological methods of preparing grain feed for poultry in order to increase the assimilation of nutrients [136,179,180]. Hereby, an additional area worthy of consideration is cereal extrudates enriched with soy and sunflower. Due to higher energy and protein nutrition values, these are valuable raw materials for the compound feed of young and adult birds [181]. Using layer breeders [19], it was shown that the maximum levels of inclusion of extrudates in the composition of a full, rational, and balanced compound feed were within 40–50% (for triticale–sunflower and triticale–soy extrudates). The use of compound feed with this level of extrudates contributed to the normalization of metabolic processes in the poultry body and had a

positive effect on the performance of chickens, increasing egg production by 3–5% and egg hatchability by 1.86–2.11% [19]. Exploration of this approach, however, is further needed, and more studies on this issue will be important and relevant in the coming years.

Triticale extrusion technology includes a series of successive grain treatments [19], as outlined below. At the beginning of the extrusion process, appropriately prepared grain (or grit) is fed to the extruder body, which is a hermetically sealed chamber in which the screw rotates. When the grain is repeatedly compressed by the screws of the auger, it is compacted and heated as a result of frictional forces. The moisture contained in it changes to a vapor state, and pressure is created, the value of which reaches 3–5 MPa. Under the influence of mechanical and physical deformation, temperature (120–180 °C), and pressure, the raw material changes from a brittle state to a highly elastic one. At the same time, the structure of grain biopolymers changes: proteins are denatured; starch is pasteurized; and the cellulose–lignin complex is destroyed. That is, deep biochemical processes occur, which lead to a significant improvement in the assimilation of feed in the bird's body. These processes continue in the homogenization zone, where the product is already in a viscous state [19].

The main and most important changes in nutrients take place in the extrusion (“explosion”) zone when the heated viscous mass is pressed through the dies (short outlet holes) and abruptly transferred from the high-pressure zone to the atmospheric one. At the same time, the energy accumulated by the product is released at a speed approximately equal to the speed of the explosion [182]. This leads to the “explosion” of the product. As a result of this, a new (extruded) feed with a microporous structure is created, which makes it more accessible to the action of digestive enzymes [19].

During extrusion, changes occur in the biopolymer complexes of the grain. Starch is hydrolyzed, as a result of which its solubility increases, the content of dextrans and amylose grows, and the amount of sugars changes [19]. In different cereals, these processes occur differently due to the natural features of the grain structure of each culture. For instance, when comparing changes in the carbohydrate complex in corn and barley groats due to extrusion, it has been noted [183–185] that the mass fraction of dextrans in corn after extrusion increased by 105 times and in barley by 40 times; amylose in corn extrudate increased by 43 times and in barley by 79 times.

In the process of extrusion, the structure of protein molecules is destroyed, the number of peptides and free amino acids increases, and, as a result, their digestibility improves [19]. Hereby, antinutrients are also inactivated, most of which are of a proteinaceous nature (these are inhibitors of proteases, hemagglutinins, lipoxidase, lipoxygenase, etc.). Excessive or prolonged overheating for the purpose of inactivating antinutrients can lead to a reduction in the availability of amino acids in the extrudate, which will be indicated by an abrupt decline in the proportion of water-soluble proteins [103].

When passing through the body of the extruder and at the moment of “explosion”, the structure of fat cells is destroyed, and intercellular membranes are torn. This leads to an increased amount of released (available) oil, due to which the energy value of the extrudates of oil crops as well as that of mixed extrudates of cereal crops with oil crops rises. Lipids retain their properties during extrusion, as oxidizing enzymes (lipases and lipoxygenases) are inactivated, which contribute to product oxidation and longer storage [19].

There are dry and wet (with a preliminary steaming of raw materials) extrusion technologies. The dry extrusion process lasts up to 30 s. During this period, raw materials are crushed under the influence of deforming loads, exposed to high temperature and pressure, disinfected, and dehydrated (with the output moisture content of the grain being 12–14%, and that of the cooled extrudate 8–10%), and they increase in volume [19]. The mass of the same volume of ground grain or grain mixture should be higher than the mass of the extruded product. This should be four or more times higher for peas and corn and two, three, or more times higher for wheat, barley, and other crops [45,186,187].

The quality of extrudates depends on many factors, including the following: the composition of the raw material, its humidity, the method of preliminary preparation, the

temperature, the duration and intensity of the mechanical impact on the raw material, the design of the screw, etc. [187]. Extrudates of grain feed are lighter in color than the raw material and have a pleasant bread-like taste and smell. After grinding, they contain a little dust-like fraction, have good flowability, and are easily mixed with other components of compound feed [45,147].

In the rations for poultry of all age groups, extruded grains are not yet as widely used as in animal husbandry. Perhaps this is due to the fact that poultry feed mainly uses easily digestible corn and wheat that, in most cases, do not require additional processing, and the use of components such as barley, triticale, rye, peas, etc., is limited by their high levels of cellulose, β -glucans, pentosans, trypsin inhibitors, and other antinutrients [19]. The extrusion of these cereals allows to partially neutralize the existing antinutritional factors and, due to the porous structure of the extrudates, obtain products with a better availability of polysaccharides and proteins for digestive enzymes, i.e., to improve the nutritional value of feed, even in the process of preparing it for feeding and, thus, expand the limits of its use in poultry diets [136].

7. Conclusions and Prospects

Triticale has a range of advantages as a poultry foodstuff compared to other crops. These include its high yield, nutritional value, favorable amino acid composition, high starch content, high fullness and weight of the grain, adaptability to climatic and soil conditions, and its positive impact on the environment. Triticale provides considerable environmental benefits in terms of sustainable agricultural practices [27,48]. Despite several advantages of triticale, however, the practical implications for poultry farmers have a series of issues (e.g., limiting amino acids and antinutrients) that require further research.

Contemporary triticale varieties among grain crops are an affordable and valuable fodder in various regions of the world, and their use in animal and poultry feed is, thereby, gradually increasing [93]. This contributes to the expansion of the fodder base, increasing multicomponent rations and reducing the competition for wheat. However, according to the literature, depending on the level of triticale in a diet, the productivity of poultry may change (increase or decrease) compared to diets based on wheat, and this is one more area that requires further investigation. These limitations of the reviewed studies and the corresponding variation in the results are probably related to the methods of conducting the experiments, different triticale varieties, and the conditions of their cultivation in different countries [93].

The use of additional feed additives is effective in some cases and has no effect in others. Moreover, it should be noted that the effectiveness of using triticale largely depends on the content of antinutrients in it. In this respect, the data obtained in various experiments can be contradictory at times.

Considering the prospective use of triticale in poultry farming and the expansion of its cultivation areas, it is essential to develop and implement new methods to use it effectively when it is present in a high proportion in the compound feed of poultry breeder flocks [24,25,27,28,30,136]. New developments will employ enzyme preparations, taking into account the characteristics of different triticale varieties and climatic conditions, the production of triticale–soy and triticale–sunflower extrudates, and the enrichment of diets using amino acids.

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