

Use of By-Products of Corn Grain Processing in Ruminant Nutrition

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Article Details: Received: 2025-08-19 | Accepted: 2025-12-02 | Available online: 2026-03-31

<https://doi.org/10.15414/afz.2026.29.01.38-46>



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The rising global demand for meat and dairy products requires sustainable approaches in ruminant nutrition that balance productivity, cost efficiency, and environmental responsibility. Traditional high-protein feeds, such as soybean meal, are associated with increasing costs, environmental impacts, and land-use pressures. Corn processing by-products – corn gluten meal, corn gluten feed, corn germ, and corn bran – offer a promising alternative due to their high protein, fiber, and nutrient content. Produced through wet and dry milling, these by-products provide favorable amino acid profiles, good digestibility, and valuable energy levels, supporting growth, lactation, and animal health. Research indicates that their inclusion in ruminant diets can improve milk yield, feed efficiency, and profitability while reducing feed costs by partially or fully replacing conventional protein sources. Economically, local sourcing enhances cost-effectiveness and supports circular economy principles by repurposing agricultural residues. Environmentally, corn by-products can lower greenhouse gas emissions, reduce reliance on land-intensive crops, and decrease competition between food and feed resources. However, careful management of nitrogen and phosphorus excretion is necessary to avoid nutrient runoff. Incorporating corn by-products into feeding strategies offers a practical and sustainable solution for the livestock sector. Their nutritional value, economic benefits, and environmental advantages position them as a viable component in modern ruminant production systems, contributing to long-term sustainability and resilience in the face of global agricultural challenges.

Keywords: ruminant nutrition, corn by-products, sustainable livestock production, feed efficiency, greenhouse gas emissions

1 Introduction

The increasing global demand for meat and dairy products has placed significant pressure on the livestock industry to enhance production efficiency while promoting environmental sustainability (Gerber et al., 2013). Ruminants, such as cattle and sheep, require high-quality protein sources to support growth and productivity. Traditionally, protein-rich feeds like soybean meal have been widely used, yet the rising costs and environmental concerns associated with these conventional feed sources have encouraged the exploration of alternative options (Ružić-Muslić et al., 2014). By-products from corn grain processing offer a promising alternative, providing both nutritional benefits and a pathway to reduce waste through sustainable feed solutions. Corn

is one of the world's most extensively cultivated crops, generating a variety of by-products through its dry and wet milling processes (FAO, 2024). These by-products, including corn gluten meal, corn gluten feed, corn germ, and corn bran, are rich in protein, fiber, and essential nutrients, making them valuable components in ruminant diets (Gwartz & Garcia-Casal, 2014). Studies indicate that these corn by-products offer a balanced amino acid profile and favorable digestibility for ruminants, positioning them as viable supplements or alternatives to conventional feeds (Loy & Lundy, 2019). Incorporating corn by-products into ruminant diets not only reduces feed costs but also aligns with circular economy principles by repurposing agricultural residues (Van Hal et al., 2019). Additionally, these by-products can help lower greenhouse gas emissions from livestock

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production by decreasing reliance on land-intensive crops, such as soybeans (Hünerberg et al., 2013). This review aims to evaluate the role of corn by-products in ruminant nutrition, focusing on their nutritional profiles, economic implications, and environmental benefits, while highlighting empirical evidence and practical considerations for their integration in sustainable livestock production. Corn by-products differ in their amino acid composition, which determines their nutritional value in ruminant feeding. Among the most relevant amino acids are methionine, cysteine, lysine, and threonine, which vary considerably among the main by-products such as corn gluten meal, corn gluten feed, germ meal, and distillers' grains.

2 Current Market Status and Challenges in Ruminant Nutrition

The protein-rich feed market is influenced by the growing demand for meat and dairy products. Health-conscious consumers are looking for higher protein and more nutritious foods, and this demand extends to the quality of animal feed, with an emphasis on non-GMO ingredients and sustainable practices. The total number of ruminants in Slovakia is decreasing. In 2000, the number of cattle was 646,148, and this number decreased to 433,175 animals in 2022. The number of sheep also shows an overall downward trend, but not as significantly as for cattle. While in 2000 the number of sheep was 347,983, in 2022 it was 301,131. The number of sheep shows an

increase in some years, for example between 2006 and 2010 and 2012, where it reached the highest number in this period (409,569).

One of the reasons for the overall decline of ruminants is the high cost of animal feed. Every year, the price of protein components increases, which causes a decrease in animal numbers. Ruminants obtain their nutrition primarily from various sources of feed, which vary considerably in their nutrient content. One of these sources is feed with a high protein content. Ružič-Musličová et al. (2014) from the Institute of Animal Husbandry in Belgrade investigated alternative sources of protein in ruminant diets due to the worldwide increase in demand for animal protein. This demand has been linked to a shortage of protein-rich feed and an increase in feed costs. The authors' research shows that when rams with an average weight of 18.0 kg were fed a diet containing different sources of protein – namely sunflower meal, soybean meal and fish meal, different average daily gains in live weight of 0.169 were manifested; 0.205 and 0.227 kg. Given that EU regulations prohibit the use of fishmeal in ruminant nutrition, the authors advocate exploring non-conventional protein sources such as peas, beans and lupins. High protein foods also include oilseeds such as soybeans and other canola, sunflower, and cottonseed foods. These feeds contain 150 to 535 grams of protein per kilogram of dry matter. These are particularly valued for their amino acid balance and low antinutrient content. Legumes, like beans and peas, also

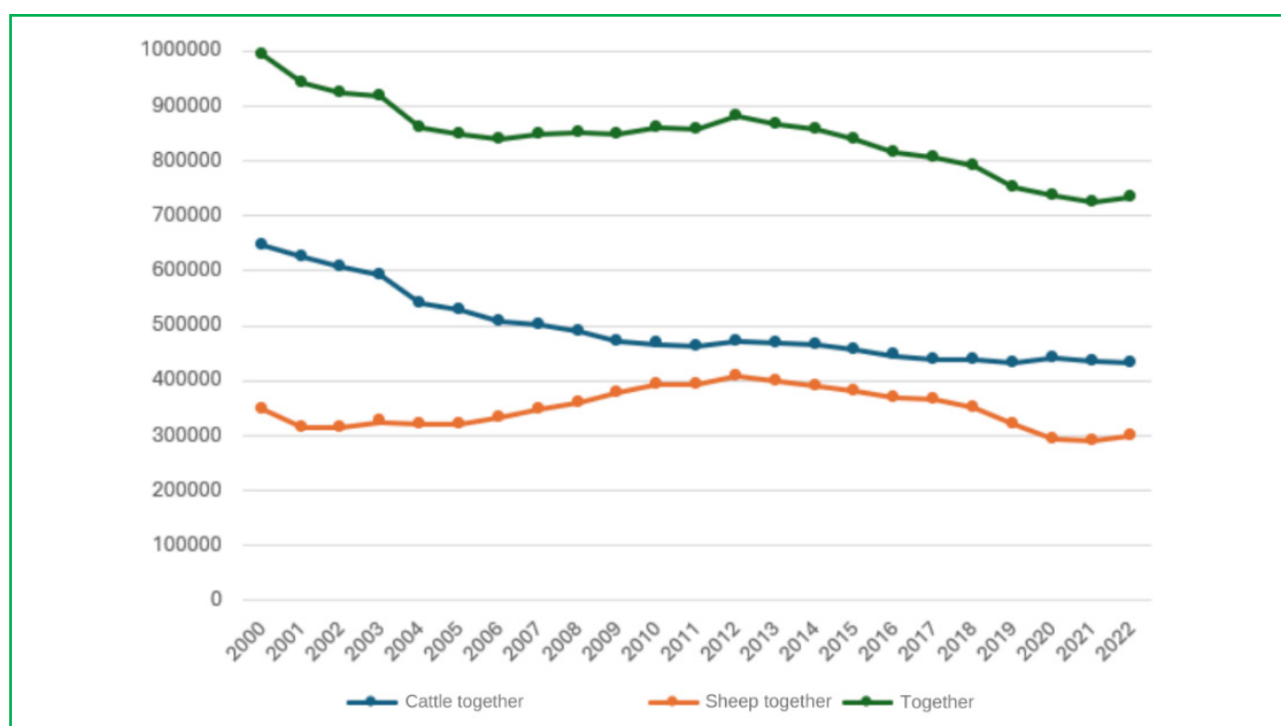


Figure 1 Status of ruminants in the Slovak Republic as of 31. 12. 2022

offer a significant proportion of protein, with around 211 grams per kilogram of dry matter. Although these feed sources are very rich in nutritional value and protein content, they are also an expensive addition to ruminant diets. In an effort to optimize the balance between cost-effectiveness and nutritional value in ruminant diets, corn processing by-products, especially the wet milling process, offer a compelling solution. Integrating these by-products, such as corn germ, into ruminant feed is consistent with sustainable agricultural practices and can be economically beneficial for farmers. Corn processing generates various nutrient-rich by-products like corn germ, corn bran, and corn gluten, which offer excellent value for non-starch applications. These by-products, high in proteins, oils, and minerals, are particularly valuable as a source of animal feed. For instance, protein-dense corn gluten is widely recognized as an effective animal feed component, while corn germ serves as a quality input for edible oils. Increasing utilization of these by-products not only reduces waste but also transforms them into valuable resources for diverse industries (Zhang et al., 2021; Rasby et al. 2003).

3 Main Corn By-products in Ruminant Nutrition

3.1 Corn Gluten Meal

Corn gluten meal (CGM) is a by-product obtained during the process of extracting starch from corn and is particularly rich in protein. This makes it a valuable ingredient for various uses, especially in animal feed, due to its high nutrient content (Li et al., 2019, Albuquerque et al., 2014). The process of acquiring CGM is described by Rausch et al. (2019), whereas during the wet milling process, mechanical dewatering of the gluten stream to 55% to 60% moisture is followed by drying to reduce the moisture content to approximately 10%. During drying, parts of the gluten are recycled due to its stickiness. The drying process must be carefully controlled and the temperature must be kept below 315°C to avoid degradation of xanthophylls and to maintain the desired golden color important for poultry feed, while the final product must contain at least 59.5% protein. The amino acid composition of corn and its by-products varies considerably and affects their nutritional suitability in

Table 1 Comparison of crude protein and selected amino acid contents (% of dry matter) in corn and its by-products

Item	Corn	Corn Gluten Feed	Gluten Meal	Germ Meal
Protein (% DM)	9.33	19.96	64.69	25.89
Lysine	0.28	0.72	1.03	1.89
Methionine	0.2	0.4	1.34	1.15
Cystine	0.22	0.53	1.12	0.28
Tryptophan	0.07	0.08	0.3	0.87
Threonine	0.32	0.85	2.01	0.99
Isoleucine	0.32	0.76	2.48	0.71
Leucine	1.09	2.25	10.91	0.83
Phenylalanine	0.44	0.87	3.91	0.41
Tyrosine	0.29	0.67	3.18	0.7
Valine	0.43	1.16	2.69	0.7
Histidine	0.27	0.77	1.47	1.3
Arginine	0.42	1.19	1.84	1.65
Glycine	0.35	0.91	1.42	3.19
Serine	0.43	0.9	2.54	1.19
Alanine	0.68	1.47	4.81	1.4
Aspartic acid	0.61	1.21	3.3	1.66
Glutamic acid	1.68	3.57	12.44	0.37
Proline	0.8	1.79	5.48	1.55

Source: Loy & Lundy (2019)

ruminant diets. Table 1 summarizes the crude protein and selected amino acid contents (% of DM) of corn, corn gluten feed, corn gluten meal, and corn germ meal, highlighting differences relevant to feed formulation.

Corn gluten meal is a protein-rich corn by-product containing between 600 and 710 g/kg of protein on a weight basis. The main proteins found in CGM are zein and glutelin, with methionine (1.34%) and cysteine (1.12%) being the dominant amino acids. Moreover, CGM is a significant source of carotenes and xanthophylls, whose concentrations range from 49–73 mg/kg and 244–550 mg/kg (Pinto, 2021). In their study, Loy and Lundy (2019) provided a detailed analysis of the composition of CGM. In terms of minerals, CGM provides an average of 0.05% sodium, 74 mg/kg iron, 29 mg/kg zinc, 6 mg/kg manganese, 13 mg/kg copper and 0.8 mg/kg molybdenum. Regarding vitamins, CGM contains significant amounts of choline (367 mg/kg), niacin (61 mg/kg), pantothenic acid (3.9 mg/kg), pyridoxine (7.7 mg/kg) and thiamin (0.3 mg/kg). CGM also contains linoleic acid at a concentration of 45.2% on a dry basis. Regarding energy content, CGM provides metabolisable energy (ME) for different groups of animals: 14,080 MJ/kg for pigs and 17,304 MJ/kg for poultry. For ruminants, it has a net energy for maintenance of 9.085 MJ/kg, a net energy for growth of 6.238 MJ/kg and a net energy for lactation of 9.965 MJ/kg. According to Lakshmi et al. (2017), CGM is suitable for use in livestock and poultry feeds, although its nutritional quality varies significantly depending on the oil extraction method used and the type of maize. Despite some limiting factors, such as high fiber, oil and phytate content, CGM is recognized as a good ingredient for inclusion in animal feed, especially in areas where the corn processing industry produces large quantities of this by-product.

3.2 Corn Gluten Feed

Corn gluten feed (CGF) is a by-product of the wet milling process of maize, which is used to produce starch (Peter & Baker, 2002; García-Lara, 2010). The process begins with soaking the corn, which softens the grain and prepares it for fractionation. During this soaking phase, soaking water is produced, which contains approximately 10% solids. This soaking water is then concentrated by evaporating part of the water, resulting in thick soaking water that contains around 40–50% dry matter. To produce CGF, this thick soaking water is mixed with the fibrous part of the corn. The result of this process is corn gluten feed.

Corn gluten feed can be used as a wet corn gluten feed, which is approximately 40% dry matter, or it can be dried to produce a dry corn gluten meal, which is approximately 87% dry matter (Ham et al., 1995). According to Rausch

et al. (2019) CGF typically contains between 18% and 21% protein and according to De Morais et al. (2021) contains CGF 12.1336 MJ of metabolizable energy per kilogram of dry matter. According to Loy & Lundy (2019), CGF provides significant energy and nutritional value for ruminants. Its net energy content for maintenance is 8.122 MJ/kg of dry matter, while it provides 5.443 MJ/kg of energy for growth. For lactating ruminants, CGF provides 7.243 MJ/kg of energy. In addition to energy, CGF contains essential minerals, including 1.41% potassium, 1.0% phosphorus, 0.43% magnesium and 0.58% sulfur on a dry matter basis. Vitamin content per kilogram of dry matter includes 1.1 mg of β -carotene, 1,742.2 mg of choline, 75.7 mg of niacin, 19.5 mg of pantothenic acid, 14.9 mg of pyridoxine and 0.2 mg of biotin. Dry corn gluten feed is a good choice for ruminants because it contains high amounts of crude protein and fiber (37 to 44.3%), but low amounts of starch (10 to 12.7%) and fat (2.0 to 5.04%). Most of the protein in dry corn gluten feed is very easily broken down in the rumen and its proteins are similar to those found in soybean meal. Studies have also shown that animals fed this feed have higher rumen pH compared to those fed corn, which may benefit their better digestion (Baldassini et al., 2021). De Morais et al. (2021) mentions in his study that CGF has a high concentration of crude proteins, ranging between 22–23.9% of dry matter and a high proportion of rumen-degradable proteins (861.6 g/kg CP). It also contains neutral detergent fiber (38–41.4% of dry weight) and non-fibrous carbohydrates (28.7% of DM), which gives it a significant nutritional value that makes it a suitable alternative to replace more expensive feeds in animal nutrition. Among amino acids, glutamic acid, leucine, and alanine are the most abundant in corn gluten feed, while methionine and lysine occur at lower levels. This profile complements the sulfur amino acid richness of corn gluten meal.

3.3 Corn Germs

Corn germs are another valuable by-product of corn processing. Initially, corn is soaked in water for about 40 hours, softening the kernels and preparing them for separation. The softened kernels then pass through hydrocyclones, which separate the germ from the endosperm based on density differences (Barrera-Arellano et al., 2019). Corn germs contain 10–12% moisture and 12–21% protein. They have the highest fat content among corn by-products, ranging from 18–41%. The fiber content is 10.4%, with up to 45.0% neutral detergent fiber (NDF). Additionally, they contain 12.2% acid detergent fiber (ADF) and 2.4% lignin. Ether extract is at 8.1%, and ash content ranges from 3–5%. Corn germs also contain 6–21% starch and provide 20.7 MJ/kg of gross energy (Zhang et al., 2021). A study by Noormohammadi

et al. (2022) found that adding corn germs to dairy cow feed increased total milk production. The authors reported that replacing 12% of corn grain with corn germs in the feed raised average daily milk production from 53.9 kg/day to 56.6 kg/day without negatively impacting milk composition. Although milk composition remained the same, there was an increase in milk protein yield (1.66 kg/day vs. 1.57 kg/day, $P = 0.03$) and lactose (2.69 kg/day vs. 2.55 kg/day). There was also a trend of increased milk fat yield (1.61 kg/day vs. 1.52 kg/day, $P = 0.10$) and total solids (5.72 kg/day vs. 5.52 kg/day, $P = 0.06$). Blood analysis during the experiment showed no effect on plasma glucose, triglycerides, non-esterified fatty acids, though cholesterol levels rose from an average of 277 mg/dL to 333 mg/dL. Including 12% corn germs in the diets of early lactation cows enhances milk production, energy-corrected milk, and yields of milk protein and lactose. Corn germs are dominated by glutamic acid, leucine, and arginine, whereas lysine and methionine are less represented. This composition provides valuable energy and amino acids but slightly lower protein quality compared with corn gluten meal. These improvements occur without adversely affecting milk composition, suggesting that corn germs can effectively replace corn grain in dairy diets, increasing feed conversion efficiency.

3.4 Corn Bran

Corn bran is a high-fiber by-product of corn processing (Grasso, 2020). It primarily consists of the outer layers of the corn kernel and contains 10–25% starch. Dietary fiber makes up 90% of corn bran's composition, with cellulose at 20–28%, hemicellulose at 70%, and lignin at around 1%. Structurally, it is a heterogeneous mix of carbohydrate polymers and lignin. Corn bran is also rich in phenylpropanoids, especially ferulic acid, comprising about 3% of its content (Akbari et al., 2024; Di Gioia et al., 2011; Dapčević-Hadnađev et al., 2018; Xin et al., 2020). According to Patel (2015), corn bran yields 8.47 g of ferulic acid with over 84% purity after alkaline hydrolysis. Corn bran has a dry matter content of 91.2%, indicating it is mostly dry with very low moisture. It contains 8.7% crude protein, providing a moderate protein level. Its high NDF content, at 74.0%, signifies that it is rich in fibers like cellulose, hemicellulose, and lignin. The acid detergent fiber (ADF) content, which includes more indigestible fibers like cellulose and lignin, is 21.3% (Hao et al., 2021). In terms of minerals, corn bran contains 0.03% calcium, 0.60% phosphorus, 0.83% potassium, and 0.37% sodium. It also provides 0.26% magnesium and notable amounts of manganese (13.0 mg/kg), zinc (233.0 mg/kg), copper (3.5 mg/kg), and iron (90.0 mg/kg). The gross energy of corn bran is 18.5 MJ/kg (Zhang et al., 2021). A study by Janicek et al. (2007) examined the effect of corn bran in

the diet of Holstein cows, focusing on milk production and composition changes with varying amounts of corn bran. Thirty-nine Holstein cows were assigned to three diets containing 10%, 17.5%, and 25% corn bran, replacing corn silage and alfalfa. Results indicated that, while dry matter intake remained stable across treatments, milk production tended to increase with higher corn bran levels, and feed efficiency improved. Milk fat percentage slightly decreased with higher corn bran levels, though total fat yield remained constant. Additionally, increased corn bran inclusion led to higher milk protein yield. These findings suggest that corn bran can enhance milk protein production and overall efficiency in dairy cows without negatively impacting milk fat yield, though fiber levels should be monitored to maintain cow health.

4 Economic Aspects of Using Corn By-products in Ruminant Diets

The economic benefits of using corn by-products in ruminant diets include reducing feed costs, enhancing profitability, and impacting the broader agricultural market. Gatto et al. (2024) found that incorporating by-products like dried distillers grains can significantly cut feed costs by reducing dependence on pricier conventional feeds, though increased demand might raise their prices, affecting other sectors. Van Meijl et al. (2018) warn that extensive by-product use may increase costs for primary crops, potentially impacting the sector's revenue. While local sourcing of by-products can stimulate regional production, it may also lead to higher land use and production costs if not managed carefully. Bernard (2017) highlights that while by-products can lower feed costs, transportation and storage expenses must be considered. Tools such as FEEDVAL, a feed valuation program developed by the University of Wisconsin, are essential for accurately assessing the economic value of feed ingredients. FEEDVAL estimates the relative value of feeds by comparing their energy, protein, fiber, and mineral content to reference feeds like corn and soybean meal. This allows producers to determine whether a by-product is cost-effective based on its nutrient composition and market price. Similarly, Alqaisi et al. (2014) demonstrated that replacing traditional feeds with food industry by-products could reduce milk production costs by up to 14%, especially for large dairy operations. Wilken et al. (2009) found that incorporating 44% wet distillers grains offered the highest profit margins and lowest gain costs in cattle finishing, while Rich (2011) used break-even and profit analyses to identify the most economical by-product inclusion levels. Erickson et al. (2007) note that the growing supply of corn milling co-products, such as distillers grains and corn gluten feed, offers cost-effective feeding options for both

pasture and feedlot systems, potentially improving cattle performance and overall profitability. They emphasize that optimal economic returns depend on adjusting grain processing methods, roughage levels, and storage strategies to match the characteristics of specific co-products. Lastly, Mullenix and West (2023) emphasize that feed costs account for 60-70% of production expenses in cattle operations. Comparing by-products like wet corn gluten feed with other feeds can help producers select more cost-effective options based on the cost per unit of digestible nutrients, optimizing feed costs and profitability.

5 Environmental Impacts of Corn By-products in Ruminant Feed

The inclusion of corn by-products such as corn gluten meal (CGM) and corn gluten feed (CGF) in ruminant diets may help reduce enteric methane emissions. The FAO estimates that global livestock supply chains emit about 7.1 Gt CO₂-eq per year, accounting for 14.5% of total anthropogenic emissions, with enteric fermentation responsible for 39% and feed production for 45% of this total (Gerber et al., 2013). Improving feed quality and digestibility through the use of nutrient-rich by-products can therefore reduce methane intensity – potentially by up to 30% when best feeding practices are applied – contributing to more sustainable and efficient livestock production. Using low-cost agricultural by-products instead of conventional, human-edible feed also reduces competition between food and feed, using resources with minimal alternative value (Van Hal et al., 2019, Bremer et al. 2011). Locally sourced by-products can decrease the environmental impact associated with transportation and import reliance (De Boer & Van Ittersum, 2018). However, careful management is essential to avoid unintended environmental trade-offs. Gatto et al. (2024) caution that policies promoting low-cost feed could lead to increased land use and emissions without proper planning. Effective land use and feed strategies are therefore necessary to mitigate these risks. Furthermore, including corn by-products can cut methane emissions by 15–20% (Hünerberg et al., 2013). Yet, they may increase nitrogen and phosphorus excretion, posing risks like nitrate leaching, which calls for thoughtful diet and manure management Yang et al. (2021). Finally, by-products containing bioactive compounds, such as tannins and polyphenols, offer additional benefits. These compounds can reduce methane emissions in the rumen and support the circular economy by recycling agricultural waste (Jalal et al., 2023; Salami et al., 2019). Life cycle assessments indicate that substituting traditional feeds with by-products significantly reduces the carbon footprint of livestock

production, promoting broader sustainability (Gerber et al., 2013; Pardo et al., 2016).

6 Empirical Approaches to Evaluating Corn By-products in Ruminant Nutrition

Empirical studies on corn processing by-products in ruminant diets emphasize their nutritional, economic, and environmental benefits. Distiller's dried grains with solubles (DDGS) are among the most researched, valued for their high rumen-degradable protein, fiber, and fat content, which improve milk yield, quality, and support cow health, particularly postpartum recovery. DDGS also enhances rumen fermentation, reduces methane emissions, and serves as a cost-effective alternative to soybean meal while promoting sustainable recycling of bioethanol by-products (Pecka-Kiełb et al., 2017, Olayiwola Adeola & Bajjalieh, 1997). Serna-Saldívar and Perez Carrillo (2019) highlight that corn, as the world's leading cereal crop, is extensively processed into food, feed, and industrial products, with dry-milled fractions serving as important components in both human diets and livestock nutrition. Yang et al. (2021) reviewed the nutritional composition and applications of corn starch wet processing by-products, noting their potential as valuable feed ingredients for pigs, poultry, and ruminants, and providing a theoretical basis for further development in livestock nutrition. For fattening cattle, Klopfenstein et al. (2007) showed that wet and dried corn milling by-products offer superior feed value compared to dry rolled corn, increasing feed efficiency, growth, and reducing costs with better manure management. Corn starch by-products like corn bran, corn germ, and corn gluten were reviewed by Zhang et al. (2021) as sustainable replacements for traditional feeds. Corn bran, for instance, can fully replace corn kernels without impacting milk quality, while corn gluten's high protein content supports increased milk production. Studies by Bakshi, Wadhwa, and Makkar (2017) on baby corn by-products found that baby corn husk and silage could be used in ruminant diets, showing higher digestibility and improving milk production when included up to 30% in rations. Jennings et al. (2018) noted that excess protein from corn by-products can increase energy costs in cattle, as nitrogen excretion raises maintenance requirements, reducing overall energy efficiency. Buttrey et al. (2013) found that including 35% WDGS (Wet Distillers Grains with Solubles) improved steer feed efficiency with minimal carcass effects, though it altered fatty acids and slightly reduced beef shelf-life. Together, these studies highlight the diverse advantages of corn by-products in ruminant diets, enhancing feed efficiency, lowering environmental impact, and reducing production costs, all while supporting animal health and productivity.

7 Conclusions

The integration of corn by-products in ruminant nutrition presents a viable and sustainable alternative to traditional feed sources, aligning with the growing demand for efficient and environmentally responsible livestock production. Corn by-products such as corn gluten meal, corn germ, and corn bran provide substantial nutritional benefits, particularly due to their high protein, fiber, and essential nutrient content. These qualities make them effective replacements or supplements to conventional feeds like soybean meal, offering balanced amino acid profiles and enhancing feed efficiency. Economically, utilizing these by-products helps reduce feed costs and enhances profitability, particularly for large-scale operations. By lowering reliance on primary crops for animal feed, corn by-products support the principles of a circular economy, allowing agricultural residues to be repurposed effectively, thus mitigating waste. However, challenges such as potential fluctuations in by-product pricing and transport and storage costs should be considered for cost-effective application. Environmentally, corn by-products offer clear advantages by reducing greenhouse gas emissions, particularly methane, and decreasing the need for land-intensive crops. The reduced competition between food and feed resources and the use of locally sourced by-products further lessen the carbon footprint associated with traditional feed sources. Nonetheless, careful management of nitrogen and phosphorus excretion is required to mitigate risks of nutrient runoff. Empirical studies support the nutritional, economic, and environmental benefits of corn by-products in ruminant diets, showing improvements in milk yield, animal health, and feed efficiency while contributing to sustainable livestock practices. In conclusion, corn by-products provide an effective strategy for enhancing ruminant nutrition, promoting sustainable production, and supporting the livestock industry's economic and environmental goals.

Acknowledgments

This research has been supported by the VEGA project Effective management of the ruminant nutrition using a modern monitoring of the internal environment, No. 1/0321/23, funded by the Slovak Grant Agency for Science.

Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Dilavar Huseynzade: writing – original draft; Ondrej Hanušovský: writing – review & editing; Miroslav

Juráček: conceptualization; Milan Šimko – project Administration.

AI and AI-Assisted Technologies Use Declaration

No generative AI tools/AI-assisted technologies were used during the preparation of the manuscript.

References

- Akbari, M., Gómez-Urrios, C., Razavi, S. H., Khodaiyan, F., Blesa, J., & Esteve, M. J. (2024). Optimization of solid-state fermentation conditions to improve phenolic content in corn bran, followed by extraction of bioactive compounds using natural deep eutectic solvents. *Innovative Food Science and Emerging Technologies*, 93, 103621. <https://doi.org/10.1016/j.ifset.2024.103621>
- Albuquerque, C. S., Rabelo, C. B. V., Santos, M. B. F., Lima, M. B. F., Silva, E. P., Lima, T. S., Ventura, D. P., & Dutra Jr, W. M. (2014). Chemical composition and metabolizable energy values of corn germ meal obtained by wet milling for layers. *Revista Brasileira de Ciência Avícola*, 16(1), 107–112. <https://doi.org/10.1590/S1516-635X2014000100014>
- Alqaisi, O., Hemme, T., Latacz-Lohmann, U., & Susenbeth, A. (2014). Evaluation of food industry by-products as feed in semi-arid dairy farming systems: The case of Jordan. *Sustainability Science*, 9(3), 361–377. <https://doi.org/10.1007/s11625-013-0240-6>
- Bakshi, M. P. S., Wadhwa, M., & Makkar, H. P. S. (2017). Nutritional evaluation of baby corn by-products as feed resources for livestock. *Livestock Research for Rural Development*, 29(7).
- Baldassini, W. A., Ferreira, M. S., Santiago, B. M., Chardulo, L. A. L., Curi, R. A., Lanna, D. P. D., Ribeiro, R. V., Martins, C. L., Arrigoni, M., & Machado Neto, O. R. (2021). Intake, performance, meat quality and fatty acid profile of Nellore bulls finished in feedlot with diets containing dry corn gluten feed. *Livestock Science*, 253, 104715. <https://doi.org/10.1016/j.livsci.2021.104715>
- Barrera-Arellano, D., Badan-Ribeiro, A. P., & Serna-Saldivar, S. O. (2019). Corn oil: Composition, processing, and utilization. In S. O. Serna-Saldivar (Ed.), *Corn* (pp. 593–610). Elsevier. <https://doi.org/10.1016/B978-0-12-811971-6.00021-8>
- Bernard, J. K. (2017). *Considerations for using by-product feeds*. University of Georgia Cooperative Extension Bulletin 862. [online], [cit. 2024-09-31]. Available at: <https://extension.uga.edu/publications/detail.html?number=B862&title=considerations-for-using-by-product-feeds>
- Bremer, V. R., Watson, A. K., Liska, A. J., Erickson, G. E., Cassman, K. G., Hanford, K. J., & Klopfenstein, T. J. (2011). Effect of distillers grains moisture and inclusion level in livestock diets on greenhouse gas emissions in the corn – ethanol – livestock life cycle. *The Professional Animal Scientist*, 27(5), 449–455. [https://doi.org/10.15232/S1080-7446\(15\)30517-9](https://doi.org/10.15232/S1080-7446(15)30517-9)
- Buttrey, E. K., Jenkins, K. H., Lewis, J. B., Smith, S. B., Miller, R. K., Lawrence, T. E., Krehbiel, C. R., Hutcheson, J. P., & Johnson, B. J. (2013). Effects of 35% corn wet distillers grains plus solubles in steam-flaked and dry-rolled corn-based finishing diets on animal performance, carcass characteristics, beef fatty acid composition, and sensory attributes. *Journal of Animal Science*, 91(7), 3355–3363. <https://doi.org/10.2527/jas.2013-5029>

- Dapčević-Hadnađev, T., Hadnađev, M., & Pojic, M. (2018). The healthy components of cereal by-products and their functional properties. In *Sustainable Recovery and Reutilization of Cereal Processing By-Products* (pp. 27–48). Elsevier Ltd. <https://doi.org/10.1016/B978-0-08-102162-0.00002-2>
- De Boer, I.J.M., & Van Ittersum, M.K. 2018. *Circularity in Agricultural Production*. Wageningen University & Research. [online], [cit. 2024-09-25]. Available at: https://www.wur.nl/upload_mm/7/5/5/14119893-7258-45e6-b4d0-e514a8b6316a_Circularity-in-agricultural-production-20122018.pdf
- De Moraes, J. S., Gomes Barreto, L. M., Menezes Wanderley Neves, M. L., Monnerat, J. P. I. dos S., Carvalho, F. F. R. de, Ferreira, M. de A., Cordeiro, E. H. A., & Vêras, A. S. C. (2021). Effect of dietary replacing of corn grain with the blend of residues from the candy industry and corn gluten feed on performance of growing lambs. *Animal Feed Science and Technology*, 282, 115130. <https://doi.org/10.1016/j.anifeedsci.2021.115130>
- Di Gioia, D., Fava, F., Luziatelli, F., & Ruzzi, M. (2011). Vanillin production from agro-industrial wastes. In *Encyclopedia of Industrial Biotechnology: Bioprocess, Bioseparation, and Cell Technology* (pp. 661–667). Elsevier B.V. <https://doi.org/10.1016/B978-0-12-385926-6.00650-0>
- Erickson, G. E., Bremer, V. R., Klopfenstein, T. J., Stalker, L. A., & Rasby, R. J. (2007). Utilization of corn co-products in the beef industry: Feeding of corn milling co-products to beef cattle. *Faculty Papers and Publications in Animal Science*, 507. University of Nebraska–Lincoln. Available at: <https://digitalcommons.unl.edu/animalscifacpub/507>
- Food and Agriculture Organization of the United Nations. (2024). Crops and livestock products. FAOSTAT. [online], 534, 76–78. [cit. 2024-09-18]. Available at: <https://www.fao.org/faostat/en/#data/QCL/visualize>
- García-Lara, S. (2010). Cereal grains: Properties, processing and nutritional attributes. *Crop Science*, 50(6), 2649–2650. [cit. 2024-09-18]. Available at: <https://www.proquest.com/scholarly-journals/cereal-grains-properties-processing-nutritional/docview/759964435/se-2>
- Gatto, A., Kuiper, M., van Middelaar, C., & van Meijl, H. (2024). Unveiling the economic and environmental impact of policies to promote animal feed for a circular food system. *Resources, Conservation & Recycling*, 200. <https://doi.org/10.1016/j.resconrec.2023.107317>
- Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., ... & Tempio, G. (2013). *Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities*. [online], Food and Agriculture Organization of the United Nations (FAO). Rome, Italy. [cit. 2024-09-25]. Available at: <https://www.fao.org/4/i3437e/i3437e00.htm>
- Grasso, S. (2020). Extruded snacks from industrial by-products: A review. *Trends in Food Science & Technology*, 99, 284–294. <https://doi.org/10.1016/j.tifs.2020.03.012>
- Gwirtz, J. A., & Garcia-Casal, M. N. (2014). Processing maize flour and corn meal food products. *Annals of the New York Academy of Sciences*, 1312(1), 66–75. <https://doi.org/10.1111/nyas.12299>
- Ham, G. A., Stock, R. A., Klopfenstein, T. J., & Huffman, R. P. (1995). Determining the net energy value of wet and dry corn gluten feed in beef growing and finishing diets. *Journal of Animal Science*, 73(2), 353–359. <https://doi.org/10.2527/1995.732353x>
- Hünerberg, M., McGinn, S., Beauchemin, K., Okine, E., Harstad, O., & McAllister, T. (2013). Effect of dried distillers grains plus solubles on enteric methane emissions and nitrogen excretion from growing beef cattle. *Journal of Animal Science*, 91, 2846–2857. <https://doi.org/10.2527/jas.2012-5277>
- Jalal, H., Giammarco, M., Lanzoni, L., Akram, M. Z., Mammi, L. M. E., Vignola, G., Chincarini, M., Formigoni, A., & Fusaro, I. (2023). Potential of fruits and vegetable by-products as an alternative feed source for sustainable ruminant nutrition and production: A review. *Agriculture*, 13(2), 286. <https://doi.org/10.3390/agriculture13020286>
- Janicek, B. N., Kononoff, P. J., Gehman, A. M., Karges, K., & Gibson, M. L. (2007). Short communication: Effect of increasing levels of corn bran on milk yield and composition. *Journal of Dairy Science*, 90(9), 4313–4316. <https://doi.org/10.3168/jds.2007-0275>
- Jennings, J. S., Meyer, B. E., Guiroy, P. J., & Cole, N. A. (2018). Energy costs of feeding excess protein from corn-based byproducts to finishing cattle. *Journal of Animal Science*. <https://doi.org/10.1093/jas/sky021>
- Klopfenstein, T. J., Erickson, G. E., & Bremer, V. R. (2007). Feeding corn milling byproducts to feedlot cattle. *Veterinary Clinics of North America: Food Animal Practice*, 23(2), 223–245. <https://doi.org/10.1016/j.cvfa.2007.05.005>
- Lakshmi, R. K. S., Kumari, K. N., & Reddy, P. R. (2017). Corn Germ Meal (CGM) – Potential feed ingredient for livestock and poultry in India – A review. *International Journal of Livestock Research*, 7(10), 1–10. <https://doi.org/10.5455/ijlr.20170928034143>
- Li, G., Liu, W., Wang, Y., Jia, F., Wang, Y., Ma, Y., Gu, R., & Lu, J. (2019). Functions and applications of bioactive peptides from corn gluten meal. *Advances in Food and Nutrition Research*, 87, 1–34. <https://doi.org/10.1016/bs.afnr.2018.07.001>
- Loy, D. D., & Lundy, E. L. (2019). Nutritional properties and feeding value of corn and its coproducts. In C. M. Galanakis (Ed.), *Corn: Chemistry and Technology* (2nd ed., pp. 633–647). AACC International, Elsevier. <https://doi.org/10.1016/B978-0-12-811971-6.00023-1>
- Mullenix, K., West, M., & Rankins, D. L., Jr. (2023). *Byproduct feeds for Alabama beef cattle operations*. Alabama Cooperative Extension System, [online], ANR-1237. [cit. 2024-09-25]. Available at: <https://www.aces.edu/blog/topics/beef/by-product-feeds-for-alabama-beef-cattle/>
- Noormohammadi, A., Ghorbani, G. R., Alikhani, M., Sadeghi-Sefidmazgi, A., Rafiee, H., & Drackley, J. K. (2022). Feeding corn germ instead of corn grain on the performance of Holstein dairy cows fed low-forage diet and human-edible feed conversion efficiency. *Animal*, 16. <https://doi.org/10.1016/j.animal.2022.100541>
- Olayiwola Adeola, N. L. Bajjalieh (1997). Energy concentration of high-oil corn varieties for pigs. *Journal of Animal Science*, 75(2), 430–436. <https://doi.org/10.2527/1997.752430x>
- Pardo, G., del Prado, A., Moral, R., del Hierro, O., & Estellés, F. (2016). Modelling the impacts of feeding strategies on environmental and economic sustainability of Mediterranean dairy farms. *Journal of Cleaner Production*, 112, 2433–2443. <https://doi.org/10.1016/j.jclepro.2015.10.028>
- Patel, S. (2015). Cereal bran fortified-functional foods for obesity and diabetes management: Triumphs, hurdles and possibilities. *Journal of Functional Foods*, 14, 255–269. <https://doi.org/10.1016/j.jff.2015.02.010>

- Pecka-Kiełb, E., Zachwieja, A., Miśta, D., Zawadzki, W., & Zielak-Steciwno, A. (2017). Use of corn dried distillers grains (DDGS) in feeding of ruminants. In *Frontiers in bioenergy and biofuels* (pp. 491–511). IntechOpen. <https://doi.org/10.5772/66357>
- Peter, C. M., & Baker, D. H. (2002). Bioavailability of phosphorus in corn gluten feed derived from conventional and low-phytate maize. *Animal Feed Science and Technology*, 95(1–2), 63–71. [https://doi.org/10.1016/S0377-8401\(01\)00307-8](https://doi.org/10.1016/S0377-8401(01)00307-8)
- Pinto, D., Cádiz-Gurrea, M. D. L., Silva, A. M., Delerue-Matos, C., & Rodrigues, F. (2021). Cosmetics – Food waste recovery. In C. M. Galanakis (Ed.), *Food Waste Recovery* (pp. 503–516). Elsevier. <https://doi.org/10.1016/B978-0-12-820563-1.00004-4>
- Rasby, R. J., Erickson, G. E., Klopfenstein, T. J., & Adams, D. C. (2003). Value and use of corn milling by-products in the cow herd. In *Range Beef Cow Symposium XVIII* (pp. 1–10). University of Nebraska – Lincoln. Available at: <https://digitalcommons.unl.edu/rangebeefcowsymp/62>
- Rausch, K. D., Hummel, D., Johnson, L. A., & May, J. B. (2019). Wet milling: The basis for corn biorefineries. In S. Singh (Ed.), *Corn chemistry and technology* (pp. 501–522). Elsevier. <https://doi.org/10.1016/B978-0-12-811971-6.00018-8>
- Rich, A. R., Erickson, G. E., Klopfenstein, T. J., Luebbe, M. K., Benton, J. R., Griffin, W. A., & Mark, D. R. (2011). Effect of feeding more than 70% wet distillers grains plus solubles on feedlot cattle performance. *Nebraska Beef Cattle Report* [online], (pp. 55–57). University of Nebraska – Lincoln. [cit. 2024-09-18]. Available at: <https://beef.unl.edu/4044efef-0525-4825-89eb-b1744cde6fa4.pdf>
- Ružić-Muslić, D., Petrović, M., Bijelić, Z., Caro-Petrović, V., Maksimović, N., & Mandić, V. (2014). Protein source in diets for ruminant nutrition. *Biotechnology in Animal Husbandry/ Biotechnology in Animal Husbandry*, 30(2), 175–184. <https://doi.org/10.2298/bah1402175r>
- Salami, S. A., Valenti, B., Bella, M., & O’Grady, M. N. (2019). Plant by-products in ruminant nutrition: Influence on animal productivity and environmental sustainability. *Journal of Cleaner Production*, 213, 143–153. <https://doi.org/10.1016/j.jclepro.2018.12.133>
- Serna-Saldívar, S. O., & Perez Carrillo, E. (2019). Food uses of whole corn and dry-milled fractions. In S. O. Serna-Saldívar (Ed.), *Corn: Chemistry and technology* (3rd ed., pp. 435–467). AACC International Press. <https://doi.org/10.1016/B978-0-12-811971-6.00016-4>
- Van Hal, O., de Boer, I.J.M., Muller, A., de Vries, S., Erb, K.H., Schader, C., Gerrits, W.J.J., van Zanten, H.H.E. (2019). Upcycling food leftovers and grass resources through livestock: Impact of livestock system and productivity. *J. Cleaner Prod.*, 219, 485–496. <https://doi.org/10.1016/j.jclepro.2019.01.329>
- Van Meijl, H., Tsiropoulos, I., Bartelings, H., Hoefnagels, R., Smeets, E., Tabeau, A., & Faaij, A. (2018). On the macro-economic impact of bioenergy and biochemicals – Introducing advanced bioeconomy sectors into an economic modelling framework with a case study for the Netherlands. *Biomass and Bioenergy*, 108, 381–397. <https://doi.org/10.1016/j.resconrec.2023.107317>
- Wilken, M. F., Luebbe, M. K., Erickson, G. E., Klopfenstein, T. J., & Benton, J. R. (2009). Effects of feeding high levels of by-products in different combinations to finishing steers. *Nebraska Beef Cattle Reports*, [online], 534, 76–78. [cit. 2024-09-18]. Available at: <https://core.ac.uk/download/pdf/17216942.pdf>
- Xin, H., Sun, F., Sun, K., Fu, Q., Li, Y., Zhang, Y., Rahman, S. U., & Khan, N. A. (2020). Batch-to-batch variation in carbohydrates molecular structures, nutritive value and biodegradation characteristics in corn coproducts. *Animal Feed Science and Technology*, 263. <https://doi.org/10.1016/j.anifeedsci.2020.114458>
- Yang, M., Long, S., He, T., & Piao, X. (2021). Research progress on application of corn starch wet processing by-products in livestock and poultry production. *Chinese Journal of Animal Nutrition*, 33(5), 2504–2514. <https://doi.org/10.3969/j.issn.1006-267x.2021.05.011>
- Zhang, R., Ma, S., Li, L., Zhang, M., Tian, S., Wang, D., Liu, K., Liu, H., Zhu, W., & Wang, X. (2021). Comprehensive utilization of corn starch processing by-products: A review. *Grain & Oil Science and Technology*, 4, 89–107. <https://doi.org/10.1016/j.gaost.2021.08.003>