

Major Intrinsic Factors Affecting the Feeding Value of Sorghum and Their Countermeasures: Postprint

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Abstract

Extensive research has shown that forage sorghum contains three substances that hinder its digestion in animals: phenolic compounds, prolamin, and phytic acid. This article provides a concise review of research developments and advances regarding sorghum application in animal feed, covering the characteristic properties of these three compound classes, their inhibitory effects on digestive enzymes, the digestibility of prolamin, starch, and amino acids, phytic acid and phytate phosphorus, and the application of enzyme preparations in livestock and poultry feeds containing sorghum-based diets.

Full Text

Main Internal Factors Influencing Sorghum Feeding Value and Countermeasures

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Abstract

Extensive research has demonstrated that three classes of compounds in feed-grade sorghum adversely affect nutrient utilization in animals: polyphenolic compounds, kafirin proteins, and phytic acid. This review synthesizes current research on the physicochemical characteristics of these compounds, their inhibitory effects on digestive enzymes, and their impact on the digestibility of

starch, amino acids, and minerals. We also examine the application of enzyme supplements in sorghum-based diets for livestock and poultry, highlighting both the challenges and opportunities in utilizing sorghum as a primary feed ingredient.

Keywords: sorghum; animal feed; polyphenolic compounds; kafirin; phytic acid

Introduction

Sorghum bicolor (L.) Moench is a vital cereal crop in global agroecosystems, ranking as the world's fifth most important cereal by annual production after maize, wheat, rice, and barley. Renowned for its drought tolerance and adaptability to saline-alkaline and nutrient-poor soils, sorghum thrives in harsh environments and represents a cornerstone of sustainable agriculture in arid and semi-arid regions. As one of the most versatile cereals, sorghum serves multiple purposes: human food, animal feed, and industrial raw material for baijiu (Chinese liquor), beer, starch, and processed feed production. While developed countries primarily use sorghum for animal feed and it remains a dietary staple in parts of Asia, Africa, and Central America, China utilizes approximately 85% of its sorghum crop for brewing and vinegar production.

Despite its agronomic advantages, sorghum contains three major anti-nutritional factors that impair nutrient digestibility: polyphenolic compounds (particularly condensed tannins), kafirin proteins, and phytic acid, which affect protein digestion and utilization through distinct but related mechanisms [1]. Starch, the primary energy source in feed, presents an additional challenge as sorghum starch granules are embedded in a protein matrix that hinders enzymatic digestion. Consequently, sorghum has been underutilized in China's industrial compound feed industry. However, since 2013, sorghum usage in animal feed has surged dramatically, with imports reaching 5 million tons in 2014—twice the domestic production—establishing sorghum as a major feed grain in China. This rapid adoption has exposed significant gaps in feed sorghum research, necessitating a comprehensive reevaluation of sorghum's feeding value, mitigation strategies, and breeding priorities. This review synthesizes current knowledge on the key anti-nutritional compounds in sorghum to inform Chinese feed nutritionists and sorghum breeders.

1.1 Polyphenolic Compounds

Phenolic compounds are aromatic hydrocarbons in which hydrogen atoms on the benzene ring are substituted by hydroxyl groups, classified as monophenols or polyphenols based on hydroxyl number. These compounds encompass diverse structures including simple phenolics, phenolic acids, hydrolyzable tannins, condensed tannins, lignin, and lignans [2]. Among cereals, sorghum uniquely contains condensed tannins, though most varieties contain flavonoids. Only

sorghum varieties with the B1_{B2} genes and pigmented testa contain condensed tannins. Modern feed sorghum cultivars developed abroad are typically tannin-free or low-tannin.

Tannin research in sorghum spans over six decades, with numerous studies confirming their negative impact on poultry growth. Nyachoti et al. [3] demonstrated that broilers fed high-tannin sorghum (25.7 g/kg) showed 19.6% lower weight gain and 10.1% reduced feed intake compared to those fed low-tannin varieties (1.12 g/kg), resulting in 14.1% poorer feed conversion. However, academic perspectives on tannin content vary considerably. Some researchers argue that low-tannin breeding has been so successful that tannins no longer limit sorghum utilization [4], while others maintain that even low-tannin varieties retain sufficient condensed tannins and phenolics to impair feed conversion and meat yield in broilers [5]. Recent research indicates that 3% dietary tannin significantly inhibits digestibility of nitrogenous compounds, starch, and minerals in laying hens without affecting lipid digestion [6]. In ruminants, tannins reduce carbohydrate and protein digestibility while inhibiting rumen microbial enzyme activity [7-8], though they also offer benefits. Rumbaugh [9] proposed that tannins bind to plant proteins, reducing their solubility in the rumen and preventing rapid microbial degradation, thereby increasing bypass protein and improving nitrogen utilization efficiency. Recent studies show that replacing corn with sorghum in lamb diets does not impair nutrient digestibility; instead, increasing sorghum content enhances carcass yield, hemoglobin levels, and meat tannin content, thereby improving meat quality [10]. Furthermore, Jayanegara et al. [11] conducted a meta-analysis revealing that high-tannin diets significantly reduce methane emissions by lowering organic matter and fiber digestibility, highlighting an environmental advantage of high-tannin sorghum in ruminant nutrition.

1.2 Sorghum Kafirin

Kafirin, the predominant protein fraction in sorghum, accounts for 42.4% to 57.6% of total crude protein across 12 sorghum varieties, averaging 48.2%. Notably, protein content correlates negatively with kafirin concentration. Kafirin comprises three types: α -kafirin (82.0% of total), β -kafirin (7.5%), and γ -kafirin (10.5%) [13]. γ -Kafirin content inversely correlates with total protein content. Kafirin is notably resistant to digestion, and numerous studies attribute sorghum's poor nutrient utilization to this protein fraction [14].

1.3 Phytic Acid and Phytate Phosphorus

Phytic acid (myo-inositol hexaphosphate) is an organic acid in sorghum grains that forms stable complexes with metal ions as phytate salts. These complexes bind to proteins, starch, and lipids, reducing the activity of endogenous amylases, proteases, and lipases and impairing nutrient digestion. Sorghum contains higher phytic acid levels than other cereals. Comprehensive analysis of 54 sorghum samples shows total phosphorus content of 2.9 g/kg, with phytate

phosphorus at 2.41 g/kg, representing 83% of total phosphorus. In comparison, 37 wheat varieties average 2.20 g/kg total phosphorus (75% as phytate), while barley contains 1.86 g/kg (68% as phytate) [15]. Doherty et al. [16] reported that phytate phosphorus concentrates primarily in the pericarp, with bran levels reaching 5.7–16.9 g/kg compared to only 0.6–1.9 g/kg in decorticated sorghum. These findings confirm that sorghum contains substantially more phytate phosphorus than other cereal grains.

2.1.1 Protein-Coagulating Properties of Tannins

Tannins possess strong protein-binding capacity. Ravindran et al. [17] found that increasing sorghum tannin content from 0.9 to 1.9 g/kg reduced average digestibility of 16 amino acids by 9.8%. Tannins also impair mineral absorption; Hassan et al. [18] demonstrated that high-tannin sorghum (1.36%) significantly reduced broiler growth performance and absorption of calcium, phosphorus, magnesium, sodium, potassium, iron, and cobalt compared to low-tannin sorghum (0.28%). In sorghum grains, tannins associate closely with kafirin proteins. Taylor et al. [19] confirmed that sorghum tannins preferentially bind γ -kafirin, which contains higher proline content (18.7 mol%) than total kafirin (11.1 mol%). This aligns with earlier findings by Shull et al. [20] showing proline levels of 22.6% in γ -kafirin, compared to 8.9% in α -kafirin and 9.7% in β -kafirin.

2.1.2 Inhibition of Digestive Enzymes by Tannins

Tannins inhibit animal digestive enzymes through protein precipitation. Nyamambi et al. [21] investigated sorghum tannin effects on trypsin and amylase activity using both in vitro and in vivo chicken digestion models. In vitro experiments showed residual activities of 70–80% for anthocyanin-degrading enzymes and 35–50% for trypsin. High-tannin sorghum diets markedly reduced 21- to 42-day-old broiler weight gain (42.6%) and feed intake (24.2%) compared to corn diets, deteriorating feed conversion by 22.2%. While corn diets maintained higher residual amylase and trypsin activities in the duodenum and ileum than sorghum diets, enzyme inhibition was less pronounced in vivo. Iji et al. [22] reported that 25 g/kg tannin reduced ileal energy digestibility by 10.7% and protein digestibility by 8.9% in broilers, though tannin levels did not affect amylase, lipase, maltase, sucrase, or alkaline phosphatase activities in the jejunum.

2.1.3 Enzymatic Degradation of Tannins to Improve Digestibility

Polyphenol oxidase extracted from pears, bananas, and avocados effectively reduces phenolic compound concentrations in high-tannin sorghum flour [23]. Towo et al. [24] achieved similar results by adding mushroom polyphenol oxidase and phytase to sorghum porridge, demonstrating the potential for developing feed enzyme preparations containing polyphenol oxidase activity for sorghum-based diets.

2.2.1 Kafirin Reduces Amino Acid Digestibility

Elkin et al. [25] examined tannin and kafirin effects on amino acid digestibility across 12 sorghum samples containing 107.1 g/kg protein and 2.0–38.8 g/kg tannins (average 16.4 g/kg). Both tannins and kafirin correlated negatively with amino acid digestibility, though kafirin exhibited stronger negative correlations for nine essential amino acids than tannins. Kafirin also showed significant negative correlation with metabolizable energy, whereas tannin did not. Among nine amino acids, kafirin affected seven more strongly than tannins; tannins only exceeded kafirin in their effect on lysine, while both had similar effects on valine.

2.2.2 Kafirin Hinders Starch Digestion

Chandrashekar and Kirleis [26] found that sorghum starch gelatinization temperature correlated negatively with kafirin content, suggesting that protein-starch interactions impede complete gelatinization. Protein affects starch digestibility after heat treatment, and sorghum starch-protein interactions may influence gelatinized starch digestibility. Ezeogu et al. [27] confirmed this hypothesis using three-dimensional fluorescence microscopy, showing that collapse of the honeycomb protein matrix in vitreous endosperm results from disulfide cross-linking with matrix proteins, preventing starch granule swelling and blocking amylase access. Consequently, cooked sorghum flour exhibits reduced starch digestibility. Emmambux et al. [28] reported that cooking decreased kafirin digestibility by 24% and overall in vitro protein digestibility by 27%, indicating that heat treatment affects both kafirin and glutelin digestibility.

2.2.3 Genetic Improvement of Endosperm Texture to Reduce Kafirin Content

Watterson et al. [29] reported that vitreous endosperm sorghum (90% corneous) contained 59.6% kafirin, whereas flourey endosperm sorghum (54% corneous) contained only 47.5% kafirin. Broilers fed soft endosperm sorghum showed superior growth performance with feed conversion ratios of 1.49 compared to 1.68 for vitreous endosperm sorghum. Ioerger et al. [30] demonstrated that vitreous endosperm contains more total protein, kafirin, and disulfide compounds than flourey endosperm, while soft endosperm proteins are more soluble. In Australia's arid regions, small-grained sorghum with hard, vitreous endosperm contains more indigestible kafirin. Extensive research shows that kafirin, particularly γ -kafirin, plays a crucial role in grain hardness, with large, soft-grained sorghum containing less kafirin and thus being more digestible. Therefore, genetic improvement of endosperm texture offers a viable breeding strategy to reduce kafirin content.

2.3.1 Anti-Nutritional Properties of Phytic Acid

Phytic acid and its salts are indigestible by humans and non-ruminant animals, forming complexes with micronutrients that reduce bioavailability and cause

mineral deficiencies. Knuckles et al. [31] demonstrated that protein digestibility correlates negatively with phytic acid content, particularly in high-protein plant feeds. Phytic acid also inhibits multiple digestive enzymes, including amylases, lipases, and proteases, affecting starch, lipid, and vitamin utilization. Additionally, phytic acid forms binary complexes with proteins, further reducing protein availability [32].

2.3.2 Phytase Supplementation to Enhance Sorghum Feed Value

Phytase (myo-inositol hexaphosphate phosphohydrolase) is an acidic phosphatase that liberates phosphorus from phytate complexes. Following recognition of its benefits, the livestock industry began supplementing feed with exogenous phytase to improve phosphorus utilization. Nelson et al. [33] pioneered this approach using *Aspergillus ficuum* phytase to enhance phosphorus availability in soybean meal for poultry. Selle et al. [34] demonstrated that adding *Aspergillus niger* phytase (600 FTU/kg) to cold-pelleted sorghum-based broiler diets improved weight gain by 76%, feed intake by 25%, and feed conversion by 47% in 7- to 25-day-old broilers. The European Parliament and Council reported that supplementing pig diets with 200 FTU/kg phytase increased phosphorus and calcium utilization by 32% and 35%, respectively, improving daily gain by 18-28% and feed conversion by 18-24%. Krasucki et al. [35] showed that phytase supplementation in sow diets increased crude protein, amino acid, and organic matter digestibility by 25%, 2%, and 7%, respectively. Liu et al. [36] confirmed that phytase significantly improved broiler growth performance, nutrient utilization, and starch and protein digestion. To address environmental phosphorus pollution from inorganic phosphate supplementation, microbial phytase use in poultry feed has increased substantially, demonstrating positive effects on growth performance, feed efficiency, amino acid digestibility, energy utilization, mineral retention, and bone development [37]. In ruminants, phytase supplementation similarly enhances phosphorus availability for microbial growth [38].

Conclusion

Decades of research have progressively improved feed sorghum quality, with low- or tannin-free varieties now widely cultivated. In the United States, feed sorghum cultivars contain minimal or no tannins, substantially enhancing feeding value. Enzyme supplementation, particularly phytase, in sorghum-based diets has markedly improved animal daily gain, amino acid digestibility, starch digestibility, and overall performance. However, research on sorghum-based diets lags far behind that of wheat-, barley-, and corn-based diets. Further investigation is needed to overcome sorghum's inherent nutritional limitations while leveraging its exceptional drought tolerance, salinity-alkalinity resistance, and adaptability to marginal soils.

Note: Figure translations are in progress. See original paper for figures.

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