Nutritional Value of Dried Distillers Grains with Solubles and Its Application in Swine Production: Postprint

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Abstract

Distillers Dried Grains with Solubles (DDGS) is an industrial by-product of ethanol production. With the increasing utilization of bioenergy, DDGS production has increased. DDGS was first used in ruminant animal production, and in recent years, numerous reports have documented its application in monogastric animal production industries such as swine and poultry. This article reviews research conducted by international scholars on DDGS over the past decade from several perspectives, including the production process of DDGS, its nutritional composition, nutritional value for swine, current application status in swine production, and improvement measures. Although DDGS can replace portions of soybean meal and corn in swine production, its variable quality, low protein quality, and high crude fiber content have limited its extensive utilization. Methods such as screening, fermentation, enzyme supplementation, and combined use with different feed ingredients can expand and enhance the application of DDGS in the livestock industry.

Full Text

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Abstract

Distillers dried grains with solubles (DDGS) are industrial by-products of ethanol production. With the increasing application of bioenergy, DDGS output has been rising. DDGS was first used in ruminant production, and in recent years, numerous studies have reported its use in monogastric animal production industries such as swine and poultry. This review summarizes research from foreign scholars over the past decade on DDGS production processes, nutritional composition, nutritional value for swine, current application status in swine production, and improvement measures. Although DDGS can replace partial soybean meal and corn in swine production, its extensive use is limited by unstable product quality, poor protein quality, and excessively high crude fiber content. Methods such as sieving, fermentation, enzyme supplementation, and combined use of different raw materials can expand and improve DDGS utilization in the animal production industry.

Keywords: DDGS; swine; crude fiber; protein

Global petroleum resources are limited, prompting the search for alternative energy sources through corn-based bioethanol production. The ethanol production process generates by-products known as distillers dried grains with solubles (DDGS). Dry milling produces 17 pounds of DDGS per bushel (approximately 50.8 kg) of corn, while wet milling yields 1.6 pounds of corn oil, 2.6 pounds of protein meal, and 13.5 pounds of gluten feed [1]. According to USDA statistics, 40.5% of corn in the United States is used for ethanol production, with the resulting DDGS utilized as follows: 50.4% for beef cattle, 33.5% for dairy cattle, 9.1% for swine, and 7.0% for poultry production. DDGS replaces 65% of corn and 35% of soybean meal in livestock production [2]. However, although 40.5% of corn is used for ethanol production, only 25% is accounted for when calculated based on the application of corn by-products in the feed industry [2], indicating that many ethanol industry by-products are discarded or not utilized in feed production. Based on current trends, the proportion of DDGS used in swine and poultry production will increase substantially by 2026. Therefore, it is necessary to investigate DDGS quality in greater detail to promote its application in monogastric animals and improve utilization efficiency. In the past, lack of attention to DDGS led to significant quality variation and reduced digestibility of crude protein and neutral detergent fiber (NDF). Over the years, continuous improvements in ethanol production technology have been accompanied by changes in the quality of its by-product DDGS. This review examines the production process, nutrient composition, and nutritional value characteristics of DDGS over the past decade to explore its potential value, current application status in swine production, and possible improvement pathways, aiming to enhance DDGS utilization and expand its application in monogastric animals as an effective solution to alleviate global energy feed shortages.

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1.1 DDGS Production Process

DDGS is a by-product of ethanol production through yeast fermentation of grains. Most fuel ethanol is produced from corn via dry milling (67%) or wet milling (33%) methods [1]. The traditional dry milling process involves adding yeast to a slurry of corn, water, and enzymes to ferment sugars into ethanol. After distillation and separation, the solid residue is dried to produce distillers dried grain protein. Wet milling involves fermenting starch solutions and fermentable sugars separated from solids. During production, the germ is removed to extract corn oil, and the remaining germ meal is mixed with fiber and hull to form corn protein feed, while the gluten portion is separated to form corn gluten meal. New processes produce non-cooking distillers grains (DDGS-BPX). High-protein distillers grains (HP-DDG) are by-products produced after removing seed coats and germs before adding enzymes and yeast for ethanol fermentation. Ethanol production process improvements focus on: 1) converting all starch and sugar into ethanol as completely as possible; 2) converting fiber in corn into starch and sugar through microbial fermentation for ethanol production. After process improvements, ethanol yield increases, but the starch content in DDGS relatively decreases while the relative proportions of crude protein and crude fiber increase.

1.2 Nutritional Composition

Since brewer’ s yeast primarily utilizes starch in grains for growth and ethanol production during fermentation, very little residual starch remains in the by-product, while crude fat, crude fiber, and crude protein are correspondingly concentrated with substantially increased proportions. Previous research on DDGS nutrients focused on crude protein, crude fiber, and phytic phosphorus, with particular concerns about lysine quality, polyunsaturated fatty acids, and crude fiber content. However, DDGS actually contains many other nutrients that can be more effectively utilized in swine production.

1.2.1 Crude Protein

DDGS protein content varies due to ethanol production processes, grain types, and DDGS processing treatments. In wet milling ethanol production, removal of polysaccharides and other soluble carbohydrates before fermentation results in crude protein contents of 48%, 52%, and 51% for DDGS protein concentrate, protein isolate, and sieved by-products, respectively, compared to 33%, 37%, and 40% for traditional DDGS. Therefore, wet sieving steps can increase DDGS protein content [3]. Additionally, DDGS-BPX shows no significant difference in protein content from DDGS, but the former contains significantly higher buffer-soluble protein and significantly lower acid detergent insoluble protein [4]. HP-DDG has higher crude protein content than corn DDGS (cDDGS) [5]. Wheat DDGS (wDDGS) has significantly higher crude protein content than cDDGS (388 vs. 302 g/kg DM), with lower neutral detergent insoluble protein and acid detergent insoluble protein contents, while cDDGS has higher glutamic acid content than wDDGS [5]. DDGS produced from corn after solvent oil extraction before fermentation has higher crude protein and amino acid content than traditional DDGS, with crude protein content of 35.6% on a dry matter basis [6-7]. DDGS from recycled distiller' s grains and re-fermentation has 30%~40% higher protein content than conventional DDGS, but 2~5 times more inhibitors [8], with greater lysine loss [9]. Regarding amino acid composition, lysine, histidine, and glycine are higher in wheat wet distillers solubles (wWDS) than in wDDGS, while other amino acids are higher in wDDGS than in wWDS [10]. After 98°C pretreatment for 1.5 h of a new corn cultivar in Korea, its DDGS total amino acid content is 230~310 mg/g, three times that of corn, with lysine accounting for 2.5%~2.7% and total essential amino acids exceeding U.S. corn by 21.1 mg/g [11].

1.2.2 Crude Fiber

Most corn by-products contain substantial amounts of insoluble fiber requiring coordinated enzymatic action for degradation. DDGS contains 36.74% NDF, 16.2% acid detergent fiber (ADF), 10.22% crude fiber [12-13], 0.77% acid-soluble lignin, and 5.84% acid-insoluble lignin [14]. The hemicellulose component in DDGS from dry milling ethanol production consists primarily of arabinoxylan and pentose-derived xylose and arabinose, with xylose at 10.2% and arabinose at 5.6% [16-17]. Changes in ethanol production processes alter DDGS fiber content. wWDS has lower NDF than wDDGS (23 vs. 312 g/kg) [10]. DDGS-BPX has significantly lower NDF, ADF, and lignin content than DDGS [4].

1.2.3 Crude Fat and Vitamins

DDGS crude fat content ranges from 8.4%~9.7% [18], with fatty acid composition dominated by unsaturated fatty acids. During production, DDGS polyunsaturated fatty acids (PUFA) are prone to oxidation, resulting in peroxide values up to 84.1 meq/kg [19]. wDDGS has significantly lower fat content than dDDGS (38 vs. 115 g/kg DM) [5]. HP-DDG has lower crude fat content than both DDGS-BPX and DDGS [4]. Low-solubles corn distillers dried grain (LS-DDG) has crude fat content of 7.95% [20]. Notably, DDGS vitamin E content positively correlates with crude fat content (R=0.6677, P=0.1473), with average vitamin E content of 6.8 mg/kg in six DDGS samples, along with other B vitamins including vitamin B1 at 7.7 mg/kg, vitamin B2 at 2.3 mg/kg, vitamin B6 at 3.5 mg/kg, and vitamin B3 at 10.9 mg/kg [21].

1.2.4 Crude Ash and Mineral Elements

Wheat DDGS crude ash content is 5.4%, but with high sulfur, nitrogen, phosphorus, and potassium content [22], with sulfur content 3~4 times that of other agricultural by-products such as palm kernel meal and olive residues [23]. DDGS-BPX contains more sulfur, sodium, manganese, copper, molybdenum, and selenium than DDGS, but DDGS has higher zinc content [4]. DDGS has high total phosphorus content, mostly as phytic phosphorus with low utilization efficiency. Total phosphorus contents in DDGS, HP-DDG, and corn germ are 0.76%, 0.33%, and 1.29%, respectively, with biological utilization efficiencies of 60%, 56%, and 25% [using potassium dihydrogen phosphate (KH2PO4) as control] [24-26]. Phytase supplementation can degrade phytic acid in clear steep liquor and whole stillage, releasing 4.52 or 0.86 mg/g of phosphorus [27]. Phytase treatment can increase DDGS protein content and reduce starch residue [28]. Using yeast with phytase during fermentation reduces phytic phosphorus content in distillers grains by 89.8% and increases free phosphorus content by 142.9% [29].

1.2.5 Other Components

DDGS phenolic acid composition is consistent with its corresponding corn, but phenolic acid content is 3.4 times that of corn. Ferulic acid and p-coumaric acid account for over 80% of total phenolic acids, with vanillic acid, caffeic acid, p-coumaric acid, ferulic acid, sinapic acid, and total phenolic acid contents at 0.22, 0.14, 0.72, 4.59, 0.33, and 5.99 mg/g DM, respectively [30]. DDGS is a severely mycotoxin-contaminated material. All 17 DDGS samples from Beijing contained vomitoxin and zearalenone, with average concentrations of 1.36 mg/kg and 882.7 g/kg, exceeding standards by 88% and 41% [31]. Among 30 DDGS samples from Taiwan, 50.8% were simultaneously contaminated with five Fusarium toxins [32]. Additionally, DDGS contains residual antibiotics and microorganisms. Testing of 20 DDGS samples from 43 factories across 9 U.S. states found 13% contained less than 1.12 mg/kg of antibiotics such as erythromycin, penicillin, and tetracycline [33]. The microbial flora in wDDGS is primarily lactobacilli such as *Lactobacillus amylolyticus*, *Lactobacillus panis*, *Lactobacillus pontis*, and occasionally detectable yeasts [19].

1.3 Physical Characteristics

Feed containing DDGS shows increased redness but decreased brightness [34-35]. Adding DDGS to bread or tortillas increases crude fat and crude fiber content, imparting a golden-yellow color [36-37].

2.1.1 Energy Value of DDGS

DDGS has higher gross energy than corn (22.75 vs. 18.82 kJ/kg DM) but lower energy digestibility (76.8% vs. 90.4%) [24], resulting in no significant difference in digestible and metabolizable energy [38]. Energy values vary slightly due to raw material differences. Analysis of 28 DDGS samples showed apparent metabolizable energy (AME) of 5.94~12.21 MJ/kg and true metabolizable energy (TME) of 7.29~13.56 MJ/kg [39]. LS-DDG has digestible and metabolizable energy of 13.53 and 12.39 MJ/kg DM, respectively, comparable to DDGS [20]. Solvent-extracted cDDGS has metabolizable and net energy of 11.96 and 8.56 MJ/kg DM, respectively, lower than DDGS [7]. In corn-soybean based diets for 18.5 kg pigs supplemented with 0, 15%, or 30% wheat-corn DDGS, net energy measured by comparative slaughter was 10.17, 10.16, and 10.17 MJ/kg DM, by indirect calorimetry was 10.82, 10.52, and 10.55 MJ/kg DM, and by chemical analysis was 10.24, 10.26, and 9.91 MJ/kg DM [40]. DDGS supplementation in diets reduces dietary dry matter and energy digestibility [10]. Even with consistent formulated net energy and digestible amino acids, apparent total tract digestibility (ATTD) of dietary dry matter and energy decreases linearly with increasing wheat-corn DDGS, while ATTD of NDF increases linearly [41]. Ethanol production processing and fermentation improve fiber digestibility to some extent, so DDGS has higher apparent ileal digestibility (AID) and ATTD of total dietary fiber (TDF) than corn, but less than 50% of TDF is fermented throughout the intestinal tract, indicating over 50% of DDGS TDF is not digested and absorbed by pigs [42]. Analysis of corn by-products shows that arabinoxylan content can extremely significantly explain variation in ATTD of dry matter (R^2=0.67), while non-starch polysaccharide xylose residues can explain variation in ATTD of dry matter (R^2=0.78), NDF (R^2=0.63), methionine (R^2=0.40), and threonine (R^2=0.11) [43]. Using T-cannulated pigs to test nutrient digestibility of deoiled DDGS, lysine AID decreases with increasing DDGS (0, 20%, and 40%), and both deoiled DDGS and soybean oil significantly affect AID and ATTD of NDF and acid-washed ether extract, with highest NDF AID and ATTD when dietary acid-washed ether extract content is highest and NDF is lowest [44].

2.1.2 Protein and Amino Acid Utilization Efficiency

Among all amino acids in wheat DDGS, lysine has the lowest AID in finishing pigs (82 kg) at only 36% [45], with standardized ileal digestibility (SID) varying greatly (9%~82%) [46-47]. Lysine digestibility in cDDGS also shows substantial variation [47]. wWDS has significantly higher coefficient of standardized ileal digestibility (CSID) for crude protein, lysine, and histidine than wDDGS, while CSID for methionine, cysteine, isoleucine, leucine, and valine is significantly lower than in wDDGS [10]. De-fatting or heat treatment of DDGS changes amino acid digestibility. When corn oil is added to equalize dietary fat content, AID and SID of protein and all essential amino acids except proline and tryptophan are significantly higher in high-fat (11.5%) DDGS groups than in low-fat groups (7.5% and 6.9%), with additional corn oil unable to compensate for this digestibility impairment [48]. After heat treatment of corn DDGS at 130°C for 10, 20, and 30 minutes, growing pig crude protein SID decreases from 77.9% to 72.1%, 66.1%, and 68.5%, respectively, and lysine SID decreases from 66.8% to 54.9%, 55.3%, and 51.9% [49]. Yoon et al. [50] confirmed that increasing

DDGS in 60 kg pig diets reduces crude protein ATTD, though mannanase can improve crude protein ATTD. Lysine SID can be predicted by lysine content in protein; corn DDGS with lysine accounting for less than 1.9% or 2.8% of crude protein is unsuitable for feeding pigs [46-47]. Lysine/crude protein ratio (R=0.63) and lysine SID (R=0.68) are significantly positively correlated with brightness, and metabolizable energy is significantly positively correlated with yellowness (R=0.39) [39], making brightness an important quality indicator for DDGS use. When supplementing DDGS in diets, formulation should be based on digestible amino acids and digestible phosphorus; 10% DDGS can replace 4.25% soybean and 5.7% corn while supplementing 0.1% lysine [51]. DDGS at 40% in diets reduces nitrogen digestibility [20], but nitrogen retention is unaffected by increasing wheat DDGS content [52], possibly related to increased nitrogen excretion [53-54].

2.1.3 Mineral Application

Phosphorus ATTD is as high as 59.1%, making available phosphorus relatively abundant in DDGS (0.36%) [24]. Compared to corn-soybean diets, when formulated based on equal available phosphorus, DDGS-fed piglets show significantly reduced fecal phosphorus, and the 200 g/kg DDGS group reduces calcium retention and calcium ATTD compared to the 100 g/kg DDGS group [55].

In summary, DDGS protein quality is not high, but this problem can be solved by supplementing crystalline amino acids. DDGS energy value is roughly equivalent to corn, though de-oiling during processing reduces energy value, so production processes must be considered during use. When using DDGS to replace corn and soybean meal in monogastric animal diets, it is recommended to balance net energy, ileal digestible amino acids, and available phosphorus to avoid production performance decline.

2.2.1 Application in Piglet Diets

With consistent net energy and digestible amino acids, adding 7.5% cDDGS to diets for 5.2 kg piglets does not affect average daily gain (ADG), average daily feed intake (ADFI), or feed conversion efficiency (G/F) [56]. For 6.4 kg piglets during days 1-7 post-weaning, 7.5% cDDGS addition is feasible, increasing to 15% during days 8-42, and 7.1 kg piglets consuming diets with up to 25% cDDGS show no impact on ADG, ADFI, or G/F [57-58]. However, cDDGS addition up to 30% in piglet diets significantly reduces ADFI [59]. If pigs are adapted for a period (21 days) post-weaning before adding up to 30% cDDGS, production performance is unaffected [60]. Naturally, if cDDGS has undergone solvent oil extraction [7] or piglets are large enough (11 kg) [57], 30% corn DDGS also does not affect performance. Adding 30% sorghum DDGS to diets for 11 kg piglets reduces G/F [61]. Adding 10% wDDGS to 6.2 kg weaned pigs does not affect feed intake or final body weight, but 15% addition significantly reduces feed intake and body weight gain [62]. Flavor addition in early-stage diets for piglets (6.7 kg) is detrimental to later DDGS or HP-DDG diet consumption and shows a significant trend of reducing ADG [63]. DDGS addition increases inflammatory factor mRNA expression in the ileum of 5.2 kg piglets [56]. High-sulfur DDGS can increase serum α-tocopherol and hepatic glutathione content in 8-week-old castrated male pigs, suggesting high-sulfur DDGS may protect piglets from damage by highly oxidized DDGS [19].

2.2.2 Application in Growing-Finishing Pig Diets

Most studies indicate that adding up to 15% [50,64], 20% [53,65], or 30% [54] cDDGS to growing-finishing pig diets does not reduce production performance. Exceptions include Xu et al. [66-67] reporting that up to 30% DDGS in 22-115 kg pig diets reduced ADFI and ADG (29.8 kg pigs). DDGS addition up to 40% significantly reduces ADG and ADFI [68]. Maintaining consistent digestible lysine and tryptophan and replacing corn and soybean meal in 33 kg growing pig formulas with DDGS significantly reduces ADG [69]. With consistent available phosphorus, digestible ileal lysine, and metabolizable energy, 30% DDGS in diets does not reduce ADFI, but simultaneous addition of 30% DDGS and 5% tallow significantly reduces ADFI compared to corn-soybean control [70]. Under the same conditions, providing 30% DDGS diets in meal form to young pigs significantly increases ADFI and reduces G/F compared to corn-soybean control, while pelleted DDGS does not affect ADFI or G/F [71]. Pigs require adaptation to DDGS; with consistent net energy and digestible lysine, adding 30% DDGS to young pig diets significantly reduces ADFI and ADG in the first phase (29-50 kg) but does not affect overall (29-120 kg) growth performance [72]. Abrupt introduction of 20% DDGS does not adversely affect 51.3 kg finishing pigs, but abrupt introduction of 40% low-digestible lysine DDGS significantly reduces ADG [73]. Raw material type also affects DDGS utilization efficacy. Adding 0-30% wheat-corn DDGS to corn-barley-soybean meal-based diets for 25.5 kg pigs with consistent net energy and digestible amino acids results in linear reduction of ADG and a trend toward reduced G/F with increasing wheat-corn DDGS [41]. Compared to corn-soybean diets, adding 15% or 30% wheat-soybean DDGS to 18.6 kg pig diets linearly reduces ADFI and ADG but does not significantly affect G/F [74]. Additionally, gradually increasing solvent-extracted cDDGS from 0 to 30% in diets significantly reduces ADG and ADFI in 29.6 kg growing pigs, with a significant trend toward reduced G/F [7]. Replacing 50% or 100% of soybean meal with HP-DDG in 22 kg growing pig diets does not affect performance [65].

2.2.3 Effects of DDGS on Carcass Quality and Meat Quality

Although most studies confirm that adding certain proportions of DDGS to diets does not affect growing-finishing pig production performance, DDGS effects on meat quality are negative and significant. With increasing dietary DDGS content (0-30%), live weight and dressing percentage decrease [7,64,66]. With consistent ileal digestible amino acids, 20% DDGS reduces dressing percentage [20]. Compared to control, 30% DDGS dietary addition reduces carcass weight by an average of 5.1 kg [75-76]. Reduced dressing percentage may be related to imbalanced DDGS protein, enhanced visceral metabolic activity, and increased visceral weight [77], or may be associated with high DDGS crude fiber content increasing feed passage rate and small intestine growth [78-79]. With consistent net energy and digestible lysine, growing pigs fed 30% DDGS diets show significantly reduced loin eye area and lean meat percentage [72]. Increasing dietary DDGS from 10% to 30% reduces marbling in back muscles [66]. The greatest DDGS impact on meat quality is increased muscle PUFA content and iodine value, making pork difficult to process and store. Replacing corn and soybean meal with 20% or 30% DDGS in 100 kg barrow diets reduces belly fat firmness at slaughter (130 kg) [65-67,70] and increases belly fat iodine value [80]. Forty percent DDGS reduces finishing pig loin eye area and increases backfat unsaturation [73]. As DDGS increases from 0 to 15%, 30%, and 45% in growing-finishing pig diets, backfat thickness decreases linearly, subcutaneous fat saturated and monounsaturated fatty acid concentrations decrease linearly, PUFA concentration increases linearly, and inner and outer backfat iodine values increase linearly [69]. Stein [24] summarized eight trials reporting DDGS effects on iodine value, with seven showing increased iodine value and one unchanged. High iodine value pork is very soft, making it unsuitable for processing, and prone to oxidative deterioration. Too high dietary DDGS proportion (30%) affects lipid peroxidation value (TBARS) during storage, reducing meat shelf life [81]. The cause of reduced belly fat firmness and increased iodine value is DDGS' s high unsaturated fatty acid content leading to increased unsaturated fatty acids in fat and muscle tissue [7,66]. Therefore, reducing DDGS fat content from 16.0% to 5.6% decreases pork PUFA concentration and iodine value [82]. Simultaneous addition of 30% DDGS and 5% tallow can reduce belly fat iodine value [70], though the improvement is small [83]. LS-DDG [20] and 10% corn germ [65] can partially alleviate DDGS negative effects on pork. Vitamin E can reduce TBARS and meat total volatile basic nitrogen (TVB-N) concentration, partially mitigating reduced meat shelf life from excessive DDGS [81]. Adding 0.6% conjugated linoleic acid (CLA) to 20% DDGS diets for 100 kg barrows reduces iodine value and increases lean meat percentage, but CLA has minimal effects on meat quality under fresh, refrigerated, or frozen storage [84]. Xu et al. [67] confirmed that 15% and 30% DDGS dietary groups show linear reduction of C18:2 and iodine value when DDGS is removed 3, 6, and 9 weeks before slaughter, so to avoid DDGS effects on pork quality, it is best to discontinue DDGS diets 3 weeks before slaughter, consistent with Hill et al. [85] recommendations.

2.3 Application of DDGS in Sow Diets

Early studies showed that adding 40%~80% DDGS to gestating sow diets did not affect sow body weight, feed intake, litter size, or piglet weight [86-87]. Hill et al. [85] showed that adding only 15% DDGS and 5% beet pulp during lactation did not significantly affect piglet weight gain, mortality, or sow lactation weight loss. After balancing metabolizable energy and lysine, simultaneous addition of

20% or 40% dietary cDDGS during late gestation and lactation in parity 2 or 3 sows did not affect reproductive performance [88]. Wilson et al. [89] showed that adding 50% DDGS during gestation and 20% DDGS during lactation increased weaned pig mortality in the first parity, but this phenomenon disappeared in the second parity, and DDGS addition in the first parity shortened the second parity estrus interval, so DDGS inclusion in lactating sow diets can reach 20%.

In summary, within certain ranges and with adaptation, DDGS can replace corn and soybean meal in pig production formulas. However, to address high iodine value meat caused by PUFA, it is recommended to add additives such as CLA and vitamin E while discontinuing DDGS 21 days before slaughter. Reports on DDGS application in sows are limited, but gestating sows can tolerate high-fiber diets, making NDF-rich DDGS theoretically suitable for gestating sows. Therefore, increased research on DDGS use in sows is necessary to observe its effects. Additionally, DDGS application research in swine production has focused on production performance and meat quality, but limited data suggest certain sulfur-rich DDGS may have antioxidant effects, and some DDGS have anti-inflammatory effects. Besides being rich in phytic phosphorus, DDGS is also rich in other minerals and phenolic acids that may affect pig immunity and antioxidant capacity, warranting further investigation.

3.1 Sieving

The biggest DDGS problem is large quality variation, low protein quality, and excessively high crude fiber content. Sampling analysis of DDGS from 27 ethanol plants using the POET (Sioux Falls, SD) system shows that 25.6% of dry matter content variation comes from time, 7.1% from different production locations, with production location differences explaining 38.9%, 12.5%, 11.1%, 17.2%, and 25.5% of variation in crude protein, crude fat, ADF, NDF, crude fiber, and sulfur content, respectively, while ADF and NDF content variation is mostly due to time (43.6% and 50.1%). Therefore, when using DDGS, raw materials from the same production period and process should be used to minimize nutrient variation [90]. The simplest and most effective method to reduce DDGS crude fiber is sieving. After sieving dried distillers grains with 1,130, 869, 582, and 389 m sieves, the obtained materials account for 27.2%, 22.8%, 21.4%, and 15.0%, with 13.5% on the bottom pan, and NDF contents of 38.8%, 36.8%, 34.6%, 32.2%, and 27.7%, respectively [91]. Sieving wDDGS through an 80-mesh sieve (249-177 m) increases crude protein from 371.6 g/kg to 432.4 g/kg in the bottom pan while significantly reducing NDF and ADF [92]. Air classification of sieved fractions can further reduce DDGS crude fiber content. Air classification of the 869-1,130 m sieve fraction with wind speed increasing from 1.75 to 1.92 ms^{-1} increases light fraction content from 7.2% to 13.6%, reduces NDF content from 63.1% to 59.0%, and decreases NDF separation coefficient from 2.7 to 2.2 [91]. This has been verified in pilot plants with good results [93]. For NDF reduction, low-speed winnowing three times is equivalent to medium-speed winnowing once, and winnowing the entire DDGS at once is less efficient than sieving before separate winnowing of sieve fractions [94]. Xylanase addition (24,000 U/kg) can increase AID of NDF in liquid DDGS diets [95]. However, enzyme action is specific, so effective DDGS fiber degradation requires multi-enzyme mixtures.

3.2 Fermentation

Fermentation process improvements can also enhance DDGS quality. Fermentation of raw starch increases sterol, phenolic compounds, and β-glucan content in Pronghorn triticale DDGS and increases tocopherol and phenolic compounds in CDC Ptarmigan DDGS [96]. Additionally, raw material pretreatment before fermentation can increase DDGS nutritional value [97]. Acid, alkali, or hot water pretreatment of DDGS can decompose cellulose to release sugars, and pretreated DDGS can continue enzymatic hydrolysis with cellulase to produce sugar [98], with the resulting fermentation by-product DDGS having improved nutritional value. Using the compound enzyme preparation STARGEN 001 containing α-amylase and glucoamylase to treat raw starch at 50°C before yeast fermentation for ethanol production yields DDGS with higher nutritional value [96].

3.3 Different Component Combinations

Studies confirm that mixing dehulled barley and grain DDGS significantly alters nutrient component structure. Detection shows that molecular spectral intensity related to fat [99] and spectral characteristics related to protein molecular structure change after mixing grains and grain by-products [100], with final feed combinations altering feed chemical and nutritional structure and changing nutrient digestibility and availability. When mixing condensed distillers solubles (CDS) and wet distillers grains (WDG), as CDS decreases, cDDGS color becomes brighter, insoluble fiber content and amino acids increase, while fat and total soluble sugar content decrease [101]. Compared to mixing saturated and unsaturated fats, partial chemical hydrogenation of fat more effectively improves digestibility, but note that when dietary iodine value is too low (20), digestibility instead decreases [102]. Research generally considers heat damage as the cause of low amino acid digestibility in DDGS, but syrup balls have amino acid AID and SID consistent with or higher than DDGS, while most amino acids in condensed solubles and stillage evaporator have lower digestibility than DDGS, especially methionine. If heat damage caused reduced amino acid digestibility in condensed solubles, lysine rather than methionine should be most severely affected, so the cause of reduced DDGS amino acid digestibility may be other factors such as excessively high dietary fiber concentration or too low lysine concentration [103].

3.4 Production of Active Substances

DDGS can be used to produce bioactive substances, such as producing 278 g/g β-carotene through co-fermentation or single fermentation of DDGS by

Phaffia rhodozyma (ATCC 24202) and *Sporobolomyces roseus* (ATCC 28988) [104]; producing lignin-degrading enzymes through white-rot fungi fermentation [105]; and producing schizophyllan through fermentation of malt extract and DDGS by *Schizophyllum commune* (ATCC 20165) [106]. Additionally, plant sterols and octacosanol can be extracted from cDDGS and sorghum DDGS [107].

Although DDGS can produce bioactive substances, its major use remains in animal production. Producers need to understand raw material nutrient composition and variation to better select and utilize this material. Ethanol producers should control production processes to stabilize DDGS quality. Attention to DDGS nutritional value should extend beyond amino acids, crude fiber, and phytic phosphorus, as DDGS is also rich in other minerals and vitamins that may improve feeding effects through immune and antioxidant functions. More research on DDGS use in sows is also necessary. Ultimately, through process improvements by ethanol producers and efforts by animal nutrition experts, comprehensive investigation of DDGS nutritional value and expanded utilization will provide an effective solution to alleviate energy feed shortages in the feed industry.

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