Comparative Study on Differences in Nutritional Composition of Different Types of Distillers' Grains: Postprint

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Abstract

This study aimed to compare the differences in nutritional composition among different types of distiller' s grains and evaluate their nutritional value. A total of 24 samples from five categories of distiller' s grains were collected, including 8 strong-flavor sorghum distiller' s grains, 4 sauce-flavor sorghum distiller' s grains, 4 highland barley distiller' s grains, 3 corn distiller' s grains, and 5 brewer' s grains. Their nutrient composition was analyzed, the Cornell Net Carbohydrate and Protein System (CNCPS) was applied to evaluate their rumen degradation characteristics, atomic absorption spectrometry was used to determine their iron, copper, manganese, and zinc contents, and their anti-nutritional factors tannin and silicon contents were measured. The results showed that: 1) The pH and initial water content of brewer' s grains were significantly higher than those of other distiller' s grains ($P<0.05$). 2) Brewer' s grains had the highest crude protein content, which was significantly higher than that of strong-flavor sorghum distiller' s grains, highland barley distiller' s grains, and corn distiller' s grains ($P<0.05$). The neutral detergent insoluble protein (NDIP) content of brewer' s grains and sauce-flavor sorghum distiller' s grains was significantly higher than that of other distiller' s grains ($P<0.05$). The acid detergent insoluble protein (ADIP) content of strong-flavor sorghum distiller' s grains and sauce-flavor sorghum distiller's grains was significantly higher than that of other distiller' s grains ($P<0.05$). The ether extract content of corn distiller' s grains was significantly higher than that of other distiller's grains ($P<0.05$). The crude fiber, neutral detergent fiber, acid detergent fiber, and acid detergent lignin contents of strong-flavor sorghum distiller' s grains were significantly higher than those of other distiller' s grains ($P<0.05$). The starch content of corn distiller' s grains was significantly higher than that of other distiller' s grains ($P<0.05$), while the starch content of brewer' s grains was significantly lower than that

of other distiller' s grains (P<0.05). 3) According to CNCPS classification, the proportion of rapidly degradable carbohydrate (CA) in brewer' s grains was significantly higher than that in other distiller' s grains (P<0.05), the proportion of moderately degradable carbohydrate (CB1) in corn distiller' s grains was significantly higher than that in other distiller' s grains (P<0.05), the proportion of non-degradable carbohydrate (CC) in strong-flavor sorghum distiller' s grains was significantly higher than that in other distiller' s grains (P<0.05), the proportion of slowly degradable true protein (PB3) in brewer' s grains was significantly higher than that in other distiller' s grains (P<0.05), and the proportion of non-degradable true protein (PC) in strong-flavor sorghum distiller' s grains was significantly higher than that in other distiller' s grains (P<0.05). 4) The iron and manganese contents of strong-flavor sorghum distiller' s grains and sauce-flavor sorghum distiller' s grains were significantly higher than those of other distiller' s grains (P<0.05), while the copper and zinc contents of brewer' s grains were significantly higher than those of other distiller' s grains (P<0.05). 5) The tannin content of brewer' s grains was significantly lower than that of other distiller's grains (P<0.05), and the silicon content of strong-flavor sorghum distiller' s grains was significantly higher than that of other distiller' s grains (P<0.05). It can be seen that the nutritional composition varies significantly among different types of distiller' s grains. Corn distiller' s grains provided the highest quality carbohydrate fraction, brewer's grains provided the highest quality protein fraction, highland barley distiller' s grains and sauce-flavor sorghum distiller' s grains were of relatively high quality, while strong-flavor sorghum distiller' s grains were of the poorest quality, and they should be added appropriately according to actual production requirements.

Full Text

Comparative Study on Nutrient Composition Differences Among Different Types of Distillers' Grains

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Abstract: This study aimed to compare the nutrient composition differences among different types of distillers' grains and evaluate their nutritional values. A total of 24 distillers' grains samples were collected across five categories: 8 Luzhou-sorghum distillers' grains (L-SDG), 4 Maotai-sorghum distillers' grains (M-SDG), 4 highland barley distillers' grains (HBDG), 3 corn distillers' grains (CDG), and 5 barley brewers' grains (BBG). Nutrient compositions were analyzed, ruminal degradation characteristics were evaluated using the Cornell Net Carbohydrate and Protein System (CNCPS), mineral elements (iron, cop-

per, manganese, zinc) were determined by atomic absorption spectrometry, and anti-nutritional factors (tannin and silicon) were measured. The results showed: 1) BBG exhibited significantly higher pH and initial moisture content compared to other distillers' grains ($P<0.05$). 2) BBG had the highest crude protein content, significantly exceeding that of L-SDG, HBDG, and CDG ($P<0.05$). The neutral detergent insoluble protein (NDIP) content in BBG and M-SDG was significantly higher than in other distillers' grains ($P<0.05$), while the acid detergent insoluble protein (ADIP) content in L-SDG and M-SDG was significantly higher than in others ($P<0.05$). CDG showed significantly higher ether extract content than other types ($P<0.05$). L-SDG had significantly higher crude fiber, neutral detergent fiber, acid detergent fiber, and acid detergent lignin contents than other distillers' grains ($P<0.05$). CDG demonstrated significantly higher starch content than other types ($P<0.05$), whereas BBG showed significantly lower starch content than others ($P<0.05$). 3) According to CNCPS classification, BBG had a significantly higher proportion of rapidly degradable carbohydrate (CA) ($P<0.05$), CDG had a significantly higher proportion of moderately degradable carbohydrate (CB1) ($P<0.05$), L-SDG had a significantly higher proportion of non-degradable carbohydrate (CC) ($P<0.05$), BBG had a significantly higher proportion of slowly degradable true protein (PB3) ($P<0.05$), and L-SDG had a significantly higher proportion of non-degradable true protein (PC) ($P<0.05$). 4) L-SDG and M-SDG contained significantly higher iron and manganese levels than other distillers' grains ($P<0.05$), while BBG had significantly higher copper and zinc contents ($P<0.05$). 5) BBG showed significantly lower tannin content than other types ($P<0.05$), and L-SDG had significantly higher silicon content than other distillers' grains ($P<0.05$). These findings indicate substantial variation in nutrient composition among different distillers' grains types. CDG provides the highest quality carbohydrate fraction, BBG provides the highest quality protein fraction, HBDG and M-SDG exhibit relatively good quality, while L-SDG shows the poorest quality. Selection and supplementation should be based on specific production requirements.

Keywords: distillers' grains; nutrient composition; CNCPS

Distillers' grains are major byproducts of the brewing industry, characterized by large production volumes, rich nutrient content, and low cost. Their utilization as animal feed can substantially conserve food grains, offering significant development prospects. Commonly used distillers' grains in production include white spirit grains and brewers' grains, with white spirit grains further classified by raw materials such as sorghum, corn, highland barley, and potato-based distillers'grains. Sorghum distillers'grains can be subdivided into strong-aroma and sauce-aroma types according to traditional fermentation processes. Corn, highland barley, and potato distillers'grains are typically pure grain byproducts from small-scale farmers or workshops, with limited sources and smaller production volumes. China exhibits great diversity in distillers' grains types, with varying brewing raw materials and processes, resulting in significant differences in nutri-

ent composition. The Cornell Net Carbohydrate and Protein System (CNCPS) effectively predicts feed biological value by calculating degradation and passage rates of carbohydrate and protein fractions to estimate rumen fermentation extent, microbial protein production, post-ruminal absorption, and total supply of metabolizable energy and protein to animals. Currently, conventional nutrient analysis methods are predominantly used for nutritional evaluation of distillers' grains. Therefore, this study aimed to compare nutrient composition differences among different distillers' grains types and evaluate their nutritional values, thereby addressing data gaps in CNCPS components for various distillers' grains, supplementing and improving nutritional value databases, and providing fundamental data to guide scientific feed formulation utilizing distillers' grains.

1.1 Sample Collection

A total of 24 distillers' grains samples were collected from Sichuan Province (Chengdu, Yibin, Luzhou, and Leshan), Qinghai Province (Haibei, Haidong, and Hezuo), Yunnan Province (Kunming and Lincang), Henan Province (Zhengzhou), and Hebei Province (Shijiazhuang). The samples included 8 Luzhou-sorghum distillers' grains (L-SDG), 4 Maotai-sorghum distillers' grains (M-SDG), 4 highland barley distillers' grains (HBDG), 3 corn distillers' grains (CDG), and 5 barley brewers' grains (BBG) (all barley-based). Geometric sampling methods were employed for collection. Fresh distillers' grains were sealed in plastic bags, transported to the laboratory in preservation boxes, oven-dried at 65°C to produce air-dried samples, ground to pass through a 40-mesh sieve for nutrient analysis, and stored at 4°C until use.

1.2 Measurement Indicators and Methods

Conventional nutrient components including bulk density, initial moisture, dry matter (DM), crude fiber (CF), crude protein (CP), ether extract (EE), neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), crude ash (Ash), calcium (Ca), and total phosphorus (TP) were determined according to standard methods in "Feed Analysis and Feed Quality Detection Technology" . Nitrogen-free extract (NFE) content was calculated by difference. Neutral detergent insoluble protein (NDIP) and acid detergent insoluble protein (ADIP) contents were determined using the Van Soest method. Soluble crude protein (SCP) content was measured following the method of Krishnamoorthy et al. Non-protein nitrogen (NPN) content was determined according to Licitra et al. Starch content was measured using the AOAC (996.11) standard method with a starch assay kit. pH was measured using a pH meter. Mineral elements iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn) were determined by atomic absorption spectrometry. Tannin content was measured using the GB/T 27985-2011 spectrophotometric method. Silicon (Si) content was determined following the method of Dai Weimin et al. Mycotoxin content was measured using enzyme-linked immunosorbent assay (ELISA) kits.

1.3 CNCPS Component Calculation

CNCPS component calculations followed the methodology proposed by Sniffen et al.

1.4 Statistical Analysis

Data were analyzed using one-way ANOVA with SPSS 22.0, followed by Duncan' s multiple comparison test. Differences were considered significant at $P<0.05$. Results are expressed as means ± standard deviation.

2.1 Physical Characteristics of Different Fresh Distillers' Grains

As shown in , CDG exhibited significantly higher bulk density compared to BBG and fresh L-SDG ($P<0.05$). BBG showed significantly higher pH than other distillers' grains ($P<0.05$), with the following ranking: BBG > M-SDG > L-SDG > HBDG > CDG. BBG had significantly higher initial moisture content than other types ($P<0.05$), while CDG showed significantly higher initial moisture than L-SDG, M-SDG, and HBDG ($P<0.05$).

2.2 Conventional Nutrient Contents of Different Distillers' Grains

As presented in , DM content did not differ significantly among distillers' grains types ($P>0.05$), while all other nutrient components showed significant variations. BBG contained the highest CP content, exceeding M-SDG by 11.78% ($P>0.05$), HBDG by 13.79% ($P<0.05$), CDG by 21.54% ($P<0.05$), and L-SDG by 38.73% ($P<0.05$). CDG exhibited significantly higher EE content than other distillers' grains ($P<0.05$). CDG showed the highest NFE content, exceeding HBDG by 17.69% ($P>0.05$), BBG by 25.13% ($P<0.05$), M-SDG by 31.90% ($P<0.05$), and L-SDG by 32.00% ($P<0.05$). L-SDG and M-SDG had significantly higher Ash content than other types ($P<0.05$). L-SDG demonstrated significantly higher CF content than other distillers' grains ($P<0.05$), while CDG showed the lowest CF content, being 26.89% lower than HBDG ($P<0.05$), 33.46% lower than M-SDG ($P<0.05$), 34.35% lower than BBG ($P<0.05$), and 60.13% lower than L-SDG ($P<0.05$).

Significant differences were also observed in fiber components and starch content among distillers' grains types. L-SDG exhibited significantly higher NDF, ADF, and ADL contents than other types ($P<0.05$), while CDG showed the lowest values for these fiber components. CDG had significantly higher starch content than the progressively decreasing levels in HBDG, L-SDG, M-SDG, and BBG ($P<0.05$).

Protein nutritional component analysis revealed that BBG and M-SDG had significantly higher NDIP content than L-SDG, HBDG, and CDG ($P<0.05$), with CDG showing the lowest value. L-SDG and M-SDG demonstrated significantly higher ADIP content than HBDG, CDG, and BBG ($P<0.05$). HBDG contained the highest SCP content, significantly exceeding other distillers' grains ($P<0.05$),

while BBG showed the lowest SCP content, significantly lower than other types ($P<0.05$). HBDG also exhibited significantly higher NPN content than other distillers' grains ($P<0.05$).

2.3 Carbohydrate and Protein Component Contents of Different Distillers' Grains

As shown in , L-SDG demonstrated significantly higher carbohydrate (CHO) content than BBG and M-SDG ($P<0.05$). However, BBG exhibited a significantly higher proportion of rapidly degradable carbohydrate (CA) than other types ($P<0.05$), while L-SDG showed the lowest CA proportion. CDG had the highest proportion of moderately degradable carbohydrate (CB1), significantly exceeding other distillers' grains ($P<0.05$), whereas BBG showed the lowest CB1 proportion, significantly lower than others ($P<0.05$). M-SDG and L-SDG demonstrated significantly lower proportions of slowly degradable carbohydrate (CB2) than other types ($P<0.05$). L-SDG exhibited a significantly higher proportion of non-degradable carbohydrate (CC) than other distillers' grains ($P<0.05$), while CDG showed a significantly lower CC proportion than other types ($P<0.05$). Overall, CDG provided the highest quality carbohydrate fraction.

BBG demonstrated the highest proportion of slowly degradable true protein (PB3), significantly exceeding other distillers' grains ($P<0.05$). HBDG and M-SDG showed PB3 proportions significantly higher than the progressively decreasing levels in CDG and L-SDG ($P<0.05$). BBG exhibited the lowest proportion of non-degradable true protein (PC), significantly lower than L-SDG, M-SDG, and HBDG ($P<0.05$). L-SDG showed the highest PC proportion, significantly exceeding the progressively decreasing levels in M-SDG, HBDG, CDG, and BBG ($P<0.05$). Overall, BBG provided the highest quality protein fraction.

2.4 Mineral Element Contents of Different Distillers' Grains

As presented in , L-SDG showed an appropriate calcium-to-phosphorus ratio, while other distillers' grains had higher phosphorus than calcium content, resulting in inappropriate ratios. L-SDG and M-SDG contained significantly higher iron content than HBDG, CDG, and BBG ($P<0.05$). BBG demonstrated significantly higher copper content than other distillers' grains ($P<0.05$). M-SDG exhibited significantly higher manganese content than other types ($P<0.05$), while CDG showed significantly lower manganese content than others ($P<0.05$). BBG had significantly higher zinc content than other distillers' grains ($P<0.05$).

2.5 Anti-nutritional Factor Contents of Different Distillers' Grains

As shown in , M-SDG demonstrated significantly higher tannin content than the progressively decreasing levels in CDG, HBDG, and BBG ($P<0.05$). L-SDG exhibited the highest silicon content, significantly exceeding other distillers' grains ($P<0.05$), being 35.47% higher than M-SDG ($P<0.05$), 53.95% higher

than HBDG (P<0.05), 77.63% higher than BBG (P<0.05), and 94.07% higher than CDG (P<0.05).

2.6 Mycotoxin Contents of Different Distillers' Grains

Among the 24 distillers' grains samples analyzed, aflatoxin B1, zearalenone, deoxynivalenol, and ochratoxin contents were extremely low. Only one CDG sample contained trace amounts of aflatoxin B1, while no mycotoxins were detected in the remaining samples.

3.1 Differences in Physical Characteristics of Different Fresh Distillers' Grains

In this study, L-SDG exhibited the lowest bulk density, while CDG showed the highest, possibly due to higher rice husk content in L-SDG resulting in lower density per unit volume. Xu et al. reported bulk densities of 401.0–614.6 g/L for nine types of white spirit grains from Sichuan, consistent with our findings. Tan et al. reported white spirit grain acidity of 3, lower than our results, likely attributable to differences in sample sources and freshness. BBG demonstrated significantly higher acidity than other distillers' grains, possibly resulting from differences between beer and white spirit brewing processes. Additionally, BBG initial moisture content was approximately 78.77%, and CDG initial moisture was about 72.12%, consistent with Jiao et al.' s report of approximately 80% moisture in brewers' grains. Overall, physical characteristics varied among different distillers' grains types, with similar characteristics within the same type. Due to minimal variation in raw materials and processes among different BBG samples, their physical characteristics showed little difference, whereas greater variation in processes and raw materials among different white spirit grains resulted in more pronounced differences in physical characteristics.

3.2 Differences in Conventional Nutrient Contents of Different Distillers' Grains

Our results demonstrate that CDG exhibited significantly higher EE, NFE, and starch contents than other distillers' grains, providing greater energy for ruminants, consistent with reports by Yang and Kelzer et al. BBG showed the lowest starch content at only 15.82% of CDG levels, aligning with Li' s findings. L-SDG and M-SDG demonstrated significantly higher Ash content than other types, likely due to rice husk content in these materials. Meanwhile, L-SDG exhibited significantly higher CF, NDF, ADF, and ADL contents than other distillers' grains. High fiber content can affect palatability, reduce digestibility of CP and other organic matter, and consequently impact animal feed intake. These results are similar to those reported by Tan et al. and Xu for white spirit grains.

BBG and M-SDG contained higher CP contents of 27.34% and 23.57%, respectively, with CF contents below 18%, classifying them as protein feeds. BBG

also showed higher NDIP content and significantly lower ADIP content than other types, indicating optimal protein composition. L-SDG demonstrated significantly higher ADIP content than other distillers' grains, showing the poorest protein composition. HBDG exhibited significantly higher SCP and NPN contents than other types, enabling rapid ruminal degradation and absorption, while also maintaining relatively high CP content (23.57%), indicating good protein quality. These findings are similar to Chen' s reports on nitrogenous substances in white spirit grains, though slightly lower than contents reported by Kelzer et al. and Yu for corn distillers' grains.

3.3 Differences in Carbohydrate and Protein Component Contents of Different Distillers' Grains

In this study, L-SDG, HBDG, and CDG contained over 60% carbohydrate, making them carbohydrate-predominant feeds. However, L-SDG showed a lower proportion of non-structural carbohydrates relative to total carbohydrates and a higher CC proportion, indicating higher indigestible content and lower utilization efficiency in the rumen. CDG and HBDG exhibited the highest proportions of non-structural carbohydrates and CB1 relative to total carbohydrates, significantly higher than other types, with lower CC content, suggesting higher ruminal degradation rates and utilization efficiency, thus providing high-quality carbohydrates for animals.

Protein component differences among distillers' grains types were substantial. BBG showed higher proportions of moderately degradable true protein (PB2) and PB3, likely because most soluble proteins were degraded by yeast during brewing, leaving undegraded true proteins primarily as moderately and slowly degradable forms. BBG' s significantly lower PC proportion than other types indicates higher PB3 content and superior protein quality. HBDG showed a higher proportion of soluble protein fraction non-protein nitrogen (PA) in CP, while CDG exhibited higher PB2 proportion and lower PC proportion, indicating higher NPN and soluble true protein contents in their CP, thus providing quality protein for animals. L-SDG demonstrated the highest PC proportion, significantly exceeding other types, indicating lower ruminal digestibility and poorest protein quality.

3.4 Differences in Mineral Element Contents of Different Distillers' Grains

In this study, calcium and total phosphorus contents in distillers' grains ranged from 0.13% to 0.87% and 0.29% to 0.77% DM, respectively, similar to results reported by Lü et al. and Adams et al. High iron content can interfere with copper and zinc absorption and cause oxidative stress. Our study found iron contents of 828–1,999 mg/kg in L-SDG and M-SDG, with M-SDG showing the highest content, consistent with findings by Zhang and Fan. Copper content across distillers' grains types ranged from 10 to 51 mg/kg, with BBG showing the highest content, exceeding Adams' results. Manganese content ranged from

21 to 252 mg/kg, with sorghum distillers' grains showing the highest content, consistent with Wang et al. and slightly higher than Fang's results. Zinc content ranged from 49 to 161 mg/kg, with BBG showing the highest content. However, high iron may competitively inhibit zinc absorption, potentially causing zinc deficiency, thus warranting attention to zinc requirements in high-iron, low-zinc distillers' grains.

3.5 Differences in Anti-nutritional Factor Contents of Different Distillers' Grains

Tannins can form insoluble complexes with proteins, reducing feed intake, digestibility, rumen bypass protein content, and nitrogen utilization while increasing nitrogen excretion and methane emissions, with effects depending on tannin source, concentration, and structure. Sorghum tannin content ranges from 0.45% to 1.68%, but microbial tannase production during white spirit brewing substantially reduces tannin content in distillers' grains compared to raw materials. Rice husk silicon content ranges from 59 to 100 g/kg. Traditional Chinese white spirit grains such as sauce-aroma and strong-aroma types contain 8%–12% and 56%–68% rice husk, respectively. High dietary silicon content reduces fiber degradability and accelerates feed passage through the digestive tract, while also increasing ash content and reducing effective nutrient concentration per unit weight, thereby decreasing nutritional value. Therefore, besides high rumen-indigestible components, high silicon content also affects ruminal degradation of L-SDG.

3.6 Mycotoxin Content Characteristics of Different Distillers' Grains

Mycotoxins are widely present in various feed ingredients, with major toxins in grains and distillers' grains including aflatoxin B1, zearalenone, deoxynivalenol, and ochratoxin. Only one sample contained trace aflatoxin B1, and since all samples were fresh, this also indicates good transportation and preservation. Xu reported minimal mycotoxin content in white spirit grains, consistent with our findings.

4 Conclusion

1. BBG exhibited the highest CP content, making it suitable as a protein feed. CDG showed high NFE, starch, and CP contents, making it suitable as both an energy and protein feed. L-SDG demonstrated the highest CF, NDF, ADF, and ADL contents, making it suitable as a roughage.
2. CNCPS evaluation indicated that BBG had the highest fermentable protein content, representing a high-quality protein source. CDG showed the highest fermentable carbohydrate content, representing a high-quality carbohydrate source. L-SDG exhibited the lowest fermentable content, indicating lower quality as a ruminant feed.

3. Among anti-nutritional factors, L-SDG contained the highest silicon content, which affects digestion and absorption of other nutrients and reduces nutritional value. Mycotoxin and tannin contents were minimal across different distillers' grains types and can be considered negligible in practical production.

References

[1] XIN Chunhui, XU Ling, YU Panpan, et al. Brief discussion on the role of grain raw materials in white spirit brewing[J]. Brewing, 2016, 43(5): 44-48.

[2] LI Dahe. Discussion on Chinese white spirit aroma types[J]. Brewing Science & Technology, 2013(10): 104-106.

[3] XIE Zhengjun, CAO Jingming, WAN Jianhua. Analysis and discussion on feed value of white spirit grains[J]. Feed Industry, 2014, 35(12): 51-53.

[4] FOX D G, TEDESCHI L O, TYLUTKI T P, et al. The Cornell net carbohydrate and protein system model for evaluating herd nutrition and nutrient excretion[J]. Animal Feed Science & Technology, 2004, 112(1/2/3/4): 29-78.

[5] ZHANG Liying. Feed Analysis and Feed Quality Detection Technology[M]. 2nd ed. Beijing: China Agricultural University Press, 2003.

[6] VAN SOEST P J. Development of a comprehensive system of feed analyses and its application to forages[J]. Journal of Animal Science, 1967, 26(1): 119.

[7] KRISHNAMOORTHY U, SNIFFEN C J, STERN M D, et al. Evaluation of a mathematical model of rumen digestion and an in vitro simulation of rumen proteolysis to estimate the rumen-undegraded nitrogen content of feedstuffs[J]. British Journal of Nutrition, 1983, 50(3): 555-568.

[8] LICITRA G, HERNANDEZ T M, VAN SOEST P J. Standardization of procedures for nitrogen fractionation of ruminant feeds[J]. Animal Feed Science and Technology, 1996, 57(4): 347-358.

[9] ALONSO V, CAVAGLIERI L, RAMOS A J, et al. Modelling the effect of pH and water activity on the growth of Aspergillus fumigatus isolated from corn silage[J]. Journal of Applied Microbiology, 2017, 122(4): 1048-1056.

[10] DAI Weimin, ZHANG Keqin, DUAN Binwu, et al. A simple method for determining silicon content in rice[J]. Chinese Journal of Rice Science, 2005, 19(5): 460-462.

[11] SNIFFEN C J, O' CONNOR J D, VAN SOEST P J, et al. A net carbohydrate and protein system for evaluating cattle diets: . Carbohydrate and protein availability[J]. Journal of Animal Science, 1992, 70(11): 3562-3577.

[12] XU Jian, CHEN Daiwen, MAO Qian, et al. Nutritional value evaluation of white spirit grains[J]. Chinese Journal of Animal Science, 2012, 48(7): 47-50.

[13] TAN Zhilei, LIU Jianhui, MA Kai, et al. New comprehensive utilization technology of white spirit grains[J]. Guangdong Chemical Industry, 2015, 42(7): 72-73.

[14] JIAO Xiaofei, LIU Jianxue, HAN Sihai, et al. Optimization of fermentation conditions for biological transformation of white spirit grains by composite microorganisms[J]. Food Science, 2015, 36(17): 164-168.

[15] YANG Jiawei. Study on extraction and defatting of corn distillers' grains[D]. Master' s thesis. Wuxi: Jiangnan University, 2013.

[16] KELZER J M, KONONOFF P J, TEDESCHI L O, et al. Evaluation of protein fractionation and ruminal and intestinal digestibility of corn milling co-products[J]. Journal of Dairy Science, 2010, 93(6): 2803-2815.

[17] LI Yingli. Establishment of CNCPS database for dairy cattle feed in Inner Mongolia[D]. Master' s thesis. Hohhot: Inner Mongolia Agricultural University, 2010.

[18] XIA Zhongsheng. Feed Science[M]. Guilin: Guangxi Normal University Press, 2005.

[19] WU Fali. Effects of different regions and seasons on quality of alpine natural forage[D]. Master' s thesis. Ya' an: Sichuan Agricultural University, 2014.

[20] XU Jian. Evaluation of nutritional value of white spirit grains for pigs[D]. Master' s thesis. Ya' an: Sichuan Agricultural University, 2011.

[21] CHEN Yan. Evaluation of nutritional value of common feedstuffs for beef cattle[D]. Master' s thesis. Ya' an: Sichuan Agricultural University, 2014.

[22] YU P Q, NUEZ-ORTÍN W G. Relationship of protein molecular structure to metabolisable proteins in different types of dried distillers grains with solubles: a novel approach[J]. British Journal of Nutrition, 2010, 104(10): 1429-1437.

[23] SHI Dandan, ZHANG Yonggen. Nutritional value of corn DDGS as energy or protein feed ingredient for ruminants[C]//Proceedings of the 5th Academic Exchange Conference of the Feed Economy Professional Committee of the Chinese Association of Animal Husbandry and Veterinary Economics. Sanya: Chinese Association of Animal Husbandry and Veterinary Economics, 2008: 92-97.

[24] LÜ Yuling, ZHOU Yuxiang, XIAO Guiping. Evaluation of nutritional value of common feedstuffs for ruminants[J]. Heilongjiang Animal Science and Veterinary Medicine, 2011(9): 86-87.

[25] ADAMS R S. Variability in mineral and trace element content of dairy cattle feeds[J]. Journal of Dairy Science, 1975, 58(10): 1538-1548.

[26] ZHANG Yaxue. Component analysis of distillers' grains fungal residue and its effects on immune function and intestinal microflora in meat ducks[D]. Master' s thesis. Ya' an: Sichuan Agricultural University, 2011.

[27] FAN Zhanlian. Safety assessment and application of unconventional feeds for dairy cattle in Shanghai region[D]. Doctoral thesis. Nanjing: Nanjing Agricultural University, 2013.

[28] WANG Xiaoli, WANG Chunmei, WANG Yonggang, et al. Study on nutrient detection and enzymatic hydrolysis of distillers' grains[J]. China Herbivore Science, 2014, 34(1): 28-31.

[29] FANG Jinguang. Study on apparent digestibility of 12 feed ingredients by Cirrhinus mrigala and optimal protein-energy ratio in feeds[D]. Master' s thesis. Wuhan: Huazhong Agricultural University, 2016.

[30] MU Zhixin, TIAN Xiang, SHI Ying. Analysis of detection methods for tannin content in sorghum[J]. Shanxi Agricultural Sciences, 2014, 42(6): 551-553.

[31] CORTÉS J E, MORENO B, PABÓN M L, et al. Effects of purified condensed tannins extracted from Calliandra, Flemingia and Leucaena on ruminal and postruminal degradation of soybean meal as estimated in vitro[J]. Animal Feed Science and Technology, 2009, 151(3/4): 194-204.

[32] GUO Xukai, YANG Ling, ZHANG Fuyao, et al. Study on relationship between physicochemical properties of sorghum grains and light-flavor Daqu white spirit brewing[J]. China Brewing, 2016, 35(12): 40-43.

[33] ZHANG Zhigang, WU Shengwen, CHEN Fei. Research status and development direction of Daqu enzyme system in white spirit production[J]. China Brewing, 2011, 30(1): 13-16.

[34] WANG Hongyan, WANG Daolong, LI Jianzheng, et al. Estimation and development utilization of rice husk resources in China[J]. Jiangsu Agricultural Sciences, 2012, 40(1): 298-300.

[35] LI Qing. Discussion on comprehensive utilization of white spirit grains in Guizhou Province[J]. Brewing Science & Technology, 2014(10): 92-93.

[36] ZHAI Guiyu, ZHANG Xinquan. Role of silicon in animal nutrition[J]. Feed and Animal Husbandry, 1992(2): 19-20.

[37] ZHOU Chuang, HE Chenghua, SI Huimin, et al. Investigation and analysis of mycotoxin contamination in feed and raw materials in China in 2012[J]. Animal Husbandry and Veterinary Medicine, 2014, 46(1): 81-84.

[38] LBRYDEN W L. Current status and future challenges of mycotoxin research[J]. China Poultry, 2014, 36(2): 34-37.

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