Nutritional Value of Mulberry Leaves and Its Applications in Animal Production (Postprint)

Authors: Zeng Zhu, Yu Bing, Yu Jie, Chen Daiwen

Date: 2018-12-20T00:00:00+00:00

Abstract

Mulberry leaves contain a relatively balanced and rich array of nutritional components and natural bioactive substances. As a feed ingredient, they exhibit good palatability and possess high nutritional and feeding values, capable of improving livestock and poultry health while enhancing product quality and flavor, thus emerging as a focal point in feed resource development. This paper provides a comprehensive review of the chemical composition and nutritional value of mulberry leaves, along with their applications in animal production, and identifies future research directions that warrant further investigation.

Full Text

Nutritional Value of Mulberry Leaf and Its Application in Animal Production

ZENG Zhu, YU Bing, YU Jie, CHEN Daiwen*

(Key Laboratory for Animal Disease-Resistance Nutrition of Ministry of Education, Institute of Animal Nutrition, Sichuan Agricultural University, Chengdu 611130, China)

Abstract: Mulberry leaf contains a relatively balanced and abundant array of nutrients and natural bioactive substances. As a feed ingredient, it exhibits good palatability and high nutritional and feeding value, and can improve livestock health and product quality. These characteristics have made mulberry leaf a focus of feed resource development. This paper reviews the chemical composition and nutritional value of mulberry leaf and its application in animal production, and proposes issues requiring further research.

Key words: mulberry leaf; chemical composition; nutritional value; application; review

Mulberry leaves, derived from *Morus alba* L., are suitable for cultivation in warm regions. China, with its vast territory and complex climate, is the origin of world sericulture production. Mulberry trees are naturally distributed and artificially cultivated across nearly the entire country, particularly concentrated in large-scale planting areas such as Jiangsu-Zhejiang region, Sichuan Basin, Guangdong, and Shandong [1]. Mulberry leaves have a 4,000-year cultivation history in China and are known as "iron fan" in traditional Chinese medicine. In 1993, mulberry was listed by the Ministry of Health as a "medicinal and edible" plant. It contains multiple functional components and is among the plants with relatively high leaf protein content [2]. Traditionally used as feed for silkworms in agricultural production, the full potential of mulberry leaves has not been fully exploited [3]. In recent years, with advances in novel feed resource development and deeper understanding of mulberry leaves, they have been gradually applied in the feed industry and animal production, demonstrating special feeding value [4]. This paper aims to provide a preliminary review of the nutritional value of mulberry leaves and their application effects in different animals to serve as a reference for further research.

1. Chemical Composition of Mulberry Leaf

The chemical composition of mulberry leaves is highly complex, with components and contents influenced by multiple factors [5]. The moisture content ranges from 61% to 79%, and the nutrient contents on an air-dry basis are shown in Table 1 [6].

Among the amino acids composing mulberry leaf protein, glutamic acid has the highest content at 13.7% of total amino acids, followed by aspartic acid at 12.3% [2]. The content of essential amino acids for animals is 3.28%, accounting for 32.61% of total amino acids, with lysine content at 0.45% (4.51% of total amino acids) [4]. The amino acid ratio coefficient score (SRCAA), calculated using the amino acid ratio coefficient method, can be used to evaluate protein nutritional value—the closer this value is to 100, the higher the nutritional value. Research has found that the SRCAA of mulberry leaf is 69.71, similar to that of pork (74) and beef (76), and higher than many plant proteins [2], making it an excellent protein resource worthy of development and utilization.

Mulberry leaves contain 13 types of saturated fatty acids and 5 types of unsaturated fatty acids, accounting for 49.31% and 43.87% of total fatty acids, respectively. Among unsaturated fatty acids, linolenic acid has the highest content (22.99%), followed by linoleic acid (13.40%), oleic acid (3.17%), palmitoleic acid (3.05%), and arachidonic acid (1.26%). Unsaturated fatty acids account for nearly half of total fatty acids [7].

The carbohydrates in mulberry leaves are primarily monosaccharides and disaccharides such as glucose, galactose, mannose, and fructose, as well as various polysaccharides. The fiber content reaches 52.9%, exceeding that of vegetables and fruits [8].

Mulberry leaves contain various bioactive substances. Korean scholar Kim et al. [9] isolated nine types of flavonoids from mulberry leaves. Flavonoids and flavonoid glycosides are the most studied class of compounds with relatively clear structures and compositions among mulberry leaf chemical constituents [10]. Mulberry leaf is also among the plants with relatively high flavonoid content in stems and leaves, with total flavonoids accounting for 1.0%~3.0% of dry weight [11].

Alkaloids are one of the main active components in mulberry leaves. Mulberry leaves contain flavonoid compounds including rutin, quercetin, isoquercetin, astragalin, and isopentenylflavanone, with relatively high contents of rutin and isoquercetin. Japanese scholar Asano et al. [12] isolated six alkaloids from mulberry leaves and determined their structures, including 1-deoxynojirimycin (DNJ). DNJ is a natural sugar analog with strong polarity, uniquely found in mulberry leaves among plants.

The polyphenol content in mulberry leaves varies significantly depending on germplasm resources, harvest season, leaf position, and growth stage, ranging from 7.84 to 17.28 mg/g, with wild varieties generally containing higher polyphenol levels than cultivated varieties [13]. Paola Dugo et al. [14] used high-performance liquid chromatography-ion trap-time of flight mass spectrometry (HPLC-MS-IT-TOF) for qualitative analysis of polyphenolic compounds in mulberry leaves, identifying 22 polyphenols, primarily chlorogenic acid and its isomers, isoquercetin, rutin, quercetin, p-hydroxycinnamic acid, caffeic acid, 7-hydroxycoumarin, quercetin glucoside and its derivatives, kaempferol glucoside and its derivatives, and isorhamnetin glucoside.

Mulberry leaves are rich in γ-aminobutyric acid (GABA), with content as high as 2.2 mg/g. GABA is converted from glutamic acid, which has a content of up to 23.23 mg/g in mulberry leaves [15]. Miyashita Susumu [16] prepared a mixture of *Lagerstroemia speciosa* and mulberry leaf extracts and found that this mixture inhibited blood glucose elevation in alloxan-induced diabetic rats, identifying corosolic acid and maron A as the main active components responsible for the hypoglycemic effect.

2. Nutritional Value and Health Functions of Mulberry Leaf

Currently, few research reports address the effect of mulberry leaves on the effective energy value of livestock and poultry. Wang et al. [17] used a pressure sensor method to estimate the metabolic energy of 29 mulberry varieties, with the highest value (5.05~8.09 MJ/kg DM) found in the improved "Shufan" variety. Liu et al. [4] calculated the metabolic energy of mulberry leaves as high as 8.94 MJ/kg through in vivo rumen degradation trials. Similarly, Huang et al. [18] measured the metabolic energy of "Guisangyou No. 12" mulberry leaves as 8.68 MJ/kg, while Wu et al. [19] determined the metabolic energy of mulberry leaves for Chinese green egg-laying hens as 9.89 MJ/kg when adding 10%

mulberry leaves to the diet. Peng [20] found that dry mulberry leaves had a gross energy of 15.79 MJ/kg and a digestible energy of 9.66 MJ/kg for pigs. Yang et al. [21] used Duroc × Large White × Landrace crossbred castrated male pigs with consistent parity to determine that mulberry leaf powder had a gross energy of 15.70 MJ/kg, digestible energy of 10.66 MJ/kg, apparent gross energy digestibility of 68.04%, apparent crude protein digestibility of 76.49%, apparent crude fat digestibility of 29.77%, apparent crude fiber digestibility of 31.52%, and apparent nitrogen-free extract digestibility of 81.91%.

As livestock feed, mulberry leaves exhibit excellent palatability for both ruminant and non-ruminant animals. Even when first introduced, animals readily accept and consume mulberry leaves; once familiar, animals will preferentially select mulberry leaves over other forages [4]. A study feeding two sheep of equal size equal amounts of alfalfa and mulberry leaves found that both sheep preferentially consumed mulberry leaves over alfalfa, with greater intake of mulberry leaves and significantly faster weight gain compared to the alfalfa-fed group [22]. Application of mulberry leaves in livestock production results in faster and healthier animal growth [23], significantly improved production performance and immunity, enhanced product quality, and reduced feeding costs.

The various bioactive substances in mulberry leaves demonstrate significant health functions. Linolenic acid (ω-3 unsaturated fatty acid) has blood lipid- and pressure-lowering effects, provides excellent therapeutic benefits against atherosclerosis and thrombosis formation, and helps prevent cardiovascular disease and hyperlipidemia [24]. Linoleic acid is an essential fatty acid that reduces blood cholesterol by promoting cholesterol and bile acid excretion, preventing cholesterol deposition in blood vessel walls [7]. Flavonoids in mulberry leaves are natural antioxidants that can scavenge superoxide anion radicals, hydroxyl radicals, and lipid organic radicals, with effects including lowering blood glucose in diabetic patients, reducing serum lipid content, and preventing atherosclerosis [25]. Kimura et al. [26] observed the hypoglycemic effects of six mulberry leaf alkaloids on streptozotocin (STZ)-induced diabetic mice, finding that N-methyl-deoxynojirimycin (N-Me-DNJ), 2-O-α-D-galactopyranosyl-deoxynojirimycin (Gal-DNJ), and fagomine significantly reduced blood glucose levels, with Gal-DNJ and fagomine showing stronger effects. Li et al. [27] extracted DNJ from different wild mulberry varieties for in vitro inhibition activity assays, demonstrating that DNJ strongly inhibits sucrase and maltase in vitro by binding to the sucrase-sucrose complex to prevent catalytic degradation of disaccharides into monosaccharides, thereby delaying intestinal carbohydrate absorption and preventing sharp blood glucose elevation. Other studies show that mulberry leaf DNJ extracts can affect lipid metabolism enzyme activity (fatty acid synthase, malic enzyme, acyl-CoA), inhibit intestinal cholesterol absorption, and reduce blood lipid levels [28-29]. Mulberry leaf polysaccharides have multiple pharmacological effects including hypoglycemic and hypolipidemic activity, antioxidant properties, anti-aging effects, and immune enhancement. Zhang [30] demonstrated that mulberry leaf polysaccharides had significant therapeutic effects on alloxan-induced diabetic rats. Wang et al. [31] showed that oral administration of mulberry leaf polysaccharides significantly reduced blood glucose in alloxan-induced diabetic mice. Xie et al. [32] found that mulberry leaf polysaccharides at 0.8 mg/mL concentration had the highest hydroxyl radical scavenging activity, reaching 90.8% scavenging rate. γ-aminobutyric acid has blood pressure-lowering effects, prevents excessive excitation of nerve cells, and provides anti-anxiety benefits [33]. However, research on the health benefits of bioactive substances in mulberry leaves for livestock and poultry has not been reported.

3.1 Poultry

Mulberry leaf powder has been widely applied in poultry production. Different studies report varying effects on laying performance when adding mulberry leaf powder to chicken diets, but all document significant improvements in egg quality. Zhang et al. [34] added 2.5%, 5.0%, 7.5%, and 10.0% mulberry leaves to Nongda dwarf layer diets, finding that the 7.5% and 10.0% groups showed slightly reduced egg weight and laying rate compared to the control. Liu et al. [35] added 3%, 6%, 9%, and 12% mulberry leaf powder to Roman layer diets, observing that daily egg production decreased with increasing addition levels; total egg production, average laying rate, and average egg weight were lower than the control group, with significant reductions in average egg weight and laying rate at 9% and 12% addition levels. Wu et al. [36] replaced 2%, 4%, 6%, and 8% of the basal diet with mulberry leaf powder for Roman brown layers, finding that average daily feed intake and daily egg production gradually decreased with increasing replacement ratios, but egg yolk color was significantly improved in all treatment groups. At 8% replacement, serum total protein, globulin, and albumin levels significantly decreased, and egg production and daily feed intake were significantly reduced, though no significant effects were observed on egg quality indicators such as yolk weight, cholesterol, high- and low-density lipoprotein content, shell thickness, or shell strength. Zhang et al. [37] showed that adding 5%, 10%, and 15% mulberry leaf powder to Hy-Line gray layer diets significantly improved egg yolk color compared to the control, with the 10% and 15% groups showing significantly higher Haugh units and whole egg protein content, and the 15% group showing significantly lower yolk cholesterol content. Zhang et al. [38] found that adding 5%, 10%, and 15% mulberry leaf powder to Hy-Line gray layer diets reduced laying rate, egg weight, and egg production compared to the control, with average laying rate decreasing as addition level increased (14.1% lower in the 15% group, significant difference). Additionally, serum glucose, total cholesterol, and triglyceride levels, as well as yolk cholesterol content, were lower than the control, with significant differences in the 15% group. All treatment groups showed significantly improved egg yolk color, and the 10% and 15% groups had significantly higher albumen Haugh units. Liu et al. [39] replaced 2.5%, 5.0%, 7.5%, and 10.0% of the basal diet with mulberry leaf powder for Nongda dwarf layers, finding that yolk color deepened with increasing addition levels. The mulberry leaf groups showed significantly reduced saturated fatty acid content and significantly increased polyunsaturated and monounsaturated fatty acid content in yolk. The 5.0% and 7.5% groups showed significantly increased total essential amino acids, and the 10% group had nearly three times higher vitamin E content in yolk than the control. Eggs from mulberry-fed groups had better odor and taste than the control. Sun et al. [40] also found that mulberry leaf powder significantly improved egg yolk color and redness values, and significantly increased β-carotene, vitamin E, monounsaturated and polyunsaturated fatty acids, and lecithin content, thereby enhancing egg nutritional quality.

Mulberry leaf powder addition also improves meat quality and reduces environmental pollution. Margareta et al. [41] found that adding 2% and 5% mulberry leaves to broiler diets had no significant effects on feed intake, daily weight gain, or feed conversion ratio, but significantly increased polyunsaturated fatty acid content in breast muscle while significantly reducing saturated fatty acid content and the ω-6 to ω-3 ratio. Lan et al. [42] reported that mulberry leaf powder reduced abdominal fat rate, intramuscular fat content, and muscle saturated fatty acid content and ω-6 to ω-3 ratio in Guangxi Qingjiaoma roosters, while increasing muscle unsaturated fatty acid and ω-3 fatty acid content. Wu et al. [43] showed that adding 3%, 5%, and 7% mulberry leaf powder to Huainan partridge chicken diets had no significant effects on weight gain, feed-to-gain ratio, or slaughter performance, but improved meat color, with the 3% addition level significantly increasing muscle threonine, isoleucine, tyrosine, phenylalanine, and histidine content. Studies have found that adding approximately 10% mulberry leaf powder to chicken diets can reduce feather pecking behavior among chicks and decrease ammonia content in chicken manure, thereby reducing environmental pollution [44].

3.2 Pigs

Adding mulberry leaf powder to pig diets significantly improves pork quality and flavor. Yang [45] showed that dietary inclusion of 10%, 15%, and 20% mulberry leaf powder had no significant effect on average daily weight gain but slowed post-slaughter muscle pH decline. Compared to the control, intramuscine fat content increased by 12.99%, 9.97%, and 17.22% in the 10%, 15%, and 20% groups, respectively. Backfat thickness in the 15% and 20% groups decreased by 6.60% and 8.03% compared to the 10% group. The 15% group showed 7.32% lower muscle saturated fatty acid content and 4.55% higher muscle unsaturated fatty acid content than the control. The 10% and 15% groups had significantly higher total muscle amino acid content, with increased umami amino acid content. Li et al. [46] demonstrated that adding 10% mulberry leaves to finishing pig diets significantly increased muscle inosine monophosphate content; at 20% addition, feed-to-gain ratio significantly increased with no significant effect on carcass rate, but intramuscular fat content significantly increased, muscle pH decline slowed, leaf lard rate and backfat thickness significantly decreased. The mechanism involves regulating fat metabolism and deposition by modulating sucrase, lipase, and liver carbohydrate metabolism enzyme activities. Song et al. [47] found that adding 15% mulberry leaf powder to Duroc × Large White × Landrace crossbred finishing pig diets significantly reduced average daily weight gain and significantly increased feed-to-gain ratio, significantly decreased average backfat thickness and muscle total cholesterol content, while adding 5%, 10%, and 15% mulberry leaf powder significantly increased muscle superoxide dismutase activity and reduced malondialdehyde content, effectively improving muscle antioxidant capacity. Guo et al. [48] found that adding 3% mulberry leaf powder to sow diets shortened postpartum estrus interval, increased litter size, improved sow body condition, and enhanced milk nutritional levels, thereby increasing piglet birth weight, weaning weight, and survival rate. Beyond basic nutritional effects, functional components in mulberry leaves play important roles when replacing portions of basal diets. For instance, DNJ and flavonoids can block carbohydrate conversion to fat, impeding body fat conversion and deposition, thereby increasing lean meat percentage and reducing leaf lard rate to meet consumer demands for healthy diets [49]. Therefore, adding appropriate amounts of mulberry leaves to pig diets can improve pork quality and flavor while reducing feeding costs.

3.3 Herbivores

Mulberry leaf addition can improve rumen fermentation in herbivores, thereby benefiting animal health. Huyen et al. [50] found that crossbred beef cattle consuming 200, 400, and 600 g of mulberry leaf powder daily showed linear increases in ruminal total volatile fatty acids, acetate, butyrate, and acetate-to-propionate ratio, improved nitrogen balance, and increased dry matter intake and digestibility of dry matter, organic matter, crude protein, neutral detergent fiber, and acid detergent fiber. Guo et al. [51] added mulberry leaf powder to finishing cattle diets, observing that treated cattle had smooth, glossy coats, well-proportioned bodies, and improved feed efficiency; at 10% addition, growth rate was significantly higher than the control. Researchers have found that replacing alfalfa with mulberry leaves in wether diets resulted in crude protein digestibility similar to alfalfa, with the same results observed in cattle trials, and mulberry addition did not affect rumen fluid pH while better controlling ruminal nitrogen balance [52]. Jeon et al. [53] reported that adding silaged mulberry leaves to beef cattle diets significantly increased fatty acid content in beef. Yang et al. [54] showed that mulberry leaf flavonoids improved total energy metabolic rate and nitrogen biological value in pre-weaning calves, increased total energy metabolic rate and nitrogen utilization in post-weaning calves, reduced fecal energy and total nitrogen excretion, and improved rumen fermentation. Li et al. [55] demonstrated that goats fed diets containing 5%, 10%, and 15% mulberry leaf powder showed no significant differences in rumen fluid pH among groups, but the 15% group had significantly reduced rumen ammonia nitrogen concentration, while the 10% group showed significantly increased total volatile fatty acids and acetate production and acetate-to-propionate ratio, indicating positive effects on rumen fermentation.

Mulberry leaf addition can also promote growth in herbivores, reduce feeding costs, and improve economic benefits. Wu et al. [56] found that adding 20% fermented mulberry leaves to finishing cattle diets had no significant effects on daily weight gain, intake, feed conversion efficiency, or blood biochemical indicators, but significantly reduced feed costs. Liu et al. [57] showed that replacing portions of soybean meal with mulberry leaf powder significantly increased milk production in Chinese Holstein dairy cows while reducing feed costs and improving economic benefits. Li [58] demonstrated that adding mulberry leaf powder to meat sheep basal diets increased daily weight gain, protein, total amino acid, and essential amino acid content in mutton, and inosine monophosphate content in the longissimus dorsi muscle, with the 15% group showing significantly higher inosine monophosphate content than the control. The 5% and 10% groups also had higher inosine monophosphate content than the control. Additionally, mulberry leaf powder enhanced total superoxide dismutase and catalase activities and total antioxidant capacity in sheep serum while reducing malondialdehyde content, thereby improving immunity.

3.4 Aquatic Animals

With increasing scarcity and rising prices of fishmeal resources, finding plant protein sources to replace fishmeal has become an urgent need. Mulberry leaf powder can be used as a protein source in aquatic feeds, but its high crude fiber content and presence of various anti-nutritional factors can negatively affect aquatic animals when added at high levels. Chen et al. [59] found that when using fermented mulberry leaf protein to replace fishmeal in low-fishmeal tilapia diets (containing 5% fishmeal), 40% replacement had no significant effect on growth performance, while 80% replacement significantly reduced growth performance. Ma et al. [60] found that 5% mulberry leaf powder addition in grass carp feed had no significant effect on growth performance, while 10% addition significantly reduced growth performance. Due to poor digestibility after ingestion, large amounts of mulberry leaves are difficult to incorporate in fish diets. Shen et al. [61] fed hyperlipidemic tilapia with different doses of fermented mulberry leaves, finding that fermented mulberry leaves could reduce blood lipid and glucose levels and improve antioxidant capacity. In summary, mulberry leaf powder can partially replace fishmeal in aquatic animal feeds at low levels without negative effects on growth performance or digestion, while improving antioxidant capacity and fish meat quality and reducing costs, but addition levels should not be too high.

4. Existing Problems and Development Trends

Although mulberry leaf as a livestock feed ingredient has achieved certain research progress, many issues require further in-depth study to better realize its value.

First is the chemical composition issue. The chemical composition and structure of mulberry leaves are extremely complex and affected by multiple factors. Modern analytical methods are needed to accurately detect the contents of various nutrients, anti-nutritional factors, and bioactive substances in fresh and dried mulberry leaves from different varieties, regions, and cultivation conditions, and to establish a chemical database for mulberry leaves or mulberry leaf powder.

Second is the nutritional value issue. Currently lacking nutritional value data, systematic animal nutritional value evaluation trials are needed to accurately determine nutrient digestibility and utilization rates of mulberry leaves for various animals, clarify effective energy and effective nutrient contents, and establish nutritional value databases.

Third is the development and utilization of fiber. Mulberry leaves have high crude fiber content, and their nutritional and feeding value must be related to crude fiber and its effects on intestinal microbial flora. However, systematic in-depth research is lacking on the composition and structure of fiber substances in mulberry leaves and their regulatory effects on intestinal flora and metabolism. Scattered studies have reported effects of mulberry leaf powder feeding on intestinal microorganisms, but these are not comprehensive. Extracted, separated, and processed mulberry leaf fiber substances could potentially be developed into fiber products with high protective effects on intestinal health.

Fourth is the development and utilization of bioactive substances. Mulberry leaves contain large amounts of ketones, phenols, alkaloids, and polysaccharides with special biological effects. Numerous animal trials are needed to evaluate the effects of these substances on animal health, intestinal microorganisms, growth and development, product quality, and excreta composition, to realize the special nutritional health or environmental protection functions of mulberry leaves.

Fifth is the deep processing issue. As a plant-derived unconventional feed, mulberry leaves have nutritional, anti-nutritional, and non-nutritional triple effects. Due to anti-nutritional factors, direct utilization cannot realize their nutritional value and special functions, requiring deep processing and modification. Various processing methods exist, such as drying and crushing, silaging, fermentation, and extraction, but systematic evaluation of processing parameters and nutritional value and safety after processing is needed.

Sixth is the feeding value and feeding technology issue. Further research is needed on appropriate feeding amounts, feeding methods, additive effects, and economic and ecological benefits of mulberry leaf products in different states or processed forms for livestock, poultry, and aquatic animals, to establish scientific and rational application technologies.

Sustainable development of animal husbandry must address issues of resources, efficiency, safety, quality, and ecology, areas where mulberry leaves have special roles. With in-depth research on mulberry leaves and their processing methods, the value of mulberry leaves and their products will become more prominent and their applications more widespread.

5. Summary

Mulberry has a long cultivation history in China. Besides its use as a traditional Chinese medicine and silkworm feed, other mulberry leaf resources have not been fully utilized, resulting in resource waste and necessitating exploration of multipurpose development. In recent years, the rich nutrients and active substances in mulberry leaves have gradually attracted attention from the animal husbandry industry. Mulberry leaves can serve not only as green forage or protein feed but also as an important source of bioactive substances, demonstrating clear effects in improving animal health and livestock product quality while also ameliorating environmental pollution. However, as a novel feed resource, many issues require further in-depth research. With technological development and its application in mulberry leaf development, the value of mulberry leaves will be more fully realized.

References

[1] Huang P, Yang FY. Application of mulberry leaves as livestock and poultry feed [J]. Sichuan Animal & Veterinary Sciences, 2011, 38(8): 28-29, 32.

[2] Wang F, Qiao L, Zhang QQ, et al. Analysis of amino acid composition and nutritional value evaluation of mulberry leaf protein [J]. Food Science, 2015, 36(1): 225-228.

[3] Du ZH, Liu JF, Zuo YC, et al. Nutritional characteristics of mulberry leaves and their value for feed development and utilization [J]. Acta Prataculturae Sinica, 2011, 20(5): 192-200.

[4] Liu H, Ye ZY. Evaluation of mulberry leaves as livestock feed [J]. Feed Research, 2001(9): 13-14.

[5] Zhang J, Yan XP, Gong X, et al. Free amino acid content and principal component analysis of mulberry leaves from 15 varieties in different seasons [J]. Science of Sericulture, 2016(1): 131-142.

[6] Zheng S, Zeng WX, Han L, et al. Comprehensive evaluation of nutritional quality of leaves from 45 mulberry germplasm and variety resources [J]. Food Science, 2017, 38(8): 159-163.

[7] Zhou YH. GC-MS analysis of fatty acids in mulberry leaves [J]. Guangxi Sciences, 2004, 11(2): 116-117, 120.

[8] Li Y, Miao JZ. Development of functional components and health products from mulberry leaves [J]. Food and Nutrition in China, 1999(3): 25.

[9] KIM SY, GAO JJ, LEE WC, et al. Antioxidative flavonoids from the leaves of *Morus alba* [J]. Archives of Pharmacal Research, 1999, 22(1): 81-85.

[10] Ouyang Z, Chen J. Research progress on chemical constituents and pharmacological effects of mulberry leaves [J]. Journal of Jiangsu University: Natural Science Edition, 2003, 24(6): 39-44.

[11] Zhang CB. Study on determination of total flavonoid content in mulberry leaves and its health beverage [J]. Food Science and Technology, 2000(2): 53.

[12] ASANO N, TOMIOKA E, KIZU H, et al. Sugars with nitrogen in the ring isolated from the leaves of *Morus bombycis* [J]. Carbohydrate Research, 1994, 253: 235-245.

[13] Shen WZ, Liao ST, Zou YX, et al. Determination of total polyphenols and monomeric phenolic substances in mulberry leaves from different types of mulberry germplasm resources [J]. Science of Sericulture, 2014, 40(3): 493-497.

[14] PAOLA D, PAOLA D, CACCIOLA F. Characterization of the polyphenolic fraction of *Morus alba* leaves extracts by HPLC coupled to a hybrid IT-TOF MS system [J]. Journal of Separation Science, 2009, 32(21): 362-371.

[15] Jin FQ, Jin QR. New functional beverage—Mulberry tea [J]. Food Science, 1999, 21(4): 30-32.

[16] Miyashita Susumu. Effects of *Lagerstroemia speciosa* and mulberry leaf extracts on blood glucose levels in rats [J]. Foreign Medical Sciences: Traditional Chinese Medicine, 2000, 22(4): 232.

[17] Wang WX, Yang HJ, Bo YK, et al. Analysis of nutritional components and evaluation of metabolic energy values of different mulberry varieties [J]. Chinese Journal of Animal Science, 2012, 38(3): 41-45.

[18] Huang X, Sun A, Li C, et al. Determination of metabolic energy and nutrient utilization rate of mulberry leaves for geese [J]. Journal of Domestic Animal Ecology, 2015, 36(1): 38-41.

[19] Wu C, Liao YC, Yu ZY, et al. Determination of apparent metabolic energy value of mulberry leaves for Chinese green egg-laying hens [J]. Feed Industry, 2014, 35(1): 60-61.

[20] Peng LB. Feed value of tree leaves [J]. Feed and Animal Husbandry, 2000(4): 27-29.

[21] Yang J, Cao HZ, Li TZ, et al. Evaluation of nutritional value of feed mulberry leaf powder for growing-finishing pigs [J]. Chinese Journal of Veterinary Science, 2015, 35(8): 1371-1374.

[22] Xu WR. Feasibility of using mulberry leaves as livestock feed [J]. China Herbivore Science, 2004, 24(5): 39-41.

[23] Qiu SX, Wu YS, Li J, et al. Research on feeding value of mulberry leaves in livestock and poultry production [J]. Sichuan Animal & Veterinary Sciences, 2015, 42(12): 32-33, 36.

[24] Chen QX, Wu NY, Gao JP, et al. Extraction and component determination of wolfberry seed oil [J]. China Oils and Fats, 2000, 25(2): 53-54.

[25] Li XR, Fang X, Yu LY. Antioxidant and protein glycation inhibitory effects of mulberry leaf flavonoids [J]. Journal of Zhejiang University: Agriculture and

Life Sciences, 2005, 31(2): 203-206.

[26] KIMURA M, CHEN F, NAKASHIMA N, et al. Antihyperglycemic effects of N-containing sugars derived from mulberry leaves in streptozocin-induced diabetic mice [J]. Wakan Iyakugaku Zasshi, 1995, 12(3): 214-219.

[27] Li YG, Chu YN, Zhong S, et al. DNJ content in leaves of 59 wild mulberry varieties and inhibitory activity of crude extracts on α-glycosidase [J]. Science of Sericulture, 2010, 36(5): 729-737.

[28] Peng YG, Ge JW, Fu CY, et al. Effects of mulberry leaf extract on coagulation mechanism [J]. Journal of Hunan University of Chinese Medicine, 2002, 22(4): 21-23.

[29] Yang XR, Xing J, Jiang Y. Research progress on isolation, purification, and biological activity of DNJ from mulberry leaves [J]. Food Industry, 2015, 36(9): 233-236.

[30] Zhang LH. Study on extraction, separation, and purification technology of mulberry leaf polysaccharides and preliminary exploration of their structural properties [D]. Master' s Thesis. Tianjin: Tianjin University, 2005.

[31] Wang XY, Yu XW, Tong YC. Extraction and hypoglycemic function of mulberry leaf polysaccharides [J]. Journal of Chinese Institute of Food Science and Technology, 2014, 14(9): 63-67.

[32] Xie KY, Lu HF, Yang HH, et al. Study on antioxidant activity of polysaccharides from mulberry leaves [J]. Academic Periodical of Farm Products Processing, 2014(7): 52-53, 57.

[33] Zhang J, Mu L. Analysis of amino acid composition in five types of mulberry leaf tea [J]. Northern Sericulture, 2005, 26(3): 39-41.

[34] Zhang XM, Ren FZ, Ge KS. Effects of mulberry feed addition on laying performance and egg quality [J]. Food Science, 2007, 28(3): 89-91.

[35] Liu XM, Cao YH. Effects of mulberry leaf powder addition on laying performance and egg quality [J]. Hunan Agricultural Sciences, 2011(6): 132-133, 136.

[36] Wu P, Li L, Yang HM, et al. Effects of dietary mulberry leaf powder on blood biochemical indices and egg quality of laying hens [J]. Feed Industry, 2014, 35(7): 36-38.

[37] Zhang L, Zhang XD, Li QH, et al. Effects of dietary mulberry leaf powder on serum proteins, blood lipids, and egg quality of Hy-Line gray layers [J]. Chinese Abstracts of Animal Husbandry and Veterinary Medicine, 2012(12): 208-209, 153.

[38] Zhang XD, Li YG, Zhang L, et al. Effects of mulberry leaf powder on laying performance, egg quality, and serum biochemical indices of layers [J]. China Poultry, 2012, 34(16): 25-28.

[39] Liu MY, Zhang XM, Lian HP, et al. Effects of mulberry leaf feed additive on egg yolk quality [J]. Food Science, 2013, 34(5): 223–227.

[40] Sun ZG, Pei LS. Effects of mulberry leaf powder on laying performance and egg quality [J]. Journal of Animal Science and Veterinary Medicine, 2011, 30(5): 18–21.

[41] MARGARETA O, DIANA CR, MARIA CG, et al. Effect of dietary mulberry (*Morus alba*) leaves on performance parameters and quality of breast meat of broilers [J]. Indian Journal of Animal Sciences, 2015, 85(3): 291–295.

[42] Lan CY, Dong GZ, Huang XZ, et al. Effects of mulberry leaf powder on growth performance, slaughter performance, and meat quality of broilers [J]. Chinese Journal of Animal Science, 2012, 48(13): 27–31.

[43] Wu D, Qian K, Zhou F, et al. Effects of dietary mulberry leaf addition at different ratios on production performance of Huainan partridge chickens [J]. Journal of Domestic Animal Ecology, 2013, 34(10): 39–43.

[44] Cao Y, Jiang HX, Zhang L. Nutritional value of mulberry leaves and their application in livestock and poultry production [J]. Contemporary Animal Husbandry, 2016(9): 30–32.

[45] Yang J. Nutritional value evaluation of feed mulberry leaf powder and its application in growing-finishing pig diets [D]. Master' s Thesis. Baoding: Hebei Agricultural University, 2014.

[46] Li YG, Zhang L, Zhong S, et al. Effects of dietary mulberry leaf addition on growth performance, fat metabolism, and meat quality of finishing pigs [J]. Chinese Journal of Animal Nutrition, 2012, 24(9): 1805–1811.

[47] Song QL, Wei QP, Zou ZH, et al. Effects of mulberry leaf powder on growth performance, meat quality, and serum biochemical indices of finishing pigs [J]. Chinese Journal of Animal Nutrition, 2016, 28(2): 541–547.

[48] Guo JJ, Li XB, Qi XM, et al. Effects of dietary mulberry leaf addition on reproductive performance of sows [J]. China Livestock and Poultry Breeding, 2010, 6(9): 63–64.

[49] Zhang L, Xu HQ, Tong XQ, et al. Effects of dietary mulberry leaf powder and compound enzymes on production performance, intramuscular fat, and blood lipids of Changchun pigs [J]. Hangzhou Agriculture and Technology, 2016(4): 32–34.

[50] HUYEN NT, WANAPAT M, NAVANUKRAW C. Effect of Mulberry leaf pellet (MUP) supplementation on rumen fermentation and nutrient digestibility in beef cattle fed on rice straw-based diets [J]. Animal Feed Science and Technology, 2012, 175(1/2): 8–15.

[51] Guo JJ, Li XB, Qi XM, et al. Effects of dietary mulberry leaf addition on weight gain of finishing cattle [J]. Contemporary Animal Husbandry, 2010(9): 31–32.

[52] KANDYLIS K, HADJIGEORGIOU I, HARIZANIS P. The nutritive value of mulberry leaves (*Morus alba*) supplement sheep [J]. Tropical Animal Health Production, 2009, 41(1): 17-24.

[53] JEON BT, KIM KH, KIM SJ, et al. Effects of mulberry (*Morus alba* L) silage supplementation on the haematological traits and meat compositions of Hanwoo (*Bos taurus coreanae*) steer [J]. African Journal of Agricultural Research, 2012, 7(4): 662-668.

[54] Yang CT, Diao QY, Qu PB, et al. Effects of *Candida tropicalis* and mulberry leaf flavonoids on nutrient metabolism and rumen fermentation in calves [J]. Chinese Journal of Animal Nutrition, 2016, 28(1): 224-234.

[55] Li HB, Zeng P, Li S, et al. Effects of mulberry leaf powder on rumen fermentation parameters of Xiangdong black goats [J]. Journal of Domestic Animal Ecology, 2016, 37(1): 19-25.

[56] Wu PQ, Ren LP, Zhou ZM, et al. Effects of feeding fermented mulberry leaves on growth performance, blood biochemical indices, and economic benefits of growing-finishing cattle [J]. Chinese Journal of Animal Science, 2011, 47(23): 43-46.

[57] Liu XZ, Zhu JL. Study on replacing portions of soybean meal or concentrate with mulberry leaf powder for dairy cows [J]. Modern Agricultural Science and Technology, 2006(5): 65-66.

[58] Li WL. Effects of mulberry leaves on production performance, blood biochemical indices, immune and antioxidant function, and meat quality of meat sheep [D]. Master' s Thesis. Hohhot: Inner Mongolia University, 2012.

[59] Chen WY, Chen YJ, Peng XH, et al. Study on replacing fishmeal with fermented mulberry leaf protein in low-fishmeal tilapia diets [J]. Chinese Journal of Animal Nutrition, 2015, 27(12): 3968-3974.

[60] Ma HJ, Liu XY, Xie N, et al. Preliminary study on application of mulberry leaf powder in grass carp feed [J]. Hangzhou Agriculture and Technology, 2013(3): 29-30.

[61] Shen HM, Peng XH, Lin SM, et al. Regulatory effects of fermented mulberry leaves on blood lipid and glucose levels in hyperlipidemic tilapia [J]. Chinese Journal of Animal Nutrition, 2016, 28(4): 1250-1256.

Corresponding author, professor, E-mail: dwchen@sicau.edu.cn

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