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Research Progress on Feed Resources of *Zanthoxylum bungeanum* By-Products

Yu Zhang[1,2], Aijuan Zheng[1], Zhimin Chen[1], Feiyun Yang[3], Guohua Liu[1,*]

1 Institute of Feed Research, Key Laboratory for Feed Biotechnology of the Ministry of Agriculture and Rural Affairs, Chinese Academy of Agriculture Sciences, Beijing 100081, China.
2 College of Animal Science and Veterinary Medicine, Shenyang Agricultural University, Shenyang 110866, China.
3 Institute of Animal Nutrition, Chongqing Academy of Animal Sciences, Chongqing 402461, China.

* Corresponding Author: Guohua Liu; E-mail: liuguohua@caas.cn

Abstract

Zanthoxylum bungeanum generates substantial by-products (e.g., branches, leaves and seeds) that are mostly discarded, leading to severe resource waste and environmental pollution.Dominated by seeds and leaves, *Zanthoxylum bungeanum* by-products are abundant in high-quality protein, unsaturated fatty acids and dietary fiber, as well as a diversity of bioactive substances (including volatile oils, amides, flavonoids, alkaloids and coumarins) and various mineral elements and amino acids, thus exhibiting great potential for development and utilization as innovative feed resources. At present, these by-products have been widely applied in the feed formulation for poultry, monogastric animals and ruminants. The appropriate supplementation of different *Zanthoxylum bungeanum* by-products can significantly improve the production performance, product quality and somatic health of livestock and poultry, enhance their antioxidant and immune capacities, regulate the structure of intestinal microflora, and boost the digestibility and utilization efficiency of nutrients. Nevertheless, the feed application of *Zanthoxylum bungeanum* by-products is still limited by anti-nutritional factors such as alkaloids and amides. In-depth research is still needed on the detoxification technologies, optimal addition levels of these by-products.

Keywords

Zanthoxylum bungeanum by-products; Feed resources; Bioactive substances; Animal production; Antibiotic-free breeding

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Introduction

Zanthoxylum bungeanum, also known as Zanthoxylum in English, is a deciduous shrub or small tree belonging to the genus *Zanthoxylum L.* of the Rutaceae family. China is the world's largest producer and consumer of Zanthoxylum, accounting for nearly 80% of global production and consumption. With an annual output of approximately 600,000 tons, it is mainly distributed in Sichuan, Chongqing, Gansu, Shaanxi, Yunnan and other provinces. Besides China, other major producing countries of *Zanthoxylum bungeanum* include India, Nepal, Vietnam, among others. Its fruit is spherical, with a bright reddish-brown epicarp dotted with numerous verrucae oil glands on the surface. As one of China's traditional "Eight Major Seasonings", it is also a commonly used traditional Chinese medicinal herb.

To date, scholars at home and abroad have conducted extensive research on the exploitation and utilization of the pericarp of *Zanthoxylum bungeanum*. Nevertheless, its by-products (including branches, leaves and seeds) are mostly discarded without full utilization, leading to considerable resource waste and environmental pollution[1]. Against the backdrop of the antibiotic-free breeding era and the increasingly acute shortage of feed resources, developing novel, green and functional feed raw materials has become an urgent requirement for the animal husbandry industry. The primary by-products of *Zanthoxylum bungeanum* are its seeds and leaves, which are rich in oils, proteins and polysaccharides, as well as diverse bioactive substances such as volatile oils, alkaloids and polyphenols. Thus, these by-products exhibit great potential for development and utilization as innovative feed resources. This paper summarizes the categories, utilization values, nutritional and bioactive constituents of *Zanthoxylum bungeanum* by-products, discusses their application effects in animal feed, and envisions future research priorities for the development and utilization of these by-product resources.

1. Types and Utilization of *Zanthoxylum bungeanum* By-Products

The by-products of *Zanthoxylum bungeanum* mainly include seeds, seed meal, and branches with leaves, among other residues.

Zanthoxylum bungeanum seeds are the residual seed fractions obtained after removing the inedible exocarp from the fruits of *Zanthoxylum bungeanum* Maxim., accounting for approximately two-thirds of the total weight of *Zanthoxylum bungeanum* fruits, and serve as the primary by-product of the *Zanthoxylum bungeanum* processing industry. Rich in various nutrients and bioactive components, *Zanthoxylum bungeanum* seeds have become a major research focus, yet their application is restricted by their complex chemical composition. During the production of *Zanthoxylum bungeanum* oil,

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the seed meal obtained by pressing or solvent extraction of the kernels is also an important derived by-product, which retains most of the protein and mineral elements and thus possesses high utilization value.

Despite the long history of *Zanthoxylum bungeanum* consumption, large quantities of residues such as *Zanthoxylum bungeanum* leaves and thorns are generated during its processing, resulting in severe resource waste[2]. *Zanthoxylum bungeanum* leaves have a pungent odor but are non-toxic; young leaves are even used as vegetables in some rural areas. In addition, *Zanthoxylum bungeanum* leaves and stems are often used as Chinese condiments or processed into beverages for flavor enhancement[3]. In the food industry, they are commonly processed into *Zanthoxylum bungeanum* leaf tea, pickles, pastes and kimchi. In the daily necessities industry, *Zanthoxylum bungeanum* leaves are added to shower gel (with obvious antipruritic effects), aromatic health soaps and air fresheners. Therefore, *Zanthoxylum bungeanum* leaves are functional products with broad application prospects[4]. Other by-products also include *Zanthoxylum bungeanum* shoots, lignified branches, rhizomes and roots. Among these, young stems and leaves are used as food and condiments, acting as rare natural products in vegetable markets[5], while lignified branches and trunks are currently mainly utilized for the production of biofuels, cultivation substrates, organic fertilizers and other products[6].

2. Nutritional Value of *Zanthoxylum bungeanum* By-Products

Zanthoxylum bungeanum by-products are rich in protein, fat, dietary fiber, flavonoids and other nutritional substances[7], making them a potential novel feed resource for animal husbandry. Among these, *Zanthoxylum bungeanum* seeds are abundant in palmitic acid, stearic acid, oleic acid, linoleic acid, α-linolenic acid, heptadecenoic acid, vitamin E, volatile oils, alkaloids, amides, coumarins, high-quality protein and phospholipids, as well as essential mineral elements including calcium, magnesium, iron, zinc and strontium [8]. The contents of many nutrients in *Zanthoxylum bungeanum* seeds are higher than those in soybeans, making them a relatively complete protein resource. Similarly, *Zanthoxylum bungeanum* branches and leaves are rich in protein, fat, cellulose, calcium, phosphorus, iron and other nutrients, with a high amino acid content.

2.1 Fat

Fat in *Zanthoxylum bungeanum* seeds is mainly concentrated in the kernel. The oil content of whole seeds ranges from 20% to 30% depending on variety and origin, while that of kernels can reach 25% – 35%. Various researchers have investigated the fatty acid profile of *Zanthoxylum bungeanum* seed oil. In general, the main fatty acids include oleic acid, linoleic acid, linolenic acid and palmitic acid, with the total unsaturated fatty acid content exceeding 70%[4]. Ma *et al*.[9] analyzed the fatty acid composition of *Zanthoxylum bungeanum* seed oil derived from Hancheng City, Shaanxi Province via GC–MS, identifying palmitic acid (20.14%), oleic acid (29.72%), linoleic acid (29.65%) and α-linolenic acid (17.91%) as the major components. Total unsaturated fatty acids accounted for 78.4%, and essential fatty acids (linoleic acid and α-linolenic acid) made up 47.56% of the total. Ran *et al*.[10] compared the fatty acid compositions of *Zanthoxylum bungeanum* seed oil from different geographic region and cultivar, and reported the content of oleic acid (16.73% – 32.96%), linoleic acid (6.94% – 27.80%), linolenic acid (7.72% – 23.71%), palmitoleic acid (1.56% – 56.78%) and palmitic acid (10.27% – 12.41%). Although individual fatty acid contents vary greatly among different varieties, samples from different sources are all rich in unsaturated fatty acids (86.41% – 89.18%). The abundant fat and unsaturated fatty acids demonstrate that *Zanthoxylum bungeanum* seeds possess significant application value in providing feed energy, as well as improving animal health and product quality. Fat content in leaves and other tissues is much lower than that in seeds. For example, fresh leaves contain only 0.3% – 0.7% g fat, while leaf-stem powder contain 3% – 5% g fat.

2.2 Protein and Amino Acids

In addition to fat, *Zanthoxylum bungeanum* by-products are rich in protein[7]. Protein in *Zanthoxylum bungeanum* seeds is unevenly distributed between the kernel and the shell. Pressed *Zanthoxylum bungeanum* seeds contain approximately 18.7% protein with a complete amino acid profile, being rich in aspartic acid, glutamic acid, arginine and other amino acids. The nutritionally worthless hulls of *Zanthoxylum bungeanum* seeds reduce the protein content of defatted seed cake. After dehulled, the protein content of defatted *Zanthoxylum bungeanum* seed kernel meal is as high as over 60%[11]. The essential amino acids in *Zanthoxylum bungeanum* seeds are relatively complete, and the contents of some essential amino acids are higher than those in soybeans. As a high-quality, non-toxic novel plant protein resource, *Zanthoxylum bungeanum* seed protein has become a major research focus[1,4].

Li *et al*.[12] found that the protein content was 30.90% in Sichuan *Zanthoxylum bungeanum* seed kernels and only 5.29% in seed coats. Defatting during oil production leads to protein concentration in the by-products: Yang *et al*.[13] reported that the protein content of Shaanxi Dahongpao *Zanthoxylum bungeanum* seeds was 19.79%, which increased to 39.45% after defatting. The crude protein content of pressed seed meal ranges from 20% to 28%, while that of solvent-extracted seed meal with lower residual oil can reach 25% – 32%, equivalent to 60% – 75% of that in soybean meal, demonstrating high potential for protein concentration.

2.3 Carbohydrates

Carbohydrates are the third major component of *Zanthoxylum bungeanum* by-products after fat and protein, existing mainly as non-starch polysaccharides (NSP), i.e., dietary fiber. In green *Zanthoxylum bungeanum* seeds, dietary fiber accounts for approximately 69.50% of the dry weight, of which soluble dietary fiber accounts for 2.49% and insoluble dietary fiber accounts for 67.00%[14]. In red *Zanthoxylum bungeanum* seeds, crude fiber content is up to 42.49%[15]. Sun *et al* (2025) determined the fiber fractions in green *Zanthoxylum bungeanum* seeds, in which cellulose content was approximately 40.4%, hemicellulose about 12%, and lignin about 19%[16]. Thus it can be seen, this excessive fiber and lignin are the main constraints affecting the nutritional value of *Zanthoxylum bungeanum* seeds, especially for monogastric farm animals. Compared with *Zanthoxylum bungeanum* seeds, air-dried *Zanthoxylum bungeanum* leaves have a lower fiber content, with a crude fiber content of approximately 15.3%[17]. This determines the wide applicability of *Zanthoxylum bungeanum* leaves in animal feed.

In addition, *Zanthoxylum bungeanum* seeds retain abundant mineral elements. Li *et al*.[18] detected 10 essential mineral elements in *Zanthoxylum bungeanum* seeds from different origins, including major elements Ca, P, K, Na and Mg, as well as trace elements Fe, Zn, Cu, Mn and Se. The contents of Na, Mn and Fe were relatively high in samples from all tested regions[19].

3. Bioactive Substances in *Zanthoxylum bungeanum* By-Products

The main bioactive components in *Zanthoxylum bungeanum*

include volatile oils, alkaloids, amides, coumarins, flavonoids, lignans and fatty acids. These compounds exhibit a variety of pharmacological effects such as anti-inflammatory, analgesic, antioxidant, insecticidal and antitumor activities[20].

3.1 Volatile Oil

Volatile oil, also known as *Zanthoxylum bungeanum* essential oil, is an important flavor component and a key bioactive substance in *Zanthoxylum bungeanum*, serving as a critical indicator for evaluating the intensity of its characteristic aroma. The aroma profiles of *Zanthoxylum bungeanum* essential oil are mainly divided into four types: citrus-lemon, woody-spicy, herbaceous-green and floral-sweet. Different aroma types are formed due to variations in volatile components among different *Zanthoxylum bungeanum* species[21], which makes *Zanthoxylum bungeanum* essential oil widely used in Chinese cuisine and deeply favored by consumers.

The main components of *Zanthoxylum bungeanum* volatile oil include olefins (e.g., limonene and α-pinene), alcohols (e.g., linalool and 4-terpineol), ketones (e.g., piperitone), esters (e.g., geranyl butyrate and linalyl acetate), as well as aldehydes and aromatic hydrocarbons[22]. At present, the main extraction methods for *Zanthoxylum bungeanum* volatile oil include steam distillation, supercritical CO_2 extraction, solvent extraction and simultaneous distillation-extraction. A total of 51 compounds were identified, dominated by olefins, esters, alcohols and ketones; the major components with relatively high contents were linalool (41.40%), limonene (21.95%), α-fenchene (7.36%), (L)-4-terpineol (5.69%) and myrcene (3.59%)[23]. Zhang *et al*.[24] preliminarily identified 114 main volatile organic compounds via headspace solid-phase microextraction combined with gas chromatography-olfactometry-mass spectrometry (HS-SPME-GC-O-MS), including 50 olefins, 28 alcohols, 16 esters, 8 alkanes, 9 aldehydes and 5 ketones. Wu *et al*.[22] determined the volatile components in the essential oils of 10 different *Zanthoxylum bungeanum* samples by GC-MS, detecting a total of 126 volatile compounds, mainly terpenes and terpenoids. Linalool and D-limonene showed high contents, with average values of 24.71% and 23.13%, respectively.

Due to the high production cost of *Zanthoxylum bungeanum* essential oil, it is mostly used in food, cosmetics and pharmaceuticals, while its application in animal production is relatively rare.

3.2 Sanshool

Zanthoxylum bungeanum is rich in pungent and numbing substances, among which amide compounds are the characteristic components responsible for the numbing taste, and their content is one of the main indicators for evaluating *Zanthoxylum bungeanum* quality. The numbing substances are widely distributed in the stems, leaves, pericarps and seeds of *Zanthoxylum bungeanum*, with the highest content in the pericarp[25].

In recent years, researchers have increasingly confirmed that the key pungent components in *Zanthoxylum bungeanum* are alkyl amides, represented by sanshool. Most of these compounds are linear unsaturated fatty amides and amides linked with aromatic rings. To date, more than 20 sanshool derivatives have been identified from *Zanthoxylum bungeanum*, mainly including α-sanshool, β-sanshool, γ-sanshool, hydroxy-α-sanshool, hydroxy-β-sanshool, hydroxy-γ-sanshool and others. Among them, hydroxy-α-sanshool and hydroxy-β-sanshool are considered the major numbing substances, and their contents can be regarded as important indicators for evaluating *Zanthoxylum bungeanum* quality[26].

The contents of sanshool derivatives in *Zanthoxylum bungeanum* vary with variety and plant parts. Wang *et al*.[27] determined the contents of numbing components in 16 *Zanthoxylum bungeanum* varieties from different origins by HPLC. The results showed that the contents of hydroxy-α-sanshool and hydroxy-β-sanshool varied significantly among different varieties: the content of hydroxy-α-sanshool ranged from 60.06 ± 1.14 to 164.13 ± 3.28 mg/g, and that of hydroxy-β-sanshool ranged from 7.81 ± 0.36 to 21.11 ± 0.75 mg/g. Xie *et al*.[28] reported that the amide content in the *Zanthoxylum bungeanum* pericarp was as high as 2.81 mg/g, about 70 times that in the leaves (0.04 mg/g), with hydroxy-α-sanshool as the most dominant component, followed by hydroxy-γ-sanshool and hydroxy-β-sanshool.

Sanshool derivatives have numerous pharmacological and physiological functions. Studies have also shown showed that *Zanthoxylum bungeanum* amides can ameliorate non-alcoholic fatty liver (NAFL) in mice, significantly reducing body weight, reversing liver lesions and fat accumulation, and alleviating hepatic oxidative stress[29]. Wei *et al*.[30] investigated the effects of *Zanthoxylum bungeanum* amides on amino acid metabolism in rats with type 2 diabetes mellitus (T2DM). The results showed that these amides could significantly normalize the abnormal expression of amino acid transporters in the jejunum, liver and skeletal muscle, thereby improving the amino acid metabolism disorders in the plasma, jejunum, liver and skeletal muscle of T2DM rats. Therefore, *Zanthoxylum bungeanum* amides (ZA) are potential anti-diabetic food or pharmaceutical agents for T2DM. In addition, these substances also exert pharmacological effects such as anti-inflammatory, analgesic and local anesthetic activities[31]. These physiological functions confer certain benefits on animal health. However, the numbing and pungent sensations caused by sanshool derivatives can reduce feed intake in livestock, especially mammalian animals, thereby adversely affecting growth performance.

3.3 Alkaloids

Alkaloids are another major class of bioactive components in *Zanthoxylum bungeanum*, characterized by a wide variety, complex structures and diverse types, mainly including isoquinolines, quinolines, acridones, carbazoles, indoles and others. Pharmacological studies have shown that most alkaloids from Rutaceae plants exhibit antitumor, anti-inflammatory, antiviral and antidiabetic activities[32].

Nguyen *et al*.[33] isolated three new alkaloids (zanthocadanine C, 7-methoxy-8-demoxynitidine and zanthonitiside I) from the stems and branches of *Zanthoxylum bungeanum* and evaluated their cytotoxic activities against five human cancer cell lines (KB, MCF-7, LNCaP, HepG-2 and LU-1). The results showed that 7-methoxy-8-demoxynitidine exhibited significant cytotoxic activity against all tested human cancer cell lines, with IC_{50} values ranging from 10.3 μM to 12.6 μM. Ji *et al*.[34] isolated ten quinoline alkaloids from *Zanthoxylum avicennae* and investigated their anti-inflammatory activities, and the results showed that one of the alkaloids significantly inhibited the gene expression and secretion of the pro-inflammatory cytokines IL-1β and IL-6 in macrophages. However, a high alkaloid content in feed can inhibit animal feed intake and cause adverse reactions such as abdominal pain, vomiting and hallucinations, making them potential anti-nutritional and toxic substances[32,33].

3.4 Flavonoids

Flavonoids are water-soluble phenolic compounds, including flavonoid glycosides, free flavonoids, phenylpropanoid anthocyanins and other aglycones. They are widely distributed in the pericarps, leaves, fruits, seeds and seeds oil of *Zanthoxylum bungeanum*, mostly in

the form of flavonoid glycosides, with the highest abundance in the leaves[35]. *Zanthoxylum bungeanum* leaves are rich in flavonoids, mainly including quercetin, hyperoside, afzelin and rutin, which are closely related to the antioxidant activity of *Zanthoxylum bungeanum*[35]. These flavonoids exert a variety of biological effects such as antioxidant, anticancer, anti-inflammatory, antitumor, immunoregulatory, cardiovascular and cerebrovascular protective, antibacterial, antiviral, hypoglycemic and hypolipidemic activities[20]. Some reports have shown that quercetin in flavonoids is the key bitter component in the *Zanthoxylum bungeanum* pericarp[20].

Karmakar *et al*.[36] identified three flavonoids (rutin, quercetin and myricetin) in the *Zanthoxylum bungeanum* extract by HPLC analysis, and these compounds not only have anticancer and antioxidant effects but also exhibit inhibitory activity against vascular fibrosis. Thus, the high flavonoid content in *Zanthoxylum bungeanum* leaves greatly improves their feeding value in addition to their use as a protein feed.

3.5 Coumarins

Coumarins are lactones of o-hydroxycinnamic acid, also known as bicyclic furan chromenones, with a characteristic aromatic odor. However, they lose their fragrance once they form glycosides with sugars[37]. To date, 73 coumarin compounds have been isolated from the genus *Zanthoxylum bungeanum*. According to the type and position of substituents in the coumarin structure, they can be divided into simple coumarins, furanocoumarins and pyranocoumarins. These compounds exhibit a variety of biological activities such as antibacterial, antitumor, vasodilative (especially for coronary vessels) and anticoagulant effects[38,39]. Unfortunately, coumarin exhibits certain hepatotoxicity in mammals at high doses, which limits its application in animal feed.

3.6 Lignans

Lignans in *Zanthoxylum bungeanum* plants are a class of compounds formed by the polymerization of bimolecular phenylpropanoid derivatives in organisms. Most of them exist in the free form, and a few exist as glycosides. According to their structural characteristics, they can be divided into three types: sesquiterpenoid lignans, monoterpenoid lignans and sesquilignans[40]. Modern studies have found that terpenoid lignans from *Zanthoxylum bungeanum* exhibit a variety of pharmacological effects such as neuroprotective, antitumor, anti-inflammatory, anti-type 2 diabetes, antibacterial, antioxidant and insecticidal activities[41]. Mukhija *et al*.[42] found that lignans isolated from the petroleum ether extract of *Zanthoxylum schinifolium* had cytotoxic potential against cells, suggesting that *Zanthoxylum bungeanum* lignans can be harmful for animals at high doses.

4. Application of *Zanthoxylum bungeanum* By-Products in Animal Production

In recent years, with the continuous maturation of processing technologies for *Zanthoxylum bungeanum* by-products, these by-products have been increasingly applied in the feed of pigs, laying hens, sheep, fish and other animals. Owing to their rich nutritional properties and diverse biological activities, the application strategies and effects of *Zanthoxylum bungeanum* by-products vary among different animal species. Consequently, their feeding value in animal production has been increasingly and extensively verified by numerous studies.

4.1 Application of *Zanthoxylum bungeanum* By-Products in Poultry Production

Studies on poultry have shown that *Zanthoxylum bungeanum* seeds can accelerate poultry growth, significantly improve growth efficiency, and enhance carcass quality and immune function. Chen *et al*.[43] found that isonitrogenous replacement of soybean meal with 5% – 10% dehulled *Zanthoxylum bungeanum* seed meal significantly improved the growth and development of broilers, as well as the digestibility and utilization efficiency of nutrients. These results indicate that the protein quality of *Zanthoxylum bungeanum* seeds is superior to that of soybean meal protein. Li *et al*.[44] reported that dietary supplementation with 3% *Zanthoxylum bungeanum* seed cake to replace bran could improve the production performance and antioxidant capacity of laying hens, and optimize the structure of cecal microbiota. It appears that the higher lignocellulose content in *Zanthoxylum bungeanum* seed cake did not affect the feeding performance of laying hens. This may be because the residual active components in *Zanthoxylum bungeanum* seed cake compensated for the negative effects of lignocellulose. Other studies demonstrated that adding 0.4% *Zanthoxylum bungeanum* powder to the diet improved the growth performance, body measurement traits and slaughter performance of yellow-feathered broilers, and effectively reduced abdominal fat deposition and serum triglyceride content[45]. Ning *et al*.[46] found that replacing 2% corn with *Zanthoxylum bungeanum* seeds in the diet enhanced the immunity and antioxidant capacity of laying hens, increased egg weight, reduced the rate of soft and broken eggs, improved yolk color and yolk proportion, and elevated the content of polyunsaturated fatty acids in eggs. Fu *et al*.[47] applied *Zanthoxylum bungeanum* leaves to late-laying hens and observed improved production performance, egg quality, egg flavor and antioxidant capacity without any adverse reactions, as well as reduced feed cost and increased economic benefits, with the optimal supplementation level being 3%. Zhang *et al*.[17] found that dietary addition of 6% fermented *Zanthoxylum bungeanum* leaves significantly improved the growth performance, slaughter performance and meat quality of Yellow-feathered broilers; meanwhile, the content of polyunsaturated fatty acids in meat, especially n-3 polyunsaturated fatty acids, was significantly increased, and the contents of umami and sweet amino acids were enhanced by 36.5% and 11.6%, respectively. Chen *et al*.[11] reported that replacing soybean meal with 2.5% *Zanthoxylum bungeanum* seed meal improved the meat quality by reducing drip loss and cooking loss, antioxidant capacity and immune function of broilers. Guo *et al*.[48] showed that dietary supplementation with 0.5% *Zanthoxylum bungeanum* powder improved the diversity and structure of cecal microbiota in laying hens, enhanced the body's protein utilization ability and anti-inflammatory capacity, and thus promoted production performance and deepen egg shell colour.

In summary, *Zanthoxylum bungeanum* by-products are currently widely used in chicken production, while their applications in other poultry species are rarely reported and require further investigation. Supplementing the diets of broilers or layers with different *Zanthoxylum bungeanum* by-products at appropriate proportions can promote production performance, immune function and egg quality to varying degrees, showing important practical significance and broad application prospects in poultry feed production.

4.2 Application of *Zanthoxylum bungeanum* By-Products in Monogastric Livestock Production

Current research on the application of *Zanthoxylum bungeanum* by-products in monogastric livestock feed has mainly focused on

Zanthoxylum bungeanum leaves, seeds, seed essential oil, and *Zanthoxylum bungeanum* extracts.

Li *et al*.[49] showed that dietary supplementation with 3% *Zanthoxylum bungeanum* leaves significantly improved the meat quality and intestinal health of growing pigs, and enhanced their antioxidant capacity and immune function. They also found that *Zanthoxylum bungeanum* leaf extract enhanced the cellular antioxidant capacity and alleviated oxidative stress injury in intestinal porcine epithelial cell line-J2 cells by activating the Nrf2/NQO1 signaling pathway by in vitro studies. Lin *et al*.[50] added 4% *Zanthoxylum bungeanum* leaves to the diet of pregnant sows and effectively improved the structure of intestinal microbiota, increased the relative abundance of fecal *Colidextribacter*, norank_o_WCHB1-41, CAG-196, *Oribacterium*, and norank_o_Oscillospirales, and significantly decreased the relative abundance of fecal [Eubacterium]_ruminantium_group, *Streptococcus*, Lachnospiraceae_AC2044_group, norank_f_Butyricicoccaceae, and *Oscillospira*. Other studies reported that dietary supplementation with 6% green *Zanthoxylum bungeanum* leaf powder improved diet palatability, increased feed intake and growth rate of meat rabbits, promoted small intestinal mucosa development, enhanced jejunal digestive enzyme activity, improved slaughter rate and meat quality, and also reduced serum glucose and lipid levels[51,52].

Liang *et al*.[53] found that replacing 5% corn with *Zanthoxylum bungeanum* seeds in the basal diet of growing-finishing pigs significantly improved the growth performance and increased n-3PUFAs content in longissimus dorsi muscle. These results are largely associated with the additional energy, fatty acids, and other bioactive substances provided by *Zanthoxylum bungeanum* seeds. Xie *et al*.[54] showed that adding 0.3% *Zanthoxylum bungeanum* extract to the diet of finishing pigs increased average daily feed intake and average daily gain, and improved carcass and meat quality. This result is evidently associated with the multiple bioactive constituents present in *Zanthoxylum bungeanum*.

In summary, *Zanthoxylum bungeanum* by-products are mainly used in pig production among monogastric animal breeding. Supplementation with *Zanthoxylum bungeanum* seeds, leaves and other by-products can improve the meat quality and intestinal health of finishing pigs, as well as regulate the intestinal microbiota and immune indices of pregnant sows.

4.3 Application of *Zanthoxylum bungeanum* By-Products in Ruminant Production

Ruminants have inherent advantages in utilizing unconventional feed resources with high fiber content and rich bioactive substances due to their unique rumen fermentation system. *Zanthoxylum bungeanum* by-products, especially their high-fiber components (seed coats) and bioactive extracts, exhibit multiple application values in ruminant nutrition.

Jin *et al*.[55] found that dietary supplementation with *Zanthoxylum bungeanum* essential oil significantly increased the average daily gain of ewes at two growth stages, improved serum albumin and glucose contents and antioxidant capacity, enhanced serum IgG, IgM and IFN-γ levels, and effectively reduced serum triglycerid and cholesterol contents as well as body fat deposition. Ma *et al*.[56] showed that dietary supplementation with 3% *Zanthoxylum bungeanum* seeds favored the development of the compound stomach and promoted rumen tissue growth of Hu sheep lambs, thereby reducing the feed-to-gain ratio. Xie *et al*.[57] reported that adding 5% *Zanthoxylum bungeanum* seeds to the diet of meat sheep significantly increased average daily gain, average daily feed intake, feed conversion ratio, and the apparent digestibility of dry matter, crude protein, acid detergent fiber and neutral detergent fiber compared with the control group. The contents of serum total protein and creatinine were also slightly higher than those in the control group, thus improving nutrient digestibility and enhancing digestive and absorptive capacity. Liu *et al*.[58] found that dietary supplementation with 3% *Zanthoxylum bungeanum* seeds promoted intestinal development and improved intestinal immune function of Hu sheep. Ma *et al*.[59] demonstrated that *Zanthoxylum bungeanum* essential oil improved the growth performance, slaughter performance and meat quality of fattening sheep, with the optimal supplementation level being 10 mL/kg.

In ruminant production, through scientific processing and precise nutritional regulation, the application of *Zanthoxylum bungeanum* by-products can fully exert multiple functions such as maintaining rumen health, promoting intestinal development and improving growth performance, thus achieving the dual goals of resource utilization and green breeding.

5. Conclusions

In summary, *Zanthoxylum bungeanum* by-products such as seeds and leaves are rich in high-quality protein, unsaturated fatty acids, and various bioactive components (e.g., volatile oils, amides, flavonoids). They show great potential in replacing conventional feed ingredients (e.g., soybean meal, corn) and acting as functional feed additives to improve animal growth performance, enhance antioxidant capacity, regulate intestinal flora and replace antibiotics in feed.

Current studies indicate that appropriate supplementation of *Zanthoxylum bungeanum* by-products can improve the production performance, product quality and health status of poultry, pigs and ruminants, providing a solid theoretical and practical basis for the feed utilization of these by-products. However, the detoxification technologies for anti-nutritional factors (e.g., alkaloids, amides), the determination of optimal supplementation levels still need further in-depth study to ensure the nutritional stability and application safety of *Zanthoxylum bungeanum* by-products in feed.

Author Contributions

Yu Zhang, Aijuan Zheng, Zhimin Chen, Feiyun Yang, Guohua Liu contributed to the conception and design of the review. Literature collection, drafting, and revision were performed by Yu Zhang, Aijuan Zheng, Zhimin Chen, Feiyun Yang, Guohua Liu. All authors have read and approved the final manuscript.

Artificial Intelligence (AI) Statements

Doubao (ByteDance) was used to help polish the English language of this paper. The authors have revised and verified all AI-aided content and bear full responsibility for the manuscript.

Data Availability

All data generated or analyzed during this study are included in this published article and its supplementary information files.

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Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] Meng Z K, Ren Y Y, Zou Y, *et al*. Research Status and Prospect of Zanthoxylum By-products[J]. *Food and Fermentation Technology*, 2021, 57 (3): 140-144. (in Chinese)

[2] Zhang Y, Luo Z, Wang D, *et al*. Phytochemical profiles and antioxidant and antimicrobial activities of the leaves of *Zanthoxylum bungeanum*[J]. *The Scientific World Journal*, 2014, 2014: 1-13. [Google Scholar] [CrossRef]

[3] Yang F X, Su Y Q, Li X H, *et al*. Studies on the preparation of biodiesel from *Zanthoxylum bungeanum* maxim seed oil[J]. *Journal of Agricultural and Food Chemistry*, 2008, 56 (17): 7891-7896. [Google Scholar] [CrossRef]

[4] Yang X M, Han X, Zhang X Y, *et al*. Research Progress on Nutritional Components, Extraction Technology and Application of Zanthoxylum Seeds[J]. *China Oils and Fats*, 2025, 50 (10): 113-117. (in Chinese)

[5] Li X S, Chen M Y, Huang C Z, *et al*. Research Progress on Resource Utilization of Zanthoxylum and Its Wastes[J]. *South China Agriculture*, 2025, 19 (15): 149-154. (in Chinese)

[6] Xie L, Meng Y, Wang Q, *et al*. *Zanthoxylum bungeanum* branches activated carbons with rich micropore structure prepared by low temperature H3PO4 hydrothermal pretreatment method for toluene adsorption[J]. *Diamond and Related Materials*, 2022, 130: 109474. [Google Scholar] [CrossRef]

[7] Tan Y X, Zhang X Q, Pei H S, *et al*. Preparation of High F-Value Oligopeptides from Zanthoxylum Seeds and Virtual Screening of Uric Acid-Lowering Activity[J]. *Science and Technology of Food Industry*, 2025, 46 (23): 118-125. [Google Scholar]

[8] Hou Y J, Xu J, Wang Y L, *et al*. Biological Functions of Zanthoxylum Seeds and Their Application in Poultry Production[J]. *Feed Review*, 2017 (8): 31-34, 38. (in Chinese)

[9] Ma Y M, Zhang Q Y, Zhu J F. GC-MS Analysis of Fatty Acid Composition in Zanthoxylum Seed Oil[J]. *Cereals and Oils*, 2010 (8): 40-41. (in Chinese)

[10] Ran J, Zhu Y, Ren T, *et al*. Effects of Geographic Region and Cultivar on Fatty Acid Profile and Thermal Stability of *Zanthoxylum bungeanum* Seed Oil. *Journal of Oleo Science*. 2022 Apr 29; 71 (5): 631-639. doi: 10.5650/jos.ess21398. [Google Scholar] [CrossRef]

[11] Chen X, Li X Z, Zheng A J, *et al*. Effects of Zanthoxylum Seed Kernel Meal Replacing Soybean Meal on Growth Performance, Slaughter Performance, Serum Biochemical Indicators, Antioxidant Capacity and Immune Function of Broilers[J]. *Chinese Journal of Animal Science and Veterinary Medicine*, 2025, 52 (1): 158-168. (in Chinese)

[12] Li C. Preparation and Properties of Isolated Protein from Zanthoxylum Seed Kernels[D]. *Ya'an: Sichuan Agricultural University*, 2019. (in Chinese)

[13] Yang L Y. Study on Isolation, Extraction and Properties of Protein from Zanthoxylum Seed Kernels of Hancheng Dahongpao[D]. *Xi'an: Shaanxi Normal University*, 2011. (in Chinese)

[14] Jiang Lina, Zhang Xiuqing, Pei Haisheng, *et al*. Effect of Superfine Grinding Technology on the Quality Characteristics of *Zanthoxylum bungeanum* Seed Powder[J]. *Science and Technology of Food Industry*, 2024, 45 (8): 67−74. [Google Scholar]

[15] Liang Y F, Gun S B, Wang P F, *et al*. Effects of replacing corn with Zanthoxylum seed at different levels on growth performance and meat quality of finishing pigs[J]. *Chinese Journal of Animal Science*, 2021, 57 (02): 112-116. (in Chinese)

[16] Sun Zhuoyan, Jiang Lina1, Zhang Xiuqing, *et al*. Preparation and physicochemical characterization of cellulose from *Zanthoxylum bungeanum* seeds by superfine grinding assisted deep eutectic solvents. [J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2025, 41 (16):308-318. (in Chinese)

[17] Zhang Y, Fu M, Yang G, *et al*. Effects of dietary supplementation with fermented zanthoxylum schinifolium leaves on growth performance, meat quality, and sensory traits in sanhuang chicken[J]. *Foods*, 2025, 14 (14) . [Google Scholar] [CrossRef]

[18] Li Q, Pu B. Comparative Study on Main Nutritional Components of Green Zanthoxylum from Different Producing Areas[J]. *China Condiment*, 2011, 36 (10): 13-17. (in Chinese)

[19] Xiao Y, Gu T, Hu S, *et al*. Assessment of nutritional components, mineral profiles, and aroma compounds in zanthoxylum armatum fruit from different harvest times, tree age and fruiting position[J]. *Horticulturae*, 2025, 11 (9). [Google Scholar] [CrossRef]

[20] Shi W J, Chai T, Lv C M, *et al*. Research progress on the main flavor components and detection methods of *Zanthoxylum bungeanum* maxim[J]. *Journal of Food Composition and Analysis*, 2025, 144: 107658. [Google Scholar] [CrossRef]

[21] Su K, Sun S, Chen R, *et al*. Identification of key aroma-active compounds in five types of *Zanthoxylum bungeanum* maxim. essential oils using a molecular sensory approach[J]. *Journal of Food Composition and Analysis*, 2025, 145: 107816. [Google Scholar] [CrossRef]

[22] Wu Y, Zhuo Z, Qian Q, *et al*. Chemotaxonomic variation of volatile components in *Zanthoxylum bungeanum* peel and effects of climate on volatile components[J]. *BMC Plant Biology*, 2024, 24 (1): 793. [Google Scholar] [CrossRef]

[23] Shi F F, Zhou M J, Liang X F, *et al*. Extraction of Volatile Oil from Leaves of Zanthoxylum armatum and GC-MS Analysis of Its Chemical Components[J]. *Chinese Medicinal Materials*, 2020, 43 (5): 1191-1195. (in Chinese)

[24] Zhang W, Tan S, Xi W, *et al*. Comparison of volatile components in fresh and dried *Zanthoxylum bungeanum* maxim[J]. *Food Science and Biotechnology*, 2019, 28 (4): 1083-1092. [Google Scholar] [CrossRef]

[25] Zhang M, Wei D, He L, *et al*. Application of response surface methodology (RSM) for optimization of the supercritical CO2 extract of oil from *Zanthoxylum bungeanum* pericarp: yield, composition and gastric protective effect[J]. *Food Chemistry: X*, 2022, 15: 100391. [Google Scholar] [CrossRef]

[26] Luo J, Ke J, Hou X, *et al*. Composition, structure and flavor mechanism of numbing substances in chinese Zanthoxylum in the genus zanthoxylum: a review[J]. *Food Chemistry*, 2022, 373: 131454. [Google Scholar] [CrossRef]

[27] Wang Z, Liu Y, Sun G, *et al*. A simple and rapid high-performance liquid chromatography method for preparation and content detection of the mainly numbing taste substances of *Zanthoxylum bungeanum* maxim[J]. *Journal of Chromatographic Science*, 2024, 62 (5): 426-431. [Google Scholar] [CrossRef]

[28] Xie W J, Zhu R X, Zhong K, *et al*. Optimization of Ultrasonic Extraction Process of Zanthoxylum Leaf Flavor Oil by Response Surface Methodology[J]. *China Condiment*, 2014, 39 (3): 50-53, 58. (in Chinese)

[29] Peng W, He C X, Li R L, *et al*. *Zanthoxylum bungeanum* amides ameliorates nonalcoholic fatty liver via regulating gut microbiota and activating AMPK/Nrf2 signaling[J]. *Journal of Ethnopharmacology*, 2024, 318 (Pt A): 116848. [Google Scholar] [CrossRef]

[30] Wei X, Yang B, Chen G, *et al*. Zanthoxylum alkylamides improve amino acid metabolism in type 2 diabetes mellitus rats[J]. *Journal of Food*

Biochemistry, 2020, 44 (10): e13441. [Google Scholar] [CrossRef]

[31] Ye Q N, Shi X F, Yang J L. Research advance on structure and function of amides in zanthoxylum plants[J]. *China Journal of Chinese Materia Medica*, 2023, 48 (9): 2406-2418. [Google Scholar]

[32] Yuan H Mei, Qiu L, Xie Z Jian, *et al.* Research progress on alkaloids constituents from zanthoxylum and their pharmacological activities[J]. *China Journal of Chinese Materia Medica*, 2016, 40 (23): 4573-4584. [Google Scholar]

[33] Nguyen T H V, Tran T T, Cam T I, *et al.* Alkaloids from zanthoxylum nitidum and their cytotoxic activity[J]. *Natural Product Communications*, 2019, 14 (5): 1934578X1984413. [Google Scholar] [CrossRef]

[34] Ji K L, Liu W, Yin W H, *et al.* Quinoline alkaloids with anti-inflammatory activity from zanthoxylum avicennae[J]. *Organic & Biomolecular Chemistry*, 2022, 20 (20): 4176-4182. [Google Scholar] [CrossRef]

[35] Chen X, Wang W, Wang C, *et al.* Quality evaluation and chemometric discrimination of *Zanthoxylum bungeanum* maxim leaves based on flavonoids profiles, bioactivity and HPLC-fingerprint in a common garden experiment[J]. *Industrial Crops and Products*, 2019, 134: 225-233. [Google Scholar] [CrossRef]

[36] Karmakar I, Haldar S, Chakraborty M, *et al.* Regulation of apoptosis through bcl-2/bax proteins expression and DNA damage by zanthoxylum alatum[J]. *Pharmaceutical Biology*, 2016, 54 (3): 503-508. [Google Scholar] [CrossRef]

[37] Su J H, Wang M Q, Zhu L P, *et al.* Coumarins and lignans from the roots of zanthoxylum nitidum[J]. *Biochemical Systematics and Ecology*, 2022, 101: 104399. [Google Scholar] [CrossRef]

[38] Wang Y, Li C H, Luo B, *et al.* Isobutylhydroxyamides from *Zanthoxylum bungeanum* and their suppression of NO production[J]. *Molecules*, 2016, 21 (10): 1416. [Google Scholar] [CrossRef]

[39] Wang K, Liu X, Xu H R, *et al.* Research Progress on Pharmacological Activity, Pharmacokinetics and Toxicity of Natural Furanocoumarins[J]. *Chinese Journal of Pharmacology and Toxicology*, 2021, 35 (4): 312-320. (in Chinese)

[40] Chen J Y, Shi C Y, Shi X Y, *et al.* Research Progress on Chemical Structure and Pharmacological Effects of Natural Terpenoid Lignans[J]. *Natural Product Research and Development*, 2024, 36 (9): 1625-1637. (in Chinese)

[41] Xu X Y, Wang D Y, Li Y P, *et al.* Plant-derived lignans as potential antiviral agents: a systematic review[J]. *Phytochemistry Reviews*, 2022, 21 (1): 239-289. [Google Scholar] [CrossRef]

[42] Mukhija M, Lal Dhar K, Nath Kalia A. Bioactive lignans from zanthoxylum alatum roxb. stem bark with cytotoxic potential[J]. *Journal of Ethnopharmacology*, 2014, 152 (1): 106-112. [Google Scholar] [CrossRef]

[43] Chen X, Li Y, Zheng A, *et al.* Dietary replacement of soybean meal with *Zanthoxylum bungeanum* seed meal on growth performance, blood parameters, and nutrient utilization in broiler chickens[J]. *Animals*, 2024, 14 (10): 1420. [Google Scholar] [CrossRef]

[44] Li X L, Li L Z, Cao S C, *et al.* Effects of Dietary Zanthoxylum Seed Cake Addition on Production Performance, Egg Quality, Antioxidant Capacity and Cecal Microflora of Laying Hens[J]. *Chinese Journal of Animal Nutrition*, 2025, 37 (11): 7547-7562. (in Chinese)

[45] Ma Y P, Jia X X, Fan Y F, *et al.* Effects of Zanthoxylum Powder on Growth Performance, Slaughter Performance, Serum Biochemical Indicators and Immune Function of Yellow-Feathered Broilers[J]. *Chinese Journal of Animal Nutrition*, 2025, 37 (2): 927-937. (in Chinese)

[46] Ning L I, Shi-yue L, Zheng-qun L I U, *et al.* Effect of *Zanthoxylum bungeanum* maxim seeds on production performance, serum indicators, and egg quality of laying hens[J]. *Feed Research*, 2024, 47 (18): 35. [Google Scholar]

[47] Fu K, Yang H M, Gong Y D, *et al.* Effects of Zanthoxylum Leaves on Production Performance, Egg Quality and Serum Antioxidant Function of Laying Hens in Late Laying Period[J]. *Feed Industry*, 2023, 44 (7): 40-45. (in Chinese)

[48] Guo Y X, Wang D H, Huang S M, *et al.* Effects of Zanthoxylum Powder on Production Performance, Egg Quality, Plasma Biochemical Indicators and Cecal Microflora of Laying Hens[J]. *Chinese Journal of Animal Nutrition*, 2022, 34 (8): 4959-4968. [Google Scholar]

[49] Li W X. Effects of Dietary Zanthoxylum Leaves on Growth Performance, Meat Quality and Intestinal Health of Growing Pigs[D]. *Chongqing: Southwest University*, 2025. (in Chinese)

[50] Lin H S, Cao S C, Yin H, *et al.* Nutritional Value Evaluation of Zanthoxylum Leaves and Its Effects on Reproductive Performance of Gestating Sows[J]. *Chinese Journal of Animal Nutrition*, 2025, 37 (12): 8217-8230. (in Chinese)

[51] Guo Z Q, Li Y Y, Yang R, *et al.* Effects of Green Zanthoxylum Leaves on Growth Performance, Nutrient Apparent Digestibility and Serum Biochemical Indicators of Meat Rabbits[J]. *China Feed*, 2022 (17): 123-126. (in Chinese)

[52] Guo Z Q, Li Y Y, Yang R, *et al.* Effects of Dietary Green Zanthoxylum Leaf Powder on Growth Performance, Small Intestinal Development, Slaughter Performance and Meat Quality of Meat Rabbits[J]. *Chinese Journal of Animal Nutrition*, 2023, 35 (5): 3228-3236. (in Chinese)

[53] Liang Yongfei, Gun Shuangbao, Wang Pengfei, *et al.* Substituting Different Proportions of Corn on Growth Performance and Meat Quality of Finishing Pigs [J]. *Chinese Journal of Animal Science*, 2021, 57 (2): 112-116. (in Chinese)

[54] Xie H B, Wang Y Q, Wei G H, *et al.* Effects of Zanthoxylum Extract on Growth Performance and Carcass Quality of Growing-Finishing Pigs[J]. *Swine Production*, 2016 (5): 42-45. (in Chinese)

[55] Jin Q, Jing Z M, Kang F E, *et al.* Effects of Zanthoxylum Essential Oil and Oregano Essential Oil on Growth Performance, Serum Biochemical and Immune Indicators of Ewes at Different Growth Stages[J]. *Feed Research*, 2025, 48 (4): 1-6. (in Chinese)

[56] Ma X Y, Li Q, Qi C H, *et al.* Effects of Zanthoxylum Seeds on Growth Performance, Visceral Organ Indexes and Rumen Tissue Morphological Development of Hu Sheep Lambs[J]. *Journal of Gansu Agricultural University*, 2024, 59 (5): 1-9. (in Chinese)

[57] Xie J P, He Z F, Wang F, *et al.* Effects of Zanthoxylum Seeds on Growth Performance, Nutrient Apparent Digestibility and Serum Biochemical Indicators of Meat Sheep[J]. *Feed Research*, 2022, 45 (22): 11-14. (in Chinese)

[58] Liu Z L, Li Q, Ma X Y, *et al.* Effects of Dietary Zanthoxylum Seeds on Nutrient Apparent Digestibility, Intestinal Development, Immune Function and Digestive Enzyme Activity of Hu Sheep[J]. *Chinese Journal of Animal Nutrition*, 2024, 36 (5): 3131-3142. (in Chinese)

[59] Ma S P, Wang C L, Liu L S, *et al.* Effects of Zanthoxylum Essential Oil on Fattening Performance and Meat Quality of Meat Sheep[J]. *Journal of Domestic Animal Ecology*, 2024, 45 (2): 82-86. (in Chinese)