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Review

Flaxseed Meal and Its Application in Animal Husbandry: A Review

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Abstract: Flaxseed meal (FSM) is rich in protein, α-linolenic acid, dietary fiber, flaxseed gum, and other bioactive substances. The total protein content of these components is up to 30%. Thus, FSM can be used as a high-quality protein feed resource. However, due to the presence of anti-nutritional factors, such as cyanogenic glycosides (CGs), phytic acid, anti-vitamin B6 factor, and other anti-nutritional factors, the application of FSM is restricted in animal diets. Recently, the interest in decreasing anti-nutritional factors and improving the nutritional value of FSM has been increasing in the field of animal nutrition. Therefore, this paper reviews the nutritional components, anti-nutritional factors, and the CG detoxification methods of FSM as well as its application in livestock and poultry, in order to provide a theoretical reference for the application of FSM in animal husbandry.

Keywords: flaxseed meal; plant protein; microbial fermentation; livestock; poultry

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1. Introduction

In recent years, conventional protein feed resources such as soybean meal have been in a long-term supply-demand imbalance, which has led to increased feed costs and reduced sustainability for animal husbandry. Therefore, it is urgent to increase the development and utilization of non-conventional feed resources to alleviate the current situation of conventional feed resource shortage and reduce feed costs. In this case, alternative protein feed resources might be useful for animal nutrition.

Flaxseed is one of the world's oldest oilseed crops. In the years 2016–2020, the average cultivated area of flaxseed in the world was about 3.39 million hectares (Figure 1A) [1]. The global production of flaxseed has remained stable at about 3000 kilotons for years, and the top five countries of flaxseed production are Kazakhstan, the Russian Federation, Canada, China, and the United States of America (Figure 1B). Flaxseed oil, which is mostly obtained via squeezing and extracting from flaxseed, is an important source of supplemental n-3 polyunsaturated fatty acids (PUFA) [2]. Despite the extraction of the beneficial component (i.e., flaxseed oil), the by-product, flaxseed meal (FSM) still has good nutritional value. However, the research on FSM is relatively limited. Like many other feed ingredients, FSM has many excellent functions and can be used as a high-quality non-conventional protein feed for livestock and poultry. However, FSM has been used in the feed industry for a short time, and one of the most notable anti-nutritional factors in flaxseed, cyanogenic glycosides (CGs), severely limits the exploitation of application in the feed industry [3]. To maximize the value of FSM as animal feed, it is necessary to reduce the content of anti-nutritional factors. Therefore, this article summarizes the nutritional components, anti-nutritional factors, the detoxification methods to enhance the quality of FSM, and the preliminary application of FSM in livestock and poultry.

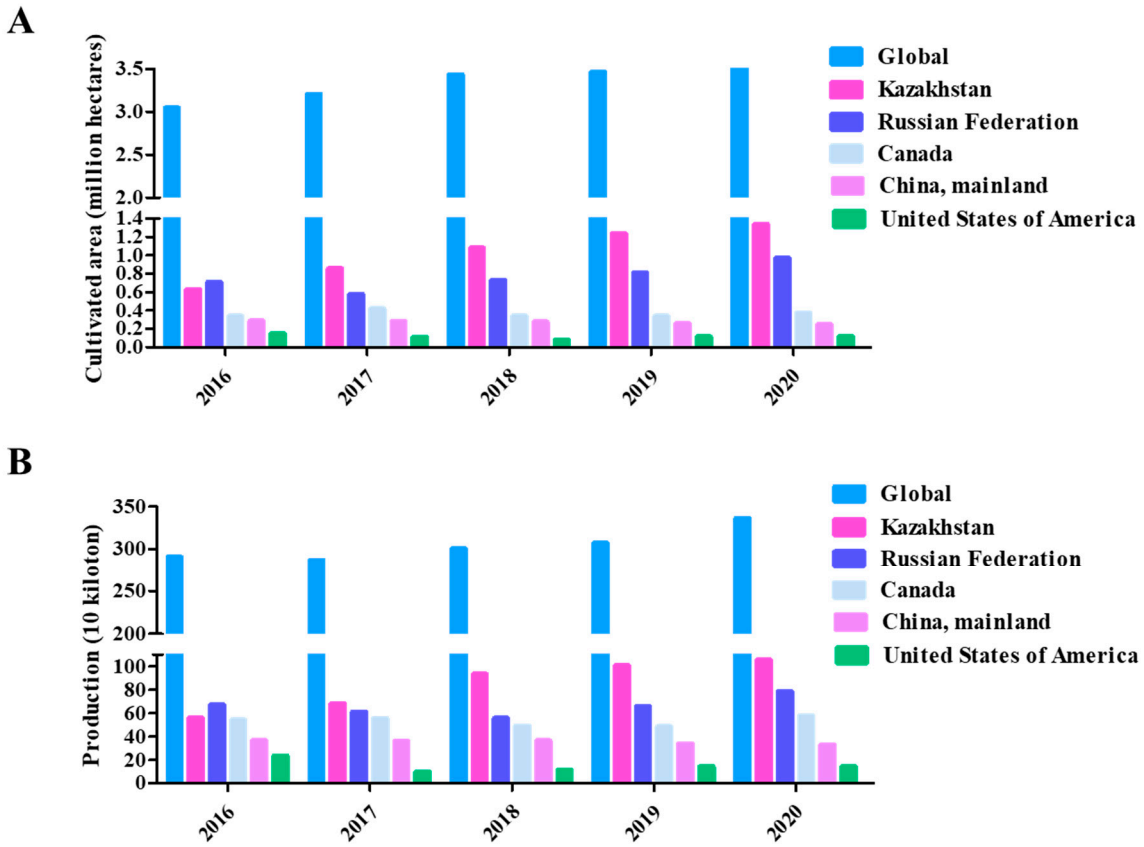

Figure 1. Flaxseed cultivated area (**A**) and production (**B**) from 2016–2020 of the top 5 countries globally (data obtained from the FAOSTAT, https://www.fao.org/faostat/en/#data/QCL, accessed on 21 November 2022).

2. Nutrition Composition and Characteristics of Flaxseed Meal

FSM is rich in n-3 PUFA, dietary fiber (DF), protein, and other nutrients. The crude protein (CP) content of FSM can be as high as 35–40% [4], which shows a comparable nutritional value with soybean protein (Table 1). Therefore, FSM has the potential to replace soybean meal as a protein raw material. In addition to being rich in protein, FSM is an essential source of α-linolenic acid (ALA) and DF [5]. However, FSM is susceptible to flax variety, origin climate, oil extraction methods, and production processes, resulting in discrepancies in nutrient composition and nutritional level [6].

2.1. Flaxseed Protein

The main components of protein in FSM are globulin and albumin [7]. The concentration and composition of essential amino acids (AAs) in FSM are similar to those in soybeans meals (Table 1) [2]. In addition, flaxseed proteins can be hydrolyzed by proteases to produce biologically active peptides. Active peptides play important physiological roles in the body with anti-inflammatory and antioxidant properties [8]. Flaxseed protein is considered a good source of plant protein. Adding an appropriate amount of FSM to livestock and poultry diets can improve animal immunity, thereby improving animal production performance and related livestock product flavor [9].

2.2. Dietary Fiber

DF in flaxseed averages about 28%, which is divided into soluble dietary fiber (SDF) and insoluble dietary fiber (IDF). The ratio of SDF to IDF varies from 20:80 to 40:60 [10]. DF ranked seventh among essential nutrients in a balanced diet. Flaxseed DF has been reported to have several beneficial effects, including increasing perceived satiety [11], enhancing fat

excretion [12], improving constipation [13], and has a specific effect on intestinal microbiota to produce short-chain fatty acids (SCFAs) that affect host metabolism [14]. Thus, flaxseed DF is an excellent source of supplemental DF, which has a variety of benefits for animals.

Table 1. The main nutritional composition of flaxseed meal and soybean meal (air dry basis, %).

Items	Flaxseed Meal	Soybean Meal
Crude protein	33.90	43.82
Ether extract	7.02	1.05
Crude ash	5.45	5.86
Neutral detergent fiber	35.96	12.44
Acid detergent fiber	16.18	5.89
Crude fiber	9.88	5.20
Calcium	0.37	0.39
Phosphorus	1.50	0.66
Arginine	3.00	3.34
Histidine	0.67	1.28
Isoleucine	1.33	1.97
Leucine	1.91	3.43
Lysine	1.19	2.95
Methionine	0.77	0.63
Phenylalanine	1.49	2.21
Threonine	1.13	1.82
Tryptophan	0.51	0.55
Valine	1.55	2.17

Note: data are obtained from the national standard GB/T 39235-2020 swine nutritional requirements of the People's Republic of China, http://c.gb688.cn/bzgk/gb/showGb?type=online&hcno=8356B650897CEE7EB81904C9C83892E5, accessed on 14 October 2022.

2.3. Polyunsaturated Fatty Acids (PUFA)

FSM is considered a superior source of n-3 PUFAs when compared to fish oil, soybean, corn, or marine algae, because of the extremely high content of ALA (about 55%) [15]. ALA is essential to the body but cannot be synthesized in vivo, hence the diet is the only way to provide this essential fatty acid (FA). Numerous studies have shown that ALA has important physiological functions in antibacterial, anti-inflammatory, and antioxidant activities [16,17]. ALA as one of the n-3 PUFAs is vital for livestock and poultry production. Studies have shown chickens can hepatically synthesize eicosapntemacnioc acid (EPA) and docosahexaenoic acid (DHA) from ALA. Moreover, when increasing concentrations of flaxseed oil in a laying hen diet, n-3 PUFA from the diet can be efficiently absorbed, transferred, and deposited into the yolk [18]. Dietary supplementation of coated n-3 PUFAs in sows' diets using flaxseed oil can improve milk IgG levels and the growth performance of suckling pigs [19]. In addition, dietary supplementation with flaxseed oil could enhance milk production and the concentration of functional FAs (ALA) in milk fat [20]. Collectively, the supplement of n-3 PUFA in the diet benefits the growth and FA metabolism of animals, thus improving the nutritional value of animal products, while it provides potential choices of FSM for the development of functional livestock products.

2.4. Flaxseed Gum

Flaxseed gum (FSG) occurs mainly in the outermost layer of flaxseed hulls, which constitutes approximately 8% of seed dry mass [21]. FSG is mainly a heteropolysaccharide composed of neutral arabinoxylan and acidic rhamnogalacturonan [22]. Flaxseed polysaccharides have been found to have special physiological functions [23]. The antioxidant capacity of soluble FSG in reducing 1,1-diphenyl-1-picrylhydrazyl (DPPH) and 2,2-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid (ABTS) free radicals and converting them to more stable products was demonstrated in vitro [24]. Furthermore, soluble FSG has been shown to exhibit strong bile acid binding ability in vitro, and decrease the enterohepatic circulation of bile acids, thereby lowering cholesterol levels and producing

SCFA profiles that are relevant in maintaining a healthy gastrointestinal tract [25]. SCFAs are known as important microbial metabolites of the organism, which participate in host metabolism and thus lower colonic pH while they may also reduce the proliferation of harmful pathogens. In addition, FSG may be used as a potential prebiotic to modulate gut microbiota. It can contribute to the regulation of lipid metabolism in the liver, and alleviate adipose tissue deposition, hence, to some extent, protecting animals from the negative effects of dyslipidemia from a high-fat diet [26]. It has also been reported that adding an appropriate amount of FSG to the diet of obese rats can inhibit obesity caused by a high-fat diet, which could be attributed to the regulation of FSG on gut microbiota by decreasing the Firmicutes/Bacteroidetes ratio [27]. Therefore, proper supplements of FSG can effectively prevent and treat the diseases caused by oxidative damage, such as reducing the incidence of obesity and preventing colon cancer.

3. Anti-Nutritional Factor of Flaxseed Meal

Although FSM contains plenty of beneficial ingredients and is a new protein feed resource in animal husbandry, there are some anti-nutritional factors such as CGs, phytic acid (PA), and anti-vitamin B6 (VB6) in FSM, which can cause adverse effects on animals and limit the application of FSM in animal diets.

3.1. Cyanogenic Glycoside

CGs are glycosylated cyanogenic organic compounds commonly found in almonds, wheat, barley, sorghum, cassava, apples, flaxseed, and other plants [28]. It has been reported that the total content of CGs in flaxseed can range from 0.74 to 1.60 g/kg CN^-. The CGs content in FSM is about 394.99 mg/kg, which is particularly affected by the pressing method of flaxseed [29]. This is because a high temperature can damage the structure of CGs, which show a large difference in FSM between cold-pressing and hot-pressing methods.

The toxicity of CGs is caused by the release of hydrocyanic acid (HCN). Hydrolysis by β-glucosidase is required in HCN generation to produce acetone cyanohydrin and sugar (Figure 2). However, acetone cyanohydrin is an unstable intermediate product, which is easily decomposed to produce toxic HCN, under the conditions of pH > 5 and temperature > 35 °C [30,31]. The presence of α-hydroxynitrile lyase can accelerate this degradation reaction [32]. CGs in the intestine are hydrolyzed by gastrointestinal β-glycosidases or by the digestive tract's acidic environment to release toxic HCN [33].

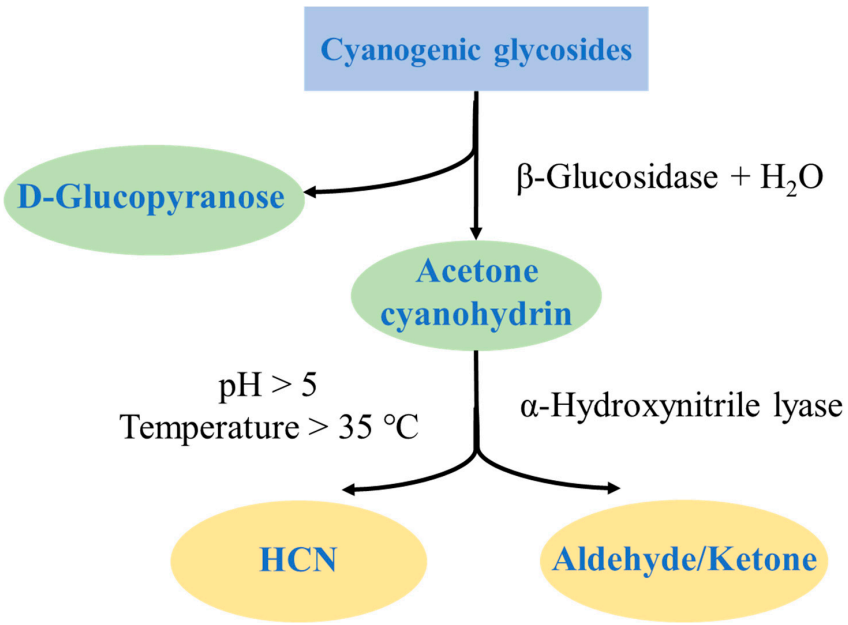

Figure 2. Degradation pathway of cyanogenic glycosides (CGs) [32,33]. HCN, hydrocyanic acid.

Under normal conditions, CGs are non-toxic and do not cause the release of HCN, due to the different locations of CGs and β-glucosidase in FSM, where contact cannot occur. However, after sufficient animal chewing, β-glucosidase is exposed and comes fully in contact with CGs, and thereafter toxic HCN is produced via enzymatic hydrolysis, which has a high chance of impairing animal health. High dietary CG content readily causes acute poisoning, leading to death within 10 to 20 min. In addition, feeding animals with diets containing CGs in the long term can result in chronic poisoning, goiter, neurological symptoms, growth retardation, and other adverse symptoms [34]. Therefore, the toxic and side effects of CGs should be considered if FSM is added to diets, and it is necessary to reduce or even eliminate the harmful and anti-nutritional effects of FSM before it can be widely used in livestock and poultry diets.

3.2. Phytic Acid

PA is a known anti-nutritional factor in FSM, which ranges from 23 to 33 g/kg of FSM [35]. PA has a strong chelating ability and can directly or indirectly bind mineral ions, proteins, and starches to form stable complexes [36], which leads to reduced digestibility and increased endogenous loss of nutrients in pigs and poultry, hence reducing the digestibility of feed. Studies have shown that PA could increase the excretion of endogenous minerals and AAs in broilers [37] and reduce the apparent ileal Na digestibility of the piglets [38]. Thus, dietary PA can reduce growth performance by reducing the absorption capacity of the small intestine.

3.3. Anti-Vitamin B6 Factor

Anti-VB6 in FSM is a dipeptide composed of glutamine and proline, and its content is about 177–437 μg/g [39]. The anti-VB6 factor can combine with the enzyme generated after VB6 phosphorylation [40]. The latter will lose its physiological function, which affects the absorption and utilization of vitamins by animals, resulting in VB6 deficiency. FSM has been already used in livestock and poultry production, while several studies have illustrated that adding excessive FSM to livestock and poultry diets will cause symptoms like loss of appetite, lethargy, and nervous disorders [3]. However, the appropriate addition of VB6 can eliminate these adverse symptoms [41]. Therefore, when an FSM is added to the ration of animal feed, it should also be supplemented with VB6 in appropriate amounts.

4. Cyanogenic Glycoside Removal Method

The presence of CG-based anti-nutritional factors in flaxseed severely limits positive impacts on health and nutritional value, so it is a necessity to strictly control its level of addition in livestock and poultry rations. CG content exceeding a certain level will reduce the feed intake of livestock and poultry and affect the digestion and absorption of nutrients in the intestine, resulting in hampered animal health [42]. Therefore, the degradation of anti-nutritional factors such as CGs in flaxseed meals by some technical means is very important in applying flaxseed in livestock and poultry production.

Researchers have tried several methods to degrade the CG content in flaxseed. For example, the physicochemical method (boiling, solvent, extrusion, roasting, autoclaving, and microwave) and biological methods (enzymatic and microbial fermentation), have been proven to remove most of the CG content from flaxseed and FSM effectively [29,43–45].

4.1. Physicochemical Method

A study found that boiling the FSM with water for 15 min can remove all CGs in FSM [46] (Table 2). Boiling will cause a loss of some proteins and available AAs in FSM. Subsequently, when using a solvent method to detoxify FSM, it was found that more than 90% of CGs could be removed using a methanol solution under optimal conditions [43]. However, solvent residue will be left in FSM when employing this method, which causes contamination. In addition, when optimizing extrusion conditions to detoxify flaxseed, it was found that under the setting of temperature 146.0 °C, feed rate 32.7 kg/h, screw

speed 152.5 rpm, and moisture content 12.5%, the highest HCN removal rate (91.62%) was achieved [47]. This method takes advantage of the increased temperature and expansion of FSM during the extrusion process to accelerate the hydrolysis of CGs to generate HCN, which is volatilized with the evaporated water. Although the HCN removal rate of this method is over 90%, it is difficult to control the operation of heating, pressurization, and detoxification during the extrusion treatment. Zhang et al. (2019) compared the effects of different processing methods (i.e., roasting, microwave, boiling, and ultrasonic treatment) on the detoxification effect of CGs. All treatments were found to reduce the CG content, and, ultrasonic treatment was the most effective [44]. Although the ultrasonic method can effectively remove CGs compared to other methods, the treatment conditions are complex, hence it is challenging to achieve industrialization.

Table 2. Effect of physicochemical method on cyanogenic glycoside (CGs) in flaxseed meal.

Methods	Treatments	Main Results	References
Boiling	Boiling water for 15 min	HCN removal rate was 100%	[46]
Boiling	Boiling at 90 °C for 50 min	CGs removal rate was 98.3%	[44]
Solvent	Use methanol solution	CGs removal rate > 90%	[43]
Extrusion	Temperature 146.0 °C, feed rate 32.7 kg/h, screw speed 152.5 rpm, and moisture content 12.5%	HCN removal rate was 91.62%	[47]
Roasting	Heating 7 h at 130 °C	CGs removal rate was 79.4%	[44]
Microwave	Microwave 7 min at 700 W	CGs removal rate was 87.2%	[44]
Ultrasonic	Ultrasonic 50 min at 700 W	CGs removal rate was 98.4%	[44]

4.2. Biological Method

In addition to the physicochemical methods described above, CGs can also be degraded by enzymes or microbial fermentation (Table 3). Fresh flaxseed contains β-glucosidase, which can decompose CGs and releases HCN. Adding 10% freshly ground flaxseed as glycosidases enzyme source into FSM was shown to completely remove CGs and the release of HCN could be further achieved after incubation in 0.1 M sodium citrate buffer (pH = 5.9) for 18 h at 30 °C [45]. Wu et al. (2012) showed that the CG concentration in FSM was decreased from 1.156 mg/g to 0.015 mg/g (CG degradation rate > 99.3%) after 48 h incubation with 12.5% β-glucosidase and 8.9% cyanide hydratase [48].

Table 3. Effect of biological method on cyanogenic glycoside in flaxseed meal.

Methods	Treatments	Main Results	References
Enzymic method	Incubated at 30 °C for 18 h in 0.1 M sodium citrate buffer (added 10% freshly ground flaxseed as glucosidase enzyme source)	CGs were completely degraded	[47]
Enzymic method	12.5% β-glucosidase and 8.9% cyanide hydratase for 48 h	CGs removal rate was 99.3%	[48]
Microbiological fermentation	*Saccharomyces cerevisiae*	CGs removal rate was 76.91%	[49]
	Bacillus sublitis	CGs removal rate was 73.28%	
	Aspergillusoryzae	CGs removal rate was 62.40%	
	Aspergillusniger	CGs removal rate was 59.16%	
Microbiological fermentation	*Pichia yeast*	CGs removal rate was 97.00%	[50]

Table 3. *Cont.*

Methods	Treatments	Main Results	References
Microbiological fermentation	*Bacillus subtilis*	CGs removal rate was 93.66%	[51]
Microbiological fermentation	Lactic acid bacteria for 72 h	HCN decreased from 351.82 mg/kg to minimum (below detection range)	[52]
Microbiological fermentation	*Lichtheimia ramose*	CGs removal rate was 89% and increased the content of CP	[53]
Microbiological fermentation	*Candidautilis* and *Aspergillusnige*	HCN level decreased from 397.76 mg/kg to 106.49 mg/kg; The contents of CP, EE, and Ca in FSM were significantly increased	[29]

There have been few reports on the degradation of CGs by microbial fermentation of FSM. The ability to degrade CGs varies across different fermentation strains (Table 3). The previous study used four strains of *Saccharomyces cerevisiae*, *Bacillus subtilis*, *Aspergillus oryzae*, and *Aspergillus niger* to ferment FSM, and the CG removal rates were 59.16%, 73.28%, 62.40%, and 76.91%, respectively [49]. With fermented FSM through *Pichia* yeast (GS115-Ch-Glu), the CG removal rate was up to 97.00% [50]. The CG removal rate of FSM was 93.66% after the treatment of *Bacillus subtilis* solid-state fermentation for 72 h [51]. It was found that by using lactic acid bacteria to ferment FSM, HCN in flaxseed was removed from 351.82 mg/kg to a minimum value (below the detection range) within 72 h [52]. Li et al. (2019) isolated and screened beta-glucosidase-producing M-2 strain with good HCN degradation performance from dairy cows' feces and found that FSM fermented by M-2 not only reduced the content of CGs (89%) but also increased its CP content (44%) [53]. In addition, using *Candida utilis* and *Aspergillus niger* in a 1:1 ratio to ferment FSM decreased the HCN level from 397.76 mg/kg to 106.49 mg/kg while improving the nutrient (CP, EE, and Ca) content of FSM, which improved the utilization rate of flaxseed in ducklings' diets [29]. From the current research results, enzymatic and microbial fermentation methods are more suitable for FSM detoxification than physicochemical methods, which can avoid the process of HCN evaporation and reduce energy consumption, but do not cause environmental pollution. From the economic point of view, the enzyme method is more complex and cost-effective than fermentation and difficult to popularize and apply in practical production. However, the microbial fermentation method not only has the advantages of safety, high efficiency, simplicity, and low cost but also can effectively degrade CGs and increase the beneficial nutrients in flaxseed [29]. In summary, microbial fermentation is the best way to improve feed nutrition and reduce HCN content among these methods.

5. Application of Flaxseed Meal in Livestock and Poultry Production

FSM has attracted much attention because it is rich in ALA and DFs, which can effectively improve the health status of livestock and poultry. FSM is an important high-quality protein source. However, so far, although there has been some investigation on producing animal products rich in n-3 PUFAs by FSM supplementation, less is known about the application of FSM used as a protein ingredient in the feed of livestock and poultry.

5.1. Application of Flaxseed Meal in Pig

The application of flaxseed or FSM in the pig diet is shown in Table 4. A previous study determined the AA standard ileal digestibility and net energy of FSM and confirmed that FSM can be added to fattening pig diets as a new high-quality livestock protein ingredient [54]. Since FSM is the richest oilseed source of n-3 PUFA, flaxseed was used in pig diets to increase n-3 PUFAs level in pork [55]. Eastwood et al. (2009) observed a significant effect on carcass FA profile when supplementing with up to 15% FSM in finishing

pig diets [56]. Continuously feeding a diet containing 2.5% flaxseed for over 46 days before slaughter, resulted in a significant reduction in n-6 PUFA levels and a significant increase in n-3 PUFA levels, which can improve the n-6/n-3 PUFA ratio in meat [57], making it more desirable for humans. Another study showed that it is possible to raise the concentrations of n-3 PUFA in pig muscle and adipose tissue fairly quickly by feeding pigs with a flaxseed diet of 6% of whole crushed flaxseed 20 d, 60 d, and 100 d before slaughter [58]. Some inconsistent results demonstrated that during the finishing period, feed intake tends to decrease linearly with increasing levels of FSM added to the diet [59]. In addition, dietary supplementing with 12% or 30% FSM reduced feed intake and negatively affected pig growth performance [60,61]. However, the reason for the reduced performance remains unclear, but it may be explained by the presence of anti-nutritional factors in FSM, which need further investigation.

Table 4. Application of flaxseed and flaxseed meal in growing pigs.

Sources	Appending Proportions	Main Results	References
Flaxseed	27.8%	Serve as a new protein feed raw material	[54]
Flaxseed meal	1.5%	Significantly impacts the carcass FA profile	[56]
Flaxseed	2.5%	Significantly increase n-3 PUFA levels in meat and backfat	[57]
Crushed flaxseed	6%	Increased n-3 PUFA level in muscle and adipose tissue	[58]
Extruded whole flaxseed	22.5–30%	Feed intake decreases linearly with increasing levels of extruded whole flaxseed	[59]
Flaxseed meal	12%	Reduced feed intake	[60]
Flaxseed meal	30%	Lower feed intakes and grew more slowly	[61]

Currently, few studies are focusing on the application of FSM to sow diets, and their results are not consistent (Table 5). Supplementation of n-3 PUFAs in the early pregnancy of gilts could reduce the synthesis of prostaglandin F2α and E2 and improve embryo survival [62]. What is more, supplementing flaxseed oil in the maternal diet could increase EPA concentrations in piglet liver, muscle, and adipose tissue [63]; supplementation of n-3 PUFA diets during lactation increased subsequent litter size born, both live born and total piglets born [64]. Previous studies investigated the effects of dietary supplementation with FSM during late pregnancy and lactation on sows and piglets and found that the addition of 6.5% FSM could increase n-3 PUFA and decrease the n-6/n-3 ratio in the milk of sows on d 20 of lactation. It could also enhance the immune response of piglets and improve the postweaning growth of piglets [65,66]. Kaur et al. (2021) reported that flaxseed supplementation at a rate of 0.5% of the dry matter, starting on day 1 of lactation until the day of subsequent farrowing, had no adverse effect, and on the contrary, the endocrine status, non-esterified fatty acids (NEFA) concentration, body composition variables, and subsequent reproductive performance of sows were improved [67]. However, the study also showed that the addition of different levels of expanded flaxseed to sow diets had no significant effect on sow litter size, average piglet birth weight, and average daily gain, but changed milk FA composition and piglet n-3 PUFA status at birth and later in life [68]. According to existing research reports, the addition of flaxseed or FSM to the diet of sows in the late gestation and lactation period would help in maintaining the health of sows and piglets and improve economic efficiency, but it is worth noting the correct proportion of FSM added to the diet, to avoid adverse effects on piglets via excessive addition of flaxseed.

Table 5. Application of flaxseed and flaxseed meal in the sow.

Sources	Appending Proportions	Main Results	References
Flaxseed oil	20%	Increased n-3 PUFA level in piglet liver, muscle, and adipose tissue	[63]
Flaxseed meal	6.5%	Increased n-3 PUFA level and decreased the n-6/n-3 ratio in the milk of sows on d 20 of lactation	[65]
Flaxseed meal	6.5%	Enhanced the immune response of piglets and improved postweaning growth of piglets	[66]
Flaxseed	0.5%	Improved endocrine profiles, NEFA concentrations, and body weight of sows	[67]
Extruded flaxseed	11.2–13.3%	Changed milk FA composition and n-3 PUFA condition of piglet after birth	[68]

5.2. Application of Flaxseed Meal in Poultry

5.2.1. Laying Hens

Producing eggs rich in unsaturated FAs by dietary flaxseed supplement has been the most widely studied in poultry production (Table 6). Numerous studies have confirmed that the addition of flaxseed to laying hens' diets could increase the deposition of n-3 PUFA in eggs [69–71]. A study found that egg yolk n-3 PUFAs increased linearly with the rising addition of flaxseed. Especially when the flaxseed level was increased to 15%, it could significantly increase yolk n-3 PUFAs to 6.83% and had no adverse effect on laying hens [69]. The addition of flaxseed to the diet also increased the amount of health-promoting ALA in the eggs as well as improved egg quality by increasing the IgY level in the yolk [70]. In addition, feeding with 10% flaxseed could alter the FA composition of the egg yolk and increase DHA levels in eggs [71]. It is evident from previous studies that the addition of flaxseed to the ration may be beneficial in the production of eggs rich in n-3 PUFAs not only because the processing cost and loss of nutrients are reduced, but also because the nutritional value is increased for human health [72,73].

However, experimental results about the effects of flaxseed on egg production parameters are not consistent. Some studies have shown that the addition of flaxseed to the diet of laying hens did not have any adverse effect on laying parameters [74,75]. In contrast, several studies have indicated that adding flaxseed may have negative effects on hen's production performance. To be more specific, feeding 20% flaxseed resulted in insufficient weight gain, reduced egg production, and increased feed intake [76], and long-term feeding of flaxseed could also reduce egg production and shell quality [77]. In addition, supplementation of extruded flaxseed in the diet of laying hens exceeded 20% harmed laying performance, even though the extruded flaxseed contained significantly fewer hydrocyanic compounds and tannins [78]. Based on these results, it can be speculated that the feed utilization was negatively impacted by low nutrient availability or the presence of anti-nutritional factors [76]. To minimize this negative effect, some researchers tried to use enzyme supplementation in flaxseed diets to alleviate the side effects caused by flaxseed, thereby ameliorating feed utilization and n-3 PUFA-enriched egg production in hens fed with a flaxseed-containing diet [77,79].

5.2.2. Broilers

Many studies have indicated that the body weight and energy efficiency of broilers decreased when increasing dietary FSM supplemental levels (Table 6). Studies showed that when the level of FSM in the diet was more than 5%, it would negatively affect the growth performance of broilers [80]. Particularly, the body weight of broilers was significantly reduced by 8.2% when an FSM was added at a 15% level [80]. However, the ALA content

in both breast and thigh meat was higher with an increasing level of FSM in the diets. In addition, similar results were observed in that FSM significantly reduced the weight gain of broilers at the level of 10% [81]. Furthermore, feeding a 10% FSM diet for at least 3 weeks (2 to 5 weeks) significantly improved the FA profile of chickens and reduced the content of fat and cholesterol in meat [9], which was beneficial to the health of broilers. Thus, to improve FAs without affecting the growth performance of broilers, the level of FSM supplementation in broiler diets should be limited to 10%.

High levels of dietary flaxseed or FSM have a detrimental effect on the performance of hens and broilers. Although the addition of enzymes can mitigate the side effects, it is not the optimal approach. Therefore, further research is needed to reduce the level of anti-nutritional factors in FSM so that its addition does not affect the growth performance of poultry, which is a key point in increasing the n-3 PUFA content in meat and eggs, and in the end, providing a healthy new food option for humans.

Table 6. Application of flaxseed and flaxseed meal in poultry.

Sources	Animals	Appending Proportions	Main Results	References
Flaxseed	Laying hens	5%, 10%, 15%	Increased n-3 PUFA level in egg yolk	[69]
Flaxseed	Laying hens	10%	Increased the IgY content of egg yolk and improved egg quality	[70]
Flaxseed	Laying hens	10%	Improved n-3 PUFA and DHA levels in eggs	[71]
Flaxseed	Laying hens	10%	No adverse effects on egg production parameters	[75]
Flaxseed	Laying hens	20%	Insufficient weight gain, reduced egg production, and increased feed intake	[76]
Flaxseed	Laying hens	15%	Reduced egg production and shell quality	[77]
Extruded flaxseed	Laying hens	20%, 30%	Harm laying performance	[78]
Flaxseed with enzyme	Laying hens	10%	Increased feed utilization and alleviated the side effects caused by flaxseed	[79]
Soaked flaxseed meal	Laying hens	12%	Had no adverse effects on reproductive performances; improved the yolk color and lipid profiles, and immune parameters	[82]
Flaxseed meal	Broilers	5%, 10%, 15%	10% FSM increased ALA level in meat; FSM > 5% reduced growth performance	[80]
Flaxseed meal	Broilers	2.5%, 5%, 7.5%, 10%	10% FSM reduced weight gain	[81]
Flaxseed meal	Broilers	10%	Improved the FA profile in the meat	[9]

5.3. Application of Flaxseed Meal in Ruminant

5.3.1. Dairy Cows

The application of FSM in ruminants mainly focuses on dairy cows. It is particularly important to provide appropriate feed for dairy cows during the milk production phase since the nutrient content of milk is susceptible to diet. It is acknowledged that flaxseed is rich in n-3 PUFAs which are beneficial to human health. Therefore, the production of n-3 PUFA-rich milk by supplementing the diet with flaxseed to improve human health has attracted more and more attention in animal production. Plenty of studies have reported that the supplementation of flaxseed in dairy cows' diets is effective in increasing the levels of n-3 PUFA in milk (Table 7) [83–85]. In addition, some studies also have focused on the transition stage of dairy cows from late gestation to lactation. During this period, dairy cows face the greatest risk of metabolic and infectious diseases or even death [86]. Flaxseed is often used as a source of FA and could mitigate the negative energy balance of early-lactating cows [87]. Studies reported that feeding dairy cows with flaxseed in the transition

period increased post-calving liver glycogen concentrations and antioxidant activity, and decreased triglyceride concentrations, which may help in preventing the development of fatty liver [88,89]. According to previous studies, the addition of flaxseed to dairy cow diets could alter the FA profile of milk, reduce lipid accumulation in the liver, and prevent the development of fatty liver, which all refer to the role of flaxseed in improving the health of cows.

Table 7. Application of flaxseed and flaxseed meal in the dairy cow.

Sources	Appending Proportions	Main Results	References
Flaxseed	6.5%	Improved FA profile in milk	[90]
Whole flaxseed	4.8%	Lowered hepatic lipids and triacylglycerol contents, increased dry matter intake and antioxidant enzyme activity in liver	[89]
Ground flaxseed/Whole flaxseed	7.2%	Increased n-3 PUFA levels in milk	[83]
Ground flaxseed/Whole flaxseed	6.38%	Increased n-3 PUFA levels in milk	[84]
Whole flaxseed	6% (prepartum) 8% (postpartum)	Increased energy balance during the postpartum period	[87]
Whole flaxseed	3.3%	Increased post-calving liver glycogen level and decreased liver triglyceride level	[88]

5.3.2. Beef Cattle

In beef cattle, flaxseed is often used to promote n-3 PUFA deposition in muscle tissue and improve beef's nutritional value (Table 8). Longissimus muscle n-3 PUFA levels were significantly increased in Hereford and Angus cattle by dietary supplementation with GF and the expression of lipid metabolism-related gene peroxisome proliferator activated receptor gamma (PPARγ) in muscle was up-regulated [91]. Similarly, the addition of 5% flaxseed in a concentrate feed to young bulls promoted fat deposition, which increased the percentage of n-3 PUFAs (mainly ALA) in intramuscular fat and decreased the n-6/n-3 PUFA ratio [92]. In Holstein cattle, the rate of n-3 PUFAs in the beef increased linearly with dietary whole flaxseed (WF) addition levels [93]. Apart from that, a study on Korean Hanwoo cattle found that there was no significant difference in daily weight gain, but feed intake tended to decrease as the level of FSM increased (>10%) [94]. Moreover, diet supplementation with 10% WF in beef cattle diets can improve several organoleptic properties of beef (reduced fat odor and increased beef flavor) [95]. Although high levels of FSM can reduce feed intake, the addition of flaxseed or FSM to beef cattle diets is considered positive overall. From the point of view of animal safety, it is recommended that no more than 5% flaxseed is employed for cattle concentrate feed, 7.5% FSM for calves' diet, and 20% flaxseed for yearlings' feed [96].

Table 8. Application of flaxseed and flaxseed meal in beef cattle.

Sources	Appending Proportions	Main Results	References
Ground flaxseed	Hereford 907 g/d, Angus cattle 454 g/d for 3 d followed by 907 g/d	Increased n-3 PUFA levels and upregulated gene expression of PPARγ in Longissimus muscle	[91]
Flaxseed	5%	Increased n-3 PUFA percentage (mainly ALA) in intramuscular fat	[92]
Whole flaxseed	3.6%, 11.2%, 18%	The deposition rate of PUFAs in beef range from 14.3% to 17.6%	[93]
Whole flaxseed	10%, 15%	Reduced feed intake but had no negative effects	[94]

6. Application Prospect of Fermented Flaxseed Meal in Livestock and Poultry Production

Although many studies have reported the use of FSM in livestock and poultry diets and the potential benefits of its addition, the dosage of FSM supplementation is severely limited and can have adverse effects on animals when added in excess. If there is evidence that FSM does not negatively affect animal growth performance and can substantially replace soybean meal as well as reduce feed costs, producers will be more willing to incorporate it into animal diets. At present, the degradation of anti-nutritional factors in FSM through microbial fermentation has already made some progress. If the microbial fermentation of FSM technology applied in the animal diet becomes more mature, it will break the bottleneck of FSM in livestock and poultry production. On the one hand, using microbial fermentation technology to degrade the anti-nutritional factors in FSM, so that the nutritional value is fully utilized, is conducive to improving the palatability of feed, enhancing the animals' immune systems, and promoting the growth performance of animals. Moreover, this ultimately can increase the proportion of FSM as an alternative to soybean meal in the animal diet. On the other hand, a variety of active ingredients in FSM (PUFAs, DFs, etc.) can be effectively combined with the beneficial bacteria in the fermentation process. This will not only retain the original beneficial nutrients in FSM but also can produce several beneficial microbial metabolites thereby enhancing the value of FSM and obtaining better feeding effects.

7. Conclusions

FSM can be used as a potential alternative new protein feed ingredient to soybean meal, but to achieve better utilization in livestock and poultry production, microbial fermentation may be the optimal choice. However, the following is worth noting: (1) the application of fermented FSM on livestock and poultry has been very limited so far, and its nutritional value has not been accurately assessed. Comprehensive chemical analysis of fermented FSM and the construction of a fermented FSM nutritional value database to formulate precise feed formula are still needed; (2) the optimal amount of fermented FSM added to animal feed has not yet been determined, therefore more research is needed to verify the practical application of fermented FSM, to ensure that the addition of fermented FSM does not adversely affect growth performance and feed conversion rate; (3) the fermentation process is also an important factor affecting the application of fermented FSM, hence more research is needed to screen out strains with a strong ability to degrade anti-nutritional factors, producing beneficial metabolites, improving the nutritional value of raw materials, and improving the level of the fermentation process so that its large-scale production also does not affect the overall fermentation effect.

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