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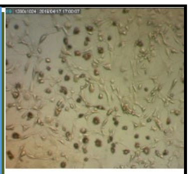

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Lipid Accumulation Staining

Nutritional, Digestibility, and Safety Perspectives of By-Product Protein Sources in Animal Feed

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Abstract

This review evaluates by-product protein sources used in animal feed, focusing on their nutritional composition, digestibility, processing methods, safety concerns, and applications across livestock and aquaculture species. By analyzing studies on amino acid profiles and protein quality, it highlights the capacity of both animal-derived and plant-based by-products to meet essential amino acid requirements. The review synthesizes evidence on digestibility metrics influenced by processing techniques such as enzymatic hydrolysis and fermentation, demonstrating improvements in nutrient bioavailability. Additionally, processing methods are explored for their efficacy in reducing contaminants including pathogens, antibiotics, and heavy metals, thereby enhancing feed safety. Safety challenges associated with chemical residues and antimicrobial resistance are addressed alongside mitigation strategies. Finally, comparative analyses underscore the impacts of these proteins on animal performance, growth, immune responses, and sustainability metrics. This integrated assessment provides valuable insights for optimizing the use of by-product proteins in sustainable animal nutrition and identifies areas warranting further investigation.

INTRODUCTION

The growing global demand for animal-derived products has intensified the need for sustainable, affordable, and nutritionally balanced feed ingredients. Protein, being one of the most expensive dietary components, plays a pivotal role in determining growth, immune function, and overall productivity of livestock and aquaculture species. Traditional protein sources, such as soybean meal and fish meal, are widely used; however,heir increasing costs, unstable supply, and environmental impacts warrant the exploration of alternative protein options [1]. Animal by-products, including feather meal, blood meal, meat and bone meal, poultry by-product meal, represent cost-effective and abundant alternatives. These materials are produced in large volumes through rendering and processing industries, and their valorization into feeds supports both economic efficiency and circular bioeconomy practices [2]. Beyond waste reduction, by-products offer considerable nutritional value when properly processed and incorporated into animal diets. Nutritional evaluation of by-products reveals distinct amino acid profiles that can complement each other in feed formulations. For example, feather meal provides a concentrated source of sulfur-containing amino acids such as cysteine, though it is limited in lysine and methionine. In contrast, blood meal is rich in lysine but deficient in sulfur amino acids. When combined, these by-products can balance amino acid deficiencies and improve growth performance across species [3]. Fish meal, long considered a benchmark protein source due to its amino acid composition and digestibility, remains highly valued in aquafeeds, although its cost and sustainability challenges limit itsroader use [4,5]. Digestibility and bioavailability remain central to the effective utilization of animal by-products. Processing methods such as enzymatic hydrolysis, fermentation, and autoclaving have been shown to enhance protein solubility and nutrient release. Enzymatic pretreatments, for instance, significantly increase nitrogen solubilization and digestibility in feather meal, improving its feeding value [6,7]. These advances enable the transformation of structurally resistant proteins, such as keratin, into more accessible nutrient sources for monogastric and aquaculture species.

Safety concerns represent another crucial dimension. By-products may carry contaminants such as antibiotic residues, pathogens, and heavy metals, which can compromise both animal and human health. Recent studies have documented the

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persistence of antimicrobial residues in poultry feathers, raising concerns about the transmission of resistance[8]. Similarly, Salmonella contamination in feed ingredients remains a recurring risk in global supply chains [9]. These issues underscore the importance of strict monitoring, quality control, and the integration of mitigation strategies, including microbial fermentation and irradiation, to ensure feed safety. This review synthesizes current knowledge on the nutritional composition, digestibility, processing strategies, and safety considerations of these products, while also comparing their performance across different species (**Fig. 1**).

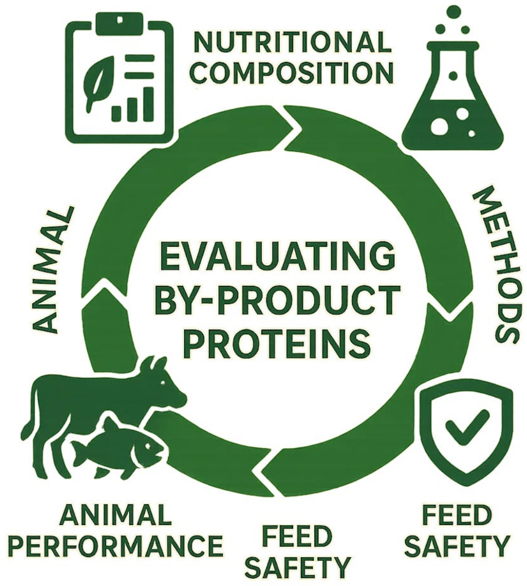

Fig. 1. Framework for evaluating by-product proteins used in animal feed. The assessment integrates nutritional composition, analytical methods, feed safety, and animal performance to ensure optimal utilization and safety of protein by-products in livestock and aquaculture systems.

Nutritional Composition and Amino Acid Profile of By-Product Protein Sources

Animal-derived protein sources, especially by-products such as feather meal, blood meal, fish meal, and meat and bone meal, are critical components in animal and aquaculture feeds due to their substantial protein content and amino acid profiles. These protein sources vary significantly in their composition, digestibility, and essential amino acid availability, which directly influences their nutritional value and applicability across diverse animal species.

Feather meal, predominantly derived from poultry feathers, is characterized by its high crude protein content and being rich in keratin protein [10]. It contains a notable concentration of sulfur-containing amino acids, particularly cysteine, though it is typically deficient in methionine, lysine, and histidine [2,3]. The keratinous nature of feather proteins requires processing to enhance its nutritional value, but inherently, feather meal provides an economical source of sulfur amino acids crucial for protein synthesis, especially for growing ruminants and poultry [3]. Blood meal, a by-product of slaughterhouse operations, is high in crude protein and exhibits favorable amino acid profiles with higher lysine content but comparatively lower sulfur amino acids [2,10]. When combined as feed ingredients, feather and blood meals can complement each other's amino acid deficiencies, thereby improving the overall nutritional balance [11,12]. Fish meal is widely recognized for its superior amino acid profile, closely resembling the amino acid requirements of many livestock and aquatic species [2,10]. It is rich in lysine, methionine, and other essential amino acids, which are typically limiting in plant-based proteins [4]. This profile supports improved growth, immune responses, and feed efficiency in species such as broilers and tilapia [4,13]. However, the availability and cost of fish meal constrain its broader use, reinforcing the importance of other by-product protein sources.

Meat and bone meal (MBM), another nutrient-dense by-product, provides a balanced protein source with high crude protein content and a diverse range of amino acids, including lysine and sulfur amino acids, but its quality varies with raw material composition and processing [10,14]. It is commonly used to supplement ruminant diets due to its high rumen undegradable protein content that can improve amino acid supply post-ruminally [15]. The amino acid profile of MBM contributes to improved nitrogen utilization and animal performance in several species, including beef cattle and dairy cows [15,16].

Plant-derived proteins such as soybean meal and wheat gluten also present important roles in feed formulations. Soybean meal typically contains high levels of lysine but limited sulfur amino acids, whereas wheat gluten is noted for its high total protein and specific amino acid contents that complement ingredients [10,17]. The combination of animal and plant proteins aims to achieve an optimal amino acid balance for enhanced growth and metabolic efficiency, as evidenced by studies on diets incorporating soybean meal with blends of blood, fish, and feather meals, which resulted in improved average daily gain and feed efficiency in goats [18]. Amino acid profiling and bioavailability assessments further inform the feeding strategy decisions. Studies assessing the fractional appearance of amino acids in plasma confirm varying absorption rates from different protein sources; for instance, leucine, methionine, and lysine exhibit high bioavailability from feather and blood meals, contributing substantially to the metabolizable amino acid pool [19]. Still, amino acid limitations in specific by-products necessitate supplementation or combinations with other protein sources to meet livestock nutritional needs [2,13].

In aquaculture, animal-derived by-products, such as feather meal, poultry by-product meal, and fish meal, are evaluated for their amino acid profiles and impact on growth and immunity. For example, hybrid tilapia fed diets partially replacing soybean or cottonseed meal with hydrolyzed feather meal maintained comparable growth performance and immune status, highlighting the potential of these by-products as aquafeeds [13]. Likewise, poultry by-product meal and fish meal improved immunological responses and survival in marron, a freshwater crustacean, showing the functional benefits of balanced amino acid supply from these by-products [4].

Collectively, the nutritional profile of by-product protein sources is a pivotal consideration in feed formulation. Understanding their amino acid composition, limitations, and complementary potential guides the development of balanced diets that optimize animal growth, production, and health across species ranging from terrestrial livestock to aquaculture systems.

Digestibility and Bioavailability of By-Product Proteins

Understanding the digestibility and bioavailability of protein by-products in animal feeds is critical for optimizing nutrient utilization and enhancing animal performance. Various digestibility metrics are employed to assess the quality of protein sources, including ileal, total tract, apparent, true, and standardized digestibility coefficients of amino acids (AA). These metrics reflect how well animals absorb and metabolize dietary protein, influencing feed formulation decisions. A study [17], evaluated derived protein sources fed to rainbow trout, such as fish meal, casein, hydrolyzed feather meal, and soybean meal. Their study showed varying digestibility values, with fish meal and casein demonstrating higher digestibilities (86% and 98%, respectively) compared to hydrolyzed feather meal (67%) and soybean meal (94%). This variation emphasizes differences in protein quality and digestibility depending on the source. Such differences translated directly into animal growth, where trout fed casein-based diets gained only about half as much weight as those fed fish meal, despite similar feed conversion ratios. Another study [20] further detailed amino acid digestibility in broiler chickens fed animal protein meals, including feather meal, blood meal, fish meal, and meat and bone meal. They found significant variation in amino acid and crude protein digestibility at the distal ileum among these protein sources. Digestion rates and the solubility of undigested proteins varied notably, affecting the mean retention time (MRT) of nutrients and, ultimately, the bioavailability of amino acids. These disparities influence feed efficiency and animal growth performance.

The measurement of standardized ileal digestibility (SID) has become a useful approach to estimate digestible amino acid content, accounting for basal endogenous losses. [21] compared methods for determining amino acid digestibility in feed ingredients for chickens, highlighting that methods such as ileal digestibility assays provide a more accurate estimate of amino acid availability than traditional total tract digestibility methods. [7] also contributed to this field by examining ileal and total tract digestibility values for various protein by-products, underscoring the importance of standardized digestibility values in feed formulation. Processing techniques significantly impact the digestibility of these protein sources. Enzymatic hydrolysis, fermentation, autoclaving, and chemical treatments have been shown to improve protein solubility and amino acid availability.

[6] Developed an enzymatic pretreatment using a commercial alkaline serine protease to enhance the digestibility of feather meal. This pretreatment significantly increased in vitro digestibility measures by optimizing nitrogen solubilization in feather meal. Similarly, [7] demonstrated thathe fermentation of feather meal with various microbes increased the amino acid content, including lysine, methionine, threonine, tryptophan, and histidine, thereby improving their nutritional value and bioavailability for broilers. The work by [13] on completely hydrolyzed feather meal showed that such enzymatic treatments could produce protein sources with digestibility comparable to more conventional ingredients like soybean meal or cottonseed meal, as evidenced by similar growth performance of hybrid tilapia fed these diets.

Chemical treatments, such as the use of NaOH and sodium sulfite, combined with autoclaving, have also been investigated for enhancing digestibility. [22] observed improved in vitro pepsin digestibility of hydrolyzed chicken feathers with these treatments, which reduced amino acid degradation, particularly preserving cystine and threonine, critical for growth. Such processing modifications not only improve digestibility but may also influence amino acid balance. Low digestibility of specific amino acids such as lysine and methionine, often limited in feather meals, can be overcome through supplementation strategies, as indicated by several studies [3,23]. Furthermore, the bioavailability of amino acids can be effectively assessed by plasma amino acid appearance, as demonstrated by [19], who estimated intestinal digestibility of feather meal at about 70% based on plasma amino acid entry rates in ruminants. Considerable variation exists in the digestibility and bioavailability of amino acids among by-product protein sources. Processing methods that include enzymatic hydrolysis, fermentation, and chemical treatments can substantially improve these parameters, leading to enhanced animal growth performance and feed efficiency across species such as poultry, fish, and ruminants.

Processing Techniques to Enhance Nutritional Value and Safety

Processing of animal by-product protein sources is essential to enhance their nutritional value, improve digestibility, and ensure feed safety by reducing contaminants such as pathogens, antibiotic residues, and heavy metals. Common processing methods include enzymatic hydrolysis, autoclaving, fermentation, gamma irradiation, and chemical treatments, each influencing protein quality, amino acid profiles, and contaminant presence in distinct ways.

Enzymatic Hydrolysis

Enzymatic hydrolysis is a widely utilized technique to improve the digestibility of keratin-rich feed ingredients such as feather meal. [6] Developed an enzymatic pretreatment using commercial serine proteases (e.g., Savinase 16L), which effectively increased nitrogen solubilization and protein digestibility in feather meal. Similarly, [24] reported that feather protein hydrolysates produced by bacterial keratinases displayed greater digestibility compared to raw feathers, with culture supernatant hydrolysates showing digestibility comparable to casein and soy protein. The bacterial degradation process also yielded a keratin hydrolysate protein rich in sulfur-containing amino acids, although it showed some deficiencies in methionine, lysine, and histidine.

Keratinase production from microorganisms such as Bacillus subtilis and Streptomyces netropsis has been optimized to boost feather degradation efficiency and protein quality [25], [26]. The inclusion of such enzymes can increase soluble protein fractions and enhance amino acid availability, as observed in broilers, where keratinase supplementation improved growth performance and redox status when fed diets containing feather meal[27].
Carbohydrase and protease enzyme supplementation in broiler diets containing feather meal improved body weight gain and feed conversion, likely by reducing digesta viscosity and mitigating gut inflammation [28]. Furthermore, enzymatic predigestion has been shown to improve the nutritional quality of prepressed feather meal in turkeys [29].

Autoclaving and Steam Treatments

Physical treatments such as autoclaving and steam flash explosion have been shown to increase feather protein digestibility by denaturing complex keratin structures. [30] demonstrated that combining 1 M NaOH with autoclaving at 21 psi significantly enhanced the in vitro protein digestibility of broiler feather protein concentrate. Similarly, [5] observed that steam flash explosion treatment improved digestibility of feather meal, suggesting the disruption of keratin matrix and increased accessibility to digestive enzymes. A study [31] found that dietary feather meals subjected to autoclaving and fermentation with Bacillus spp. and Aspergillus niger increased the amino acid content, including lysine, methionine, and threonine. This highlights the synergy between physical and microbial treatments in augmenting protein quality.

Fermentation
Solid-state fermentation utilizing microbes such as *Bacillus amyloliquefaciens* has been investigated for enhancing feather meal nutritional properties. [32] reported that feather meal-soybean meal products fermented with *Bacillus amyloliquefaciens* CU33 improved intestinal morphology and growth performance in broilers, achieving feeding effects comparable to high-quality fish meal. Fermentation modifies physiochemical characteristics and optimizes amino acid composition, thus improving digestibility. Similarly, fermentation processes contribute to the production of extracellular proteases and bioactive hydrolysates from agro-industrial by-products including feather meal, further aiding nutritional enhancement [33].

Chemical Treatments
Chemical treatments, including the use of sodium hydroxide (NaOH), sodium sulfite (Na_2SO_3), and hydrogen peroxide, are employed to solubilize keratin and reduce microbial contamination. [22] showed that NaOH and Na_2SO_3 treatments combined with autoclaving increased feather meal solubility and in vitro digestibility. Na_2SO_3 treatments were particularly effective in lowering amino acid losses such as threonine, arginine, and tyrosine compared to NaOH alone, thus better preserving amino acid profiles critical for animal nutrition.

Hydrogen peroxide treatment of feather meal was reported by [34] to enhance in situ protein degradability, although without significant effects on performance or carcass traits in heifers. This oxidative treatment may contribute to detoxification and improved nutritional value by breaking down disulfide bonds within keratin.

Gamma Irradiation
Gamma irradiation serves as an effective method for microbial decontamination in feed ingredients. [35] demonstrated that gamma irradiation doses of 6 to 9 kGy eliminated *Escherichia coli* contamination in fishmeal and other rendered animal meals, including feather meal. While high doses caused some vitamin losses, the treatment improved growth performance and gut health in weaning piglets by mitigating bacterial pathogens in feed. The application of irradiation thus represents a promising non-chemical intervention to enhance feed safety.

Contaminant Reduction and Safety Considerations
Processing techniques not only improve digestibility but also target the reduction of feed contaminants such as *Salmonella* and antibiotic residues. Chemical mitigation with formaldehyde, medium-chain fatty acids, and organic acids has been shown to reduce Salmonella prevalence in animal proteins [36]. Fermentation and enzymatic hydrolysis may also influence feed hygienic quality by reducing pathogen loads and antibiotic residues indirectly through microbial competition or degradation [37].

In summary, physiological, enzymatic, and chemical treatments of by-product protein sources, especially feather meal, have demonstrated improvements in protein digestibility and amino acid availability while mitigating contaminant risks. Optimization of processing parameters, including enzyme selection, incubation conditions, and combined treatment sequences, remains a crucial research area for maximizing feed ingredient value and ensuring animal nutrition safety.

Safety, Contaminants, and Residue Concerns
Feed safety remains a critical aspect in the utilization of animal-derived protein by-products such as feather meal, blood meal, and fish meal. Contaminants, including antibiotic residues, pathogenic bacteria such as Salmonella, antimicrobial-resistant organisms, heavy metals, and chemical residues, have been identified as potential hazards, necessitating vigilant assessment and mitigation. Antibiotic residues in feed ingredients, particularly in feathers, pose a significant concern for both animal health and public safety. [8] demonstrated that sulfadiazine, trimethoprim, and oxytetracycline persist in the feathers of treated broiler chickens even after withdrawal periods, highlighting the potential for feed contamination when such feathers are repurposed as feed ingredients. These residues are not merely chemical concerns, but also contribute to the prevalence of antibiotic-resistant bacteria within feed materials, which complicates disease management and increases the risk of spreading resistance. Complementary work by Dréano *et al*. [38] further illustrated the widespread presence of multiple antimicrobial residues in poultry feathers, emphasizing the need for residue monitoring and control in feedstuffs derived from poultry by-products.

Salmonella contamination remains an ongoing threat in feed ingredients, posing risks for both animal and human health due to zoonotic potential. [9] assessed Salmonella prevalence in feedstuffs available in Costa Rica over several years and reported not only the presence of Salmonella but also tetracycline resistance among isolates. This antimicrobial resistance further complicates containment and eradication efforts. Chemical mitigation methods such as formaldehyde, essential oils, medium-chain fatty acids, organic acids, and sodium bisulfate have been explored for their efficacy in reducing Salmonella loads in rendered proteins [36]. These treatments are critical to ensure the microbial safety of animal feed ingredients. Beyond bacterial contamination, chemical residues of concern include organophosphate esters detected in both animal-derived and plant-derived protein supplements [39,40]. These contaminants stem from environmental and anthropogenic sources and can accumulate in feed ingredients, requiring careful quality control and sourcing to mitigate potential adverse effects.

Heavy metals, such as copper and zinc, which are often present as feed additives or contaminants, also merit scrutiny due to their potential for bioaccumulation. [41] noted that feather meal did not provide bioavailable copper, whereas meat and bone meals displayed varying copper bioavailability. EFSA safety assessments for feed additives involving copper (II) chelates and zinc chelates of amino acids hydrate have confirmed both the safety and efficacy of these compounds while highlighting the necessity for precise monitoring of zinc exposure via dust inhalation in feed processing environments [42,43].

Microbial contamination control strategies have increasingly incorporated gamma-ray irradiation, which is effective in eradicating pathogenic microorganisms without significant detrimental effects on feed nutrient quality. [35] reported that gamma irradiation at doses between 6 and 9 kGy successfully eliminated *E. coli* contamination in fishmeal, feather meal, meat meal, and other feed components, thus improving growth performance and gut health in weaning piglets. However, higher irradiation doses may induce vitamin losses, requiring balancing of microbial safety and nutritional retention. Additional physical and chemical feed processing methods contribute to reducing contaminant loads and enhancing feed safety. The use of enzymatic treatments, fermentation, and autoclaving also plays a role in lowering pathogen prevalence and degrading harmful residues [6,7]. Fermentation processes have specifically yielded improvements in nutritional quality, along with decreased contamination levels, as observed in studies on fermented feather meal 7]. Maintaining safety in animal-derived protein by-products as feed ingredients necessitates comprehensive contaminant monitoring and the integration of multiple mitigation strategies. Chemical decontamination, physical treatments including gamma irradiation, microbial inhibition via fermentation, and rigorous sourcing standards collectively provide a robust approach to minimize risk from antibiotic residues, pathogens including Salmonella, antimicrobial resistance, heavy metals, and chemical contaminants.

Applications and Comparative Performance in Animal and Aquaculture Species

By-product protein sources such as feather meal, blood meal, fish meal, meat and bone meal, and poultry by-product meal serve important roles in animal nutrition across multiple livestock and aquaculture species, contributing to growth performance, nutrient utilization, immune responses, and carcass quality. In poultry nutrition, supplementation with feather meal and feather meal–soybean meal fermented products has demonstrated tangible improvements in growth performance. [32] reported that broilers fed diets supplemented with 5% *Bacillus amyloliquefaciens* fermented feather meal-soybean meal product (FFSMP) exhibited improved intestinal morphology, particularly in the duodenum, which correlated with superior growth metrics comparable to feeding high-quality fish meal. Moreover, keratinase enzyme supplementation to feather meal-based diets improved broiler growth performance, meat quality, and oxidative status, indicating that enzymatic processing can enhance the nutritional efficacy of this by-product [27]. In experimental trials with quail, feather meal supplemented with keratinolytic bacteria significantly increased body weight gain and improved feed conversion ratios, demonstrating its utility beyond standard poultry species [25]. These microbial processing approaches highlight the potential for improved digestibility and amino acid availability in feather-derived proteins.

Cattle production also benefits from by-product proteins, particularly for rumen undegradable protein (RUP) supply. Studies by Grant *et al*. [15] and Polan *et al*. [44] demonstrated increases in nitrogen utilization and milk production when blends of feather meal, blood meal, fish meal, and meat and bone meal were included in diets for dairy cows. Specific performance outcomes include increased apparent nitrogen digestibility, nitrogen absorption, and improved nitrogen balance, which positively influence growth and lactational productivity [16]. Supplemental feather meal, combined with other protein sources, has been shown to improve average daily gains (ADG) and feed efficiency in beef cattle, especially when balanced appropriately with rumen-degradable and undegradable protein fractions [3,19,45]. Additionally, supplementation of rumen-protected lysine and histidine with hydrolyzed feather meal further enhanced milk yield and protein synthesis in lactating Jersey cows, indicating that amino acid balancing is important when using these by-products [23,46].

In swine diets, feather meal is commonly evaluated for its amino acid content and digestibility as an alternative protein source. Apple *et al*. [47] observed that feather meal inclusion did not adversely affect carcass quality or composition in growing-finishing swine and maintained adequate growth performance. However, the low digestibility and balance of certain amino acids in feather meal may require supplementation with synthetic amino acids. Divakala *et al*. [48] demonstrated that adding amino acids to hydrolyzed feather meal diets improved growth performance in finishing pigs. Comparative studies between broilers and pigs indicate variability in the amino acid digestibility of poultry by-products, which affects growth responses [49]. The use of processed feather meal and poultry protein by-products, which offer improved digestibility, shows promise for enhancing swine nutrition efficiency.

Aquaculture species also utilize by-product proteins, primarily fish meal, feather meal, and poultry by-product meal. Pfeffer and Henrichfreise [17] evaluated these protein sources for rainbow trout, reporting protein digestibility that varied widely, with casein and fish meal generally superior to feather meal, which showed the lowest digestibility but remains a feasible ingredient with proper processing. Zhang *et al*. [13] studied hybrid tilapia and found that partial replacement of soybean or cottonseed meal with completely hydrolyzed feather meal did not impair growth or disease resistance, suggesting feather-derived proteins can substitute plant-based proteins effectively in aquafeeds. Saputra *et al*. [4] reported that marron fed poultry by-product meal and fish meal had improved survival rates and immune responses compared with those fed feather meal, indicating species-specific responses to different by-product proteins. Improvements in gut morphology and immune competence with these protein types suggest functional benefits beyond basic nutrition.

From an energy utilization perspective, Morris *et al*. [2] used indirect calorimetry to assess inclusion of hydrolyzed feather meal in diets for lactating Jersey cows, observing effects on energy metabolism that support the continued use of feather meal in energy-demanding production phases. Similar studies in finishing pigs and other animals underline that digestible energy from by-product meals varies with processing, emphasizing the need for accurate energy value estimation in diet formulation [14]. Economically and environmentally, utilization of by-product proteins contributes significantly to sustainable animal production by valorizing waste streams such as feathers, blood, and meat industry residuals. This reduces reliance on primary feedstuffs, improves resource efficiency, and supports circular economy principles in livestock and aquaculture sectors [1]. Processed by-products, when well-balanced and safely incorporated, provide cost-effective and functional protein sources that can support robust animal performance across species.

Collectively, these findings demonstrate that by-product protein sources have broad applicability in diverse animal feeding systems. Optimization through processing and supplementation can further enhance their nutritional value and functional benefits, contributing to improved growth, health, and production outcomes in poultry, ruminants, swine, and aquaculture species.

CONCLUSION

The evaluation of by-product protein sources reveals their substantial potential as sustainable and cost-effective feed ingredients capable of meeting essential amino acid requirements across diverse animal species. However, digestibility and bioavailability vary considerably depending on the protein source and processing methods applied, underscoring the importance of optimized processing techniques to enhance nutritional quality and reduce contaminants. Safety concerns related to microbial pathogens, antibiotic residues, heavy metals, and antimicrobial resistance remain critical challenges that require ongoing monitoring and innovative mitigation strategies. Comparative assessments demonstrate that incorporating these proteins can positively influence animal growth performance, health, and production efficiency while contributing to environmental sustainability. Future research should focus on refining processing technologies, advancing contaminant detection and removal, and evaluating long-term impacts on animal health and product safety to harness the benefits of by-product proteins in animal nutrition fully.

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