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Animal by-products: From waste to wealth— sustainable valorization for agriculture, veterinary medicine, and food science

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Abstract

The livestock and meat processing sectors produce large amounts of animal by-products that were once treated as waste and discarded, creating environmental concerns. Today, advances in biotechnology, food science, veterinary medicine, and processing technologies have enabled these materials to be converted into valuable products. By-products such as blood, bones, skin, feathers, and internal organs contain proteins, collagen, minerals, lipids, and other bioactive compounds that can be recovered for diverse applications. They are widely used in the manufacture of animal feed, fertilizers, collagen, gelatin, pharmaceuticals, cosmetics, pet foods, and bioenergy. Their efficient utilization supports the principles of a circular bioeconomy by reducing waste, conserving natural resources, and minimizing environmental pollution. Despite these benefits, issues related to biosafety, disease prevention, regulatory requirements, and consumer perception remain important considerations. Overall, effective management of animal by-products promotes sustainable livestock production while creating economic value and supporting environmental conservation.

Keywords: Animal by-products, blood meal, bone meal, collagen, gelatin

1. Introduction

The global demand for meat and livestock products has grown steadily in recent decades, driven by rapid population growth, urbanization, rising incomes, and changing food preferences. According to the Food and Agriculture Organization (FAO, 2023) ^[1], the livestock sector contributes nearly 40% of the world's agricultural gross domestic product and provides livelihoods for more than one billion people. As livestock production expands, slaughterhouses and meat-processing industries generate large volumes of animal by-products, including blood, bones, skin, fat, feathers, internal organs, and connective tissues. These materials generally account for 30–50% of an animal's live weight and represent a substantial source of valuable biological resources that are often not fully utilized.

In recent years, advances in biotechnology, food science, veterinary medicine, and processing technologies have transformed the way animal by-products are viewed. Instead of being considered waste, they are increasingly recognized as valuable raw materials containing proteins, collagen, gelatin, essential amino acids, minerals, lipids, enzymes, and other bioactive compounds with wide industrial applications (Jayathilakan *et al.*, 2012) ^[3]. Their efficient recovery and utilization not only reduce environmental pollution but also improve the economic sustainability of the livestock sector by generating additional value from materials that would otherwise be discarded.

The growing emphasis on the circular bioeconomy has further accelerated the adoption of sustainable by-product utilization practices. By promoting resource recovery, recycling, and waste reduction, this approach replaces the traditional linear production model and supports the development of environmentally responsible livestock systems (Lynch *et al.*, 2018) ^[5]. It also contributes to achieving several United Nations Sustainable Development Goals, particularly those related to sustainable agriculture, responsible consumption and production, and climate action.

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Animal by-products are now widely used in the production of animal feed, organic fertilizers, collagen, gelatin, pharmaceuticals, cosmetics, pet foods, and renewable bioenergy. This review discusses the major animal by-products, their processing methods, and their diverse applications in agriculture, veterinary medicine, and food science, with emphasis on their role in promoting environmental sustainability and a circular livestock economy.

2. Blood and Blood Meal

Among all slaughterhouse by-products, blood is one of the most abundant and nutritionally valuable materials, accounting for approximately 3–4% of the live body weight of food animals. Despite its high nutritional value, untreated blood possesses an extremely high biological oxygen demand (BOD) and chemical oxygen demand (COD), making it one of the most polluting slaughterhouse wastes if discharged

directly into the environment (Jayathilakan *et al.*, 2012) [3]. Therefore, efficient collection and processing of blood are essential for both environmental protection and resource recovery.

Animal blood consists of approximately 55% plasma and 45% cellular components, containing 17–19% high-quality proteins along with essential amino acids, iron, minerals, vitamins, enzymes, and bioactive compounds. Plasma proteins, including albumin, globulins, and fibrinogen, exhibit excellent emulsifying, foaming, and gel-forming properties, while hemoglobin serves as an important source of highly bioavailable heme iron (Lynch *et al.*, 2018) [5]. These functional characteristics make blood an attractive raw material for food, feed, pharmaceutical, and agricultural applications.

2.1 Processing of Blood into Blood Meal

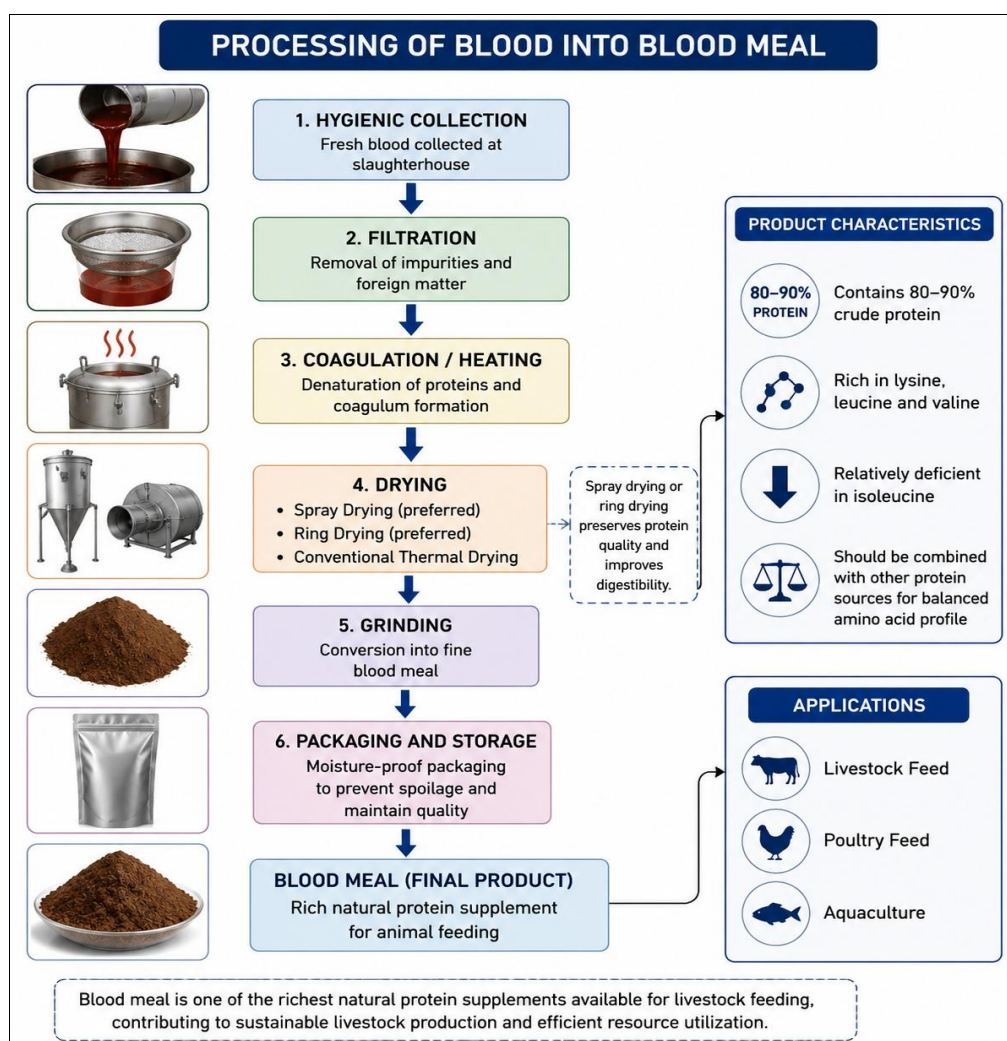


Fig 1: Processing of blood into blood meal

2.2 Applications in Animal Nutrition

Blood meal is widely incorporated into poultry, swine, aquaculture, and pet food formulations because of its high protein content and digestibility. Several studies have demonstrated that moderate dietary inclusion of blood meal can improve growth performance and feed conversion efficiency while reducing dependence on expensive conventional protein sources such as soybean meal and fish meal (Jayathilakan *et al.*, 2012) [3]. However, excessive inclusion may reduce feed palatability and should therefore be

carefully balanced according to species-specific nutritional requirements.

2.3 Agricultural Applications

In agriculture, blood meal is primarily valued as a slow-release organic nitrogen fertilizer. Unlike synthetic fertilizers, blood meal gradually releases nitrogen into the soil, reducing nutrient leaching while promoting healthy vegetative growth. It also improves soil microbial activity and contributes to sustainable nutrient recycling in organic farming systems. The

increasing demand for environmentally friendly agricultural inputs has further enhanced the importance of blood meal as an alternative to chemical fertilizers (FAO, 2023) ^[1].

2.4 Industrial and Biomedical Applications

Recent research has expanded the utilization of blood-derived proteins beyond feed and fertilizers. Plasma proteins are increasingly used as functional ingredients in processed meat products due to their superior water-binding, emulsifying, and gelling properties. Haemoglobin has been investigated as a natural iron fortificant in functional foods, while enzymatically hydrolyzed blood proteins yield bioactive peptides possessing antioxidant, antimicrobial, and antihypertensive activities (Lynch *et al.*, 2018) ^[5]. These findings demonstrate that animal blood is not merely a waste product but a valuable renewable resource with significant industrial potential.

3. Bone and Bone Meal

Animal bones constitute one of the most abundant by-products generated during livestock slaughter and meat processing, representing approximately 15–20% of the carcass weight depending on species, age, and production system. Traditionally, bones were considered low-value waste and disposed of through landfilling or incineration. However, growing awareness of sustainable resource management has transformed bones into valuable raw materials for producing fertilizers, feed ingredients, collagen, gelatin, hydroxyapatite, and biomedical products. Their utilization exemplifies the principles of the circular bioeconomy by recovering nutrients and biomolecules that would otherwise be lost.

3.1 Processing of Bone Meal

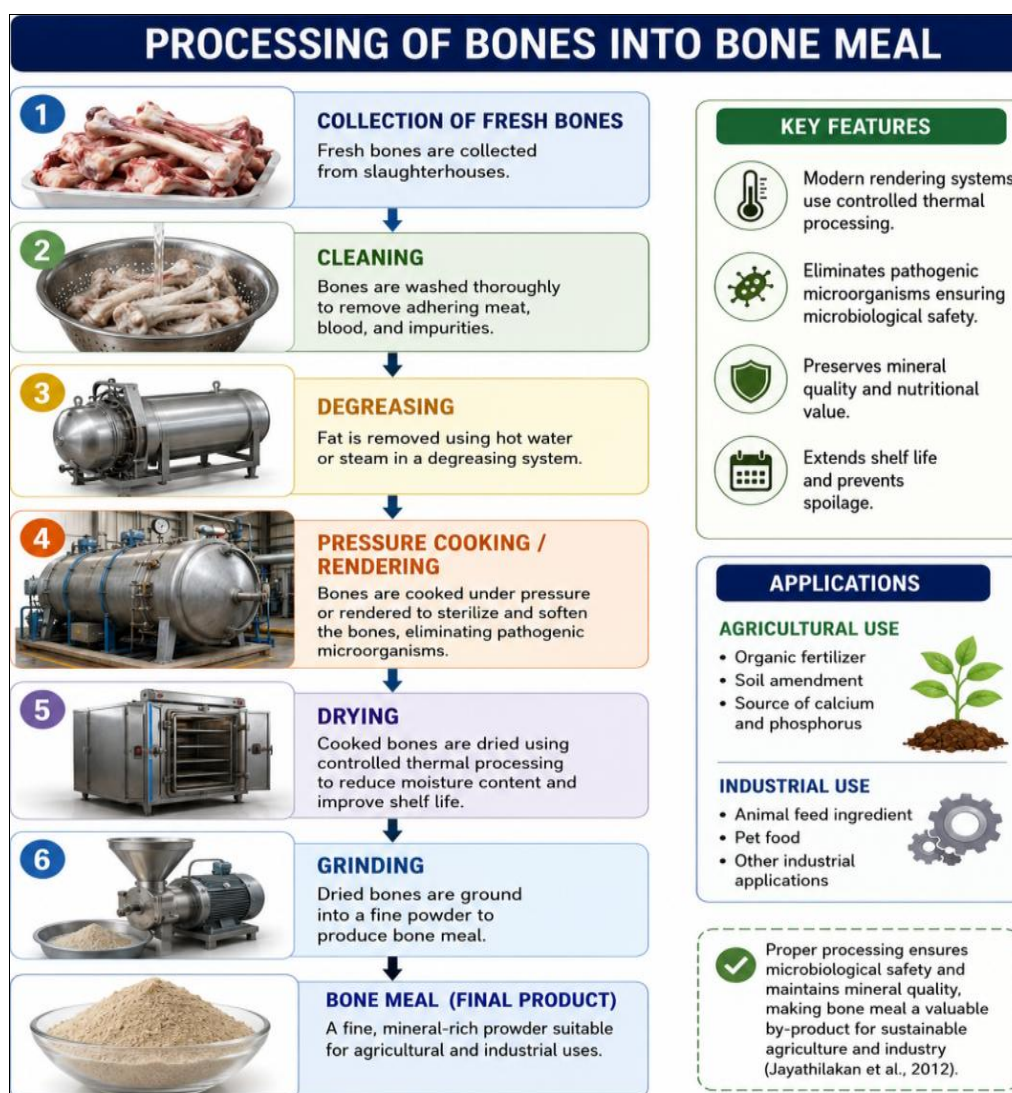


Fig 2: Processing of bone into bone meal

3.2 Nutritional Composition

Bone meal is a concentrated source of essential minerals, particularly calcium and phosphorus. It generally contains 20–30% calcium and 10–15% phosphorus, along with magnesium, sodium, potassium, and trace elements such as zinc, copper, and manganese. These nutrients play critical roles in skeletal development, metabolic processes, and plant nutrition. Residual collagen present in bones also serves as an important precursor for gelatin and collagen peptide production (Liu *et al.*, 2015) ^[4].

3.3 Agricultural Applications

One of the major applications of bone meal is its use as an organic phosphorus fertilizer. Unlike chemical fertilizers that release nutrients rapidly, bone meal provides a slow and sustained release of phosphorus and calcium, improving nutrient availability throughout the growing season. This gradual nutrient release supports root development, flowering, fruit formation, and overall crop productivity while minimizing nutrient leaching. In addition, organic fertilizers derived from animal by-products improve soil microbial

activity and contribute to long-term soil fertility, making them valuable components of sustainable and organic farming systems (FAO, 2023) ^[1].

3.4 Industrial and Biomedical Applications

Beyond agriculture, animal bones have become an important source of hydroxyapatite, a calcium phosphate mineral widely used in orthopedics and dentistry because of its excellent biocompatibility and similarity to human bone. Bone-derived hydroxyapatite is used in bone graft substitutes, dental implants, tissue engineering scaffolds, and drug delivery systems. Advances in biomaterials research have further expanded the applications of bone-derived products in regenerative medicine, demonstrating the potential of slaughterhouse by-products as high-value biomedical resources (Liu *et al.*, 2015) ^[4].

Historically, bone meal was also incorporated into livestock feed as a mineral supplement. However, following outbreaks of bovine spongiform encephalopathy (BSE), the use of mammalian-derived protein meals has become highly regulated in many countries. Current utilization therefore depends on national regulations governing feed safety and traceability.

Overall, efficient recovery and utilization of bones reduce slaughterhouse waste while generating commercially valuable products for agriculture, healthcare, and industrial manufacturing.

4. Collagen and Gelatin

Among the numerous products derived from animal by-products, collagen and gelatin represent some of the highest-value biomaterials. Collagen is the most abundant structural protein in animals, accounting for nearly one-third of total body protein. It is primarily found in connective tissues such as skin, tendons, cartilage, bones, and ligaments. During meat processing, large quantities of collagen-rich materials—including bovine hides, porcine skin, poultry skin, fish skin, scales, bones, and tendons—are generated as by-products. Rather than being discarded, these materials can be converted into commercially valuable collagen and gelatin through appropriate extraction technologies (Gómez-Guillén *et al.*, 2011) ^[2].

4.1 Extraction Technologies

Commercial collagen extraction generally involves pre-treatment to remove minerals and non-collagenous proteins, followed by acid, alkaline, or enzymatic extraction. Acid extraction is commonly used for fish and young animal tissues because it preserves collagen structure, whereas alkaline pre-treatment is preferred for highly cross-linked bovine tissues. Enzyme-assisted extraction using pepsin has gained considerable attention because it improves collagen recovery while maintaining structural integrity and reducing chemical consumption (Liu *et al.*, 2015) ^[4].

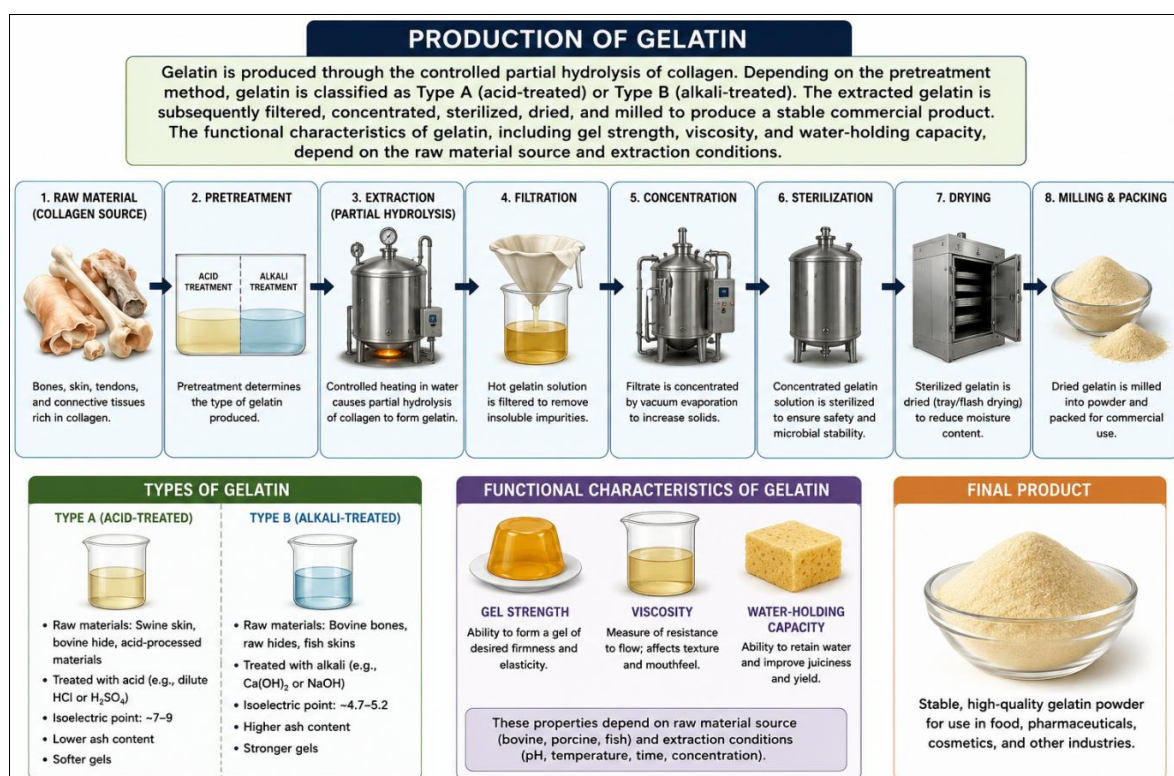


Fig 3: Extraction of gelatin

4.2 Applications in Food Science

Collagen and gelatin possess exceptional functional properties that make them indispensable ingredients in the food industry. Gelatin functions as a gelling, stabilizing, thickening, emulsifying, and water-binding agent in confectionery products, dairy desserts, meat products, beverages, and bakery formulations. In addition, collagen peptides are increasingly incorporated into functional foods and dietary supplements because of their high digestibility and potential health

benefits.

Numerous clinical studies have suggested that collagen peptide supplementation may improve skin elasticity, joint mobility, muscle recovery, and bone health, although additional long-term studies are required to establish definitive therapeutic benefits (Liu *et al.*, 2015) ^[4]. The growing demand for nutraceuticals has significantly increased the commercial value of collagen extracted from animal by-products.

4.3 Pharmaceutical and Biomedical Applications

The excellent biocompatibility, biodegradability, and low antigenicity of collagen have resulted in widespread biomedical applications. Collagen-based biomaterials are routinely employed in wound dressings, tissue engineering scaffolds, bone regeneration, surgical sponges, and controlled drug delivery systems. Likewise, gelatin serves as a major pharmaceutical excipient in hard and soft capsules, tablet coatings, plasma expanders, and vaccine stabilizers (Shoulders & Raines, 2009) [6].

Collagen also plays an increasingly important role in regenerative medicine, where natural collagen matrices provide structural support for cell growth and tissue repair. Such applications highlight the significant potential of animal by-products in developing advanced biomaterials for healthcare.

4.4 Cosmetic Applications

The cosmetic industry represents another rapidly expanding market for collagen and gelatin. These proteins are widely incorporated into anti-aging creams, facial masks, moisturizers, hair-care products, and oral beauty supplements due to their moisturizing and film-forming properties. Marine collagen extracted from fish skin and scales has gained increasing popularity because of its high bioavailability and broader consumer acceptance in regions where bovine- or porcine-derived ingredients face cultural or religious restrictions (Gómez-Guillén *et al.*, 2011) [2].

5. Pet Food and Biofertilizers

5.1 Pet Food

The global pet food industry has witnessed remarkable growth over the last decade, creating an increasing demand for sustainable and nutritionally balanced ingredients. Animal by-products, including liver, heart, lungs, kidneys, spleen, meat trimmings, poultry by-product meal, fish meal, blood meal, and rendered animal fats, have become valuable components of commercial pet foods because of their high nutritional quality and digestibility. These by-products are excellent sources of high-quality proteins, essential amino acids, vitamins (particularly vitamins A and B-complex), minerals, and fatty acids required for the growth and maintenance of companion animals (Swanson *et al.*, 2013) [7].

Unlike human food markets, where consumer preference often limits the utilization of organ meats, many of these tissues possess superior nutritional value and are highly suitable for pet nutrition. Their incorporation into pet foods not only reduces feed costs but also improves carcass utilization by converting edible yet underutilized materials into valuable products. Modern pet food manufacturing emphasizes stringent quality control, traceability, and compliance with food safety regulations to ensure product safety and nutritional adequacy. According to Swanson *et al.* (2013) [7], the utilization of animal by-products in pet foods represents one of the most efficient examples of sustainable nutrient recycling within the livestock production chain.

6. Environmental and Economic Importance

The efficient utilization of animal by-products offers substantial environmental, economic, and social benefits. Improper disposal of slaughterhouse waste contributes to water contamination, greenhouse gas emissions, offensive odors, and the spread of pathogens. Consequently, the recovery and processing of these materials into valuable products represent an effective strategy for reducing

environmental burdens while promoting sustainable livestock production (Jayathilakan *et al.*, 2012) [3].

From an economic perspective, by-product valorization significantly increases carcass value by transforming low-value materials into commercially valuable products, including blood meal, bone meal, collagen, gelatin, pharmaceuticals, cosmetics, pet food ingredients, biofertilizers, biodiesel, and biomedical materials. This diversification generates additional income for slaughterhouses and meat processing industries while reducing waste disposal costs. Toldrá *et al.* (2016) emphasized that complete utilization of slaughtered animals enhances both profitability and resource efficiency, making livestock production more sustainable.

Furthermore, the valorization of animal by-products contributes directly to several United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) by promoting resource conservation, waste reduction, and sustainable food production systems.

7. Future Perspectives and Challenges

Despite significant technological advancements, several challenges continue to limit the full utilization of animal by-products. Biosafety concerns, disease transmission risks, consumer perception, religious and cultural considerations, inconsistent raw material quality, and varying international regulations remain important constraints. Maintaining traceability and implementing strict hygienic processing practices are essential to ensure product safety and public confidence.

Future research should focus on the development of sustainable biorefineries capable of recovering multiple high-value products from a single by-product stream. Emerging technologies such as enzyme-assisted extraction, membrane filtration, supercritical fluid extraction, ultrasound-assisted processing, artificial intelligence-based process optimization, and precision fermentation offer promising opportunities for improving extraction efficiency while minimizing environmental impacts (Liu *et al.*, 2015) [4].

Growing demand for biodegradable biomaterials, functional foods, bioactive peptides, renewable energy, and organic fertilizers is expected to further expand the commercial potential of animal by-products. Strengthening collaborations among researchers, veterinarians, food technologists, agricultural scientists, and industry stakeholders will be essential for accelerating innovation and promoting the sustainable utilization of livestock resources.

8. Conclusion

Animal by-products should no longer be regarded as waste but as valuable biological resources capable of supporting sustainable agriculture, veterinary medicine, and food science. Blood, bones, skin, connective tissues, feathers, and internal organs contain proteins, minerals, lipids, collagen, and bioactive compounds that can be transformed into a wide range of value-added products through modern processing technologies. Their utilization contributes to waste reduction, environmental protection, improved resource efficiency, and increased profitability of livestock industries.

The transition toward a circular bioeconomy has further emphasized the importance of recovering valuable biomolecules from slaughterhouse by-products rather than disposing of them. Products such as blood meal, bone meal,

collagen, gelatin, pet food ingredients, biofertilizers, pharmaceuticals, and renewable energy demonstrate the enormous potential of animal by-products in supporting sustainable food systems. Continued research, technological innovation, and harmonized regulatory frameworks will be crucial for maximizing the value of these renewable resources while ensuring biosafety, product quality, and environmental sustainability.

Conflict of Interest

Not available

Financial Support

Not available

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