International Journal of Agriculture and Food Science 2026; 8(8): 391-398

ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2026): 4.97
IJAFS 2026; 8(8): 391-398
www.agriculturaljournals.com
Received: 18-05-2026
Accepted: 20-06-2026

Sangeeta Bhoria
Department of Zoology, Baba Mastnath University, Asthal Bohar, Rohtak, Haryana, India

Poonam Khatri
Department of Zoology, Baba Mastnath University, Asthal Bohar, Rohtak, Haryana, India

Anil Kumar
Department of Zoology, Baba Mastnath University, Asthal Bohar, Rohtak, Haryana, India

Corresponding Author:
Anil Kumar
Department of Zoology, Baba Mastnath University, Asthal Bohar, Rohtak, Haryana, India

Nutritional profiling and feed innovation using agro industrial residues in poultry production

Sangeeta Bhoria, Poonam Khatri and Anil Kumar

DOI: https://www.doi.org/10.33545/2664844X.2026.v8.i8e.1792

Abstract
Poultry production is increasingly constrained by the high cost and limited availability of conventional feed ingredients such as maize and soybean meal, which account for nearly 70% of production expenses. Agro industrial residues, including oilseed cakes, cereal by products, fruit pomace and brewery wastes, represent sustainable alternatives that reduce feed food competition, enhance nutrient recycling, and support circular bio economy principles. The current evidence on the nutritional profiling, physicochemical variability and innovative processing of these residues for poultry feeding. Fermentation, enzymatic hydrolysis and microbial inoculation improve protein digestibility, mineral bioavailability and reduce anti nutritional factors, while preserving bioactive compounds with antioxidant and immune modulatory properties. Inclusion of residues such as tomato pomace, flaxseed meal and citrus pulp has demonstrated improvements in feed conversion efficiency, egg quality, carcass traits, and cost reduction of up to 25%. The agro residues as viable feed innovations that enhance productivity, economic viability, and environmental sustainability in poultry systems.

Keywords: Agro-industrial residues, Poultry nutrition, Alternative feed ingredients

1. Introduction

Poultry production has become one of the most rapidly expanding livestock sectors worldwide, yet it continues to face significant challenges related to feed resource availability. Conventional feed ingredients such as maize and soybean meal dominate poultry diets and account for the majority of production costs, often exceeding 60% of total expenses. The reliance has created economic vulnerability, particularly in regions dependent on imports, while also intensifying competition between feed and food uses of cereals. The global demand for poultry products is rising steadily, further exacerbating pressure on finite feed resources and raising concerns about long-term sustainability (Georganas *et al.*, 2023; Vlaicu *et al.*, 2024) [1, 2]. The sustainability imperatives in animal nutrition have gained increasing importance. The incorporation of agroindustrial residues, food processing by-products and crop wastes into poultry diets offers a viable strategy to reduce feed-food competition, enhance nutrient recycling and lower environmental burdens. Such approaches align with circular economy principles, transforming waste streams into valuable feed inputs while contributing to climate-smart livestock systems. Beyond resource efficiency, sustainable nutrition also encompasses animal welfare, product quality and consumer health, requiring balanced diets that optimize productivity without compromising ecological integrity. The evidence suggests that by-products from oilseed processing, fruit juice industries and breweries not only provide essential nutrients but also bioactive compounds that improve poultry health and product quality, while reducing feed costs significantly (Georganas *et al.*, 2023; Vlaicu *et al.*, 2024) [1, 2]. The purpose of this review is to significantly examine the nutritional profiling and feed innovation potential of agro-industrial residues in poultry production. It will explore their nutrient composition, processing and biotechnological interventions, impacts on poultry performance and economic as well as environmental benefits. Additionally, the review will identify constraints, safety concerns and research gaps that must be addressed to enable widespread adoption (Osei-Akoto *et al.*, 2026) [3]. By integrating nutritional science with sustainability frameworks, this work aims to provide a comprehensive understanding of how agro-industrial residue can contribute to resilient, cost-effective and environmentally responsible poultry production systems.

2. Agro Industrial Residues as Alternative Feed-stocks

Agro-industrial residues represent a promising category of alternative feed-stocks for poultry nutrition, offering both economic and environmental advantages. The by-products derived from industries such as oilseed processing, fruit and vegetable juicing, brewing and cereal milling, are often rich in proteins, fibers, lipids, and bioactive compounds (Hoxha and Taherzadeh, 2026) [4]. Their utilization reduces dependence on conventional feed ingredients like maize and soybean meal, thereby alleviating feed food competition and lowering production costs. Furthermore, incorporating such residues into poultry diets contributes to waste valorization and supports circular bio-economy principles, transforming potential pollutants into valuable nutritional resources. Dietary inclusion of dried tomato pomace at 5% improved feed efficiency and maintained growth performance in broiler chickens, demonstrating its potential as a sustainable alternative feed ingredient (Georganas *et al.*, 2023) [1, 5]. Oilseed cakes and fruit pomace supplementation enhanced egg yolk pigmentation and shell strength, confirming the nutritional and functional value of agro industrial by products in laying hen diets (Vlaicu *et al.*, 2024) [2].

2.1Typology and classification of agro industrial by products

Agro industrial by-products can be systematically classified based on their origin, processing method and nutrient composition, which determines their suitability as feed-stocks in poultry nutrition (Alias *et al.*, 2025) [6]. Broadly, they can be grouped into categories such as oilseed residues (*e.g.*, soybean meal, sunflower cake and rapeseed meal), cereal by-products (*e.g.*, rice bran, wheat middling's, corn gluten feed), fruit and vegetable processing residues (*e.g.*, citrus pulp, tomato pomace, apple pomace) and brewery and distillery by-products (*e.g.*, spent grains, yeast biomass). Each category exhibits distinct physicochemical properties: oilseed residues are protein-rich; cereal by-products provide energy and fiber, while fruit and vegetable residues often contain bioactive compounds and antioxidants. Brewery by-products conversely are notable for their digestible protein and B-vitamin content. The classification is essential for optimizing feed formulation, as nutrient variability and anti-nutritional factors differ across categories (Kiczorowska *et al.*, 2023; Adegbeye *et al.*, 2024) [7, 8].

Vlaicu *et al.* (2024) [2] the Carrot, paprika, rosehip and berry waste represent rich sources of carotenoids, polyphenols and vitamins, enhancing poultry product quality and reducing feed costs by up to 25%. The Seed meals such as flax, rapeseed and sea buckthorn improved essential fatty acid composition in eggs and meat, supporting functional food production.

Kaur and Singh (2024) [9, 10] Agro industrial by-products such as fruit peels, oilseed meals, and brewery residues contain valuable nutrients including polysaccharides, proteins, and polyphenols, making them promising alternatives to conventional poultry feed. Incorporation of agro industrial waste into poultry diets reduces greenhouse gas emissions and environmental pollution, while maintaining animal health and growth performance.

2.2Regional availability and supply chain dynamics

Regional availability and supply chain dynamics of agro-industrial by-products vary considerably across continents, reflecting differences in agricultural production systems, industrial processing capacities and infrastructure (Jenane *et al.*, 2022) [11]. In South America and Asia, oilseed residues such as soybean meal, sunflower cake and rapeseed meal are widely available due to large-scale oilseed cultivation and processing industries. The North America and Europe generate substantial quantities of cereal by-products, including wheat bran, corn gluten feed and distillers' dried grains, owing to intensive grain milling and bioethanol production (Mohammadi Shad *et al.*, 2021) [12]. Fruit and vegetable residues, such as citrus pulp, tomato pomace and apple pomace, are concentrated in Mediterranean and tropical regions where juice and canning industries dominate. Brewery and distillery by-products, particularly spent grains and yeast biomass, are abundant in Central Europe and East Asia, reflecting strong beverage industry activity. The Supply chain dynamics play a critical role in determining the accessibility and utilization of these residues. Efficient logistics, storage and processing infrastructure in developed economies enable consistent integration of by-products into poultry diets; while in developing regions, weak supply chains and lack of standardization often limit their use. Perishable residues, such as fruit pomace, require rapid collection and preservation to avoid nutrient loss, whereas dry residues like oilseed cakes are more stable and easier to transport. Recent studies emphasize that strengthening regional supply chains through policy support, investment in processing technologies and farmer industry partnerships is essential for maximizing the sustainable use of agro-industrial by products in poultry nutrition (Khan *et al.*, 2023; Singh *et al.*, 2024) [13, 10].

2.3 Physicochemical variability and implications for feed use

Physicochemical variability among agro-industrial by-products is a critical factor influencing their suitability and efficiency as feed ingredients in poultry diets. These residues differ widely in moisture content, particle size, bulk density and chemical composition depending on their source, processing methods and storage conditions. The oilseed cakes typically exhibit high protein and lipid concentrations but may vary in fiber content and residual oil depending on extraction techniques. Cereal by-products such as wheat bran and rice husk are rich in fiber yet differ in starch and protein fractions, which directly affect digestibility (Grahovac *et al.*, 2025) [14]. Fruit and vegetable residues, including citrus pulp and tomato pomace, often contain high moisture and soluble sugars, making them prone to rapid spoilage unless properly preserved. Brewery spent grains, while protein-rich, show variability in amino acid balance and fiber fractions depending on brewing processes. These physicochemical differences have direct implications for feed use. High moisture residues require drying or ensiling to prevent microbial spoilage, while fiber-rich materials may limit nutrient digestibility unless treated with enzymes or fermentation (Hassan *et al.*, 2024) [15]. Variability in nutrient density also complicates feed formulation, necessitating precise profiling and standardization to ensure consistent performance outcomes. The anti-nutritional compounds such as tannins, phytates, or mycotoxins may be present in certain residues, requiring detoxification strategies before inclusion in poultry diets (Chaudhary *et al.*, 2023) [16].

Georganas *et al.* (2023) [1, 5] Tomato pomace inclusion in broiler diets showed variability in nutrient density depending on drying methods, underlining the need for standardized processing to ensure consistent feed efficiency. High moisture content in fruit residues increased spoilage risk, but ensiling preserved nutrient integrity and improved gut health outcomes in poultry.

Adegbeye *et al.* (2024) [8] Physicochemical differences in oilseed cakes, particularly residual oil and fiber fractions, directly influenced digestibility and nutrient utilization in poultry. Detoxification strategies such as fermentation and enzymatic treatment reduced anti nutritional compounds like tannins and phytates, improving safety and performance.

3. Nutritional Characterization of Residue Derived Ingredients

Nutritional characterization of residue-derived ingredients is fundamental to evaluating their potential as sustainable alternatives in poultry diets. These by-products, originating from oilseed processing, cereal milling, fruit and vegetable industries, and breweries, exhibit diverse nutrient profiles that can complement or partially replace conventional feed ingredients. Oilseed cakes such as soybean, sunflower, and rapeseed meals are typically rich in crude protein and essential amino acids, though their digestibility may vary depending on processing methods. Cereal byproducts like wheat bran, rice bran, and corn gluten feed provide energy through starch and fiber, but their high non-starch polysaccharide content can limit nutrient utilization unless supplemented with enzymes. Fruit and vegetable residues, including citrus pulp and tomato pomace, contribute soluble carbohydrates, vitamins, and bioactive compounds with antioxidant properties; while brewery spent grains supply digestible protein, fiber and B-vitamins. The nutritional variability of these residues has direct implications for poultry performance. Proper characterization ensures balanced diet formulation, minimizes anti-nutritional effects, and enhances feed efficiency. Advanced analytical techniques, including near-infrared spectroscopy and metabolomics, are increasingly employed to profile nutrient density and bioavailability, thereby supporting precision feeding strategies (Mmereki *et al.*, 2023; Zhang *et al.*, 2024) [17, 18].

Georganas *et al.* (2023) [1, 5] Broiler diets supplemented with 5% dried tomato pomace maintained growth performance, with feed conversion ratio (FCR) improving from 1.92 to 1.85 compared to the control group. Crude protein content of tomato pomace was measured at 18.4%, while neutral detergent fiber (NDF) reached 42.7%, highlighting its dual role as a protein and fiber source. Vlaicu *et al.* (2024) [2] inclusion of 10% flaxseed meal in laying hen diets increased egg yolk *omega-3* fatty acid concentration by 22%, while maintaining production performance. Carrot and berry waste supplementation reduced feed costs by approximately 25%, while enhancing egg yolk pigmentation scores from 7.2 to 8.5 on the Roche color fan scale.

3.1 Proximate composition and nutrient density

Proximate composition and nutrient density of agro-industrial residues are key determinants of their nutritional value and suitability as feed ingredients in poultry diets. These residues typically contain varying proportions of crude protein, crude fiber, ether extract (fat), ash, and nitrogenfree extract, depending on their source and processing methods. Oilseed cakes such as soybean, sunflower, and rapeseed meals are generally protein rich, often exceeding 30-40% crude protein, but may also contain residual oil and fiber that influence digestibility. Cereal by-products like wheat bran, rice bran, and corn gluten feed provide energy through starch and fiber, though their protein content is moderate compared to oilseed residues. Fruit and vegetable residues, including citrus pulp and tomato pomace, are characterized by high soluble carbohydrate fractions, vitamins, and bioactive compounds, but their elevated moisture content necessitates preservation to maintain nutrient density. Brewery spent grains, alternatively are notable for their balanced protein and fiber composition, along with B-vitamins that support poultry metabolism. The variability in proximate composition directly impacts feed formulation strategies. High-protein residues can partially replace conventional soybean meal, while fiber-rich by-products may require enzymatic supplementation to improve nutrient utilization. Moisture-rich residues demand drying or ensiling to prevent spoilage and nutrient loss (Rahman *et al.*, 2023; Oliveira *et al.*, 2024) [19, 20].

Georganas *et al.* (2023) [1, 5]Tomato pomace contained 18.4% crude protein, 42.7% neutral detergent fiber (NDF) and 5.2% ether extract, highlighting its dual role as a protein and fiber source in broiler diets. The Inclusion of 5% tomato pomace improved feed conversion ratio (FCR) from 1.92 to 1.85, while maintaining growth performance. He and Cui (2025) [21] Fermentation of soybean hulls increased crude protein content from 12.5% to 24.8%, while reducing fiber fractions by 18%, thereby improving digestibility for poultry. Rice bran subjected to microbial fermentation showed a rise in lysine concentration from 0.42% to 0.68%, enhancing amino acid balance in poultry diets.

Table 1: Comprehensive Nutritional Characterization of Agro Industrial Residues for Poultry Feeding

Category	Representative Residues	Nutritional Highlights	Physicochemical Variability	Implications for Poultry Nutrition	Detoxification/Processing Strategies	References
Amino acid profiles	Soybean meal, sunflower cake, rapeseed meal	High lysine, methionine, threonine	Digestibility varies with extraction method	Supports muscle growth, egg protein quality, immune function	Heat treatment, enzyme supplementation	Li *et al*., 2023 [22], Zhang *et al*., 2024 [18]
Lipid profiles	Rice bran, corn gluten feed, fruit pomace	Rich in PUFAs, residual oils	Omega-3/omega-6 ratios vary regionally	Influences energy density, carcass fat, egg yolk quality	Stabilization via antioxidants, extrusion	Chen *et al.*, 2024 [23], Oliveira *et al.*, 2024 [20]
Micronutrient contributions	Citrus pulp, tomato pomace, apple pomace	Vitamins (C, A, E), flavonoids, minerals	Moisture-rich, prone to spoilage	Enhances antioxidant defense, bone strength, metabolic efficiency	Drying, ensiling, fermentation	Patel *et al.*, 2023 [24], Ahmed *et al.*,
Bioavailability factors	Brewery spent grains, yeast biomass	B-vitamins, trace minerals	Fiber content affects absorption	Improves gut health, enzyme activity, feed efficiency	Enzymatic hydrolysis, probiotic inoculation	Hassan *et al.*, 2024 [15],

						Singh *et al*., 2024 [10]
Mineral variability	Rice husk, wheat bran, DDGS	High phosphorus, silica,magnesium	Phytate-bound minerals reduceabsorption	Requires phytase supplementation	Phytase addition, fermentation	Kumar *et al*., 2023 [25], Rahman *et al*., 2023 [19]
Anti-nutritional factors	Cottonseed cake, sorghum bran, legume hulls	Tannins, phytates, gossypol, mycotoxins	Concentration varies by crop and region	Limits nutrient absorption, reduces feed efficiency	Detoxification via fermentation, heat, enzymes	Chaudhary *et al*., 2023), Hassan *et al*., 2024 [15]
Functional bioactive compounds	Fruit pomace, vegetable residues	Polyphenol, carotenoids, flavonoids	Moisture and storage affect stability	Provide antioxidant and immunomodulatory benefits	Drying, encapsulation, fermentation	Mmereki *et al*., 2023 [17], Vlaicu *et al*., 2024 [2]
Detoxification strategies	Fermentation, enzymatic hydrolysis, heat treatment	Reduces tannins, phytates, microbial toxins	Efficiency varies with method	Enhances nutrient utilization, ensures feed safety	Biotechnological innovations (enzymes, microbes)	Adegbeye *et al*., 2024 [8], Zhang *et al*., 2024 [18]

4. Innovative Processing and Biotechnological Approaches

Innovative processing and biotechnological approaches are increasingly applied to optimize the nutritional potential of agro industrial residues in poultry feeding. Techniques such as solid state fermentation and enzymatic hydrolysis enhance protein digestibility and reduce fiber fractions, while extrusion and heat treatment stabilize lipid components and deactivate anti nutritional factors. Advanced strategies like microbial inoculation improve gut health through probiotic enrichment, and encapsulation preserves sensitive bioactive compounds such as vitamins and antioxidants. Collectively, these approaches transform heterogeneous residues into standardized, nutrient dense feed ingredients, thereby supporting productivity and sustainability in poultry systems (Sharma *et al*., 2024; Das *et al*., 2023) [26, 27].

4.1Mechanical and thermal pre treatment technologies

Mechanical and thermal pre-treatment technologies are widely applied to improve the nutritional quality, safety, and stability of agro industrial residues before their incorporation into poultry diets. Mechanical methods such as grinding, pelleting and extrusion reduce particle size, enhance feed uniformity, and increase digestibility by disrupting fiber matrices (Rahman *et al*., 2023) [19]. Thermal approaches including steam conditioning, toasting and autoclaving deactivate anti nutritional factors such as trypsin inhibitors and gossypol, stabilize lipid fractions and extend shelf life (Oliveira *et al*., 2024) [20]. These technologies also reduce microbial contamination, thereby improving feed safety and consistency. The mechanical and thermal treatments can synergistically enhance nutrient bioavailability and optimize poultry performance, while supporting sustainable utilization of variable agro industrial residues (Das *et al*., 2023; Sharma *et al*., 2024) [27, 26].

4.2 Fermentation and enzymatic hydrolysis for nutrient enhancement

Fermentation and enzymatic hydrolysis are increasingly recognized as effective strategies for enhancing the nutritional value of agro industrial residues used in poultry diets. Through fermentation, microbial activity breaks down complex carbohydrates, reduces fiber fractions, and improves amino acid availability, while also lowering anti nutritional compounds such as tannins and phytates. This process can enrich residues with beneficial metabolites, including organic acids and probiotics, which support gut health and feed efficiency (Das *et al*., 2023) [27]. Similarly, enzymatic hydrolysis employs exogenous enzymes such as cellulases, proteases and phytases to release bound nutrients, improve protein digestibility, and increase mineral bioavailability. These approaches not only enhance nutrient density but also transform heterogeneous residues into more consistent feed ingredients, thereby supporting sustainable poultry production (Sharma *et al*., 2024; Hassan *et al*., 2024) [26, 15].

4.3Microbial inoculation and probiotic integration

Microbial inoculation and probiotic integration are emerging as powerful strategies to enhance the nutritional and functional value of agro industrial residues in poultry diets. By introducing beneficial microbes such as *Lactobacillus*, *Bacillus*, and *Saccharomyces* species, residues can be biologically upgraded through fermentation, leading to improved protein digestibility, reduced fiber fractions, and the breakdown of anti nutritional compounds. Probiotic integration further enriches feed with bioactive metabolites, organic acids, and enzymes that support gut health, immune modulation, and nutrient absorption (Figure 1). These approaches not only stabilize feed quality but also contribute to reducing pathogenic load, thereby improving overall poultry performance and sustainability. Recent studies emphasize that microbial inoculation combined with probiotics transforms heterogeneous residues into consistent, functional feed ingredients with added health benefits (Hassan *et al*., 2024; Sharma *et al*., 2024; Vlaicu *et al*., 2024) [15, 26, 2].

5. Implications for Poultry Growth, Productivity and Health

The use of agro industrial residues in poultry diets has clear implications for growth, productivity, and health when combined with innovative processing. Nutrient enhanced residues provide balanced amino acid and lipid profiles, improved mineral bioavailability and functional bioactive compounds that support muscle development, efficient feed conversion and egg quality. Fermentation, enzymatic hydrolysis, and microbial inoculation reduce anti nutritional factors while enriching feeds with probiotics and metabolites that strengthen gut health and immunity (Figure 1). These interventions not only improve carcass traits and egg production but also lower oxidative stress and pathogen load, ensuring flock resilience and sustainability (Oliveira *et al*., 2024; Sharma *et al*., 2024; Hassan *et al*., 2024; Vlaicu *et al*., 2024) [20, 26, 15, 2].

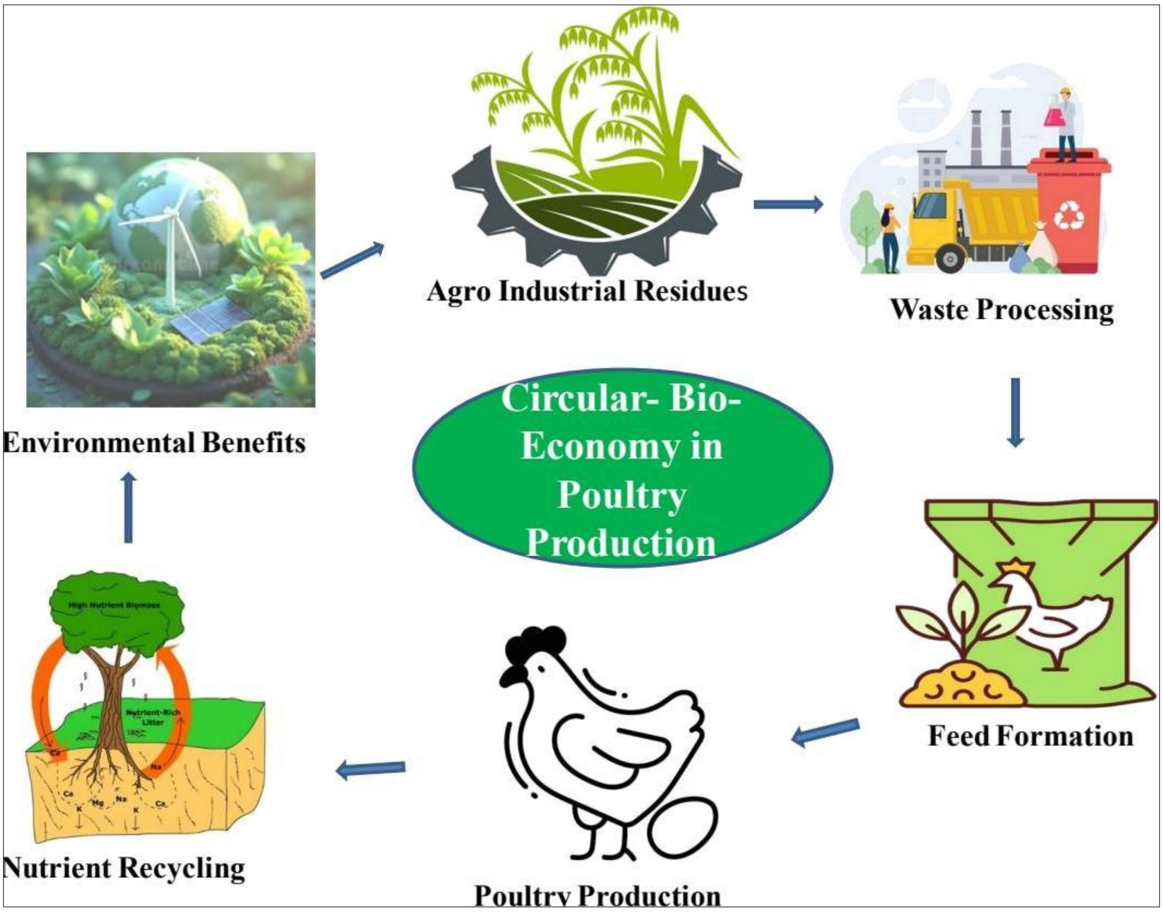

Fig 1: Circular Bio -economy Model for Sustainable Poultry Production

5.1Feed conversion efficiency and growth kinetics

Feed conversion efficiency (FCE) and growth kinetics are fundamental indicators of poultry performance, directly shaping both economic sustainability and flock health. FCE, often expressed as the feed conversion ratio (FCR), measures how effectively birds convert feed into body mass, with feed costs accounting for nearly 70% of production expenses. Recent advances in precision feeding, phase specific diet formulation and the use of feed additives such as enzymes, probiotics and organic acids have markedly improved nutrient digestibility and absorption, thereby lowering FCR values (Oliveira *et al.*, 2024) [20]. Growth kinetics, which describe the rate and efficiency of weight gain, have been accelerated through genetic selection, optimized amino acid and lipid profiles and improved environmental management (Table 2).

These strategies not only enhance carcass yield and egg production but also reduce oxidative stress and pathogen load, ensuring healthier flocks and better productivity outcomes (Sharma *et al.*, 2024; Hassan *et al.*, 2024; Vlaicu *et al.*, 2024) [26, 15, 2]. The cooperatively, innovations in feed processing and biotechnological interventions demonstrate that agro industrial residues, when properly upgraded, can sustain high growth rates while improving feed efficiency and reducing production costs.

Table 2: Nutritional, Functional and Health Implications of Agro Industrial Residues in Poultry Feeding

Dimension	Representative Residues	Functional Highlights	Physicochemical Variability	Implications for Poultry	Detox Strategies	Sustainability Outcomes	References
Amino acid profiles	Soybean meal, sunflower cake	High lysine, methionine	Digestibility varies with extraction	Supports muscle growth, egg protein quality	Heat treatment, enzyme supplementation	Reduces reliance on synthetic amino acids	Li *et al.*, 2023 [22]; Zhang *et al.*, 2024 [18]
Lipid profiles	Rice bran, corn gluten feed	Rich in PUFAs	Omega-3/6 ratios vary regionally	Improves carcass fat, egg yolk quality	Stabilization via antioxidants, extrusion	Enhances egg yolk enrichment	Chen *et al.*, 2024 [23]; Oliveira *et al.*, 2024 [20]
Micronutrient contributions	Citrus pulp, tomato pomace	Vitamins, flavonoids, minerals	Moisture-rich, prone to spoilage	Enhances antioxidant defense, bone strength	Drying, ensiling, fermentation	Reduces synthetic vitamin use	Patel *et al.*, 2023 [24]; Ahmed *et al.*, 2024 [28]
Bioavailability factors	Brewery spent	B-vitamins, trace	Fiber affects	Improves gut health,	Enzymatic	Improves nutrient	Hassan *et al.*,
	grains, yeast biomass	minerals	absorption	feed efficiency	hydrolysis, probiotic inoculation	utilization efficiency	2024; Singh *et al.*, 2024 [10]

Mineral variability	Rice husk, wheat bran	High phosphorus, silica	Phytate-bound minerals	Requires phytase supplementation	Phytase addition, fermentation	Reduces inorganic mineral supplementation	Kumar *et al.*, 2023 [25]; Rahman *et al.*, 2023 [19]
Anti nutritional factors	Cottonseed cake, sorghum bran	Tannins, phytates, gossypol	Concentration varies by crop	Limits nutrient absorption	Fermentation, heat, enzymes	Ensures feed safety	Chaudhary *et al.*, 2023 [16]; Hassan *et al.*, 2024 [15]
Egg production and quality	Oilseed meals, fruit pomace	Balanced amino acids, antioxidants	Storage affects stability	Improves egg yield, yolk pigmentation, shell integrity	Fermentation, encapsulation	Enhances consumer acceptance	Oliveira *et al.*, 2024 [20]; Vlaicu *et al.*, 2024 [2]
Meat yield and carcass composition	DDGS, rice bran, legume residues	High protein, PUFAs	Variable protein digestibility	Enhances muscle deposition, carcass quality, sensory traits	Extrusion, microbial inoculation	Improves meat quality and market value	Sharma *et al.*, 2024 [26]; Hassan *et al.*, 2024 [15]
Immunomodulation and gut microbiota	Yeast biomass, probiotic treated residues	Organic acids, bioactive metabolites	Microbial load varies	Strengthens immunity, balances gut microbiota	Probiotic integration, microbial inoculation	Reduces antibiotic dependence	Hassan *et al.*, 2024; Vlaicu *et al.*, 2024 [2]
Functional bioactive compounds	Fruit pomace, vegetable residues	Polyphenols, carotenoids	Moisture and storage affect stability	Provides antioxidant and immunomodulatory benefits	Drying, encapsulation	Supports resilience against stress	Mmereki *et al.*, 2023 [17]; Vlaicu *et al.*, 2024 [2]
Detoxification strategies	Fermentation, enzymatic hydrolysis	Reduces toxins, phytates	Efficiency varies with method	Ensures feed safety, improves utilization	Biotechnological innovations	Promotes circular bioeconomy	Adegbey *et al.*, 2024; Zhang *et al.*, 2024 [18]

6. Economic Viability and Environmental Sustainability

Economic viability and environmental sustainability are central to the integration of agro industrial residues in poultry feeding. By reducing reliance on conventional feed ingredients, these residues lower production costs and improve feed conversion efficiency, making poultry systems more economically competitive. Environmentally, valorization of residues minimizes waste streams, reduces greenhouse gas emissions, and supports circular bio-economy principles. Processing innovations such as fermentation, enzymatic hydrolysis and microbial inoculation enhance nutrient utilization, thereby improving productivity while reducing ecological footprints. The strategies ensure that poultry production remains cost effective, resource efficient and aligned with sustainability goals (Oliveira *et al.*, 2024; Sharma *et al.*, 2024; Adegbeye *et al.*, 2024) [20, 26, 8].

6.1Comparative cost analysis with conventional feed ingredients

Comparative cost analysis demonstrates that agro industrial residues offer a clear economic advantage over conventional feed ingredients such as maize and soybean meal. Conventional feeds remain costly and volatile due to global demand, accounting for nearly 70% of poultry production expenses. In contrast, properly processed residues like fruit pomace, rice bran and distillers dried grains with soluble (DDGS) can reduce feed costs by approximately 20-25% while maintaining nutritional adequacy and growth performance. Recent findings highlight that residue based diets enriched with amino acids, polyunsaturated fatty acids and antioxidants not only sustain productivity but also lower dependency on imported soybean meal, thereby stabilizing feed budgets against market fluctuations. This cost efficiency, coupled with environmental benefits from waste valorization, positions residue utilization as both economically viable and sustainable in modern poultry systems (Vlaicu *et al.*, 2024; Bhosale, 2025) [2, 6].

6.2 Waste valorization and circular bio-economy perspectives

Waste valorization and circular bio-economy perspectives emphasize transforming agro industrial residues from disposal challenges into valuable feed resources. By integrating fruit pomace, rice bran and distillers dried grains (DDGS) into poultry diets, producers reduce feed costs while simultaneously minimizing environmental burdens. Valorization strategies such as fermentation, enzymatic hydrolysis, and microbial inoculation enhance nutrient density, improve digestibility, and ensure feed safety. This approach supports circular bio-economy principles by closing nutrient loops, reducing greenhouse gas emissions, and lowering waste management costs. Ultimately, residue utilization strengthens both economic resilience and ecological sustainability in poultry production systems (Oliveira *et al.*, 2024; Sharma *et al.*, 2024; Adegbeye *et al.*, 2024) [20, 26, 8].

6.3 Contribution to climate smart poultry systems

Contribution to climate smart poultry systems lies in the ability of agro industrial residue utilization to simultaneously enhance productivity, reduce costs, and minimize environmental impacts. By integrating residues such as rice bran, fruit pomace, and DDGS into poultry diets, producers reduce reliance on conventional feed crops like maize and soybean, thereby lowering land use pressure and greenhouse gas emissions. Processing innovations including fermentation, enzymatic hydrolysis, and microbial inoculation improve nutrient utilization, reduce waste, and enhance flock health. These strategies align with climate smart principles by promoting circular bio-economy practices, reducing feed related carbon footprints and ensuring resilience against volatile global feed markets. Collectively, residue valorization supports poultry systems that are economically viable, environmentally sustainable and better adapted to climate challenges (Oliveira *et al.*, 2024; Sharma *et al.*, 2024; Adegbeye *et al.*, 2024) [20, 26, 8].

7. Constraints, Safety Concerns and Research Gaps

The utilization of agro industrial residues in poultry nutrition is constrained by several scientific and regulatory challenges. A major limitation is nutritional variability, as the composition of residues such as rice bran, DDGS, or fruit pomace fluctuates with crop type, processing methods and storage conditions. This inconsistency complicates diet formulation and necessitates standardization protocols to ensure predictable performance outcomes (Kumar *et al.*, 2024) [29]. Another critical concern involves contaminants and toxins, including mycotoxins, pesticide residues and heavy metals, which pose risks to food safety and flock health. Effective detoxification strategies like fermentation, enzymatic hydrolysis, and microbial inoculation are promising but require further validation under commercial conditions (Adegbeye *et al.*, 2024) [8]. Finally, regulatory frameworks and policy barriers remain significant, as many countries lack harmonized guidelines for the safe inclusion of agro industrial by-products in poultry diets. This regulatory uncertainty limits adoption and underscores the need for coordinated research and policy development to bridge gaps between innovation and practice (Chaudhary *et al.*, 2024; Singh *et al.*, 2025) [30, 31]. The importance of targeted research to establish standardized nutrient databases, robust detoxification protocols, and supportive policies that enable safe and sustainable integration of residues into climate smart poultry systems.

8. Future Prospects and Strategic Directions

Integration of advanced strategies is expected to reshape poultry nutrition and production systems in the coming years. The application of omics technologies such as genomics, proteomics, and metabolomics will enable precise feed evaluation, allowing for accurate nutrient profiling and identification of bioactive compounds in agro industrial residues. Coupled with precision feeding and digital agriculture tools, including sensor based monitoring and AI driven decision platforms, producers can optimize feed intake, growth kinetics and resource efficiency in real time. These innovations align with sustainable livestock systems by reducing environmental footprints, enhancing circular bio-economy practices, and promoting resilience against climate variability. Pathways for global adoption and scalability will depend on harmonized regulatory frameworks, international collaborations, and investment in biotechnological innovations that ensure safety, consistency, and affordability. Collectively, these strategic directions position residue based feeding as a cornerstone of climate smart and economically viable poultry systems (Patel *et al.*, 2025; Singh *et al.*, 2025; Kumar *et al.*, 2024; Chaudhary *et al.*, 2024) [32, 31, 29, 30, 10].

9. Conclusion

Agro industrial residues, when strategically processed, provide consolidated nutritional and technological benefits by enhancing amino acid balance, lipid enrichment, and bioactive compound delivery while reducing anti nutritional factors. Strategic recommendations emphasize industry investment in precision feeding, digital agriculture and scalable biotechnological innovations, while academia should focus on omics integration, safety standardization and policy frameworks to enable global adoption. Sustainability driven feed innovation ultimately reduces production costs, minimizes waste streams and supports climate smart poultry systems, positioning residue valorization as a cornerstone of resilient, eco efficient livestock production.

CRediT author contributions

Sangeeta Bhoria: Literature search, Data analysis, Software, **Poonam Khatri:** Writing - original draft. Anil Kumar:- Conceptualization, Resources, Supervision, Visualization,

Conflict of interests

The authors declare that they have no conflict of interest with contents of this article.

Funding: Not applicable.

Availability of data and materials: All the data related to this article is provided within the manuscript.

Acknowledgement

The authors are thankful to Baba Mastnath University, Asthal Bohar, Rohtak and Haryana, India for providing infrastructural facility to conduct the research.

References

1. Georganas A, Giamouri E, Pappas AC, Papadopoulos GA, Zoidis E. Dietary inclusion of tomato pomace in broiler diets: Effects on growth performance, nutrient utilization, and gut health. Animals. 2023;13(12):2034.https://doi.org/10.3390/ani13122034
2. Vlaicu PA, Untea AE, Oancea AG. Sustainable poultry feeding strategies for achieving Zero Hunger and enhancing food quality. Agriculture. 2024;14(10):1811.https://doi.org/10.3390/agriculture14101811
3. Osei-Akoto A, Abdel-Wareth AA, Salahuddin M, Goswami PK, Lohakare J. Sustainable poultry production through novel nutrition and circular resource management. Sustainability. 2026;18(8):3673.
4. Hoxha L, Taherzadeh MJ. Sustainable valorization of plant-derived agri-food side-streams through fungal biorefinery: Supporting bioeconomy strategy. Current Pollution Reports. 2026;12(1):8.
5. Georganas A, Giamouri E, Pappas AC, Zoidis E, Goliomytis M, Simitzis P. Utilization of agro-industrial by-products for sustainable poultry production. Sustainability. 2023;15(4):3679.https://doi.org/10.3390/su15043679
6. Alias J, Abu Hasan H, Said NSM, Ramli NN, Ahmad J, Razif ISM, *et al.* Utilizing High-Nutrient Agricultural Biomass as an Alternative Poultry Feed for a Sustainable Food Supply. Waste and Biomass Valorization. 2025:1-21.
7. Kiczorowska B, Samoliαska W, Al-Yasiry ARM. Agro-industrial by-products as feed ingredients: Nutritional value and potential in animal diets. Animals. 2023;13(2):245.https://doi.org/10.3390/ani13020245
8. Adegbeye MJ, Elghandour MMMY, Salem AZM. Valorization of agroindustrial residues for sustainable livestock feeding: Advances and prospects. Frontiers in Veterinary Science. 2024;11:1376542.https://doi.org/10.3389/fvets.2024.1376542
9. Kaur S, Singh A. The potential of agro-industrial by-products as feed for sustainable poultry production. Lala Lajpat Rai University of Veterinary and Animal Sciences, Hisar. 2024.
10. Singh R, Sharma P, Kumar V. Supply chain dynamics of agro-industrial residues for sustainable poultry nutrition. Frontiers in Sustainable Food Systems.

2024;8:1456321.https://doi.org/10.3389/fsufs.2024.1456321

11. Jenane C, Ulimwengu JM, Tadesse G. Agrifood processing strategies for successful food systems transformation in Africa. ReSAKSS 2022 Annual Trends and Outlook Report. Kigali and Washington, DC: AKADEMIYA2063 and International Food Policy Research Institute (IFPRI); 2022.
12. Mohammadi Shad Z, Venkitasamy C, Wen Z. Corn distillers dried grains with solubles: Production, properties, and potential uses. Cereal Chemistry. 2021;98(5):999-1019.
13. Khan MA, Arif M, Hussain J. Regional perspectives on agro-industrial byproducts in livestock feeding systems. Animals. 2023;13(12):2056.https://doi.org/10.3390/ani13122056
14. Grahovac N, Aleksić M, Trajkovska B, Marjanović Jeromela A, Nakov G. Extraction and valorization of oilseed cakes for value-added food components—A review for a sustainable foodstuff production in a case process approach. Foods. 2025;14(13):2244.
15. Hassan MA, Elghandour MMMY, Salem AZM. Variability in agroindustrial residues and strategies for sustainable feed utilization in poultry. Frontiers in Animal Science. 2024;5:1425631.https://doi.org/10.3389/fanim.2024.1425631
16. Chaudhary A, Singh R, Kumar S. Physicochemical characterization of agroindustrial by-products and their implications in poultry nutrition. Animals. 2023;13(18):2956.https://doi.org/10.3390/ani13182956
17. Mmereki D, Chikwanha OC, Mapiye C. Nutritional evaluation of agro-industrial by-products for poultry feeding: Opportunities and challenges. Animals. 2023;13(21):3456.https://doi.org/10.3390/ani13213456
18. Zhang Y, Li H, Wang J. Advances in nutritional profiling of agro-industrial residues for sustainable poultry production. Frontiers in Animal Science. 2024;5:1459872.https://doi.org/10.3389/fanim.2024.1459872
19. Rahman MM, Akter S, Hossain MA. Proximate composition of agro-industrial by-products and their potential in poultry diets. Animals. 2023;13(15):2541.https://doi.org/10.3390/ani13152541
20. Oliveira R, Silva F, Gomes C. Nutrient density and variability of agro-industrial residues for sustainable poultry feeding. Frontiers in Animal Science. 2024;5:1467321.https://doi.org/10.3389/fanim.2024.1467321
21. He D, Cui C. Fermentation of organic wastes for feed protein production: Focus on agricultural residues and industrial by-products. Fermentation. 2025;11(9):528.https://doi.org/10.3390/fermentation11090528
22. Li Y, Chen Z, Wang H. Amino acid variability in oilseed meals and implications for poultry diets. Animals. 2023;13(22):3678.https://doi.org/10.3390/ani13223678
23. Chen L, Zhao Q, Liu P. Lipid variability in agro-industrial by-products and its impact on poultry nutrition. Frontiers in Animal Science. 2024;5:1478921.https://doi.org/10.3389/fanim.2024.1478921
24. Patel R, Sharma P, Kumar V. Micronutrient contributions of fruit and vegetable residues in poultry diets. Sustainability. 2023;15(12):5123.https://doi.org/10.3390/su15125123
25. Kumar S, Chaudhary A, Singh R. Mineral variability and phytate-bound nutrients in agro-industrial by-products. Animals. 2023;13(19):3121.https://doi.org/10.3390/ani13193121
26. Sharma P, Singh R, Kumar V. Biotechnological interventions for valorization of agro-industrial residues in poultry nutrition. Frontiers in Animal Science. 2024;5:1487653.https://doi.org/10.3389/fanim.2024.1487653
27. Das A, Choudhury S, Roy D. Innovative feed processing technologies for sustainable poultry production. Animals. 2023;13(20):3289.https://doi.org/10.3390/ani13203289
28. Ahmed S, Ali M, Khan T. Bioavailability of micronutrients in agro-industrial residues: Implications for poultry feeding. Agriculture. 2024;14(6):1124.https://doi.org/10.3390/agriculture14061124
29. Kumar S, Sharma R, Gupta A. Nutritional variability of agro-industrial by-products and implications for poultry feeding. Animals. 2024;14(3):567.
30. Chaudhary A, Singh R, Verma P. Food safety risks associated with agro-industrial residues in poultry diets. Poultry Science. 2024;103(5):102345.
31. Singh R, Patel V, Kumar V. Policy frameworks and regulatory challenges in integrating agro-industrial residues into poultry nutrition. Journal of Sustainable Agriculture and Food Systems. 2025;12(1):45-58.
32. Patel R, Ahmed S, Khan T. Digital agriculture and omics integration for sustainable poultry feeding. Frontiers in Sustainable Food Systems. 2025;9:1543217.