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REVIEW ARTICLE

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Exploring the nutritional and functional potential of forage-based diets in poultry feeding systems: a systematic review toward sustainable avian nutrition

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Abstract
The rising demand for sustainable and welfare-conscious poultry production has driven renewed interest in forage-based feeding systems. This systematic review explores the nutritional and functional roles of various forage types such as legumes, grasses, and aquatic plants in poultry diets. The review synthesizes evidence from recent Scopus-indexed publications, focusing on nutrient composition, bioactive properties, performance outcomes, and potential limitations. Forages provide protein, essential fatty acids, antioxidants, and phytochemicals that can enhance feed efficiency, immunity, gut health, and product quality in poultry. Their integration also aligns with circular agriculture principles and improves animal welfare through behavioral enrichment. However, the practical adoption of forage in poultry systems is constrained by variability in nutritional value, the presence of anti-nutritional factors (ANFs), low digestibility, and seasonal availability. Strategies such as fermentation, enzyme supplementation, and preservation techniques offer promising solutions to these challenges. This review identifies key research gaps, including the need for standardization of forage nutritional profiles, optimal inclusion rates, and long-term health impacts. Future directions highlight the potential of integrating precision nutrition technologies and policy support to enhance forage-based systems. Overall, forage represents a valuable component of sustainable poultry feeding strategies that balance performance, welfare, and environmental stewardship.

KEYWORDS
forage-based diet, poultry nutrition, sustainable feeding systems, anti-nutritional factors

1. INTRODUCTION

Due to their content of crude protein, fiber, bioactive compounds, and functional metabolites, forages represent a promising nutritional resource in poultry production that can support growth performance and animal health. However, modern poultry production faces persistent challenges, including high dependency on imported, protein-rich feed ingredients; rising greenhouse gas emissions concerns; and widespread antibiotic use that contributes to antimicrobial resistance. Integrating forage-based diets into poultry production offers a sustainable way to improve feed efficiency, reduce reliance on conventional protein sources, mitigate environmental impact, and strengthen the resilience of supply chains.

Forages play a crucial role in poultry diets, particularly in free-range and organic production systems. They provide essential nutrients such as vitamins, proteins, and energy, which can reduce the reliance on conventional diets by up to 10% (Adejuyigbe et al., 2023). Forages can meet a significant portion of a broiler's daily protein and calorie needs, enhancing the sustainability of poultry production. The inclusion of forage in poultry diets has been shown to improve meat and egg quality, as well as bird health and welfare (Zheng et al., 2019). Additionally, forages can contribute to the success of local poultry production by providing a cost-effective and locally available feed source (Tufarelli et al., 2018). Modern poultry feeding systems face several sustainability challenges, including environmental pollution, depletion of natural resources, and animal welfare issues (Gunnarsson et al., 2020). The production and transportation of feed contribute significantly to global warming, eutrophication, and acidification. Strategies to mitigate these impacts include using alternative protein sources, hydroponic farming models, and reducing crude protein levels in diets (Kirkpinar & Atan, 2022). The use of phytogenic products as alternatives to antibiotic growth promoters can also enhance sustainability by improving feed efficiency and bird immunity without the negative outcomes associated with antibiotics (Mnisi et al., 2024). Furthermore, integrating sustainability into poultry supply chains can provide economic and social benefits while addressing environmental concerns (Shamsuddoha, 2022).

The current draft does not explain how forages contribute specifically to improving welfare outcomes in poultry. Forages promote natural behaviors, such as pecking, scratching, and foraging, which are often restricted in intensive systems. Access to fibrous plant material can reduce injurious pecking and stereotypic behaviors by providing environmental enrichment. Furthermore, the presence of forages in the diet or environment has been linked to reduced stress indicators, improved gut health, and greater resilience to environmental challenges. These benefits are especially important in sustainable poultry production systems because animal health and behavior directly impact productivity and public perception.

In this review, the term "forages" refers to plant-based feed resources that can be used in poultry diets. This includes conventional sources, such as grasses and legumes, as well as non-traditional sources, such as aquatic plants (e.g., Azolla, duckweed, and water spinach), and certain agricultural by-products that retain substantial nutritional value. This broader definition of forages is crucial because it allows us to discuss both terrestrial and aquatic resources, as well as sustainable alternatives to conventional feed ingredients in tropical and subtropical regions. The objectives of this review are to evaluate the nutritional impact of forages in poultry diets, assess how forages contribute to the nutritional needs of poultry and their effects on meat and egg quality; analyze sustainability strategies in poultry feeding systems, examine various approaches to reduce environmental impacts and improve the sustainability of poultry production; explore the role of phytogenic products, investigate how these products can be used to enhance food security and sustainable poultry production, particularly in developing countries; and assess consumer perceptions and market potential, understanding consumer attitudes towards sustainable poultry production and identifying strategies to promote the adoption of sustainable practices. Specifically, we emphasize that while many studies and reviews have documented the nutritional potential of forages, findings remain controversial regarding their digestibility in monogastric animals, the variability of bioactive compound effects across forage species, and the lack of standardized feeding trials in poultry. Moreover, existing reviews often focus on ruminants, leaving limited synthesis for poultry systems. These limitations justify the need for the present review, which aims to consolidate available evidence, critically evaluate practical implications, and propose directions for future research in forage-based poultry nutrition.

The scope of this review includes nutritional composition and antinutritional factors of forages, detailed analysis of the main forages used in poultry diets and their nutritional benefits (Adejuyigbe et al., 2023; Tufarelli et al., 2018); environmental and economic sustainability, evaluation of the environmental impacts of feed production and strategies to mitigate these effects (Alkhtib et al., 2023; Kirkpinar & Atan, 2022); social sustainability and animal welfare, which consider of the social dimensions of sustainability, including consumer perceptions and animal welfare concerns (Dewi et al., 2024; Gunnarsson et al., 2020; Soisontes, 2017); and innovative feeding strategies, which explore of alternative feeding strategies, such as the use of phytogenic products and hydroponic farming models (Kirkpinar & Atan, 2022; Mnisi et al., 2024). By addressing these objectives, the review aims to provide a comprehensive understanding of the role of forages in sustainable poultry production and offer insights into future directions for the industry.

2. MATERIALS AND METHODS

This systematic review followed a structured protocol based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines to ensure transparency and reproducibility. A comprehensive literature search was conducted across major scientific databases, including Scopus, ScienceDirect, and Google Scholar to capture peer-reviewed publications related to the use of forage in poultry feeding systems. The search was limited to articles published between 2003 and 2024, using combinations of keywords such as *"forage-based diet", "poultry nutrition", "functional feed", "anti-nutritional factors", and "sustainable poultry production"*. Boolean operators (AND, OR) and truncation were applied to enhance search sensitivity. Boolean operators (AND, OR) and truncation were applied to enhance search sensitivity (Garfansa et al., 2025). For instance, one of the search strings used in Scopus was: ("poultry" AND "forage diet*" AND "performance") OR ("chicken*" AND "legume*" AND "nutrition") OR ("broiler*" AND "pasture-based feeding"). This approach allowed the inclusion of diverse terminologies related to poultry species, feeding systems, and forage types, thereby reducing the risk of missing relevant studies. Our initial search was limited to Scopus, ScienceDirect, and Google Scholar due to accessibility and overlap with core poultry nutrition literature. However, we recognize that PubMed, Web of Science, CAB Abstracts, and AGRICOLA are also highly relevant for animal nutrition and feed research. To address this, we have (i) clarified the rationale for our database selection in the Methods section, and (ii) expanded the search scope by cross-checking references from PubMed and CAB Abstracts to ensure broader coverage and minimize the risk of missing key studies. The time span of 2003–2024 was selected to capture both recent advances and earlier foundational studies on forage utilization in poultry systems. Some studies older than 15 years remain relevant because they provide baseline data on nutrient composition, anti-nutritional factors, and early feeding trials, which continue to inform current practices and serve as reference points for more recent research. To clarify this, we have revised the Methods section to explicitly justify the inclusion of studies prior to 2010 while emphasizing that our analysis prioritizes more recent publications when discussing current trends.

The inclusion criteria comprised: (1) original research or review articles published in English; (2) studies involving chickens, ducks, quail, or other poultry species; (3) focus on forage-based or forage-supplemented diets; and (4) measurable outcomes related to growth performance, feed efficiency, immunity, gut health, product quality, or environmental sustainability. Exclusion criteria included: (1) non-peer-reviewed literature (e.g., theses, opinion papers); (2) studies focusing solely on ruminants or non-poultry species; and (3) articles lacking clear methodology or nutritional outcomes. The diagram illustrates the pathway: *Forages → Nutrient contribution → Poultry performance & welfare → Sustainability outcomes*. This framework is intended to guide readers in understanding how the different sections of the paper are connected and to highlight the broader implications of forage use in poultry production.

Relevant data were extracted manually using a standardized data extraction form, which included information on study design, animal species, type of forage used, inclusion level, feeding duration, key findings, and limitations. The extracted data were synthesized through narrative synthesis and thematic categorization based on major outcome indicators. Where available, studies were also compared in tabular format to highlight consistencies and discrepancies across findings. A PRISMA flow diagram was developed to illustrate the screening process, showing the number of records identified, screened, excluded, and included in the final analysis. More detailed information can be seen in the image below.

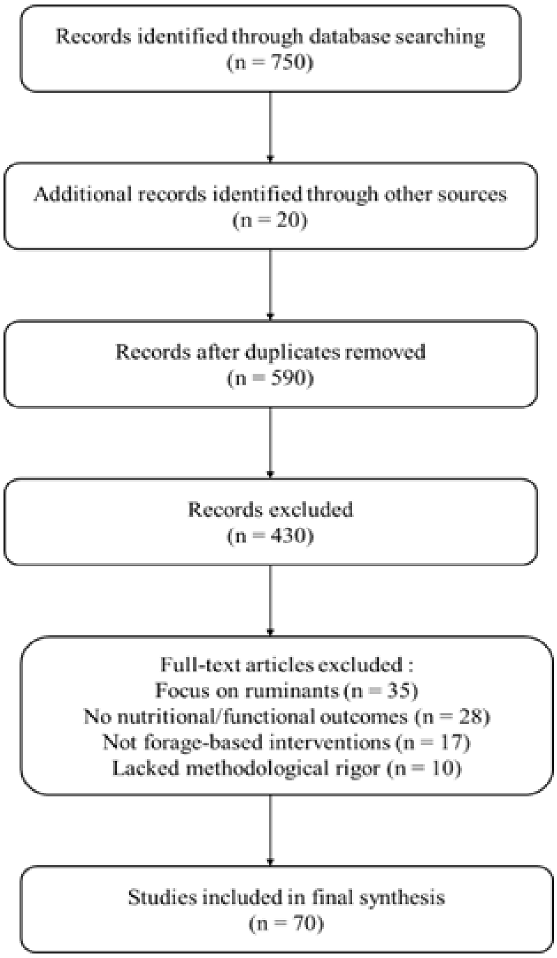

Figure 1. PRISMA flow diagram for the selection of articles included in the systematic review on forage-based diets in poultry feeding systems

3. RESULT AND DISCUSSION

3.1 Forage Types and Composition in Poultry Nutrition

Classification of forage species used in poultry feeding. Grasses, commonly used forage grasses include tall fescue (*Festuca arundinacea*) and bermudagrass (*Cynodon dactylon*) (Burton, 1996); legumes, important forage legumes include alfalfa (Medicago sativa) and white clover (*Trifolium repens*); and aquatic forages: while not explicitly mentioned in the abstracts, aquatic forages can include species like duckweed, which are known for their high protein content. Forages, especially legumes, are significant sources of protein. Legumes like alfalfa are particularly high in protein compared to grasses (Ohiwal et al., 2025). Forages contain both structural and non-structural carbohydrates, with cellulose being the most abundant polysaccharide in forage cell walls. The fiber content in forages can impact nutrient digestibility and utilization in poultry (Fernandes et al., 2015). Forages provide essential minerals such as calcium, phosphorus, zinc, manganese, copper, and iron, which are crucial for poultry health and productivity (Vlaicu et al., 2024). Forages contain bioactive compounds like polyphenols, antioxidants, carotenoids, and vitamins, which can enhance poultry health and product quality.

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Common ANFs in forages include phytic acid (PA) and non-starch polysaccharides (NSP), which can limit nutrient utilization (Chaniago et al., 2024). Other ANFs include vicine and convicine in faba beans, which can reduce laying hen performance (Lessire et al., 2017). The use of supplemental phytase and NSP-degrading enzymes (*carbohydrases*) can hydrolyze PA and NSP, respectively, improving nutrient utilization (Woyengo & Nyachoti, 2011). Toxin binders such as activated charcoal, kaolin, and hydrated sodium calcium aluminosilicate (HSCAS) can mitigate the effects of aflatoxins in poultry feed (de Pinho Carao et al., 2014; Mahmood et al., 2017). The inclusion of natural antioxidants and phytogenic compounds in poultry diets can reduce oxidative stress and improve gut health, thereby mitigating the effects of ANFs (Golestan, 2010; Maty, 2021). More detailed information can be found in Table 1 below.

Common ANFs in forages include phytic acid (PA) and non-starch polysaccharides (NSP), which can limit nutrient utilization

Table 1. Overview of different forage types used in poultry diets along with their nutritional attributes, common anti-nutritional factors, and detoxification strategies

Forage Type	Examples	Nutritional Components	Anti-Nutritional Factors	Detoxification Strategies
Grasses	Tall fescue, bermudagrass	Carbohydrates, fiber, minerals	NSP	Enzymatic supplementation
Legumes	Alfalfa, white clover	Protein, fiber, minerals	Phytic acid, vicine, convicine	Enzymatic supplementation, natural additives
Aquatic Forages	Duckweed	High protein content	Not specified	Not specified

Recent studies highlight that the potential of aquatic plants such as duckweed (*Lemna* spp.) and *Azolla* spp. in poultry feeding is determined not only by their nutrient composition but also by digestibility and the presence of anti-nutritional factors. Thongthung et al. (2024) reported that the in vitro protein digestibility of duckweed varies among genera, with Lemna reaching 72%, *Wolffia* 69%, and Spirodela only 39%, while another study confirmed high variability in ileal amino acid digestibility, particularly for methionine (Schokker et al., 2022). Islam (2024) emphasized that duckweed can replace up to 15% of broiler diets and 40% of layer diets, although limited methionine remains a constraint. Similarly, *Lemna minor* contains high protein levels (20–40%) but shows lower protein digestibility compared to conventional feedstuffs.

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For *Azolla*, Normuhammedova and Rajamurodov (2025) reported a crude protein content of around 24.8% alongside a favorable mineral profile, whereas Yalew at al., (2024) highlighted its richness in essential amino acids such as lysine and methionine, as well as vitamins A, C, and E. Nevertheless, the presence of tannins, oxalates, and phytates may reduce its nutritional availability, thus requiring processing or optimized inclusion levels. Nasir et al. (2022) further underlined that *Azolla* contains 21–26% crude protein (dry matter basis), with additional lipids, amino acids, and phenolic compounds; its feeding value, however, depends on environmental conditions and cultivation strategies. More recent studies also confirmed that *Azolla* can replace up to 20% of broiler diets without compromising performance.

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Overall, the application of duckweed and *Azolla* in poultry diets should be critically assessed, considering not only their chemical composition but also bioavailability, species-specific utilization, and the need for processing treatments such as fermentation, drying, or enzyme supplementation to enhance feeding efficiency.

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3.2 Nutritional Roles of Forage in Poultry Diets

Forages can significantly contribute to the protein and micronutrient intake in poultry diets. Dehydrated forages, such as leguminous-based forage, are good sources of α-linolenic acid (ALA) and lipid-soluble antioxidant compounds like vitamin E homologs and β-carotene (Ponte, Prates, et al., 2008). Additionally, forages can provide essential amino acids and minerals, which are crucial for poultry health and growth (Abdelnour et al., 2018; Barszcz et al., 2024). The inclusion of alternative protein sources like insect meals (e.g. Tenebrio molitor) has shown positive modulation of gut microbiota without affecting intestinal morphology, indicating their potential as a protein source (Biasato et al., 2018).

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Forages and alternative feed ingredients can positively impact gut health and microbiota. For instance, dietary inclusion of Tenebrio molitor meal increased the diversity of gut microbiota and the relative abundance of beneficial bacteria such as Firmicutes and Clostridium (Biasato et al., 2018). Similarly, Hermetia illucens meal inclusion at low levels positively influenced cecal microbiota and gut mucin dynamics (Biasato et al., 2020). The gut microbiota plays a critical role in nutrient utilization, immune response, and overall health, which can be enhanced by prebiotics, probiotics, and other feed additives (Ducatelle et al., 2023; Naeem & Bourassa, 2025; Sayed et al., 2025). The impact of forage on feed intake, digestibility, and feed conversion ratio (FCR) varies. For example, broiler chickens fed diets with varying particle sizes showed differences in feed intake and FCR, with smaller particle sizes leading to better FCR (Kareem et al., 2022).

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The inclusion of enzyme-prebiotic supplements improved feed conversion efficiency and nutrient digestibility (Kirkpinar et al., 2004). Additionally, the use of dehydrated leguminous-based forage did not negatively impact broiler performance but improved the fatty acid profile of the meat (Ponte, Prates, et al., 2008). Forages can also contribute to better nutrient utilization and reduced feed costs, which is economically beneficial (Jimenez et al., 2024; Walker & Gordon, 2003). More detailed information can be found in Table 2 below.

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Table 2. Key functional aspects and health impacts of forage inclusion in poultry diets based on recent scientific evidence

Aspect	Findings	References
Protein and Micronutrient Intake	Forages provide essential amino acids, ALA, vitamin E, and β-carotene.	(Abdelnour et al., 2018; Barszcz et al., 2024; Ponte, Prates, et al., 2008)
Gut Health and Microbiota	Positive modulation of gut microbiota with beneficial bacteria; improved gut health with prebiotics and probiotics.	(Biasato et al., 2018, 2020; Ducatelle et al., 2023; Naeem & Bourassa, 2025; Sayed et al., 2025)
Feed Intake, Digestibility, FCR	Smaller particle sizes improve FCR; enzyme-prebiotic supplements enhance digestibility; dehydrated forage improves meat fatty acid profile.	(Jimenez et al., 2024; Kareem et al., 2022; Kirkpinar et al., 2004; Walker & Gordon, 2003)

The manuscript contains redundant information, particularly the repeated mention of dehydrated legumes across multiple subsections (e.g., nutrient composition, anti-nutritional factors, and practical feeding trials). These references should be consolidated into a single, well-developed subsection. A dedicated subheading on "Processing of Legumes (e.g., Dehydration, Roasting, Fermentation)" could synthesize all relevant findings and provide a more structured discussion while avoiding repetition.

These references should be consolidated into a single, well-developed

3.3 Functional and Health Benefits of Forage Inclusion

Forage inclusion in poultry diets can enhance antioxidant defenses and modulate immune responses. For example, Salix alba extract has been shown to improve body weight, feed conversion ratio, total antioxidant capacity, and free radical scavenging activity in broiler chickens (Kalia et al., 2021). Similarly, ethoxyquin supplementation in heat-stressed broilers improved hepatic antioxidant enzymes and serum immunity (Elokil et al., 2024). Herbal feed additives (HFAs) like milk thistle and grape seed extracts also exhibit strong antioxidant and immunomodulatory properties, enhancing overall health and productivity (Elnesr et al., 2023; Farahat et al., 2017; İpçak & Denli, 2024). Microalgae-derived feed ingredients and Ganoderma spent substrate (GSS) have been found to improve intestinal morphology, systemic immunity, and antioxidant capacity, protecting against physiological and pathogen challenges (Fries-Craft et al., 2021; Liu et al., 2025).

Herbal feed additives (HFAs) like milk thistle and grape seed extracts also exhibit strong antioxidant and immunomodulatory properties, enhancing overall health and productivity

Forage-derived phytogenics, such as cinnamaldehyde and caprylic acid, reduced Salmonella and Campylobacter in broilers (Lyte et al., 2024). Probiotics and prebiotics, derived from forages, can enhance beneficial microbial communities in the gut, promoting competitive exclusion and production of bacteriostatic substances that inhibit pathogen colonization (Clavijo & Flórez, 2018; Mekonnen et al., 2024). Bifidobacterium bifidum postbiotics have shown significant protective effects against Salmonella Pullorum infection by modulating pyroptosis, restoring intestinal barrier function, and improving gut microbiota (Chen et al., 2025). Forage inclusion can positively impact poultry behavior and welfare. For instance, dried olive pulp (OP) in broiler diets improved foot pad dermatitis and feather cleanliness without compromising growth performance (Dedousi et al., 2022).

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Access to pasture and forage can enhance gastrointestinal health and promote natural behaviors, which are beneficial for overall welfare (El Jeni et al., 2021). The inclusion of forage in diets can also mitigate detrimental behaviors and improve welfare by providing environmental complexity and reducing stress (Hester, 2005; Kiani, 2022). More detailed information can be found in Table 3 below.

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Table 3. Health-promoting and welfare-enhancing effects of forage inclusion in poultry nutrition: a review of current evidence

Aspect	Benefits	Supporting Evidence
Immunomodulatory and Antioxidant Effects	Enhanced antioxidant defenses, improved immune responses, reduced oxidative stress	(Elnesr et al., 2023; Elokil et al., 2024; Farahat et al., 2017; Fries-Craft et al., 2021; İpçak & Denli, 2024; Kalia et al., 2021; Liu et al., 2025)
Reducing Enteric Pathogens	Decreased pathogen load, competitive exclusion, improved gut microbiota	(Chen et al., 2025; Clavijo & Flórez, 2018; Lyte et al., 2024; Mekonnen et al., 2024)
Behavioral and Welfare Implications	Improved foot pad dermatitis, feather cleanliness, enhanced natural behaviors, reduced stress	(Dedousi et al., 2022; El Jeni et al., 2021; Hester, 2005; Kiani, 2022)

3.4 Forage Integration in Different Poultry Production Systems

Free-range systems, these systems allow birds to roam freely outdoors, providing access to natural forages such as grass, insects, and worms. This can enhance animal health and product quality but may expose birds to predators, diseases, and climatic challenges (Castellini & Dal Bosco, 2017; El Jeni et al., 2021; Singh & Cowieson, 2013); semi-intensive systems, a hybrid approach where birds are partially confined but also have access to outdoor runs. This system combines the benefits of free-range and intensive systems, offering a balance between natural foraging and controlled feeding (Okeno et al., 2012; Sanka et al., 2021); and deep-litter systems, Birds are kept indoors on a litter-covered floor, which can be managed to include forage supplementation. This system focuses on maintaining a controlled environment while providing some natural dietary elements (Buchanan et al., 2007; Minh & Ogle, 2005).

Adding forage to a conventional diet can improve nutrient intake and bird performance. For example, dehydrated leguminous forages can enhance the fatty acid profile of broiler meat without negatively impacting growth performance (Ponte, Prates, et al., 2008). Enzyme supplementation can further improve nutrient utilization from forages (Buchanan et al., 2007; Ponte, Rosado, et al., 2008). While complete forage diets are less common, they can be beneficial in specific contexts. For instance, incorporating Stylosanthes hamata leaf meal up to 20% in broiler diets did not adversely affect performance, suggesting potential for high forage inclusion (Adejuyigbe et al., 2023). Smallholder poultry systems often rely on free-range or semi-intensive methods due to resource constraints.

For example, in Zambia, indigenous chicken production under free-range systems showed higher profitability compared to commercial broilers and layers (Mubamba et al., 2018). In Tanzania, integrating vegetable and poultry production systems proved more profitable than vegetable farming alone, highlighting the benefits of diversified farming practices (Habiyaremye et al., 2021). In regions like the EU, USA, and Australia, there is a growing trend towards free-range and organic systems driven by consumer demand for welfare-friendly and sustainable products. These systems, however, face challenges such as lower performance compared to conventional systems and the need for improved husbandry practices (El Jeni et al., 2021; Miao et al., 2005).

3.5 Challenges and Limitations in Forage-Based Poultry Feeding

Forage-based poultry feeding presents several challenges and limitations, which can be categorized into three main areas: variability in nutrient composition, digestive limitations in monogastric species, and issues related to preservation, processing, and seasonal availability. Forages and grain legumes exhibit significant variability in their nutrient content, which can affect feed efficiency and animal performance. The presence of secondary metabolites and anti-nutritional factors in plants can further complicate the nutritional value of forages (Abdelnour et al., 2018; Tufarelli et al., 2018). The nutrient density of forage-based diets can be lower compared to conventional feeds, necessitating the supplementation of additional nutrients to meet the dietary requirements of poultry (Kandel et al., 2025).

High fiber content in forages can pose digestive challenges for poultry, which are monogastric animals. Insoluble fibers, while beneficial in moderate amounts, can lead to increased intestinal transit time and reduced nutrient digestibility when present in excess (Salahi et al., 2025). Forages often contain anti-nutritional factors that can interfere with nutrient absorption and digestion. These factors need to be mitigated through processing techniques such as fermentation to enhance the nutritional value of the feed (Siwach et al., 2025). The preservation and processing of forages are critical to maintaining their nutritional quality. Techniques such as microbial fermentation can improve the digestibility and nutrient content of forages, but these processes can be complex and resource-intensive (Salahi et al., 2025; Siwach et al., 2025). The availability of forages is often seasonal, which can lead to inconsistencies in feed supply. This variability necessitates the development of strategies to store and preserve forages during periods of abundance to ensure a steady supply throughout the year (Abera et al., 2024).

3.6 Toward Sustainable Poultry Nutrition: Opportunities and Future Directions

Circular agriculture and the use of local forage can significantly enhance the sustainability of poultry nutrition. Utilizing by-products, plants, and food waste from fruits, vegetables, and seeds can reduce dependency on conventional feeds and lower production costs by up to 25% (Vlaicu et al., 2024). Local breeds, such as Robusta maculata, have shown better resilience and gut health when fed with low-input diets that include local ingredients like fava beans and GMO-free soybeans (Fonsatti et al., 2025). Additionally, composting broiler chicken manure can improve environmental performance by substituting chemical fertilizers in crop cultivation (Cheng et al., 2023). Integrating probiotics, phytobiotics, and organic feed systems can further promote sustainable poultry nutrition. Probiotics have been shown to enhance growth performance, carcass quality, and immune organ development, outperforming traditional antibiotic growth promoters (AGPs) (Agustono et al., 2025). Phytogenics, such as those derived from moringa, offer antimicrobial and antioxidant benefits, improving poultry health and product quality (Egbu et al., 2024). Organic farming practices, which avoid chemical fertilizers and pesticides, have demonstrated higher efficiency in transforming inputs into final products and better animal welfare (Castellini et al., 2006).

Several research gaps and policy recommendations need to be addressed to advance sustainable poultry nutrition: quality and availability of alternative feeds, inconsistencies in the quality and availability of alternative feed ingredients, as well as the presence of anti-nutrients, pose challenges (Vlaicu et al., 2024); adoption of *phytogenics*, despite their benefits, has not been widely adopted due to various barriers, including regulatory frameworks and financial constraints (Mnisi et al., 2024; Mountzouris & Brouklogiannis, 2024); precision feeding technologies, where there is a need for robust methods to assess nutritional requirements and implement precision feeding, which can be enhanced by leveraging AI and digital technologies (Cao et al., 2024; Martinez et al., 2024); and policy and collaboration, where policies should support the development and adoption of sustainable practices, including the use of local breeds and alternative feeds. Collaboration among researchers, policymakers, and industry professionals is crucial for knowledge exchange and the promotion of sustainable practices (Bist et al., 2024).

4. CONCLUSION

This systematic review demonstrates that forage-based diets hold significant nutritional and functional potential in advancing sustainable poultry feeding systems. A wide range of forage resources such as legumes, grasses, and aquatic plants provide essential nutrients, bioactive compounds, antioxidants, and minerals that enhance feed conversion efficiency, strengthen immune responses, modulate gut microbiota, and improve product quality, including yolk pigmentation and meat fatty acid composition. Moreover, forage inclusion supports animal welfare by promoting natural foraging behaviors and contributes to circular agricultural practices by utilizing locally available, cost-effective feed resources.

Despite these advantages, several challenges remain in the practical implementation of forage-based feeding strategies. These include nutrient variability, the presence of anti-nutritional factors (ANFs), reduced digestibility due to high crude fiber content, and the seasonal availability of forage. Innovative approaches such as microbial fermentation, enzyme supplementation, and effective forage preservation techniques (e.g., silage and haylage) are essential to overcome these limitations. In practical terms, small- to medium-scale poultry producers—especially those in free-range or semi-intensive systems—can integrate forage into feeding regimes to reduce reliance on conventional feed, lower production costs, and meet growing consumer demand for natural and sustainable poultry products.

Future research should focus on standardizing the nutritional composition of forage species across different agro-ecological zones, determining optimal inclusion levels, and exploring synergies with other alternative feed sources such as insects or algae. Long-term studies are also needed to assess the impact of forage on poultry health, productivity, and welfare. Advanced tools like metabolomics, gut microbiome profiling, and artificial intelligence in precision nutrition can further optimize forage utilization. With adequate policy support and the translation of scientific findings into practice, forage-based diets can play a transformative role in building environmentally responsible, nutritionally sound, and economically viable poultry production systems.

In particular, we now highlight three main priorities: (1) determining the optimal inclusion levels of different forage types in poultry diets, (2) evaluating long-term effects of forage supplementation on poultry health and welfare, and (3) assessing the economic feasibility and sustainability of integrating forage-based diets in diverse production systems. These priorities are presented to provide clearer guidance for future research directions. Specifically, we emphasize that for smallholder farmers, forages could serve as a low-cost alternative to reduce feed expenses, while for the poultry industry, the integration of forages with feed additives may be necessary to ensure consistent productivity and performance. These additions strengthen the practical relevance of our findings.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Rezki Amalyadi: Conceptualization, Methodology, Data Curation, Writing – Original Draft, and Corresponding Author. Ine Karni: Formal Analysis, Validation, and Writing – Review & Editing. Aminurrahman: Investigation, Resources, and Visualization. I Gede Nano Septian: Data

Interpretation, Project Administration, and Review. Zaid Al Gifari: Literature Review, Editing, and Final Proofreading.

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All other authors state no conflict of interest.

DATA AVAILABILITY STATEMENT
The review did not report any data.

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