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Azolla as a functional feed ingredient: Growth, immunity, and economic impacts in Broiler chicken

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Abstract

This comprehensive review synthesizes current knowledge on the use of Azolla as a functional feed ingredient in broiler nutrition. With growing global demand for cost-effective and sustainable poultry feed alternatives, Azolla emerges as a promising solution due to its symbiotic relationship with nitrogen-fixing cyanobacterium Anabaena azollae. Rich in protein, essential amino acids, vitamins, carotenoids, and minerals, Azolla offers both nutritional benefits and functional properties. Experimental studies demonstrate that dietary inclusion of Azolla at 2.5–5% improves growth performance, feed conversion efficiency, and immune response while lowering feed costs, without adverse effects on carcass traits. Furthermore, Azolla cultivation supports environmental sustainability through biological nitrogen fixation and integration into circular farming systems. Despite limitations such as high fiber and moisture content, this review examines Azolla's nutritional value, impacts on broiler growth, immunity, carcass quality, and economic viability. It also addresses current constraints and suggests future directions including fermentation, enzyme supplementation, and adoption in climate-smart agriculture. As the world shifts toward sustainable animal production, Azolla represents a multifunctional ingredient that can increase broiler productivity while reducing dependence on expensive traditional protein sources.

Keywords: *Azolla, Broiler chickens, Growth performance, Immune response, Economic feasibility, Sustainable nutrition*

1. Introduction

Poultry production continues to be one of the fastest-growing livestock sectors globally, serving as a vital source of affordable animal protein. However, the industry remains heavily dependent on feed, which constitutes approximately 60–70% of total production costs.[1,2] Among feed ingredients, protein sources such as soybean meal and fish meal are particularly expensive, and their rising demand has led to price volatility, competition with human food resources, and sustainability concerns.[3] Consequently, the exploration of unconventional, sustainable feed resources has become a critical research priority.

Azolla, a small floating aquatic fern from the family Salviniaceae, offers distinctive advantages for animal nutrition. Its symbiotic relationship with the cyanobacterium Anabaena azollae enables atmospheric nitrogen fixation, resulting in rapid biomass production and high crude protein content.[4] Azolla can be cultivated with minimal inputs, harvested continuously, and processed into meal, rendering it both accessible and cost-effective. Beyond its nutritional value, Azolla contains bioactive compounds such as carotenoids and flavonoids, which contribute to antioxidant and immune-enhancing properties.[5,6]

In broiler production, Azolla has been investigated as a partial substitute for soybean meal. Research consistently indicates that when incorporated at appropriate levels, Azolla can maintain or even improve growth performance and carcass yield while reducing feed costs.[7] The schematic pathway illustrating Azolla cultivation and its utilization in poultry production is presented in Figure 1.

Notwithstanding these promising outcomes, practical constraints including high moisture content, perishability, and compositional variability impede its widespread adoption. This review synthesizes contemporary knowledge on Azolla in broiler nutrition, emphasizing its impacts on growth, immune response, carcass characteristics, and economic feasibility, while proposing strategies to optimize its utilization.

1.1. Objectives of the Review

This review aims to: (1) evaluate the effects of dietary Azolla inclusion on broiler growth performance and carcass traits, (2) analyze its immunomodulatory and antioxidant properties, (3) assess the economic implications of Azolla incorporation in broiler diets, and (4) identify research gaps and future directions for optimizing its utilization in sustainable poultry production.

1.2. Literature Search Methodology

This narrative review was conducted through a system-

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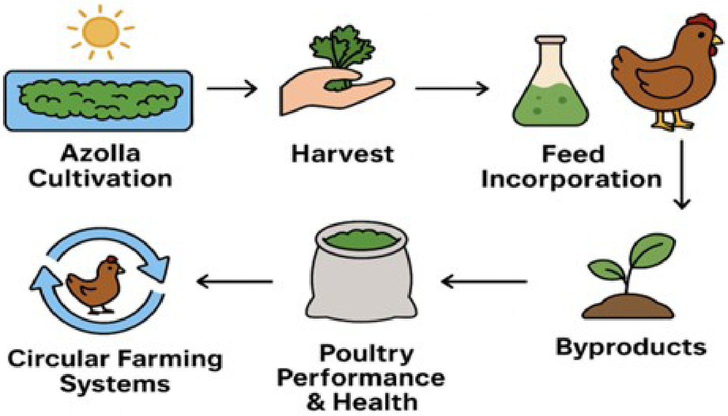

Figure 1. Schematic of Azolla Cultivation and Utilization in Poultry Nutrition

atic search of electronic databases including PubMed, ScienceDirect, Scopus, and Google Scholar for relevant literature published between 2000 and 2024. Search terms included combinations of: "Azolla", "broiler chickens", "growth performance", "immune response", "antioxidant", and "economic analysis". Inclusion criteria encompassed peer-reviewed original research articles, review papers, and conference proceedings examining Azolla in broiler nutrition. Studies were selected based on relevance to nutritional evaluation, growth parameters, immune function, and economic impact. Data from selected studies were extracted and synthesized thematically.

2. Nutritional Value of Azolla

Azolla's comprehensive nutrient profile justifies its dual classification as both a protein-rich supplement and a multifunctional feed additive. On a dry matter basis, crude protein content ranges from 20% to 30%, while crude fiber varies between 15% and 20%.[4,8] Azolla contains a spectrum of essential amino acids, with particularly high levels of lysine and arginine, though methionine concentrations remain limiting compared to soybean meal, potentially necessitating supplementation in practical formulations. The mineral composition is nutritionally significant, featuring elevated concentrations of calcium (0.4-0.6%), magnesium, iron (250-300 mg/kg), and potassium. The vitamin profile includes substantial amounts of vitamin A (primarily as β-carotene: 700-1000 μg/100g), vitamin B12, and riboflavin. Notably, the carotenoid content not only enhances skin and shank pigmentation in broilers by 15-25% compared to controls but also provides potent antioxidant protection through free radical scavenging mechanisms.[9]

Fresh Azolla's high moisture content (85–90%) presents preservation challenges that influence its practical application.[10] Common processing methods include shade-drying, sun-drying, and oven-drying; however, these thermal approaches can adversely affect heat-sensitive nutrients, particularly vitamins and antioxidants. Recent innovations demonstrate that controlled fermentation and ensiling with beneficial microbial consortia significantly improve protein digestibility (by 20-30%) and reduce anti-nutritional factors such as tannins and lignin[8]. Critically, Azolla cultivated in contaminated aquatic environments may accumulate heavy metals (e.g., lead, cadmium) or microbial pathogens, underscoring the necessity for rigorous quality control protocols in cultivation systems.[11]

Compared with conventional protein sources, Azolla represents a renewable and environmentally sustainable alternative with a lower carbon footprint. Nevertheless, its relatively high fiber content reduces nutrient digestibility at inclusion levels exceeding 7%.[12] Strategic interventions including targeted enzyme supplementation (xylanase, cellulase) and optimized microbial fermentation can effectively mitigate these limitations by breaking down fibrous components and enhancing nutrient bioavailability.[13] The comprehensive proximate and nutrient composition of Azolla is systematically summarized in Table 1, which provides referenced quantitative data for formulation purposes.

3. Growth Performance

Growth performance serves as the primary indicator of a feed ingredient's efficacy in broiler production. Multiple investigations have demonstrated that incorporating Azolla meal at appropriate levels enhances body weight gain and improves feed conversion ratio (FCR).[17] Optimal inclusion levels range between 2.5-5% as summarized in Table 2, with higher levels (>7%) potentially reducing nutrient digestibility due to fiber content. Basak et al.[18] reported significantly higher weight gain in broilers supplemented with 5% Azolla, while Mali et al.[7] observed performance metrics comparable or superior to conventional diets. These improvements are attributed not only to Azolla's protein content but also to its bioactive compounds that may enhance nutrient absorption and intestinal health through modulation of gut microbiota and improvement of villus architecture.

Variability in research outcomes may stem from differences in broiler genetics, basal diet composition, and Azolla processing methods (fresh, dried, or fermented). Studies employing fermented Azolla consistently report enhanced nutrient digestibility and diminished performance depression at higher inclusion levels.[19] The underlying mechanisms likely involve microbial degradation of fiber components and reduction of anti-nutritional factors. Overall, scientific consensus indicates that moderate inclusion levels (2.5–5%) optimize growth benefits while avoiding performance limitations.[20] The effect of Azolla on body weight gain is further illustrated in Figure 2.

This synthesized analysis illustrates the non-linear relationship between Azolla inclusion levels and key performance metrics. The parabolic response curve demonstrates clear optimization at 5% inclusion, with body weight gain peaking at 12-15% improvement over controls and feed conversion ratio achieving 8-12% enhancement. The shaded optimal zone (2.5-5%) represents the recommended inclusion range where biological benefits align with economic feasibility. Performance degradation beyond 7% inclusion is attributed to dietary fiber interference with nutrient digestibility. Data points represent mean values derived from multiple studies summarized in Table 2, with error bars indicating inter-study variation.

4. Immune and Physiological Responses

Azolla supplementation significantly enhances immune status and physiological functions in broilers. Alalade and Iyayi[25] and Shukla et al.[26] documented increased hemoglobin concentrations and packed cell volume in chicks fed Azolla meal, suggesting improved oxy-

Table 1. Proximate and Nutrient Composition of Azolla (Dry Matter Basis)

Nutrient	Content Range (%)	Remarks / Notes	Source
Crude Protein (CP)	20 – 30	Comparable to soybean meal, but variable	14
Crude Fiber (CF)	15 – 20	Higher than conventional feedstuffs	14
Ether Extract (Fat)	2 – 4	Low fat content	4
Ash	10 – 15	Rich in minerals	8
Lysine	0.8 – 1.2	Higher than maize	4
Methionine	0.2 – 0.3	Limiting amino acid	15
Calcium (Ca)	0.4 – 0.6	Supports skeletal growth	14
Iron (Fe)	250 – 300 mg/kg	Improves hematological status	16
β-carotene	700 – 1000 µg/100g	Enhances pigmentation, antioxidant	15

Table 2. Summary of Studies on Azolla Inclusion in Broiler Diets

Study	Level of Inclusion	Form Used	Duration(day)	Key Findings
21	5%	Fresh meal	42	Improved weight gain, acceptable FCR
22	2.5 – 5%	Dried meal	35	Improved growth, higher antibody titers
7	2.5 – 5%	Dried/Fermented	42	Improved gut health and villi length
20	3-7%	Processed powder	42	Improved biochemical indices, enhanced intestinal morphology
23	4-6%	Leaf meal	36	Better performance metrics, improved product quality

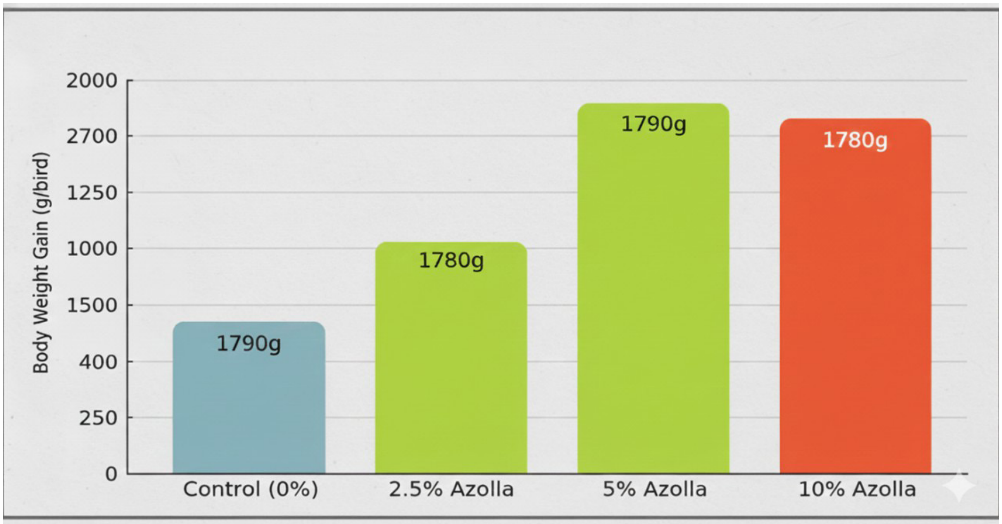

Figure 2. Effect of Azolla Inclusion on Growth Performance[7,24]

gen-carrying capacity. Kumar et al.[27] observed elevated antibody titers against Newcastle disease virus in Azolla-supplemented broilers, indicating enhanced humoral immunity.

4.1. Mechanisms of Immunomodulation

The immunomodulatory effects of Azolla are attributed to its bioactive compounds.[9] Polysaccharides and flavonoids stimulate macrophage activity and enhance cytokine production, while β-glucans activate toll-like receptors (TLR-2) leading to improved innate immune response.[28] Additionally, Azolla's antioxidant components (carotenoids, polyphenols) upregulate endogenous antioxidant enzymes including superoxide dismutase (SOD) and glutathione peroxidase (GPx), reducing oxidative stress markers such as malondialdehyde (MDA) by 20-35% in broiler tissues.[24]

The antioxidant properties of Azolla assume particular importance under the oxidative stress conditions prevalent in intensive poultry production systems. By neutralizing reactive oxygen species, carotenoids and polyphenols reduce oxidative damage to cellular components, thereby supporting enhanced health outcomes and disease resistance.[29,30] Additionally, Azolla's mineral-rich composition, especially its iron and calcium content, supports hematopoiesis and skeletal development.[27]

Physiological improvements extend to the gastrointestinal system, where Mali et al.[7] reported increased intestinal villus height in broilers fed Azolla, resulting in enhanced nutrient absorption surface area and overall feed efficiency. These findings collectively indicate that Azolla functions not merely as a nutrient source but as a functional additive that confers resilience against disease challenges and promotes overall health maintenance. Figure 3 demonstrates the enhanced immune response and antioxidant activity observed in Azolla-fed broilers. Collectively, these findings confirm the role of Azolla as a natural immunostimulant in broiler diets.

5. Carcass Traits

Carcass traits represent crucial determinants of consumer acceptance and commercial value in broiler production. Research consistently demonstrates that dietary inclusion of Azolla up to 5% does not adversely affect dressing percentage, breast muscle yield, or internal organ development.[30,33] Interestingly, several studies have reported enhanced breast muscle yield and reduced abdominal fat deposition in Azolla-supplemented broilers.[4] These beneficial modifications may be attributed to Azolla's balanced nutrient profile and its potential influence on lipid metabolism, possibly through modulation of enzymatic activities involved in fat synthesis and deposition.

Skin pigmentation constitutes another significant benefit of Azolla inclusion. The natural carotenoids, particularly β-carotene, present in Azolla impart desirable yellowish pigmentation to broiler skin, shanks, and legs.[5,34] This enhancement improves consumer preference in markets where skin coloration serves as a visual indicator of product quality. Importantly, sensory evaluations have detected no detrimental effects on meat attributes including tenderness, juiciness, or flavor profiles.

Histopathological examinations of liver, kidney, and spleen tissues from Azolla-fed broilers reveal no pathological abnormalities,[8] further corroborating its safety as a dietary component. Therefore, Azolla not only maintains fundamental carcass quality but may also enhance specific market-preferred characteristics such as pigmentation, offering combined biological and economic advantages to producers.

6. Economic Implications

Feed cost reduction represents the most compelling economic advantage of Azolla integration in broiler production systems.[35] As global prices of soybean meal and fish meal experience continued volatility, Azolla emerges as a cost-effective, renewable alternative. Abd El-Ghany[5] documented that broiler diets containing 2.5–5% Azolla achieved significant reductions in feed cost per kilogram of body weight gain. Similarly, Mali et al.[7] reported superior cost-benefit ratios in Azolla-supplemented flocks compared to control groups receiving conventional diets.

On-farm Azolla cultivation requires minimal infrastructure investment: typically shallow ponds, adequate water supply, and organic manure substrates. Its rapid

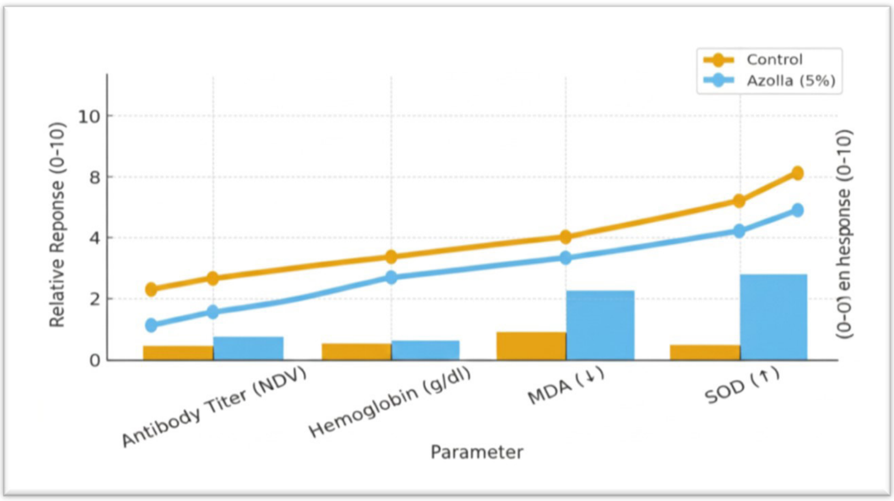

Figure 3. Immune and Antioxidant Responses to Azolla Inclusion[31,32]

Table 3. Economic Implications of Azolla Use in Broiler Diet

Inclusion Level	Feed Cost/kg BW Gain	Relative Cost Reduction	Remarks	Studies
Control (0%)	100%	-------	Standard soybean meal diet	7
2.5% Azolla	92 – 95%	~5 – 8%	Significant improvement in cost- benefit ratio	38
5% Azolla	90 – 94%	~6 – 10%	Optimal balance of performance and economy	39
>7% Azolla	Variable	Inconsistent	Reduced performance offsets savings	40

growth enables daily harvesting, ensuring consistent availability of fresh or processed biomass. Beyond direct economic benefits, Azolla provides valuable ecological services.[36] As an efficient nitrogen fixer, it enhances soil fertility when integrated into mixed farming systems, thereby reducing dependence on synthetic fertilizers. Furthermore, its utilization aligns with global sustainability initiatives by diminishing the carbon footprint associated with soybean importation and transport.[37]

Nevertheless, economic viability remains contingent upon processing and handling methodologies. The high perishability of fresh Azolla necessitates drying or ensiling procedures, which incur additional labor and energy costs. Consequently, comprehensive cost-benefit analyses must incorporate these processing overheads. Despite these considerations, Azolla's substantial contribution to feed cost reduction and production economic stability positions it as a promising candidate for scaling within sustainable poultry operations. The economic implications of Azolla utilization in broiler diets are quantitatively summarized in Table 3, and the relationship between inclusion level and feed cost efficiency is depicted in Figure 4.

7. Limitations and Future Prospects

Despite its considerable promise, widespread Azolla adoption faces several practical challenges. The high moisture content (85–90%) complicates storage and transportation, while elevated crude fiber levels reduce nutrient digestibility at inclusion rates exceeding 5%.[8] Furthermore, nutrient variability induced by environmental conditions, including light intensity, temperature, and nutrient availability in growth media, poses difficulties for consistent feed formulation.

To address these constraints, researchers have investigated microbial fermentation techniques, which enhance protein digestibility and reduce anti-nutritional compounds. Enzyme supplementation, particularly cellulase and xylanase, has demonstrated efficacy in fiber degradation and nutrient availability improvement.[4]

7.1. Future Research Perspectives

Future studies should focus on:

1. Standardization of processing methods (drying, fermentation) to optimize nutrient retention.

2. Long-term effects of Azolla inclusion on broiler reproductive performance and meat quality.

3. Molecular mechanisms underlying Azolla's effects on gut microbiota and immune function.

4. Large-scale economic analyses under diverse production systems.

5. Integration strategies for Azolla in circular farming models.

From a sustainability perspective, integrating Azolla into circular farming systems offers multifaceted benefits. Its dual functionality as a feed ingredient and soil enhancer renders it particularly suitable for integrated poultry-aquaculture-agriculture models. Climate-resilient farming approaches incorporating Azolla can significantly contribute to food security while promoting resource efficiency. Scaling such integrated models through demonstration projects and policy support could accelerate mainstream adoption of Azolla in poultry nutrition systems.

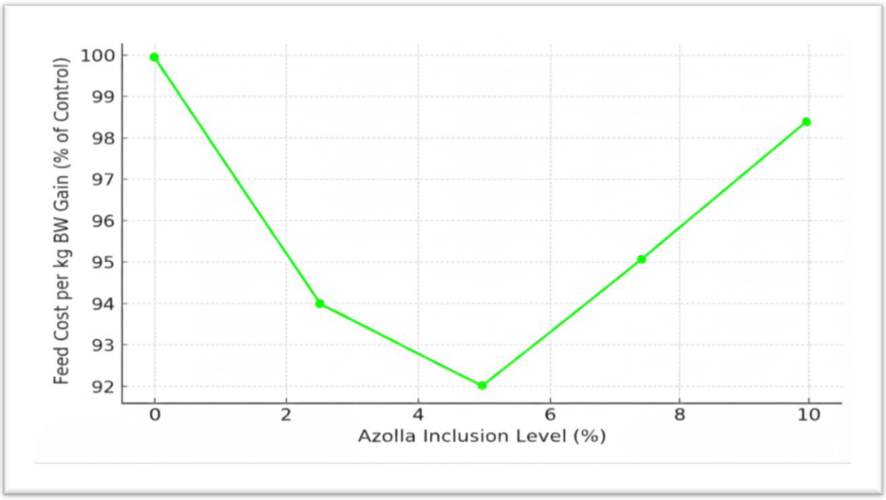

Figure 4. Economic Benefit of Azolla Inclusion in Broiler Diets[19,41]

8. Conclusion

Azolla represents a multifunctional feed resource with transformative potential in broiler nutrition. When incorporated at moderate levels (2.5–5%), it consistently enhances growth performance, strengthens immune responses, and reduces feed costs without compromising carcass yield or quality. The carotenoids and bioactive compounds in Azolla provide functional benefits that extend beyond basic nutrition, establishing it as a valuable functional feed ingredient rather than merely a protein substitute. Although challenges including high moisture content, fiber levels, and nutrient variability persist, advances in processing technologies and integration into circular bioeconomy systems offer promising solutions. Given the global imperative for sustainable and resilient livestock production systems, Azolla emerges as a practical, environmentally sound, and economically viable feed ingredient capable of enhancing broiler production efficiency while reducing dependence on costly conventional protein sources. Future research should focus on standardization of processing methods, elucidation of mechanisms underlying its functional properties, and development of integrated production systems to maximize its potential.

Ethical Statement

This article is a comprehensive review of previously published literature. No new animal experiments were conducted by the authors for this review.

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