Effects of Partial Replacement of Soybean Meal with Lemna minor Meal in Cobb 500 broiler Diets on Growth, Carcass Characteristics, and Profitability

Habtom Negussie
habtomn60@gmail.com

Wolaita Sodo University

Yesehak Kechero
Arba Minch University

Yilkal Tadele
Arba Minch University

Abebe Bashe
Arba Minch University

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Abstract

This study evaluated the effects of graded inclusion levels of *Lemna minor* meal (LMM) as a partial replacement for soybean meal on growth performance, feed efficiency, carcass characteristics, and economic efficiency of broiler chickens. At ten days of age, broilers were allocated to dietary treatments containing 0, 8, 16, and 24% LMM in a completely randomized design, and data were analyzed using one-way ANOVA with polynomial contrasts. *Lemna minor* meal showed high crude protein and mineral content but lower metabolizable energy compared with conventional ingredients, confirming its potential as an alternative protein source. Dietary LMM significantly affected feed intake, growth performance, and feed efficiency. Birds fed moderate LMM inclusion showed superior body weight and average daily gain compared with higher inclusion levels ($P < 0.05$). Feed conversion ratio increased significantly with increasing LMM inclusion during grower, finisher, and whole production periods, while protein and energy efficiency ratios declined significantly ($P < 0.01$). Quadratic regression analysis indicated significant ($P < 0.05$) relationships between LMM inclusion percentage and average daily feed intake, final body weight, average daily gain, carcass weight, and breast meat yield. Carcass yield and dressing percentage were not significantly affected by dietary treatments ($P > 0.05$), whereas breast meat yield was significantly improved at moderate inclusion levels ($P < 0.05$). Economic analysis showed significant reductions in feed cost and improvements in profitability with increasing LMM inclusion ($P < 0.01$). In conclusion, moderate LMM inclusion (8–16%) optimizes growth performance and carcass characteristics, while higher inclusion levels improve economic returns, supporting LMM as a sustainable alternative protein source in broiler nutrition.

1. Introduction

Poultry production is the fastest growing livestock sector in terms of production and consumption globally, with developing economies playing a major role in this expansion [1]. This growth is attributed to the short generation interval of poultry, high feed conversion efficiency, strong consumer preference, and the ability to provide affordable and readily available animal protein [2]. Moreover, poultry production has significant potential to alleviate malnutrition, stimulate economic growth, and create employment opportunities [3]. In Ethiopia, increasing population growth, urbanization, and rising income levels have significantly increased demand for poultry meat and eggs [4]. Consequently, intensive poultry production systems are expanding, with annual growth rates of meat and egg production estimated at approximately 6% and 10%, respectively [5]. This rapid expansion has increased demand for high-quality feed ingredients and balanced compound diets to sustain high productivity.

Protein feed ingredients, particularly soybean meal and other oilseed meals, remain the major conventional protein sources in broiler diets due to their high protein content, balanced amino acid profile, and high digestibility [6]. However, feed accounts for approximately 60–75% of total broiler production costs, making it the most critical factor determining profitability and sustainability [7]. Increasing prices, limited supply, and variable quality of conventional feed ingredients have substantially increased feed formulation costs. Price trend analyses have shown continuous increases in feed ingredient and compound diet prices, with particularly high increases recorded for SBM in recent years [8–9]. In addition, competition for feed resources with other livestock and human food systems remains a major constraint to poultry production in developing countries, including Ethiopia [10–11]. These challenges have intensified the search for sustainable, cost-effective, and locally available alternative protein sources.

Duckweed has emerged as a promising non-conventional protein source due to its rapid growth rate, high biomass productivity, and favorable nutritional composition. Duckweeds are small floating aquatic plants belonging to the Lemnaceae family, consisting of five genera and 36 species distributed worldwide [12]. Among these species, the common duckweed, *Lemna minor* L. is widely distributed and well adapted to diverse environmental conditions, with increasing interest in its application for food, feed, phytoremediation, and bioenergy production [13–14].

The growing interest in *L. minor* for sustainable feed production is mainly due to its exceptional biological productivity. They grow rapidly in nutrient-rich and slow-moving water bodies. Under optimal conditions, duckweed biomass can double within

1–3 days, representing one of the fastest growth rates in the plant kingdom [15]. Annual dry matter (DM) biomass yields can reach 10–30 t ha^{-1} under tropical and subtropical conditions [16–17]. Duckweed accumulate high protein in biomass ranging from 30–44%DM with relatively balanced amino acid profiles, due to their efficient uptake and assimilation nitrogen and other nutrients from growth media [18–19]. Thus, compared with soybean, duckweed can potentially produce substantially higher protein yield per unit land area [20].

Moreover, optimally harvested duckweed may contain relatively low fiber content, making it suitable for feeding monogastric animals such as poultry [21]. Duckweed is also rich in minerals, vitamins, and bioactive compounds with potential health benefits [22–23]. From an agronomic perspective, duckweed can be cultivated on marginal lands, requires minimal fertilizer inputs, is easy to propagate and harvest, and can be integrated into existing farming systems, contributing to circular bioeconomy and income diversification [24–26]. These characteristics highlight its potential as a locally produced, environmentally sustainable alternative protein source for poultry feeding systems.

Previous studies have demonstrated the feeding value of duckweed in various livestock species, including poultry, fish, pigs, and dairy cattle [21, 27–28]. However, available studies evaluating duckweed inclusion in broiler diets are limited and show variable results regarding optimal inclusion levels and performance responses [29–30]. These variations are largely attributed to differences in duckweed nutrient composition, due to cultivation conditions, growth media nutrient status, and environmental factors [20, 31–32]. Therefore, establishing optimal cultivation and inclusion strategies is essential to ensure consistent feed quality and maximize feeding value [33–34].

Despite the promising nutritional and agronomic potential of duckweed, limited studies have evaluated duckweed cultivated using organic manure under local production conditions and its effects on broiler performance. Therefore, the present study was conducted to evaluate the effects of partial substitution of soybean meal with graded levels of cultivated *Lemna minor* meal on feed intake, growth performance, nutrient utilization efficiency, carcass characteristics, and economic efficiency of broiler chickens.

2. Materials and Methods

2.1. Experimental site and preparation of pens

The experiment was conducted in private poultry farm in Dukem, Bishoftu city, Ethiopia. The city is located in the central highlands of Ethiopia at about 47 km south-east of Addis Ababa. Geographically, the area is located at an altitude of 1800 meters above sea level, 9° North latitude and 40° East longitude. The area has tepid to cool sub-moist with moderate weather condition. The annual mean rainfall, minimum and maximum temperatures were 1152 mm and 11.7 and 26.4 °C, respectively with mean relative humidity of 61.3%. The area has two rainy seasons; main season (June-Sept.) and short rainy season (March-April) [35]. The city is one of the fastest growing metropolitan and the hub of modern livestock production in Ethiopia. Due to closeness to the capital city there is huge demands for livestock products, there are large number of market-oriented livestock production system, particularly modern poultry farms, and also appreciable number of dairy farms, and swine farms. Almost all large scale commercial integrated broiler production agro-industries of the country are located in this city.

Two weeks before placing the chicks, naturally ventilated poultry house was partitioned into 12 individual experimental pens using timber and mesh wire (1.1 m x 2.0 m). Pen floor covered with dry wheat straw to a depth of 10 cm. Then, the house and pens were thoroughly cleaned, and disinfected by spraying mixture of formalin (40%), Hydrogen peroxide (Bio-safe), Chlorine (Berekena) and water. Before chick arrival each pen was setup with electric bulb brooder (200 watt), thoroughly cleaned drinker and feeders enclosed in brooder guard.

2.2. Preparation of feed ingredients

The feed ingredients used in the diets were *Lemna minor* meal (LMM), soybean meal (SBM), maize grain (white), wheat middling, beef tallow, limestone, common salt, vitamin-mineral premix, Lysine and Methionine. Except LMM all raw ingredients were procured from local markets in Bishoftu city.

The *Lemna minor* meal (LMM) was produced from pilot-scale duckweed cultivation ponds in Arba Minch University, Southern Ethiopia. The site is located at an altitude of 1,280 m above sea level, 7°03'27.8" N latitude and 38°28'06.2" E longitude. The area is characterized by a hot humid to semi-arid climate, with annual rainfall ranging 768 to 1,270 mm, and mean annual temperature of 22.9°C (15-32°C). Duckweed was produced under optimum cultivation fertilized with anaerobically digested mixture of poultry and cattle manure (1:1) applied on weekly basis at the rate of 16–24 mg NH_4^+-N/L according to recommended practices (Habtom et al., 2026 unpublished data). The fresh duckweed biomass was harvested every two to three days interval using metal sieve, rinsed with fresh water and dried for 3–4 days under shade with frequent turning to facilitate uniform drying. The air dried *L. minor* was ground to 2–3 mm particle size using hammer mill to produce LMM and stored in airtight bags. Soybean meal and maize grain were ground separately in hammer mill to similar size and stored in bags. Representative samples of LMM, SBM, maize grain, and wheat middling were sampled and analyzed in duplicate for proximate chemical composition [36] as shown in Table 1 before preparation of experimental diets.

2.3. Experimental birds, treatments and design

A total of 194 day-old mixed sex Cobb 500 broiler chicks were purchased from reputable commercial hatchery (Alema PLC., Bishoftu city, Ethiopia). The chicks were feed on commercial starter crumble (Alema Koudijs Feed Factory PLC) with 21% CP and 2900–3000 kcal ME kg^{-1}. On day 10 of age, 180 healthy chicks with comparable body weight were selected, weighed individually, and randomly divided in to 12 groups each with 15 birds, and then randomly transferred to 12 experimental pens. Four dietary treatments each replicated three times were randomly allocated to pens according to completely randomized design (CRD). The experimental unit was pen of birds, thus, 3 pens per treatment or 45 birds per treatment. The dietary treatments (T) were graded level of *L. minor* meal (LMM) inclusion partially substituting soybean meal (SBM) as main protein source in diets of both grower and finisher phases. Treatment 1 (T1) was the control diet with 0% LMM, T2 (8% LMM), T3 (16% LMM) and T4 (24% LMM) containing diets as shown on Table 2. The diets were formulated separately for the grower phase (10–24 days) and finisher phase (25–45 days) on iso-protein and iso-caloric basis that meet the recommended nutrient requirements of broiler chicken for final market weight of 2.5 kg at 45 days of age [37–38]. The beef tallow was milted into liquid form to facilitate uniform mixing, and then feed ingredients based on their proportion in each respective dietary treatment (Table 2) were weighed using digital balance and mixed thoroughly manually in mesh form, and kept in bags and stored in dry well ventilated house until use. The bulk density of feed ingredients and dietary treatments were measured by weighting samples in a container of known volume using digital sensitive balance [39]. The experiment lasted a total of 45 days (Oct. – Nov., 2025).

2.4. Management of birds and Measurements

All dietary treatments were fed in mesh form on regularly cleaned bell feeders. The daily feeds offered to all experimental pens were accurately measured, recorded and the leftover feed was collected and measured in the next morning before new feed was offered. The feeds were offered twice a day between 8:00 A.M and 6:00 PM throughout the trial period by dividing the total daily allowance in to equal part. The amount of feed offered was increased by 10% than previous day intake for *ad libitum* consumption. Drinkers were cleaned daily in the morning and filled with clean cool water mixed with vitamin-mineral supplement (Vita-chick) for *ad libitum* consumption. Regularly measured amount of water were provided and the amount of leftover was measured in the next morning to assess the influence of dietary treatments on water consumption rate.

Individual body weight of birds in each pen was measured on day 10 of age as initial weight and then on weekly basis, BW at the end of the experiment on day 45 was taken as final body weight (FBW). Body weight was measured in the morning before feeding throughout the experimental period using digital sensitive balance. The ambient and house temperature and relative humidity was regularly monitored using digital sensor throughout the study period. During the first 3 days, the room temperature was maintained at 33 ºC, 30 ºC on day 7 then gradually lowered to 24 ºC on 21 days of age by adjusting the height of suspended bulb. Light regime of 23 hr. light and 1 hr. dark was maintained throughout experimental period. Thus, adequate heat, light and ventilation were provided to maintain optimum environmental requirements and comfortable zones.

The chicks were vaccinated against major poultry diseases including Marek's disease at day-old, Newcastle disease (Lasota) on day 8 and 42, and infectious bursal disease on 14 day of age. The vaccines were obtained from National Veterinary Institute (Bishoftu). The health status of birds was daily monitored and prophylactic medications against coccidiosis (Amprolium) and antibiotic (Oxytetracycline) were administered during the first week of grower and finisher phases in drinking water according to manufacturer instruction. Mortality of birds in pens were monitored at least twice daily, any dead birds were recorded and disposed promptly by burial. The dead birds from each pen were used to calculate percent mortality and Livability per pen, and to adjust feed offer. The statuses of litter moisture, feces consistency were also monitored, and wet litter was changed regularly. Sanitation of the pens and house were maintained regularly. Standard broiler chicken management and animal welfare practices were implemented uniformly for all the birds throughout the experimental period. The effects of dietary inclusion of LMM in the diets of broilers were evaluated in terms of feed intake, body weight, body weight gains, livability, feed and nutrient utilization efficiency, carcass traits, performance indices, and economic efficiency.

2.4.1. Feed and nutrient intake

The average daily feed intake (ADFI, g/bird/day) was calculated as a difference between feed offered and feed leftover divided by the number of birds per pen each day, cumulative weekly feed intake, feed intake during grower, finisher phase and whole experimental period (g/bird) were also calculated. Nutrient intake of birds was calculated by multiplying the ADFI by respective nutrient composition of diet. Feed and nutrient intakes of birds are reported on dry matter basis. Overall acceptance and palatability of the dietary treatment was calculated according to Fiordelmondo et al., [40] as: ((Feed intake/Feed offered) × 100).

2.4.2. Growth performance and Nutrient Utilization Efficiency

The growth of broiler chicken was determined for weekly mean live body weight BW, mean weekly BW gain calculated as the difference between two consecutive weekly BW records. Average Daily Gain (ADG, g/bird/day) for each week, grower, finisher, and whole experiment period were also calculated as a difference between two BW measures by the numbers of days. Livability percentage (%) calculated as: percentage ratio of the number of birds at the end per pen to the number of birds per pen at the beginning calculated for grower, finisher and whole period. Mortality calculated as 100−L%. Feed conversion and nutrient utilization efficiencies, and Broiler Index were calculated [39, 41] as:

- Feed Conversion Ratio (FCR) = Feed Intake (g DM/bird) / BW gain (g/bird)
- Feed utilization efficiency (FUE) = 1/FCR = BW gain (g/bird) / Feed Intake (g DM/bird)
- Protein Efficiency Ratio (PER) = ADG (g/bird/day) / Protein Intake (g/bird/day)
- ME efficiency ratio (EER) = ADG (g/bird/day) / ME intake (kcal/bird/day)/100
- Broiler Index (BI) = Livability (%) * ADG (g/bird/day) / (FCR * 10)

2.4.3. Carcass Analysis

At the end of the experimental period (at 45 days of age) all birds in each pen were leg tagged and BW recorded as final BW. Two birds (1 male and 1 female) per pen, i.e. six birds per treatment who had BW close to the mean of respective pens were selected and kept in a separate pen without feed but plenty of water. After fasting for at least six hours, the selected birds were weighed, and recorded as slaughter live BWs. Then the birds were slaughtered by severing the jugular vein, bled (for two minute), scalded at 65℃ for 90 seconds, defeathered and eviscerated manually. Dressed carcass weight was measured after removing head and shanks from eviscerated carcass while skin included. The dressed carcass was cut up into component parts and the yields were weighed individually. The wings were removed by a cut through the shoulder joint at the proximal end of humerus. The thigh and drumstick portions were obtained by cutting through the joint between the femur and ilium bone of the pelvic girdle. The drumstick was separated from the thigh by a cut through the joint formed by the femur, fibula and tibia [42]. The dressed carcass, thighs, drumsticks, wing, neck and back were weighed inclusive of bones. The breast was separated to breast meat and breast bone. The offal and giblets includes: skin, heart, liver, gizzard, and abdominal fat were carefully separated and weighed. The weight of heart, weight of liver without gall bladder, empty gizzard (gizzard without food contents and internal lining membrane) and abdominal fat weight (fat surrounding gizzard, bursa, and cloaca) were recorded. All weight measurements were using a sensitive electronic balance (± 0.1 g precision). Dressing percentage (DP) was calculated as percent of dressed carcass weight to slaughter live BWs. The weight of individual carcass parts and organs were recorded as yields, and their relative yields were calculated as yield of carcass parts and organs percentage to slaughter live BW. Commercial carcass yield was calculated as sum of carcass parts, and total edible offal yield was determined as the sum of liver, heart, gizzard, skin and abdominal fat.

2.4.4. Economic Efficiency

Economic efficiency analysis involves calculations of costs and profits to determine economic potentials of dietary inclusion of LMM in the diet as described by Melkamu [43]. The production costs including feed cost, chick cost and miscellaneous costs (starter feed, medication, vaccines, labor, electric & water), and profits from sale price of live broiler based on final body weight at 45 days. The costs and prices were based on the prevailed local market prices at Bishoftu city during experimental period (Oct. – Nov., 2025). The calculated feed costs include formulated diet unit price, feed cost per chick, feed cost per kg BW, and feed cost per kg BW gain. Diet unit price (ETB/kg) was determined by multiplying the proportion of each feed ingredient with its price and then adding all prices, separately for grower and finisher phases. The price of LMM was estimated from unit price of SBM (115 ETB/kg) based on the same unit price per kg of protein (assuming equal price per kg protein for SBM and LMM) this result in LMM unit price of 14 ETB/kg feed. Performance Index Score (PIS) and Economic Index Score (EIS) were also calculated [44].

Economic efficiency (EE %) = Net profit per chick *100 / feed cost per chick

Relative Economic efficiency (%) = EE % *100/ EE% control

PIS = Mean final BW (g) x % Livability / (FCR x No. of days reared x 10)

EIS = EIS = PIS/ (mean diet unit price (ETB/kg)

2.5. Chemical Analysis

Representative samples of LMM and ingredients were dried in an oven at 60 ℃ to constant weight, and then ground to pass through 1mm mesh screen and stored in air tight bags until analysis. Analyses of proximate compositions were carried for dry matter (DM), crude protein (CP), crude lipid (CL), crude fiber (CF) and total ash (TA) following methods of [36]. Nitrogen (N) content was analyzed using Kjeldahl method, and CP was obtained by multiplying N content with 6.25. The nitrogen free extract (NFE) content was estimated by difference: DM- (CP + CF + CL + Ash). The Metabolizable energy (ME) of ingredients and dietary treatments were estimated using the equation of Wiseman [45]: ME (kcal/kg DM) = 3951 + 54.4CL (%) – 88.7CF (%) – 40.80Ash (%). The samples were analyzed in duplicates at Chemistry Laboratory of Arba Minch University, Ethiopia.

2.6. Statistical Analysis

All collected data were analyzed according to One-Way Analysis of Variance using SPSS software (SPSS version 20.0 Inc. Chicago, IL, USA). Normality of data and homogeneity of variance were checked using Kolmogorov-Smirnoff and Levene test, respectively before analysis. Statistical difference among treatment means were declared significant at $p < 0.05$, and treatment means were separated using Tukey HSD test. Furthermore, orthogonal polynomial contrast analysis was carried out to test Linear and Quadratic effects of LMM inclusion percentage levels on broiler performance [46]. Person's correlation and regression analysis was carried out to evaluate the strength of linear and quadratic relationship among key variables. The results are reported as means ± pooled standard error of mean (SEM), and the p-values of ANOVA and polynomial contrast analysis.

3. Results

3.1. Nutritional potential of *Lemna minor* meal as an alternative feed ingredient

The proximate chemical composition and nutritive value of maize grain, soybean meal (SBM), *Lemna minor* meal (LMM), and wheat middling are presented in Table 1. Dry matter content varied moderately among ingredients, ranging from 87.5% in LMM to 91.1% in SBM. These values indicate acceptable storage quality, and air dried LMM has comparable DM characteristics to conventional feedstuff. Crude protein (CP) content differed substantially among ingredients. SBM recorded the highest CP content 36.12% (39.6% DM), followed closely by LMM 31.93% (36.5% DM), highlighting the strong protein potential of LMM. In contrast, wheat middling and maize grain contained considerably lower protein levels. Crude lipid content was highest in SBM, while LMM and wheat middling showed similarly low lipid concentrations. Crude fiber content was moderate in LMM and wheat middling but lower in maize grain, reflecting structural carbohydrate differences among feed sources.

Ash content was markedly higher in LMM compared with the other ingredients, indicating a higher mineral contribution. Consistent with this, LMM contained the highest calcium and available phosphorus concentrations. Nitrogen-free extract and metabolizable energy were highest in maize grain and lowest in LMM. Bulk density differed widely among ingredients, with LMM exhibiting the lowest value, which has implications for feed handling, diet formulation, and voluntary feed intake.

Table 1. Proximate chemical compositions of feed ingredients (*as feed basis*)

Nutrients & energy	Feed ingredients, average			
	Maize grain	Soybean meal	*Lemna minor* meal	Wheat middling
DM (%)	88.82	91.13	87.49	89.51
Moisture (%)	11.18	8.87	12.51	11.49
Crude protein (%)	8.67	36.12	31.93	14.54
Crude lipid (%)	2.24	6.77	1.88	1.55
Crude fiber (%)	5.03	11.78	9.64	6.81
Ash (%)	1.01	6.65	16.64	2.07
NFE (%)	71.88	29.82	27.41	64.54
ME (kcal/kg DM)[1]	3,540	2,912	2,316	3,277
Lysine (%)[2]	0.20	2.51	2.43	0.61
Methionine (%)[3]	0.20	0.57	0.78	0.21
Calcium (%)[4]	0.03	0.29	1.21	0.12
Available P (%)[5]	0.26	0.55	0.65	0.67
Bulk density (kg m^{-3})	807^a	800^a	192^c	565^b

[1]ME, Estimated Metabolizable energy; DM, dry matter; NFE, nitrogen free extract; the compositions of Lysine[2], Methionine[3], Ca[4] and P[5] of maize grain, wheat middling, and SBM adapted from [39]; while the respective contents for *Lemna minor* were based on reported values for *L. minor* cultured with organic manure [18, 19, 48].

3.2. Ingredient and nutrient composition of grower and finisher diets containing *Lemna minor*

The ingredient composition of the grower and finisher diets is summarized in Table 2. Increasing inclusion levels of LMM from 0 to 24% progressively replaced SBM and wheat middling in both feeding phases. To maintain dietary energy balance, maize grain and beef tallow levels were adjusted upward with increasing LMM inclusion. All diets were formulated to meet nutrient requirements for broiler chickens during the respective growth phases.

The calculated nutrient composition of the experimental diets showed only minor variation across treatments. Dry matter content declined slightly with increasing LMM inclusion in both grower and finisher diets. Crude protein levels remained relatively consistent among treatments, indicating effective formulation despite substantial replacement of soybean meal. Metabolizable energy showed a marginal decline as LMM inclusion increased, reflecting the lower energy density of LMM compared with maize and soybean meal.

Ether extract increased progressively with higher LMM inclusion due to increased beef tallow supplementation, while crude fiber showed a slight decreasing trend across treatments. Ash, calcium, lysine, and methionine concentrations increased with increasing LMM inclusion, whereas available phosphorus showed a slight decline, particularly in finisher diets. Bulk density decreased significantly with increasing LMM inclusion.

Table 2. Feed ingredients and nutrient compositions of dietary treatments

Ingredients	Dietary Treatments (T)							
	Grower diet (10-24 days)				Finisher diet (25-45 days)			
	T1	**T2**	**T3**	**T4**	**T1**	**T2**	**T3**	**T4**
Maize grain	40.0	41.0	42.0	44.0	45.0	47.0	48.5	50.0
Soybean meal	36.0	30.0	24.0	18.0	32.0	27.0	21.0	16.0
L. minor meal	**0.0**	**8.0**	**16.0**	**24.0**	**0.0**	**8.0**	**16.0**	**24.0**
Wheat middling	18.0	14.0	10.5	6.0	17.0	11.0	7.0	2.0
Beef tallow	3.0	4.0	4.5	5.0	3.0	4.0	4.5	5.0
L−Lysine HCl	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
DL−Methionine	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Limestone powder	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Salt	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Premix*[1]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Calculated composition								
Dry matter (%)	90.32	90.14	89.92	89.69	90.23	90.05	89.83	89.62
Crude protein (%)	19.32	19.21	19.17	19.08	18.16	18.21	18.14	18.29
ME (kcal kg^{-1})	3082	3092	3072	3055	3103	3110	3093	3072
Ether extract (%)	6.61	7.32	7.53	7.75	6.44	7.20	7.42	7.69
Crude fiber (%)	7.48	7.32	7.20	7.06	7.19	7.07	6.93	6.85
Ash (%)	5.75	6.61	7.49	8.35	5.51	6.41	7.28	8.19
NFE (%)	51.10	49.65	48.51	47.45	52.86	51.13	50.03	48.58
Calcium (%)	0.90	0.97	1.05	1.12	0.89	0.96	1.04	1.11
Av. phosphorus (%)	0.42	0.42	0.42	0.41	0.41	0.40	0.39	0.39
Lysine (%)	1.21	1.23	1.26	1.28	1.12	1.15	1.17	1.22
Methionine (%)	0.47	0.49	0.52	0.54	0.46	0.48	0.51	0.53
Bulk density (kg m^{-3})	719a	570b	534b	420c	777a	698b	646c	509d

[a,b,c,d] Row means with different superscript letters are significantly different $p<0.05$; ME, Metabolizable Energy; NFE, nitrogen free extract. *[1]vitamin-mineral premix (BIO-VITAMINERAL®) composition per kg diet: Vit A 19,200 IU, Vit. D_3 4,400 IU, Vit. E 6.0 IU, Vit. K_3 2.0 mg, Vit. B_1 3.2 mg, Vit. B_2 4.8 mg, Vit. B_6 3.6 mg, Vit. B_{12} 6.0 mcg, Vit. C 12.0 mg, Pantothenic acid 8.8 mg, Nicotinamide 20.0 mg, Folic acid 0.1 mg, Sodium bicarbonate 300 mg, Sodium Chloride 24 mg, Potassium Chloride 40 mg, L-Lysine HCl 32 mg, DL-Methionine 20 mg, Manganese 60 mcg, Biotin 40 mcg.

3.3. Effects of *Lemna minor* inclusion on feed intake, palatability, and nutrient intake

Feed intake responses to dietary LMM inclusion on DM bases are presented in Table 3. During the early grower period (days 10–17), birds fed moderate LMM levels (T2 and T3) consumed more feed than those fed the highest level (T4). From day 18 onward, feed intake generally increased with increasing LMM inclusion, with birds fed LMM-based diets consuming more feed than control diet.

Cumulative feed intake during the grower phase was significantly higher in T2 and T3 compared with T1, while birds fed T4 showed intermediate values. During the finisher phase and over the whole experimental period, feed intake increased progressively from T1 to T4. Average daily feed intake followed a similar pattern, with the highest values consistently observed in birds fed higher levels of LMM.

Dietary palatability improved significantly with increasing LMM inclusion, suggesting good acceptability of LMM-based diets. Water-to-feed ratio decreased significantly in LMM-based birds, particularly during the finisher phase and over the whole period. Daily intakes of crude protein, lipid, fiber, ash, and metabolizable energy increased linearly with increasing LMM inclusion. The metabolizable energy-to-protein intake ratio which indicate balanced supply of both energy and protein for growth was maximized at T2 followed by T3, and then declined at higher LMM.

Table 3. Feed and Nutrient intake of broiler chickens fed on graded level of LMM based diets

Age in days	Dietary Treatments				SEM	p-value		
	T1	T2	T3	T4		A	L	Q
FI (g/bird)								
Day 10–17	402^{ab}	413^{a}	414^{a}	391^{b}	3.69	0.006	0.101	0.001
Day 18–24	638^{b}	673^{a}	661^{a}	662^{a}	4.30	0.002	0.014	0.004
Day 25–31	737^{b}	836^{a}	847^{a}	859^{a}	13.9	0.001	0.001	0.014
Day 32–38	870^{c}	1020^{b}	1063^{ab}	1070^{a}	11.1	0.001	0.001	0.001
Day 39–45	1103^{c}	1157^{b}	1172^{ab}	1218^{a}	11.1	0.001	0.001	0.727
Grower (10–24)	1040^{b}	1087^{a}	1075^{a}	1053^{ab}	7.6	0.009	0.411	0.002
Finisher (25–45)	2710^{b}	3013^{a}	3083^{a}	3147^{a}	34.4	0.001	0.001	0.008
Whole period (10–45)	3750^{b}	4100^{a}	4158^{a}	4200^{a}	39.2	0.001	0.001	0.004
Palatability (%) (10–45)	88.1^{b}	94.3^{a}	94.8^{a}	95.3^{a}	0.99	0.003	0.001	0.02
ADFI (g/bird/day)								
Day 10–17	57.4^{ab}	59.1^{a}	59.2^{a}	55.9^{b}	0.53	0.006	0.101	0.001
Day 18–24	91.1^{b}	96.2^{a}	94.4^{a}	94.5^{a}	0.61	0.002	0.014	0.004
Day 25–31	105.3^{b}	119.4^{a}	121.1^{a}	122.7^{a}	1.99	0.001	0.001	0.014
Day 32–38	124.2^{c}	145.8^{b}	151.9^{a}	152.9^{a}	1.59	0.001	0.001	0.000
Day 39–45	157.5^{c}	165.3^{b}	167.5^{b}	174.0^{a}	1.58	0.001	0.001	0.727
Grower (10–24)	74.2^{b}	77.6^{a}	76.8^{a}	75.2^{b}	0.54	0.009	0.414	0.002
Finisher (25–45)	129.1^{c}	143.5^{b}	146.8^{ab}	149.9^{a}	1.64	0.001	0.001	0.008
Whole period (10–45)	107.1^{b}	117.1^{a}	118.8^{a}	120.1^{a}	1.12	0.001	0.001	0.004
WFR[1]								
Grower (10–24)	2.75^{a}	2.58^{b}	2.62^{ab}	2.68^{ab}	0.03	0.023	0.269	0.007
Finisher (25–45)	2.69^{a}	2.30^{b}	2.25^{b}	2.17^{b}	0.05	0.001	0.001	0.012
Whole period (10–45)	2.72^{a}	2.41^{b}	2.40^{b}	2.38^{b}	0.04	0.001	0.001	0.004
Nutrient (g/bird/day)								
Crude protein	19.8^{b}	21.6^{a}	22.0^{a}	22.2^{a}	0.21	0.001	0.001	0.006
Lipid	6.97^{d}	8.49^{c}	8.87^{b}	9.25^{a}	0.08	0.001	0.001	0.001
Crude fiber	7.82^{b}	8.40^{a}	8.36^{a}	8.32^{a}	0.08	0.003	0.004	0.005
Ash	6.01^{d}	7.61^{c}	8.75^{b}	9.91^{a}	0.07	0.001	0.001	0.016

ME (kcal/bird/day)	332^{b}	364^{a}	367^{a}	368^{a}	3.47	0.001	0.001	0.002
ME: Protein intake ratio	16.76^{c}	16.81^{a}	16.77^{b}	16.59^{d}	0.002	0.001	0.001	0.001

^{a,b,c,d}, row means with different superscript letters significantly different p<0.05; WFR[1], mean daily water to feed consumption ratio per pen; FI, feed intake; ADFI, average daily feed intake; ME, metabolizable energy; SEM, standard error of mean; A, p-value of one-way ANOVA; L, p-value of linear analysis; Q, p-value of quadratic analysis. T1, T2, T3, and T4, dietary treatments partially substituting SBM with LMM included at 0%, 8%, 16%, and 24% in the diet, respectively.

3.4. Growth performance of broiler chickens

Initial body weight at day 10 did not differ significantly among dietary treatments, indicating uniformity of birds at the start of the experiment (Table 4). From day 17 onward, significant differences in body weight were observed among treatments. Birds fed 8% LMM (T2) consistently recorded the highest body weights at subsequent ages; while birds fed 24% LMM (T4) showed the lowest values.

Body weight gain and average daily gain during the grower phase were significantly higher in birds fed T2 and T3 compared with T4. During the finisher phase, birds fed T4 achieved relatively high weight gains, although this did not consistently translate into superior final body weight. Over the entire experimental period, total body weight gain and average daily gain were highest in T2.

Livability remained high across all treatments, exceeding 95% throughout the study, with no significant dietary effects. Broiler performance index during the grower phase was significantly higher in birds fed T2 and T1 compared with T4, while no significant differences were observed during the finisher phase or over the whole period.

Table 4. Growth performance of broiler chickens fed on graded level of LMM based diets

Age in days	Dietary Treatments				SEM	p-value		
	T1	T2	T3	T4		A	L	Q
Live BW (g/bird)								
Day 10 (Initial)	260.1	259.2	259.3	254.8	3.32	0.682	0.322	0.599
Day 17	509.8^{ab}	528.1^{a}	517.6^{ab}	494.0^{b}	5.80	0.018	0.057	0.007
Day 24	800.0^{b}	832.7^{a}	804.1^{ab}	748.0^{c}	8.96	0.001	0.002	0.001
Day 31	1119.3^{b}	1181.0^{a}	1135.0^{b}	1041.0^{c}	5.88	0.001	0.001	0.001
Day 38	1482.8^{b}	1540.1^{a}	1507.4^{b}	1430.5^{c}	7.07	0.001	0.001	0.001
Day 45 (Final)	1905.2^{b}	1950.7^{a}	1924.8^{ab}	1910.2^{b}	6.69	0.005	0.724	0.002
BW gain (g/bird)								
Day 10–17	249.7	268.9	258.2	239.2	7.20	0.091	0.228	0.029
Day 18–24	290.3^{ab}	304.6^{a}	286.5^{b}	254.0^{c}	3.99	0.001	0.001	0.001
Day 25–31	319.3^{b}	348.3^{a}	330.9^{ab}	293.0^{c}	5.61	0.001	0.005	0.001
Day 32–38	363.5	359.1	372.4	389.4	8.84	0.154	0.050	0.260
Day 39–45	422.4^{b}	410.6^{b}	417.4^{b}	479.7^{a}	8.00	0.001	0.001	0.002
Grower (10–24)	539.9^{a}	573.5^{a}	544.8^{a}	493.2^{b}	10.27	0.004	0.006	0.003
Finisher (25–45)	1105.2^{b}	1118.0^{ab}	1120.7^{ab}	1162.2^{a}	10.42	0.023	0.006	0.205
Whole period (10–45)	1645.1^{b}	1691.5^{a}	1665.5^{ab}	1655.4^{b}	6.99	0.008	0.884	0.004
ADG (g/bird/day)								
Day 10–17	35.7	38.4	36.9	34.2	1.03	0.091	0.228	0.029
Day 18–24	41.5^{b}	43.5^{a}	40.9^{b}	36.3^{c}	0.57	0.001	0.001	0.001
Day 25–31	45.6^{b}	49.8^{a}	47.3^{ab}	41.9^{c}	0.80	0.001	0.005	0.001
Day 32–38	51.9	51.3	53.2	55.6	1.26	0.154	0.050	0.259
Day 39–45	60.3^{b}	58.7^{b}	59.6^{b}	68.5^{a}	1.14	0.001	0.001	0.002
Grower (10–24)	38.6^{a}	41.0^{a}	38.9^{a}	35.2^{b}	0.73	0.004	0.006	0.003
Finisher (25–45)	52.6^{b}	53.2^{ab}	53.4^{ab}	55.3^{a}	0.50	0.022	0.006	0.205
Whole period (10–45)	47.0^{b}	48.3^{a}	47.6^{b}	47.3^{b}	0.20	0.009	0.883	0.004
Livability %								
Grower (10–24)	100.0	100.0	97.8	97.8	1.57	0.596	0.242	1.000
Finisher (25–45)	95.6	100.0	97.8	97.8	2.72	0.728	0.725	0.438
Whole period (10–45)	95.6	100.0	95.6	95.6	2.72	0.594	0.717	0.439

Broiler Index								
Grower (10–24)	200.3^{a}	216.6^{a}	192.6^{ab}	161.6^{b}	8.00	0.008	0.004	0.018
Finisher (25–45)	205.6	197.5	189.4	200.0	7.97	0.573	0.506	0.275
Whole period (10–45)	197.4	199.4	182.1	178.0	6.48	0.113	0.031	0.652

^{a,b,c} Row means with different superscript letters significantly different p<0.05; SEM, standard error of mean; BW – body weight; ADG – average daily weight gain; A, p-value of one-way ANOVA; L, p-value of linear effect; Q, p-value of quadratic effect. T1, T2, T3, and T4 dietary treatments with inclusions of *Lemna minor* meal (LMM) in the diet at 0, 8%, 16%, and 24%, respectively by partially replacing SBM in diets.

3.5. Feed efficiency and nutrient utilization

Feed conversion ratio varied significantly among dietary treatments and growth phases (Table 5). During the grower phase, birds fed the highest level of LMM exhibited poorer FCR compared with birds fed lower inclusion levels. A similar pattern was observed during the finisher phase, where higher LMM inclusion resulted in increased FCR values. Over the entire experimental period, FCR increased progressively with increasing LMM inclusion, indicating reduced feed efficiency at higher substitution levels.

Feed utilization efficiency, protein efficiency ratio, and energy efficiency ratio were highest in birds fed the control diet and declined significantly with increasing LMM inclusion. These findings suggest that although LMM improved feed intake and reduced feed cost, excessive inclusion may compromise nutrient utilization efficiency.

Table 5. Feed Conversion and Nutrient Utilization of broiler chicken fed on graded level of LMM based diets

Age in days	**Dietary Treatments**				**SEM**	**p-value**		
	T1	**T2**	**T3**	**T4**		**A**	**L**	**Q**
FCR								
Day 10–17	1.61	1.54	1.61	1.64	0.06	0.670	0.537	0.450
Day 18–24	2.20^{b}	2.21^{b}	2.31^{b}	2.61^{a}	0.04	0.001	0.001	0.008
Day 25–31	2.31^{c}	2.40^{bc}	2.56^{b}	2.93^{a}	0.04	0.001	0.001	0.008
Day 32–38	2.40^{b}	2.84^{a}	2.85^{a}	2.75^{a}	0.06	0.002	0.004	0.002
Day 39–45	2.62^{ab}	2.82^{a}	2.81^{a}	2.54^{b}	0.06	0.019	0.357	0.003
Grower (10–24)	1.93^{b}	1.90^{b}	1.98^{ab}	2.13^{a}	0.05	0.039	0.013	0.101
Finisher (25–45)	2.45^{b}	2.70^{a}	2.75^{a}	2.71^{a}	0.03	0.001	0.001	0.001
Whole period (10–45)	2.28^{b}	2.42^{a}	2.50^{a}	2.54^{a}	0.028	0.001	0.001	0.103
FUE (10–45)	0.439^{a}	0.413^{b}	0.40^{b}	0.394^{b}	0.005	0.001	0.001	0.087
PER (10–45)	2.36^{a}	2.22^{b}	2.16^{bc}	2.12^{c}	0.03	0.001	0.001	0.109
EER (10–45)	14.2^{a}	13.3^{b}	13.0^{b}	12.9^{b}	0.15	0.001	0.001	0.052

[a,b,c] – row means with different superscript letters significantly different $p<0.05$; SEM,, standard error of mean; FCR, feed conversion ratio; FUE, feed utilization efficiency; PER, protein efficiency ratio; EER, metabolizable energy efficiency ratio; A, p-value of one-way ANOVA; L, p-value of linear analysis; Q, p-value of quadratic analysis; T1, T2, T3, and T4 dietary treatments with inclusions of *Lemna minor* meal (LMM) in the diet at 0, 8%, 16%, and 24%, respectively.

3.6. Carcass characteristics and edible organ yields

Carcass traits and edible organ yields are presented in Table 6. Slaughter live body weight, dressed carcass weight, and dressing percentage were not significantly affected by dietary LMM inclusion, indicating that overall carcass yield was maintained across treatments.

Dietary LMM inclusion significantly influenced breast meat yield. Birds fed 8% LMM recorded the highest absolute and relative breast meat yields, suggesting an optimal inclusion level for muscle deposition. Other carcass cuts, including thigh, drumstick, wing, and back, were not significantly affected by diet. Edible organ weights showed some response to dietary LMM. Gizzard weight increased significantly with increasing LMM inclusion, reflecting greater dietary fiber content and mechanical digestion activity. Total edible offal increased linearly with LMM inclusion, while abdominal fat tended to increase at the highest inclusion level.

Table 6. Carcass characteristics of broiler chickens fed on graded level of LMM based diets

Parameters	Dietary Treatments				SEM	P-value		
	T1	T2	T3	T4		A	L	Q
Slaughter live BW, g/bird	1,807	1,872	1,876	1,884	29.7	0.31	0.12	0.37
Dressed carcass weight, g	1,279	1,352	1,344	1,343	18.3	0.07	0.06	0.07
Dressed percentage, %	70.7	72.3	71.6	71.3	0.46	0.20	0.65	0.08
Absolute (g) & Relative yield (%BW)								
Breast meat, g	291.9^{b}	326.0^{a}	302.8^{ab}	292.1^{b}	6.06	0.01	0.43	0.01
Breast meat, %	16.1^{ab}	17.4^{a}	16.2^{ab}	15.5^{b}	0.34	0.02	0.07	0.02
Breast[3], g	440.1^{b}	495.2^{a}	464.7^{ab}	451.6^{b}	10.7	0.03	0.94	0.01
Breast[3], %	24.3^{b}	26.5^{a}	24.8^{ab}	24.0^{b}	0.43	0.02	0.19	0.01
Thigh, g	177.3	188.0	182.7	192.6	6.47	0.42	0.19	0.95
Thigh, %	9.80	10.05	9.74	10.22	0.29	0.63	0.47	0.47
Drumstick, g	167.9	168.3	168.4	171.5	5.45	0.96	0.67	0.81
Drumstick, %	9.28	8.99	8.99	9.10	0.27	0.85	0.66	0.47
Neck, g	50.7	54.1	49.6	63.5	3.09	0.05	0.04	0.13
Neck, %	2.81	2.89	2.65	3.37	0.19	0.12	0.13	0.13
Wing, g	72.6	74.1	74.1	72.2	1.91	0.85	0.91	0.41
Wing, %	4.01	3.96	3.95	3.84	0.08	0.50	0.17	0.73
Back, g	108.2	105.6	110.3	110.3	6.26	0.94	0.70	0.84
Back, %	5.99	5.64	5.88	5.86	0.32	0.89	0.93	0.62
Commercial carcass[4], g	1017	1085	1050	1062	19.1	0.16	0.28	0.18
Organs & Giblets								
Skin, g	114.9	125.6	118.5	125.1	5.29	0.45	0.35	0.71
Skin, %	6.36	6.72	6.31	6.64	0.30	0.73	0.06	0.55
Liver, g	42.7	40.0	38.6	37.4	2.56	0.53	0.17	0.77
Liver, %	2.36	2.13	2.06	1.98	0.13	0.25	0.57	0.94
Heart, g	13.5	14.9	12.1	13.7	1.11	0.42	0.83	0.97
Heart, %	0.73	0.80	0.65	0.73	0.06	0.37	0.04	0.23
Gizzard, g	25.8^{b}	30.6^{ab}	37.5^{a}	37.8^{a}	2.54	0.03	0.01	0.40
Gizzard, %	1.43^{b}	1.64^{ab}	2.00^{a}	2.01^{a}	0.13	0.03	0.01	0.44
Abdominal Fat, g	34.8	36.0	43.9	66.0	8.91	0.12	0.03	0.28
Abdominal Fat, %	1.93	1.93	2.36	3.51	0.49	0.15	0.05	0.36
Total edible offal, g	231.8	247.1	250.7	280.0	10.9	0.07	0.02	0.54

Total edible offal, %	12.83	13.21	13.38	14.87	0.64	0.20	0.05	0.41

The value for each treatment represents the mean of six birds (2 birds per replicate, and 3 replicates per treatment).

[a, b ,c] row mean within the same category with different superscript letters significantly different $p<0.05$; BW, live body weight; [3]yield of breast meat and bone; [4]yield of total carcass parts; SEM, standard error of mean; A, p-value of one-way ANOVA; L, p-value of linear response; Q, p-value of quadratic response; T1, T2, T3, and T4 dietary treatments with inclusions of *Lemna minor* meal (LMM) in the diet at 0, 8%, 16%, and 24%, respectively.

3.7. Economic performance of broiler chickens

Economic evaluation of the dietary treatments is summarized in Table 7. Diet unit price per kg declined progressively as SBM was replaced by LMM in the diet. Grower, finisher, and total feed costs per bird were significantly lower in diets containing higher levels of LMM.

Total feed cost per kilogram body weight gain and production cost per bird decreased significantly with increasing LMM inclusion, with the lowest values recorded in T4. These reductions were primarily driven by the lower cost of LMM relative to SBM.

Net profit, benefit–cost ratio, economic efficiency, and relative economic efficiency increased with increasing LMM inclusion, indicating improved profitability of LMM-based diets. Although production index score did not differ significantly among treatments, the overall economic advantage favored higher inclusion levels.

Table 7. Economic Efficiency of broiler chickens fed on graded level of LMM in diet

Items	Dietary Treatments					p-value
	T1	T2	T3	T4	SEM	
Grower diet unit price, ETB/kg	77.70	72.80	67.10	61.40		
Finisher diet unit price, ETB/kg	75.20	70.60	65.40	60.50		
Grower FI, kg/bird	1.150^{b}	1.205^{a}	1.196^{a}	1.174^{ab}	0.008	0.007
Finisher FI, kg/bird	3.003^{b}	3.346^{a}	3.432^{a}	3.511^{a}	0.038	0.001
Total FI, kg/bird	4.152^{b}	4.551^{a}	4.627^{a}	4.687^{a}	0.044	0.001
Final BW, kg/bird	1.905^{b}	1.951^{a}	1.925^{ab}	1.910^{b}	0.007	0.005
Grower BWG, kg/bird	0.540^{a}	0.574^{a}	0.545^{a}	0.493^{b}	0.010	0.004
Finisher BWG, kg/bird	1.105^{b}	1.118^{ab}	1.121^{ab}	1.162^{a}	0.010	0.023
Grower feed cost, ETB/bird	89.4^{a}	87.7^{a}	80.3^{b}	72.1^{c}	0.584	0.001
Finisher feed cost, ETB/bird	225.8^{a}	236.2^{a}	224.5^{ab}	212.5^{b}	2.751	0.002
Grower feed cost per kg BWG, ETB/kg	165.6^{a}	153.2^{ab}	147.6^{b}	146.2^{b}	3.798	0.025
Finisher feed cost per kg BWG, ETB/kg	204.3^{a}	211.4^{a}	200.3^{a}	182.8^{b}	2.507	0.001
Total Feed cost per kg BWG, ETB/kg	191.6^{a}	191.5^{a}	183.0^{b}	171.9^{c}	2.241	0.001
Total Feed cost per kg BW, ETB/kg	165.4^{a}	166.1^{a}	158.3^{a}	149.0^{b}	1.871	0.001
Total Feed cost per broiler, ETB/bird	315.2^{ab}	324.0^{a}	304.7^{b}	284.5^{c}	3.115	0.001
Chick cost, ETB/bird	115	115	115	115		
Miscellaneous costs, ETB/bird	41.8	41.8	41.8	41.8		
Production cost per broiler, ETB/bird	472.0^{ab}	480.8^{a}	461.5^{b}	441.3^{c}	3.13	0.001
Production cost per kg BW, ETB/kg	247.8^{a}	246.5^{a}	239.8^{ab}	231.0^{b}	2.05	0.002
Total profit, ETB/bird	762.1^{b}	780.3^{a}	770.0^{ab}	764.1^{b}	2.68	0.005
Net profit, ETB/bird	290.1^{b}	299.5^{b}	308.4^{ab}	322.8^{a}	4.67	0.006
Benefit Cost ratio	1.61^{b}	1.63^{b}	1.67^{b}	1.73^{a}	0.02	0.001
Economic Efficiency, EE%	92.2^{b}	92.5^{b}	101.3^{ab}	113.4^{a}	2.38	0.001
Relative EE, %	100^{b}	100.4^{b}	110.0^{b}	123.0^{a}	2.60	0.001
PIS	228.7	230.0	210.4	205.5	7.51	0.110
EIS	3.01^{b}	3.23^{ab}	3.20^{ab}	3.38^{a}	0.10	0.04

$^{a, b, c}$ Row means within the same category with different superscript letters significantly different $p<0.05$; FI, feed intake; SEM standard error of mean; ETB, Ethiopian Birr (Ethiopian currency, 1 US Dollar =150.0 ETB) ; BW, body weight; BWG, body weight gain; EE, Economic Efficiency; PIS – production index score; EIS – economic index score; ; T1, T2, T3, and T4 dietary treatments with inclusions of *Lemna minor* meal (LMM) in the diet at 0, 8%, 16%, and 24%, respectively.

3.8. Correlation, regression, and overall response to *Lemna minor* inclusion

Correlation analysis revealed strong relationships between LMM inclusion level and performance parameters (Table 8). LMM inclusion was negatively correlated with diet bulk density and positively correlated with feed intake and feed conversion ratio. In contrast, protein and energy efficiency ratios were negatively associated with increasing LMM inclusion.

Quadratic regression analysis demonstrated that average daily feed intake, growth performance, carcass weight, and breast meat yield increased with LMM inclusion up to an optimum level, after which performance declined (Eq. 1 to 5). These relationships indicate a biological threshold beyond which additional LMM inclusion offers diminishing returns.

Table 8. Pearson's linear correlation and quadratic regression analysis

	LMM	DBD	ADFI	FBW	ADG	FCR	EER	PER	CW	BMY	GW	AF
LMM	1	-0.98**	**0.85****	-0.10	0.03	**0.89****	**-0.85****	**-0.88****	0.52	-0.27	**0.77****	**0.61***
DBD		1	-0.83**	-0.01	-0.12	**-0.86****	**0.81****	**0.85****	**-0.54**	0.20	**-0.72****	0.63*
ADFI			1	0.29	0.35	**0.97****	**-0.98****	**-0.97****	**0.60***	0.06	**0.64***	0.39
FBW				1	**0.97****	0.04	-0.12	-0.10	0.57	**0.73****	-0.01	-0.20
ADG					1	0.10	-0.17	-0.12	0.54	**0.64***	0.04	-0.11
FCR						1	**-0.99****	**-0.99****	0.49	-0.11	**0.66***	0.44
EER							1	**0.99****	-0.49	0.04	**-0.63***	-0.40
PER								1	-0.48	0.10	**-0.66***	-0.45
CW									1	0.37	0.54	0.10
BMY										1	-0.09	-0.19
GW											1	0.50
AF												1
	Quadratic Regression Equations											
	Equations							**R**	**R^2**	**SE**	**P-value**	
Eq.1	ADFI (g/b/d) = 1.33LMM – 0.035LMM^2 + 107.50							0.940	0.89	2.09	<0.001	
Eq.2	FBW (g/b) = 5.50LMM – 0.235LMM^2 + 1905.35							0.750	0.57	15.27	0.024	
Eq.3	ADG (g/b/d) = 0.153LMM – 0.006LMM^2 + 47.13							0.709	0.50	0.46	0.043	
Eq.4	CW (g/b) = 9.31LMM – 0.292LMM^2 + 1283.04							0.708	0.50	32.0	0.044	
Eq.5	BMY (%BW) = 0.241LMM – 0.011LMM^2 + 24.57							0.705	0.50	0.93	0.047	

* significant correlation at p<0.05; ** significant at p<0.01; LMM, Lemna minor meal % inclusion level in diet, DBD, diet bulk density; ADFI, average daily Feed Intake on DM bases; BW, body weight, FBW, Final body weight; ADG, average daily gain;

FCR, feed conversion ratio; PER, protein efficiency ratio; EER, energy efficiency ratio; CW, Carcass weight; BMY, relative breast meat yield (%BW); GW, Gizzard weight; AF, Abdominal fat. R, correlation coefficient; R^2, coefficient of determination; SE, standard error of estimate. The correlation and regression analysis values based on 12 observations.

3.9 Overall biological and economic responses of broiler chickens to graded inclusion of *Lemna minor* meal

Overall response patterns illustrated in Figure 1 showed that moderate LMM inclusion (approximately 8-16%) optimized growth performance, carcass traits, and economic efficiency. Higher inclusion levels primarily enhanced cost reduction rather than biological efficiency, highlighting the importance of balancing nutritional and economic objectives.

4. Discussion

4.1. Nutritional potential of *Lemna minor* meal as an alternative feed ingredient

The relatively high crude protein content of *Lemna minor* meal (LMM) (36.5% DM) observed in this study confirms its suitability as a plant-based protein source in poultry nutrition. Recent studies have shown that L. minor protein content can range from 30% to 41%, depending on growth conditions and nutrient availability, making it competitive with conventional protein sources [18–19, 47–48]. This supports the present findings and highlights the potential of LMM to partially replace soybean meal in broiler diets.

The high ash content and elevated mineral concentrations, particularly calcium and phosphorus, observed in LMM are consistent with earlier reports describing duckweed as a mineral-rich biomass [18, 48]. While this characteristic may reduce the need for inorganic mineral supplementation, it also contributes to lower metabolizable energy values of the diet. Similar reductions in dietary energy density associated with duckweed inclusion have been reported in broiler feeding trials [30, 49].

The low bulk density of LMM observed in this study has important implications for feed formulation and intake regulation. Reduced bulk density has been associated with increased feed volume and compensatory feed intake in poultry, particularly when dietary energy density is low [50]. However, excessive reductions in bulk density may negatively affect feed handling and nutrient utilization efficiency, especially at high inclusion levels.

4.2. Effects of *Lemna minor* inclusion on diet composition and formulation characteristics

The successful formulation of nutritionally balanced diets despite progressive replacement of soybean meal with LMM demonstrates the flexibility of duckweed as a feed ingredient. Previous studies have reported that duckweed can be incorporated into poultry diets without compromising crude protein content when energy and amino acid adjustments are applied [50, 51]. This supports the present formulation strategy, where maize grain and supplemental fat were adjusted to maintain dietary energy. However, the increase in ether extract with higher LMM inclusion reflects the need to compensate for the lower inherent energy density of duckweed biomass. Similar formulation approaches have been documented in studies evaluating alternative protein ingredients, where supplemental fat was used to sustain performance [52]. However, excessive reliance on dietary fat may alter nutrient partitioning and carcass composition.

The observed reduction in bulk density with increasing LMM inclusion is consistent with the physical properties of dried duckweed meal, fluffy and voluminous nature [30, 53]. According to Taylor et al. [54], bulk density is a critical but often overlooked factor affecting feed intake behavior and processing efficiency, suggesting the importance of considering physical as well as chemical diet characteristics, particularly during formulating diets for young birds, due to gut fill limit effect.

4.3. Effects of *Lemna minor* on feed intake, palatability, and nutrient utilization

The increase in feed intake observed with LMM-based diets is likely a compensatory response to reduced dietary energy concentration. Broiler chickens are known to regulate feed intake primarily to satisfy energy requirements, resulting in higher consumption when energy density is low. Similar intake responses or comparable to control diet at the optimum inclusion level have been reported in broilers fed diets containing duckweed and other low-energy plant ingredients [7, 49, 55–57]. Thus, the improved palatability scores associated with LMM inclusion suggest that duckweed biomass is readily accepted by broilers. Duckweed contains pigments, minerals, and bioactive compounds that may enhance feed attractiveness [23, 25, 58]. Conversely, others reported reduced feed intake compared to control diet at low to moderate inclusion level [29, 30, 53]. The variability in intake responses across studies indicates that palatability and digestibility may depend on processing method, inclusion level, age of the birds, nutrient composition of duckweed and total diet.

Although total nutrient intake increased with higher LMM inclusion, the declining metabolizable energy to protein ratio suggests potential inefficiencies in nutrient utilization at high inclusion levels. Reduced amino acid digestibility of duckweed protein has been reported previously and may partially explain this observation [49].

4.4. Effects of *Lemna minor* on growth performance of broiler chickens

The improved growth performance observed at moderate LMM inclusion levels indicates that duckweed can effectively support broiler growth when incorporated within optimal limits. Concurrently, comparable body weight gain in broilers fed diets containing moderate levels of duckweed meal relative to conventional soybean and other protein rich based diets have been reported [30, 49, 59–61]. Conversely, the decline in growth performance at the highest LMM inclusion level is consistent with reports that excessive duckweed inclusion may reduce nutrient digestibility and energy availability [29, 30, 62]. High fiber and ash contents may limit nutrient absorption and increase maintenance energy requirements, thereby reducing growth efficiency.

High livability across all treatments confirms that LMM does not pose health or toxicity risks to broiler chickens. This agrees with previous studies indicating that duckweed and other aquatic species are safe for poultry consumption when properly processed and included at appropriate levels, due to health promoting vitamins and bioactive compounds in duckweed with immunomodulatory and antibiotic effects [7, 23, 30, 63].

4.5. Effects of *Lemna minor* on feed efficiency and nutrient utilization

The increase in feed conversion ratio with higher LMM inclusion reflects reduced feed efficiency, a trend commonly reported when low-energy, high-fiber ingredients are included at excessive levels [57, 64]. Although birds increased feed intake, this did not translate proportionally into weight gain. Similarly, the decline in protein and energy efficiency ratios suggests that nutrients supplied by LMM were not utilized as efficiently as those from soybean meal. The reduction in digestibility of duckweed protein and amino acids, and bioavailability of nutrients due to high fiber and anti-nutritional factors may explain the reduced efficiency observed at higher inclusion levels [49, 65]. These findings highlight the trade-off between reduced feed cost and biological efficiency. As noted by Hugel [25], economic benefits from alternative feed ingredients must be weighed against potential reductions in nutrient utilization efficiency.

4.6. Effects of *Lemna minor* on carcass characteristics and edible organ yields

The lack of significant differences in dressing percentage among treatments suggests that LMM inclusion does not adversely affect carcass yield. Similar findings have been reported in broilers fed alternative protein sources, where overall carcass traits remained stable when diets were nutritionally balanced [11, 59, 63, 66]. Conversely, the enhanced breast meat yield observed at moderate LMM inclusion may be attributed to improved amino acid availability, particularly lysine, which plays a key role in muscle protein synthesis [67–68]. This supports the use of LMM as a functional protein source when included within optimal limits.

The increase in gizzard weight with higher LMM inclusion likely reflects greater dietary fiber content, consistent with adaptive enlargement reported in poultry fed fibrous diets [29, 57, 66]. While moderate gizzard development may improve digestion, excessive enlargement may increase energy expenditure.

4.7. Economic implications of *Lemna minor* inclusion in broiler diets

The progressive reduction in feed cost with increasing LMM inclusion highlights the economic advantage of replacing soybean meal with locally available alternative protein sources. Previous studies have emphasized duckweed's potential to reduce feed costs, particularly in regions where conventional protein ingredients are expensive [69]. Similarly, Demann et al. [49] reported inclusion of duckweed in broiler diet could be effective to improve profitability as it could be produced at minimal cost and potential to integrate with poultry farming.

Despite reduced feed efficiency at higher inclusion levels, overall economic efficiency improved due to lower feed costs. This pattern has been reported in other evaluations of unconventional feed ingredients, where savings cost outweighed modest reductions in growth performance [51, 55, 60, 61]. However, the divergence between biological and economic optima suggests that moderate inclusion levels may provide the best balance between performance and profitability. Strategic inclusion of LMM is therefore essential to maximize economic returns without compromising production efficiency.

4.8. Overall response patterns and optimal inclusion level of *Lemna minor*

The nonlinear response of growth performance and efficiency parameters to increasing LMM inclusion reflects a typical quadratic pattern reported for alternative feed ingredients [7, 25, 62]. Such responses indicate the presence of an optimal inclusion range beyond which performance declines. Variability in duckweed nutrient composition and digestibility underscores the importance of standardized cultivation and processing methods. Improving protein digestibility through addition of enzyme and processing techniques may enhance the feeding value of LMM and allow higher inclusion levels [30, 49, 66].

Overall, the present findings confirm that *Lemna minor* meal can be effectively used as a partial replacement for soybean meal in broiler diets when included at moderate levels. Continued research integrating nutrition, processing, and economics is essential to fully exploit its potential as a sustainable feed resource.

Conclusion

The present study demonstrated that *Lemna minor* meal (LMM) can be effectively used as a partial replacement for soybean meal in broiler diets without compromising overall performance, carcass yield, or livability. *Lemna minor* exhibited high crude protein and mineral contents, confirming its potential as a locally available alternative protein source. Dietary inclusion of LMM significantly influenced feed intake, growth performance, nutrient utilization, carcass traits, and economic outcomes. Broilers fed moderate inclusion levels of LMM (approximately 8–16%) achieved superior body weight gain, average daily gain, feed efficiency, and breast meat yield, indicating optimal biological performance at these levels. In contrast, higher inclusion levels increased feed intake and feed conversion ratio, reflecting reduced nutrient utilization efficiency, likely associated with lower dietary energy density and bulk density. Despite this, higher LMM inclusion substantially reduced feed cost and improved net profit, benefit–cost ratio, and overall economic efficiency. Quadratic regression analysis further confirmed that growth performance and carcass traits responded optimally to moderate LMM inclusion, while economic advantages increased with higher substitution levels. Overall, *Lemna minor* meal represents a nutritionally viable and economically attractive alternative protein source for broiler production. Strategic inclusion at moderate levels optimizes biological efficiency, whereas higher inclusion favors cost reduction, supporting flexible use of LMM depending on production objectives.

Future Lines of Work

Future research should focus on amino acid digestibility, nutrient bioavailability, and energy utilization of *Lemna minor* meal in broilers. Studies evaluating enzyme supplementation, processing methods, and standardized cultivation practices are needed to improve feed efficiency at higher inclusion levels. Long-term trials assessing meat quality, gut health, and environmental impacts will further strengthen recommendations for large-scale adoption.

Declarations

Ethics Approval

The study was conducted in accordance with the ARRIVE guidelines involving animal research. Ethical approved was granted by the Arba Minch University Ethics Committee.

Consent to publish

Not Applicable

Consent to Participate

Not Applicable

Competing interest

The authors declare that there is no conflict of interest.

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Author Contribution

H.N.; Design the experiment, Investigation, methodology, formal analysis, writing - original draft and editing. Y.K.: Supervision, Funding acquisition, methodology, statistical analysis, writing - review & editing. Y.T.; Supervision, methodology, writing - review & editing. A.B.; formal laboratory analysis, writing - review & editing. All authors have consent to the published version of the manuscript.

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Data Availability

The data supporting the findings of this study is available from corresponding author upon reasonable request.

References

1. FAO. World Food and Agriculture Statistical Yearbook: 2024. Rome; 2024.
2. OECD/FAO Agricultural Outlook 2024–2033. Rome; 2024. https://doi.org/10.1787/4c5d2cfb-en
3. Fenet B, Alemayehu T. Contribution of poultry to household food security in Ethiopia. J Dev Stud. 2019;55:178–90.
4. Fekadu T, Esatu W, Takele D, Tesfaye E, Zewdie Y, Amssalu K, et al. Ethiopia National Poultry Development Strategy 2022–2031. Federal Government of Ethiopia, Ministry of Agriculture. Addis Ababa; 2022.
5. ENTAG (Ethio-Netherlands Trade for Agricultural Growth). Invest in the Ethiopian Poultry Sector, Business Opportunity Report. Addis Ababa, Ethiopia. 2020. https://entag.org/download/business-opportunity-report-investethiopian-poultry-sector-2020
6. Tavaniello S, Fatica AP, Zejnelhoxha S, Wu M, Marco LD, et al. Carcass and Meat Quality Traits of Medium-Growing Broiler Chickens Fed Soybean or Pea Bean and Raised under Semi-Intensive Conditions. Animals. 2022;12:2849. https://doi.org/10.3390/ani12202849.
7. Sugiharto ST, Yudiarti I, Widiastuti IE, Wahyuni HI, Sartono TA. Recent advances in the incorporation of leaf meals in broiler diets. LRRD, 2019, 31 (7).
8. Seyoum B, Gemechu N, Harinder M. Ethiopian feed industry: current status, challenges and opportunities. Broaden horizon #50. 2018.
9. Demisse N. Study on Compound Animal Feed Demand and Animal Products, Supply, Price and Marketing in Ethiopia. Biomed J Sci Tech Res. 2022;41(3):32808–17.
10. Admasu S, Demeke S, Molla M. Poultry feed resources and chemical composition of crop content of scavenging indigenous chicken. J Anim Feed Res. 2019;9(6):247–55.
11. Edache D, John S, Edache S, Emmanuel D, Edache J. Growth performance & carcass characteristics of broiler chickens fed diets containing differently processed finger millet supplemented with enzyme. Int J Poult Sci. 2025;24:1–6.
12. Bog M, Appenroth KJ, Sree KS. Key to the determination of taxa of Lemnaceae: an update. Nord. J. of Botany; 2020.
13. Liu Y, Fang Y, Wang Q. Applications of duckweed in food and feed systems. Bioresource Tech. 2021;319:124152.
14. Karimov A, Saidov A, Mamatov B. *Lemna minor* biomass for feed and bioeconomy applications. Renewable Agric Food Syst. 2024;39:e12.
15. Xu J, Shen Y, Zheng Y, Smith G, Susan XS, et al. Duckweed (Lemnaceae) for potentially nutritious human food: A review. Food Reviews Int. 2021. https://doi.org/10.1080/87559129.2021.2012800.
16. Li Y, Zhang F, Maurycy D, Jie T. Positive effects of duckweed polyculture on starch and protein accumulation. Biosci Rep. 2016;36:e00380. https://doi.org/10.1042/BSR20160158.
17. Toyama T, Hanaoka T, Tanaka Y, Morikawa M, Mori K. Comprehensive evaluation of nitrogen removal rate and biomass, ethanol, and methane production yields by combination of four major duckweeds and three types of wastewater effluent. Biores Technol. 2018;250:464–73. http://doi.org/10.1016/j.biortech.2017.11.054.
18. Chakrabarti R, Clark WD, Sharma JG, Goswami RK, Shrivastav AK, Tocher DR. Mass Production of *Lemna minor* and Its Amino Acid and Fatty Acid Profiles. Front Chem. 2018;6:479. https://doi.org/10.3389/fchem.2018.00479.
19. Sonta M, Wiecek J, Szara E, Rekiel A, Zalewska A, Batorska M. Quantitative and Qualitative Traits of Duckweed (*Lemna minor*) Produced on Growth Media with Pig Slurry. Agronomy. 2023;13. https://doi.org/10.3390/agronomy13071951.
20. Petersen F, Demann J, Restemeyer D, Olfs HW, Westendarp H, Appenroth KJ, Ulbrich A. Influence of Light Intensity and Spectrum on Duckweed Growth and Proteins in a Small-Scale, Re-Circulating Indoor Vertical Farm. Plants.

2022;11:1010. https://doi.org/10.3390/plants11081010.

21. Sonta M, Anna R, Martyna B. Use of duckweed (*Lemna* spp.) in Sustainable Livestock Production and Aquaculture: Review. Annals Anim Sc. 2019;19(2):257–71. https://doi.org/10.2478/aoas-2018-0048.
22. Demmig-Adams B, López-Pozo M, Polutchko SK, Fourounjian P, Stewart JJ, Zenir MC, Adams WWIII. Growth and Nutritional Quality of Lemnaceae Viewed Comparatively in an Ecological and Evolutionary Context. Plants. 2022;11:145. https://doi.org/10.3390/plants11020145.
23. Lopez-Pozo M, William W, Adams III, Maureen M, Demmig-Adams BA. Preharvest finishing procedure for *Lemna* to produce high levels of zeaxanthin that is retained post-high-light exposure. Future Foods. 2024;10:100517. https://doi.org/10.1016/j.fufo.2024.100517.
24. FAO. The future of food and agriculture – Trends and challenges. FAO Report; 2017.
25. Hugel VS. Duckweed and Azolla as Livestock Feed for Improving Resource Efficiency and Nutritional Quality [dissertation]. Hamburg University; 2020.
26. Coughlan NE, Walsh E, Paul B, Gavin B, Niall O, Maria O, et al. Duckweed bioreactors: Challenges and opportunities for large-scale indoor cultivation of Lemnaceae. J Clean Prod. 2022;336:130285.
27. Emana AN. Assessment of the effect of duckweed (*Lemna minor*) on monosex Nile Tilapia (*Oreochromis niloticus*) farming at Ambo Ethiopia. J Pet Environ Biotechnol. 2021;11:414.
28. Tanuwiria UH, Mushawwir A. Hematological and antioxidants responses of dairy cows fed with a combination of feed and duckweed (*Lemna minor*) as a mixture for improving performance. Biodiversitas. 2020;21(10):4741–6. https://doi.org:10.13057/biodiv/d211038.
29. Foluke OA, Adeyemi OA, Sogunle OM. Evaluation of duckweed meal in broiler diets. Nigerian J Anim Prod. 2018;45:210–8.
30. Zaffer B, Sheikh IU, Banday MT, Adil S, Ahmed HA, Khan AS, et al. Effect of Inclusion of Different Levels of Duckweed (*Lemna minor*) on the Performance of Broiler Chicken. Indian J Anim Res. 2021;55:1200–5.
31. Femeena P, Nair RR, Mathew J. Variability in nutrient composition of duckweed under different culture systems. Aquaculture Rep. 2023;29:101496.
32. Miltko R, Majewska M, Wojtak W, Białek M, Kowalik B, Czauderna M. Comparing the chemical composition of lesser duckweed (*Lemna minor* L.) grown in natural and laboratory settings. J Anim Feed Sc. 2024;33(3):357–67. https://doi.org/10.22358/jafs/189963/2024.
33. Schemted R, Jones P. Standardization challenges in alternative feed protein production. Anim Nutr. 2023;12:45–55. https://doi.org/10.1016/j.heliyon.2022.e12194.
34. Sosa D, Alves FM, Prieto MA, Pedrosa MC, Heleno SA, Barros L, et al. *Lemna minor*: Unlocking the Value of This Duckweed for the Food and Feed Industry. Foods. 2024;13:1435. https://doi.org/10.3390/foods13101435.
35. Yared AE. Evaluation of Chicken Production Systems and Effects of Homemade Ration on Growth and Carcass Characteristics of Cobb500 Broiler Chicken in Bishoftu, Ethiopia [dissertation], Addis Ababa University; 2019.
36. AOAC. Official methods of analysis. 20th ed. Washington, DC: Association of Official Analytical Chemists; 2015.
37. NRC. Nutrient requirements of poultry. 9th ed. Washington, DC: National Academies; 1994.
38. BMG. Cobb Broiler Management Guide. L-1020-06, Dec. 2018. Cobb-vantress.com Available online: https://eliasnutri.wordpress.com/wp-content/uploads/2018/09/requerimentos-pollos-cobb500-2018.pdf
39. Leeson S, Summers JD. Commercial poultry nutrition. 3rd ed. Guelph: University Books; 2006.
40. Fiordelmondo E, Ceschin S, Magi G, Mariotti F, Iaffaldano N, Galosi L, Roncarati A. Effects of Partial Substitution of Conventional Protein Sources with duckweed (*Lemna minor*) Meal in the Feeding of Rainbow Trout (*O. mykiss*) on Growth Performances and Quality Product. Plants. 2022;11:1220. https://doi.org/10.3390/plants11091220.
41. Al-Nasrawi MA. The impact of different dietary forms on some growth traits and carcass characteristics of broilers. J Anim Health Prod. 2016;4(2):31–6. http://dx.doi.org/10.14737/journal.jahp/2016/4.2.31.36.

42. Melesse A, Temesgen A, Sandip B, Kefyalew B. The effect of the partial substitution of roasted soybean seed with graded levels of sweet potato (*Ipomoea batatas*) leaf meal on growth performances and carcass components of broiler chickens. Asian-Australas J Anim Sci. 2017;00:1–7. https://doi.org/10.5713/ajas.15.0642.
43. Melkamu BY. Management practices and constraints of small-scale commercial poultry farms and performance evaluation of broilers fed diets containing graded levels of dried blood rumen content mixture [dissertation]. Bishoftu, Addis Ababa University; 2017.
44. Ghosh N, Samanta R. Manual on Avian Production and Management. 1st ed. Lucknow, India, International Book Distributing Co.; 2008.
45. Wiseman J. Feeding of non-ruminant livestock. London: Butterworths; 1987.
46. Kaps M, Lamberson WR. Biostatistics for Animal Science. Cromwell Press, UK: CABI publishing; 2004.
47. Devlamynck R, de Souza MF, Leenknegt J, Jacxsens L, Eeckhout M, Meers E. Lemna minor cultivation for treating swine manure and providing micronutrients for animal feed. Plants. 2021a;10:1124. https://doi.org/10.3390/plants10061124.
48. Devlamynck R, de Souza MF, Michels E, Sigurnjak I, Donoso N, Coudron C, et al. Agronomic & Environmental Performance of *Lemna minor* cultivated on agricultural wastewater streams—A. Practical Approach Sustain. 2021b;131570. https://doi.org/10.3390/su13031570.
49. Demann J, Petersen F, Dusel G, Bog M, Devlamynck R, Ulbrich A, et al. Nutritional Value of Duckweed as Protein Feed for Broiler Chickens—Digestibility of Crude Protein, Amino Acids and Phosphorus. Animals. 2023;13:130. https://doi.org/10.3390/ani13010130.
50. Ataei AH, Moheghi MM, Fazel Y. Effect of Grower Dietary Energy Level on Feed Intake and Performance of Modern Broiler Chickens. Poult Stud. 2022;19(1):1–6. https://doi.org/10.34233/jpr.1111291.
51. Dhyey D, Mavani A, Vyas AA. Utilization of duckweed (Lemna minor) meal as partial supplementation in the diet of Catla catla fry. Int J Sc Env Tech. 2020;9(2):206–18.
52. Wang M, Shemil M, Peter HS, Sonia YL. Interactive effects of dietary grain and supplemental fat sources on growth performance and carcass characteristics of broiler chickens. Poult Sci. 2025;104:105076. https://doi.org/10.1016/j.psj.2025.105076.
53. Iram S, Abrar S, Ahmad I, Khanam T, Azim A, Nadeem MA. Use of Duckweed growing on sewage water as poultry feed. Int J Sci Res Publication. 2015;5:1–8.
54. Taylor J, Sakkas P, Kyriazakis I. What are the Limits to Feed Intake of Broilers on Bulky Feeds? Poult. Sci. 2021;100:100825.
55. Ahammad MU, Swapon MSR, Yeasmin T, Rahman MS, Ali MS. Replacement of Sesame oil cake by Duckweed (Lemna minor) in broiler diet. Pak J Biol Sci. 2003;6(16):1450–3.
56. Hu X, Li X, Xiao C, Kong L, Zhu Q, Song Z. Effects of Dietary Energy Level on Performance, Plasma Parameters, and Central AMPK Levels in Stressed Broilers. Front Vet Sci. 2021;8:681858.
57. Zhang C, Hao E, Chen X, Huang C, Liu G, Chen H, Wang D, Shi L, Xuan F, Chang D, Chen Y. Dietary Fiber Level Improve Growth Performance, Nutrient Digestibility, Immune and Intestinal Morphology of Broilers from Day 22 to 42. Animals. 2023;13:1227. https://doi.org/10.3390/ani13071227.
58. Zhou Y, Borisjuk N. Small Aquatic Duckweed Plants with Big Potential for the Production of Valuable Biomass and Wastewater Remediation. Int J Env Sci Nat Res. 2019;16(4):555942. https://doi.org/10.19080/IJESNR.2019.16.555942.
59. Kusina J, Mutisi C, Govere W, Mhona R, Murenga K, Ndamba J, Taylor P. Evaluation of Duckweed (*Lemna minor*) as a feed ingredient in the finisher diets of broiler chickens. South Afr J Appl Sci. 1999;5(1):25–34. https://doi.org/10.4314/jassa.v5i1.16905.

60. Kabir J, Islam MA, Ahammad MU, Howlider MAR. Use of duckweed (*Lemna minor*) in the diet of broiler. Indian J Anim Res. 2005;39:31–5.
61. Paguia HM. Evaluation of Corn-Duckweed Meal (*Lemna minor*) Based Diets as Practical Ration for Native Chicken. J Adv Agricultural Technol. 2021;8(2):30–4.
62. Irabor A, Obakanurhie EO, Nwachi FO, Ekokotu PA, Ekelemu, Awhefeada JK. Duckweed *Lemna minor* meal as partial replacement for fish meal in catfish (*Clarias gariepinus*) juvenile diets. LRRD, 2022, 34 (1).
63. Rengma DJ, Savino N, Vidyarthi VK. Effect of Dietary Inclusion of Azolla Powder on Performance of Broiler Chicken. Livest Res Int. 2019;7(2):144–50.
64. Singh AK, Kim WK. Effects of dietary fiber on nutrients utilization and gut health of poultry: A Review of Challenges and Opportunities. Animals. 2021;11:181. https://doi.org/10.3390/ani11010181.
65. Jha R, Mishra P. Dietary fiber in poultry nutrition and their effects on nutrient utilization, performance, gut health, and on the environment: a review. J Anim Sci Biotechnol. 2021;12:51.
66. Zaffer B, Sheikh IU, Banday MT, Adil S, Ahmed HA, Khan AS, Mirza U, Nissa S. Carcass characteristics of broiler chicken fed different levels of Duckweed & Enzyme Supplementation. Veter Res Inter. 2020;08(2):68–72.
67. Mlaba PP, Ciacciariello M, Gous RM. The effect of dietary protein on breast meat yield of broilers reared on different day lengths. South Afr Soc Anim Sci. 2015;45:39–48. http://dx.doi.org/10.4314/sajas.v45i1.5.
68. Musigwa S, Cozannet P, Asiamah CA, Wu SB. Effects of Dietary Protein Levels, Net Energy Levels, and Essential Amino Acid-to-True Protein Ratios on Broiler Performance. Animals. 2024;143065. https://doi.org/10.3390/ani14213065.
69. Leng RA, Stambolie JH, Bell R. Duckweed as a low-cost feed resource for livestock. LRRD. 2022;34:92.

Figures

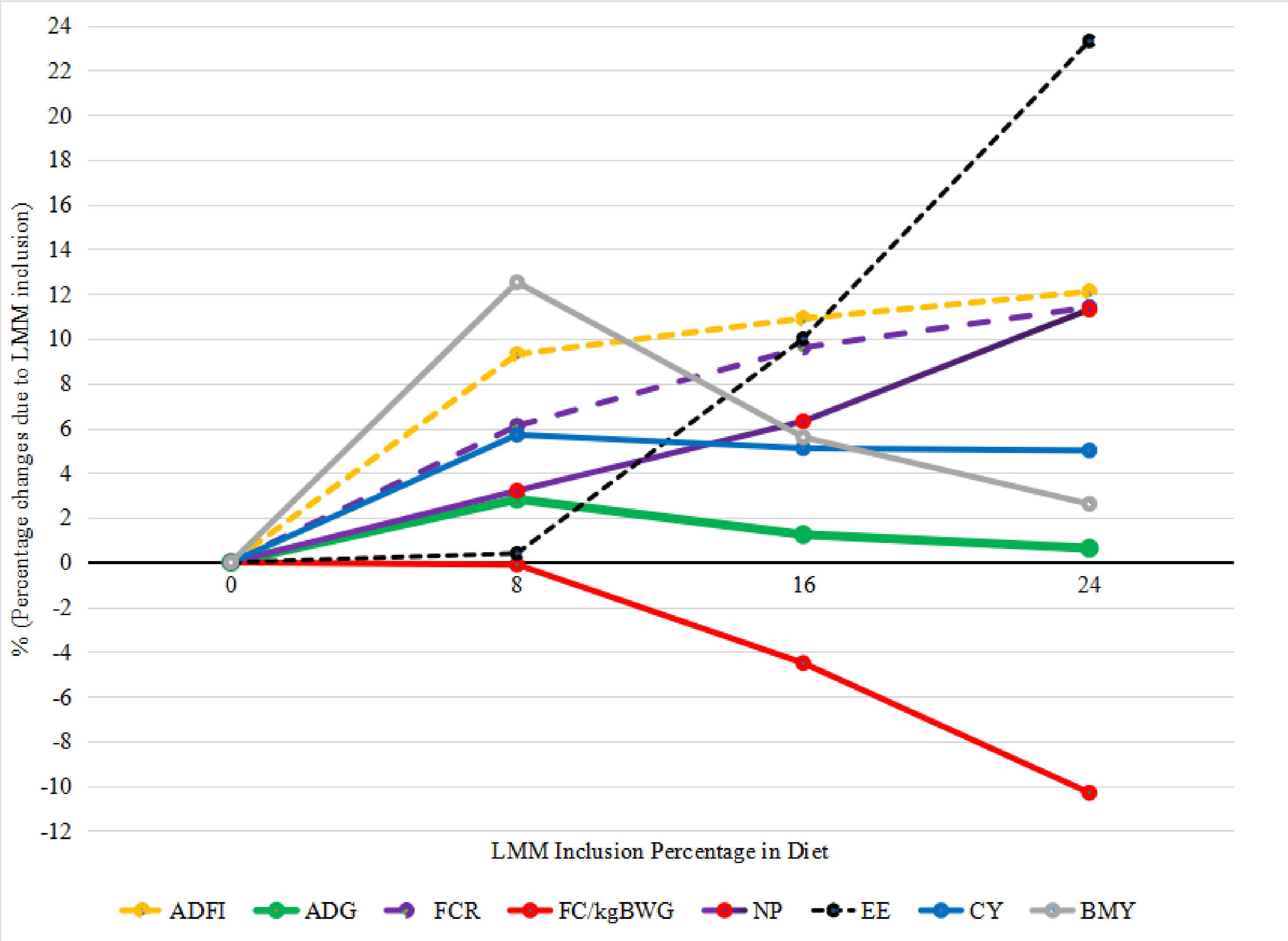

Figure 1

Percentage change in productive performances and Economic Efficiency of broiler chicken feed on graded percentage of *Lemna minor* meal (LMM) in the diet compared to the control diet. **(Key:** ADFI, Average Daily Feed Intake; ADG, Average Daily Gain; FCR, Feed Conversion Ratio; FC/kg BWG, feed cost per body weight gain; NP, Net Profit; EE, economic efficiency; CY, carcass yield; BMY, breast meat yield (each data point average of three replication per treatment).