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Effects of finisher diet nutrients density and slaughter age on energy and protein efficiency, productive and economic performance and meat quality of broilers

Mahdie Nikbakhtzade | **Heydar Zarghi** | **Abolghasem Golian**

Department of Animal Science, Faculty of Agriculture, Ferdowsi University of Mashhad, Mashhad, Iran

Correspondence
Heydar Zarghi, Department of Animal Science, Faculty of Agriculture, Ferdowsi University of Mashhad, P. O. Box 91779-48944, Mashhad, Iran.
Email: h.zarghi@um.ac.ir

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Abstract

Background: The current broilers have been greatly optimized for weight gain and breast yield, which necessitates the provision of nutrients-dense diets for maximum potential.

Objectives: The current study aimed to evaluate the effect of finisher diet nutrients density (ND) on energy and protein efficiency, productive and economic performance and breast meat quality of broilers raised until different slaughter age.

Methods: A total of 600 23-day-old broiler male chicks (Cobb-500) were assigned to 10 treatments with six replicates and 10 birds each. Experimental treatments were included factorial arrangement of five increment (2.5%) levels of finisher diet ND (92.5%, 95%, 97.5%, 100% and 102.5% as strain recommendation) and slaughtered at 38 or 46 days of age. The relative difference in the energy level of experimental diets was used to increase ND levels at the same ratio.

Results: Feed intake (FI) and breast meat quality traits exception water holding capacity (WHC) were not affected by finisher diet ND. In response to increasing finisher diet ND, energy and protein efficiency, productive traits, bio-economic index (BEI) and breast relative weight (BRW) linearly improved. However, residual feed intake and breast meat WHC improved with a quadratic trend. By using broken-line regression analysis, the optimum dietary ND was obtained at 97.5%–102% of strain recommendation. Energy and protein efficiency, feed conversion ratio and BEI deteriorated by prolonging rearing period. The BRW, meat lightness (*L**), redness (*a**), hue angle (*h**) and WHC values for the birds slaughtered at 46 days of age were significantly higher, and cooking loss was lower than those slaughtered at 38 days old.

Conclusions: Broilers during the finisher period are not able to regulate their FIs with diet ND. The energy and protein efficiency, productive and economic performance were reduced when broilers were fed diluted diet or the rearing period was prolonged.

KEYWORDS
bio-economic index, broiler, meat quality, nutrient density, residual feed intake

1 | INTRODUCTION

An economically and environmentally accepted approach to poultry meat production is to produce broilers with faster weight gain (WG) and higher final live body weight (LBW) while using less feed (Maharjan et al., 2021). Broilers genetic selection for quantitative traits such as growth rate and lean muscle mass without increasing the fat mass led to more rate of muscle protein turnover (Ikeobi et al., 2002; Maharjan et al., 2020). Dietary nutrients density (ND) is one of the most important nutritional factors that has a significant effect on productive performance and health (Brickett et al., 2007; Ebeid et al., 2022), carcass quality (Zhao et al., 2009), economic performance (Kamran et al., 2008; Nikbakhtzade et al., 2020), nitrogen excretion (Bregendahl et al., 2002; Naseem & King, 2018) and metabolic disorders (Mirshekar et al., 2013).

It is confirmed that, in broiler chickens, the digestive tract capacity is the main factor for feed intake (FI) regulation (Sahraei & Shariatmadari, 2007). So, feed consumption was less influenced by dietary energy and nutrient concentration (Dozier et al., 2006, 2007). Broiler chickens may not be able to maintain energy intake with high levels of diet dilution (Nielsen, 2004), which may adversely effect on growth rate. In return, feeding broilers with high-nutrient and energy-density diet led to improving productive performance (Fan et al., 2008; Nahashon et al., 2005) and carcass yield (Nahashon et al., 2005). On the other hand, feeding broilers with very dens diet may allow them to consume more energy than required (Fan et al., 2008; Mushtaq et al., 2014; Nahashon et al., 2005; Sikur et al., 2004), which leads to abdominal fat accumulation and reduced carcass quality.

Slaughter age (SA) is a critical factor that significantly influences production and economic performance, carcass yield and meat quality (Abougabal & Taboosha, 2020). Rearing broilers until older age and weight is associated with decreasing feed efficiency and increasing abdominal fat deposition (Lippens et al., 2000). In the broilers by increasing age, decreasing in growth rate is associated with a progressive reduction on protein deposition, whereas the rate of fat deposition is still high. Therefore, the availability of nutrients for lipogenesis increases if feeding is not limited after the maximum growth period (Albuquerque et al., 2003). The objective of current study was to elucidate the effects of finisher diet ND and SA on energy and protein efficiency, productive and economic performance and breast meat quality of broilers.

2 | MATERIALS AND METHODS

2.1 | Feedstuff analysis

Before to the trial, protein, amino acids and digestible amino acids of feed ingredients were measured by using near-infrared analysis through Evonik Co. (Evonik Nutrition & Care GmbH) agent in Tehran, Iran. These values were used in a least-cost equation for the formulation experimental diets.

2.2 | Birds, housing and diets

A total of 840 1-day-old male broiler chicks (Cobb-500) were allocated into 60 pens (14 birds/pen, 100 × 100 cm^2) and raised until 22 days on a common condition. The ambient temperature initially was maintained at 32 ± 2°C; after 3 days, it decreased by 0.5°C per day to reach 20–22°C and after that, it was kept constant, the relative humidity was 50%–60%; and a lighting schedule of 18L: 6D was imposed throughout the experimental period.

At 23 days of age, with removing the highest and the lowest weight birds, 10 birds were fixed in each pen (average LBW was 695 ±11 g/bird). The pens were randomly assigned to a 5 × 2 factorial arrangement of feeding five levels of finisher diet ND 92.5%, 95%, 97.5%, 100% and 102.5% as strain recommendation (Cobb-Vantress, 2019), and two SAs (38 vs. 46 days old) with six replicates per treatment. The experimental diets were formulated in a minimum cost equation by user-friendly feed formulation done again (UFFDA, 1992) software, University of Georgia, Athens, GA, United States (Table 1). The relative difference in the experimental diets' energy level was used to change protein, indispensable amino acids and minerals inclusion levels at the same ratio. All birds had free access to drinking water and feed throughout the experiment period. Birds and housing facilities were inspected three times daily.

2.3 | Data collection and sampling

2.3.1 | Growth performance

The chicks of each pen were weighed in groups at the beginning (23 days old) and at the end (38 and or 46 days old). In order to minimize the error resulting from the digestive tract contents, the birds were starved for 4 h before weighing. The feed consumption of each pen was calculated by subtracting the amount of feed remaining at the end from the total feed given during the experimental period and adjusted for mortality. The growth performance traits, such as LBW, FI, WG, feed conversion ratio (FCR), yield per unit area (YUA) (Abougabal & Taboosha, 2020), bio-economical index (BEI) (Santos et al., 2008) and European production efficiency factor (EPEF) (Cobb-Vantress, 2019), were calculated. The YUA, BEI and EPEF were calculated by the following equations:

$$\text{YUA} = \frac{\text{Pen live body weight (kg)} \times \text{Livability (\%)}}{\text{Pen area } (\text{m}^2)}$$

$$\text{BEI} = \text{Weight gain (kg)} - \left[\left(\frac{\text{Feed cost}}{\text{Production cost}}\right) \times \text{Feed intake (kg)}\right]$$

$$\text{EPEF} = \frac{\text{Weight gain (kg)} \times \text{Viability (\%)}}{\text{Feed conversion ratio} \times \text{Age (day)}} \times 100$$

TABLE 1 Ingredients and nutrients composition of the experimental diets.

Items	Finisher diet nutrients density[a]				
	92.5%	95%	97.5%	100%	102.5%
Ingredients, g/kg as-fed basis					
Corn	652.8	636.2	619.6	603.0	586.4
Soya bean meal	236.0	253.5	271.1	288.8	306.3
Wheat bran	68.1	53.6	39.1	24.5	10.0
Soya bean oil	10.0	22.7	35.4	48.1	60.8
Limestone	7.9	8.0	8.0	8.1	8.2
Dicalcium phosphate	11.2	11.9	12.6	13.3	14.0
Common salt	3.9	4.0	4.1	4.1	4.2
Vitamin premix[b]	2.5	2.5	2.5	2.5	2.5
Mineral premix[c]	2.5	2.5	2.5	2.5	2.5
DL-Methionine	2.3	2.4	2.5	2.6	2.7
L-Lysine-HCL	1.9	1.8	1.7	1.6	1.5
L-Threonine	0.9	0.9	0.9	0.9	0.9
Determined nutrients composition[d], as-fed basis					
Metabolizable energy, kcal/kg	2928	3007	3087	3166	3246
Crude protein, g/kg	175.7	180.5	185.2	190.0	194.7
ME/CP ratio	16.6	16.6	16.6	16.6	16.6
Crude fibre, g/kg	35.2	34.2	33.2	32.2	31.2
Calcium, g/kg	7.0	7.2	7.4	7.6	7.8
Available phosphorus, g/kg	3.5	3.6	3.7	3.8	3.9
Sodium, g/kg	1.8	1.8	1.8	1.9	1.9
Digestible lysine, g/kg	9.2	9.5	9.7	10.0	10.3
Digestible methionine, g/kg	4.7	4.9	5.0	5.2	5.3
Digestible Sulphur amino acids, g/kg	7.2	7.4	7.6	7.8	8.0
Digestible threonine, g/kg	6.3	6.5	6.7	6.8	7.0

Abbreviations: CP, crude protein; ME, metabolizable energy.

[a]Percentage of nutrient recommendations stated by the Cobb-500 (Cobb-Vantress, 2019) commercial management guide.

[b]Vitamin premix supplied the following per kilogram of diet: vitamin A (all-trans-retinol), 12,000 IU; vitamin D3 (cholecalciferol), 5000 IU; vitamin E (α-tocopherol), 18 IU; vitamin K3 (menadione), 2.65 mg; vitamin B1 (thiamin), 2.97 mg; vitamin B2 (riboflavin), 8.0 mg; vitamin B3 (niacin), 57.42 mg; vitamin B5 (pantothenic acid), 17.86 mg; vitamin B6 (pyridoxine), 4.45 mg; vitamin B9 (folic acid), 1.9 mg; vitamin B12 (cyanocobalamin), 0.02 mg; vitamin H2 (biotin), 0.18 mg; choline chloride and 487.5 mg, antioxidant 1.0 mg.

[c]Mineral premix supplied the following per kilogram of diet. Zn (zinc sulphate), 110 mg; Mn (manganese sulphate), 120.6 mg; Fe (iron sulphate), 40.5 mg; Cu (copper sulphate), 16.1 mg; I (calcium iodate), 1.26 mg; Se (Sodium Selenite) and 0.31 mg; choline chloride, 474.0 mg.

[d]The determined ingredient analysis data was used to calculate nutrients composition; crude protein, calcium and sodium were measured by the AOAC (2002) methods; metabolizable energy, digestible amino acids, and available phosphorus were measured by using the near-infrared analysis.

2.3.2 | Energy and protein efficiency

The following equations were used to calculate fat content of gain (FCG), protein content of gain (PCG), energy and protein efficiency and energy requirements (maintenance + gain) by using the function of initial and final LBW, WG and gain composition (Carré & Méda, 2015). The expected feed intake (EFI) was estimated by dividing the total energy requirements to diet AME. Residual feed intake (RFI) was obtained by subtracting the EFI from the observed FI (Nikbakhtzade et al., 2020).

$$\mathrm{FCG} = 12.3\left[0.025 + 0.137\,\frac{\left(\mathrm{BW}_{\mathrm{initial}}^{0.418} + \mathrm{BW}_{\mathrm{final}}^{0.418}\right)}{2}\right] e^{\left(-1.082\,\frac{\mathrm{CP}_{\mathrm{diet}}}{\mathrm{AME}_{\mathrm{diet}}} - 2.09\mathrm{PE}\right)}$$

$$\mathrm{PCG} = \left[0.179 + 0.00169\,\frac{\left(\mathrm{Age}_{\mathrm{initial}} + \mathrm{Age}_{\mathrm{final}}\right)}{2}\right] \times (1 - \mathrm{FCG})$$

$$\text{Energy efficiency} = \frac{\text{WG}\,(9.13\text{FCG} + 5.64\text{PCG})}{\text{FI} \times \text{AME}_{\text{diet}}}$$

$$\text{Protein efficiency} = \frac{\text{WG} \times \text{PCG}}{\text{FI} \times \text{CP}_{\text{diet}}}$$

$$\text{Energy requirements for maintenance} = \left[0.680\frac{\left(\text{BW}_{\text{initial}}^{0.643} + \text{BW}_{\text{final}}^{0.643}\right)}{2}\right]$$

$$\text{Energy requirements for gain} = \text{WG}\,(0.03288\text{PCG} + 0.04372\text{FCG})$$

where FCG is the fat content of gain, PCG is the protein content of gain, BW_{initial} is the live body weight at the start of the test, BW_{final} is the live body weight at the end of the test, WG is the weight gain, CP_{diet} is the diet crude protein, AME_{diet} is the diet metabolizable energy and FI is the feed intake.

2.3.3 | Carcass and cut-up parts

At 38 and 46 days old, 2 birds from each pen (12 birds/treatment), after 6 h of feed withdrawal but had free access to drinking water, were randomly selected and slaughtered by severing the jugular vein, allowed bleeding for the 90 s, scalded for 2 min at 60°C, and picked (Zarghi et al., 2020). The gastrointestinal tract (GIT) was emptied, and abdominal fat was collected carefully. After carcass chilling for 24 h at 4°C (Tabatabaei et al., 2017), carcasses were weighed to determine the carcass yield as a percentage of LBW. The carcass parts – legs (thigh + drumstick), breast and frame (carcass without breast and legs) – were cut according to a standardized procedure (Tabatabaei et al., 2017) and weighed by a digital weighing scale (0.001^{-g}; Model GF 400, A&D Weighing).

2.3.4 | Breast meat's physicochemical properties

The right side of the breast muscle was used to assess physicochemical properties. Water holding capacity (WHC) was measured as (100% expressed juice), following a modification of the press method (Zarghi et al., 2020). Cooking loss (CL) was measured as proportionate weight loss of a sample after cooking in an open plastic bag in a water bath at 70°C for 40 min, followed by cooling in cold-running tap water for 15 min (Honikel, 1998). The equation is shown as follows:

$$\text{Cl\%} = \left(\frac{\text{Weight before cooking} - \text{Weight after cooking}}{\text{Weight before cooking}}\right) \times 100$$

Colour intensity was measured on breast muscle samples with a Chroma-Meter (CR-410 Konica Minolta, INC). The optical density of meat, lightness (L^*), redness (a^*) and yellowness (b^*) values. The hue angle (h^*) and Chroma (c^*) were calculated using the following formula (Zarghi et al., 2020). The equations are shown as follows:

$$h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right)$$

$$c^* = \left(a^{*2} + b^{*2}\right)^{0.5}$$

The left side of skinless and boneless breast meat, after freezing, was homogenized in a cutter for approximately 3 min until a homogeneous paste-like mixture was obtained, then about 100 g of them were removed and freeze-dried, which was then used to determine the breast meat composition such as moisture, crude protein, fat and ash according to standardized methods (AOAC, 2002).

2.4 | Statistical analysis

The experimental data were analysed for normality via the univariate procedure and then analysed by ANOVA using general linear model procedure of SAS 9.4 software (SAS Institute, 2014) appropriate for treatments in a randomized completely design with factorial arrangement. Means were compared using the Tukey test at the level of 0.05 probability (Tukey, 1991). Orthogonal polynomials contrast coefficients were used to determine linear and quadratic effects of increasing finisher diet ND levels on all measurements. To estimate the optimized responses, liner broken-line, quadratic broken-line and quadratic polynomial equation models were used via the NLIN procedure Gauss–Newton method of SAS 9.4 software. The iterative procedure makes repeated estimates for coefficients and minimizes residual error until the best-fit lines are achieved (Robbins et al., 2006). The equations are shown as follows:

$$\text{For linear broken line } Y = L + U \times (R - X) \times I$$

$$\text{For quadratic broken line } Y = L + U \times (R - X)^2 \times I$$

$$\text{For quadratic polynomial equation } Y = a + bX + cX^2$$

$$R^2 = \frac{(\text{corrected total sum of squares} - \text{sums of squares for error})}{\text{corrected total sum of squares}}$$

where Y is the dependent variable, L is the theoretical maximum, R is the optimized dietary ND, X is the independent variable, I is the 1 (if $X < R$) or $I = 0$ (if $X > R$) and U, a, b and c = rate constant.

3 | RESULTS

3.1 | Growth performance

The effects of finisher diet ND and SA on productive and economic traits are shown in Table 2. There were considerable improver reactions to increasing finisher diet ND on WG, YUA, FCR, BEI and

TABLE 2 Growth performance traits of male Cobb-500 broilers in response to finisher diet nutrients density and slaughter age.[a]

Effects	Live body weight, g/b Initial	Live body weight, g/b Final	Weight gain, g/b/d	Feed intake, g/b/d	FCR, g/g	EPEF[b]	YUA, kg/m^2	BEI[c]
Slaughter age, day								
38	694	2178[b]	89.9[a]	138.2[b]	1.542[b]	257	36.32[b]	56.1[a]
46	695	2680[a]	84.4[b]	144.3[a]	1.718[a]	256	44.67[a]	49.2[b]
SEM	2.22	15.58	0.68	0.75	0.012	3.39	0.26	0.591
Nutrients density[d], %								
92.5	696	2288[d]	80.1[d]	142.3	1.783[a]	213[c]	38.14[d]	48.1[c]
95.0	699	2372[c]	84.0[c]	141.0	1.682[b]	236[c]	39.55[c]	50.9[b]
97.5	691	2463[b]	89.0[b]	141.5	1.594[c]	264[b]	41.06[b]	54.3[a]
100	697	2477[a,b]	89.7[b]	140.8	1.575[c,d]	279[a,b]	41.30[a,b]	53.9[a]
102.5	695	2544[a]	93.0[a]	140.4	1.514[d]	290[a]	42.42[a]	55.9[a]
SEM	3.38	24.80	1.08	1.19	0.019	5.37	0.41	0.934
Source of variation, *p*-value								
Slaughter age	0.990	0.001	0.001	0.001	0.001	0.847	0.001	<0.001
Nutrients density	0.573	0.001	0.001	0.833	0.001	0.001	0.001	<0.001
Interaction (SA × ND)	0.990	0.533	0.684	0.983	0.280	0.536	0.534	0.516
Nutrients density response								
Linear	0.674	0.015	0.001	0.396	0.001	0.001	0.016	<0.001
Quadratic	0.783	0.702	0.284	0.914	0.218	0.184	0.705	0.309

Note: In each column for each effect, values with different superscripts (a–c) are significantly different ($p < 0.05$).
Abbreviations: BEI, bio-economic indices; EPEF, European production efficiency factor; FI, feed intake; FCR, feed conversion ratio; ND, nutrients density; WG, weight gain; YUA, yield per unit area.
[a]Every values are the means of 30, 12 and 6 replicates for slaughter age, nutrient density and interaction effects, respectively.
[b]EPEF calculated as: [viability (%) × live body weight (kg) × 100]/ [Age (day) × FCR].
[c]Bio-economic indices calculated as: Weight gain (kg)—[(Feed cost/Production cost) × Feed intake (kg)].
[d]Percentage of the nutrient recommendations stated by the Cobb-500 (Cobb-Vantress, 2019) commercial management guide.

EPEF. Growth performance traits exception FI improved (linear effect, $p < 0.01$) as finisher diet ND increased. The average FI was nearly identical between birds fed finisher diet with different ND ($p > 0.05$). The broilers fed finisher diet with ND 102.5% of strain recommendation performed the highest WG, YUA, BEI and EPEF, and the lowest FCR, which were 3.70%, 2.71%, 3.71% and 3.94% higher and 3.87% lower than those fed finisher diet with energy and nutrient density at strain recommendation (100% ND), respectively. With decreasing finisher diet ND, growth performance traits are numerically decreased. In the birds fed finisher diet with 92.5% ND, the WG, YUA, BEI, EPEF and FCR values deteriorated by 11.87%, 8.29%, 12.05%, 30.99% and 11.67% to those fed finisher diet with 100% ND, respectively. By increasing SA, the performance indices except YUA significantly deteriorated. By increasing slaughtering age from 38 to 46 days, YUA was improved. No significant interaction effect between finisher diet ND and SA on performance traits was observed.

3.2 | Energy and protein efficiency

The effects of finisher diet ND and SA on gain content, energy and protein efficiency, energy requirement (maintenance + gain) and RFI are shown in Table 3. By increasing finisher diet ND, the energy and protein efficiency linearly improved ($p < 0.05$). Energy and protein efficiency in the birds fed finisher diet with ND at the levels of 97.5%, 100% and 102.5% was significantly higher than those fed diet with ND at the levels of 92.5% and 95% of strain recommendation. By increasing the SA from 38 to 46 days of age, energy and protein retention efficiency decreased significantly ($p < 0.001$). By increasing finisher diet ND, the maintenance and total energy requirements for WG decreased (linear effect, $p < 0.02$). Maintenance energy requirements per unit of WG in the birds fed finisher diet with 97.5%, 100% and 102.5% ND are significantly lower than those fed diets with 95% and 92.5% ND. By increasing finisher diet ND, the RFI improved with a quadratic trend ($p < 0.02$). Lowest RFI belonged to the chickens fed diet with 97.5% ND as strain recommendation. No significant interaction effect between finisher diet ND and SA on energy and protein efficiency, energy requirement for gain and maintenance and RFI was observed.

3.3 | Carcass and cut-up parts

The effects of experimental treatments on carcass and parts yields, abdominal fat and GIT relative weights are shown in Table 4. In response to increasing finisher diet ND, the breast relative weight

TABLE 3 Gain contain, energy and protein efficiency and residual feed intake (RFI) of male Cobb-500 broilers in response to finisher diet nutrients density and slaughter age.[a]

	Gain contain, %		Efficiencies, %		Feed intake, g/b			Energy requirement, kcal/g gain		
Effects	Fat	Protein	Energy	Protein	OFI	EFI	RFI	Maintenance	Gain	Total
Slaughter age, day										
38	12.40[b]	20.20[a]	49.33[a]	73.14[a]	2210[b]	2483[b]	−272[b]	2.28[b]	2.88[b]	5.16[b]
46	14.82[a]	19.64[b]	45.61[b]	60.76[b]	3463[a]	3718[a]	−255[a]	2.69[a]	3.09[a]	5.78[a]
SEM	0.10		0.17	0.48	15.23	17.15	12.46	0.013	0.008	0.02
Nutrients density[b], %										
92.5	13.80	19.83	46.26[c]	64.21[b]	2860	3108	−248[a]	2.62[a]	3.02	5.64[a]
95.0	13.63	19.91	47.12[b]	66.30[a,b]	2834	3096	−262[a]	2.54[b]	2.99	5.53[b]
97.5	13.33	19.98	47.94[a,b]	68.35[a]	2841	3137	−296[b]	2.44[c]	2.97	5.41[c]
100	13.60	19.92	47.78[a,b]	67.45[a]	2829	3085	−256[a]	2.44[c]	2.99	5.43[c]
102.5	13.49	19.95	48.27[a]	68.44[a]	2821	3075	−255[a]	2.38[d]	2.98	5.36c
SEM	0.16	0.04	0.27	0.76	24.09	27.11	19.70	0.02	0.01	0.03
Source of variation, *p*-value										
Slaughter age	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Nutrients density	0.065	0.071	0.001	0.001	0.818	0.639	0.005	0.001	0.062	0.001
Interaction (SA × ND)	0.480	0.418	0.491	0.495	0.968	0.822	0.113	0.667	0.479	0.512
Nutrients density response										
Linear	0.408	0.407	0.017	0.030	0.888	0.923	0.001	0.004	0.408	0.028
Quadratic	0.477	0.488	0.446	0.489	0.981	0.886	0.001	0.567	0.475	0.526

Note: In each column for each effect, values with different superscripts (a–c) are significantly different ($p < 0.05$).
Abbreviations: EFI, expected feed intake; ND, nutrients density; RFI, residual feed intake; OFI, observed feed intake.
[a]Every values are the means of 30, 12 and 6 replicates for slaughter age, nutrient density and interaction effects, respectively.
[b]Percentage of the nutrient recommendations stated by the Cobb-500 (Cobb-Vantress, 2019) commercial management guide.

(BRW) as a percentage of skinless carcass weight linearly improved ($p < 0.01$). Abdominal cavity fat ($p < 0.01$) and GIT ($p < 0.05$) relative weight as a percentage of LBW linearly decreased with increasing finisher diet ND. No significant ($p > 0.05$) ND effect was observed on carcass, thigh and drumstick weight. Birds slaughtered at 46 days of age showed significantly higher BRW and leg (thigh and drumstick) relative weight than birds slaughtered at 38 days of age ($p < 0.01$). Similarly, relative abdominal fat weight was significantly higher ($p < 0.02$), and relative GIT weight was significantly lower ($p < 0.01$) in the birds slaughtered at older age (46 days) than in younger age (38 days). The interaction effects between SA and finisher diet ND were not significant ($p > 0.05$) for all carcass traits.

3.4 | Breast meat quality

The effects of different treatments on breast meat chemical composition, physicochemical properties, WHC and CL are shown in Table 5. No significant ($p > 0.05$) differences due to finisher diet ND level were observed in the breast meat's chemical composition and its physicochemical properties except breast meat WHC ($p < 0.01$). The breast meat WHC ($p < 0.01$) changed as quadratic polynomial curve in response to decreasing finisher diet ND. The highest WHC values belonged to birds fed a diet with 97.5% ND. The SA had a significant effect ($p < 0.05$) on the breast meat's chemical and physicochemical properties. Breast meat obtained from the chickens slaughtered at 46 days contained significantly higher ether extract and lower moisture ($p < 0.01$) than those slaughtered at 38 days of age. The values of lightness (L^*), redness (a^*) and hue angle (h^*) for the breast meat obtained from chickens slaughtered at 46 days of age were significantly higher, and CL and WHC were significantly lower than those slaughtered at 38 days of age. No significant interaction effect between finisher diet ND and SA on breast meat quality traits was observed.

3.5 | Estimated optimum finisher diet nutrient density

In this study, we investigated the effects of finisher diet ND on energy and protein efficiency, productive and economic performance and breast meat quality of broilers. A critical goal of this study was to optimize the dietary ND of Cobb-500 broiler chickens during the finisher

TABLE 4 Carcass, abdominal fat and gastrointestinal tract relative weight of male Cobb-500 broilers in response to finisher diet nutrients density and slaughter age.[a]

Effects	Thigh and drumstick[b], %	Breast[b], %	Carcass[c], %	Abdominal fat[d], %	Gastrointestinal tract[d], %
Slaughter age, day					
38	29.75[b]	37.66[b]	65.93	1.67[b]	4.66[a]
46	31.15[a]	39.41[a]	66.70	1.97[a]	4.08[b]
SEM	0.22	0.31	0.48	0.08	0.07
Nutrients density[e], %					
92.5	30.89	37.35[b]	66.62	2.01[a,b]	4.68[a]
95.0	30.18	38.20[a,b]	65.99	2.18[a]	4.34[b]
97.5	30.67	38.63[a,b]	66.15	1.67[b,c]	4.34[b]
100	30.49	39.34[a]	66.45	1.53[c]	4.26[b]
102.5	30.04	39.18[a]	66.38	1.72[b,c]	4.25[b]
SEM	0.36	0.49	0.75	0.13	0.11
Source of variation, *p*-value					
Slaughter age	0.001	0.001	0.261	0.016	0.001
Nutrients density	0.443	0.044	0.979	0.006	0.046
Interaction (SA × ND)	0.359	0.136	0.608	0.211	0.219
Nutrients density response					
Linear	0.941	0.009	0.993	0.009	0.035
Quadratic	0.928	0.415	0.656	0.475	0.282

Note: In each column for each effect, values with different superscripts (a–c) are significantly different ($p < 0.05$).
Abbreviation: ND, nutrients density.
[a]Every values are the means of 30, 12 and 6 replicates for slaughter age, nutrient density and interaction effects, respectively.
[b]Calculated as a percentage of carcass weight (skinless).
[c]Calculated as a percentage of live body weight (skinless).
[d]Calculated as a percentage of live body weight.
[e]Percentage of the nutrient recommendations stated by the Cobb-500 (Cobb-Vantress, 2019) commercial management guide.

period. The optimization model was solved using the NLIN program SAS 9.1 procedure. Fitted regression plots for the growth performance traits as a function of finisher diet ND are shown in Figures 1–5. The break-points occurred at 101.7 ± 1.46%, $p < 0.001$ and $R^2 = 0.50$ for WG (Figure 1); 98.72 ± 1.17%, $p < 0.001$ and $R^2 = 0.42$ for FCR (Figure 2); 102 ± 1.02%, $p < 0.001$ and $R^2 = 0.69$ for EPEF (Figure 3), 99.7 ± 3.51%, $p < 0.021$ and $R^2 = 0.13$ for BRW (Figure 4) and 97.51 ± 1.56%, $p < 0.021$ and $R^2 = 0.29$ for RFI (Figure 5).

4 | DISCUSSION

4.1 | Growth performance

Although it was expected that chickens receiving a low dens diet would consume more feed than chickens feed a high dens diet. Current experiment showed broiler chickens could not able to regulate feed consumption concerning to finisher diet ND levels. Feed consumption was nearly the same between birds fed diet with different ND levels. These results are consistent with the reports of some researchers (Sahraei & Shariatmadari, 2007) and in disagreement with the findings of other researchers (Ghazanfari et al., 2010; Teimouri et al., 2005). In modern high-performance broiler chickens, the volume of GIT is the main factor limiting the amount of feed consumption. Broilers eat to almost full-gut capacity (Ebeid et al., 2022), thus suggesting that GIT capacity is the main factor controlling the FI. Additionally, the fact that the low-density mash diet is more massive and less palatable than the high-density mash diet may be the reason for the inability of a bird to regulate its FI.

In the current study, in agreement with other studies (Brickett et al., 2007; Dozier et al., 2007, 2008), the WG, FCR, BEI, EPEF and YUA were significantly affected by finisher diet ND. Growth performance traits linearly were improved by increasing the finisher diet ND. The experimental rations were mashed with different oil content. The highest ND finisher diet contained 60 g/kg soya bean oil, whereas in the lowest ND diet oil level was at 10 g/kg. A higher fat content of the diet improves nutrients digestibility (Cho et al., 2008; Mirshekar et al., 2013) and leads to better performance. Similarly, it has been reported that increased nutrient density increased WG and improved FCR in growing pigs (Meng et al., 2010; Yan et al., 2010) and broilers (Brickett et al., 2007). Depression in dietary amino acid density is another reason for weaker performance in chickens that received the low-density diet

TABLE 5 Breast meat chemical composition, physicochemical properties and water-holding capacity (water holding capacity (WHC), 100% expressible juice) of male Cobb-500 broilers in response to finisher diet nutrient density and slaughter age.[a]

	Chemical composition (% as is)				Physicochemical properties						
Effects	Mo	CP	EE	Ash	L^*	a^*	b^*	h^*	C^*	CL	WHC
Slaughter age, day											
38	73.08[a]	23.14	2.19[b]	1.21	49.31[b]	8.48[b]	10.46	0.33[b]	13.50	31.80[a]	71.92[a]
46	72.04[b]	23.63	2.47[a]	1.12	52.36[a]	9.04[a]	10.21	0.47[a]	13.65	30.39[b]	70.37[b]
SEM	0.23	0.13	0.11	0.03	0.46	0.18	0.19	0.03	0.23	0.43	0.56
Nutrients density[b], %											
92.5	72.57	23.54	2.19	1.15	51.38	8.60	10.31	0.38	13.45	31.20	67.54[b]
95.0	72.52	23.55	2.30	1.12	50.88	8.93	10.25	0.44	13.64	30.65	73.72[a,b]
97.5	73.37	22.95	2.21	1.20	50.64	8.67	10.65	0.35	13.75	30.11	75.73[a]
100	72.72	23.37	2.36	1.08	50.86	9.17	10.47	0.44	13.95	31.54	69.58[a,b]
102.5	72.35	23.53	2.58	1.25	50.42	8.43	9.97	0.41	13.08	31.97	69.15[a,b]
SEM	0.31	0.20	0.17	0.05	0.73	0.28	0.29	0.04	0.36	0.68	0.89
Source of variation, p–value											
Slaughter age	0.011	0.109	0.006	0.090	0.001	0.032	0.349	0.001	0.642	0.026	0.046
Nutrients density	0.110	0.187	0.505	0.177	0.914	0.391	0.563	0.480	0.503	0.346	0.001
Interaction (SA × ND)	0.178	0.110	0.753	0.349	0.608	0.427	0.567	0.186	0.625	0.110	0.069
Nutrients density response											
Linear	0.122	0.117	0.484	0.298	0.850	0.215	0.176	0.948	0.133	0.179	0.001
Quadratic	0.121	0.119	0.469	0.292	0.859	0.213	0.173	0.950	0.122	0.174	0.001

Note: In each column for each effect, values with different superscripts (a and b) are significantly different ($p < 0.05$).
Abbreviations: a^*, Redness; b^*, Yellowness; C^*, Chroma; CL, cooking loss; CP, crude protein; EE, ether extract; h^*, Hue angle; L^*, Lightness; Mo, moisture; ND, nutrients density; WHC, water holding capacity..
[a]Every values are the means of 30, 12 and 6 replicates for slaughter age, nutrient density and interaction effects, respectively.
[b]Percentage of the nutrient recommendations stated by the Cobb-500 (Cobb-Vantress, 2019) commercial management guide.

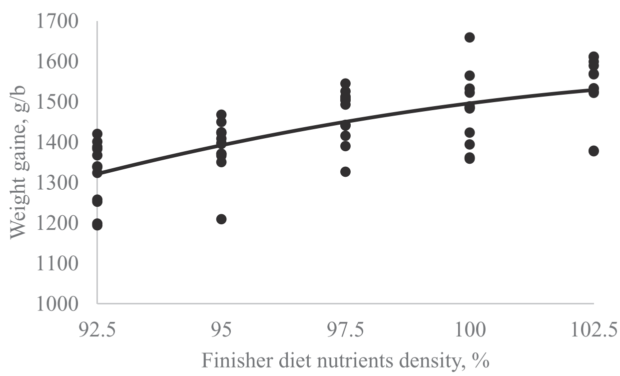

FIGURE 1 Fitted broken-line plot of weight gain (g/bird) of male Cobb-500 broilers during the finisher period as a function of diet nutrients density (% of strain recommendation). $Y = 1534 – 1.345 (101.7 – X) \times I$, $I = 1$ (if $X < 101.7$ or $I = 0$ (if $X > 101.7$), $p < 0.001$ and $R^2 = 0.50$, the break point occurred at 101.7 ± 1.46.

(Mirshekar et al., 2013). It is reported that reducing the dietary amino acid density of broilers during 1–11 (Ghavi et al., 2020), 11–24 (Ghavi et al., 2021), 23–38 (Nikbakhtzade et al., 2020) and 36–59 (Dozier et al., 2006) days of age limited growth rate and adversely affected feed conversion.

In the current study, the BEI values linearly improved with increasing dietary ND. The BEI is a function of WG, diet cost, product cost and FI. Therefore, the higher value of these traits represents a higher economic performance. Unprecedented increases in feed prices over the past several years have prompted the interest of producers in the feasibility of lowering the dietary nutrient level, especially that of CP and ME. There has been extensive study of the effect of diets formulated with suboptimal concentrations of nutrients in modern, high-performing broilers, and these birds usually did not adapt well (Kamran et al., 2008; Zhao et al., 2009). Brickett et al. (2007) and Zhao et al. (2009) reported that dietary density is the most critical nutritional factor in commercial production, not only because it has a significant effect on growth performance, carcass quality and health of broiler chickens but also because it in turn affects the economics of broiler production.

The birds that were slaughtered at 38 days of age showed better growth and economic performance traits than birds that were slaughtered at 46 days of age. In accordance to our result in this experiment,

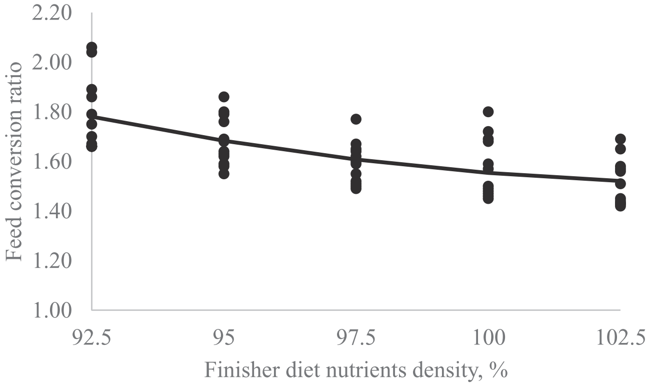

FIGURE 2 Fitted broken-line plot of feed conversion ratio (g feed intake [FI]/g weight gain [WG]) of male Cobb-500 broilers during the finisher period as a function of diet nutrients density (% of strain recommendation). $Y = 1.544 + 0.0382\ (98.72–X) \times I$, $I = 1$ (if $X < 98.72$ or $I = 0$ (if $X > 98.72$), $p < 0.001$ and $R^2 = 0.42$, the break point occurred at 98.72 ± 1.17.

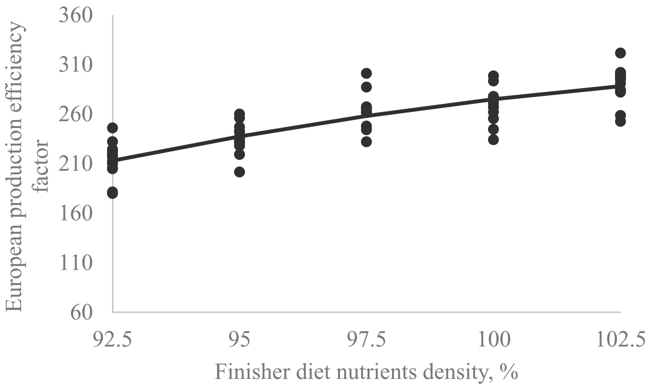

FIGURE 3 Fitted broken-line plot of European production efficiency factor (EPEF) of male Cobb-500 broilers during the finisher period as a function of diet nutrients density (% of strain recommendation). $Y = -7.86 + 290\ (102–X) \times I$, $I = 1$ (if $X < 102$ or $I = 0$ (if $X > 102$), $p < 0.001$ and $R^2 = 0.69$, the break point occurred at 102 ± 1.02. The EPEF calculated as: [viability (%) × Live body weight (kg) × 100]/[age (day) × feed conversion ratio (FCR)].

Albuquerque et al. (2003) evaluated the growth pattern of Ross meal broilers from 1 to 112 days, and they reported growth rate was maximum at day 39 and decreased after day 42 (Albuquerque et al., 2003). Increasing SA from 38 to 46 days significantly deteriorated WG, BEI and FCR. According to the results of this study, the highest daily WG was reported in the female broilers during the days 21–28 and in the male broilers during the days 28–35 of age (Marcato et al., 2008). Increasing SA from 38 to 46 days leads to 4.5% increasing in daily feed consumption (138 g/b vs. 144 g/b). In agreement with the current study, Abougabal and Taboosha (2020) and Goliomytis et al. (2003) reported that daily and cumulative feed consumption increasing continuously with increasing SA. It is a well-known fact that FCR increases as the bird gets older. Schmidt (2008) reported that with the increase in the SA of broiler chickens, the FCR showed an increasing trend of 2.1% per day. The current results fully agree with Abougabal and Taboosha

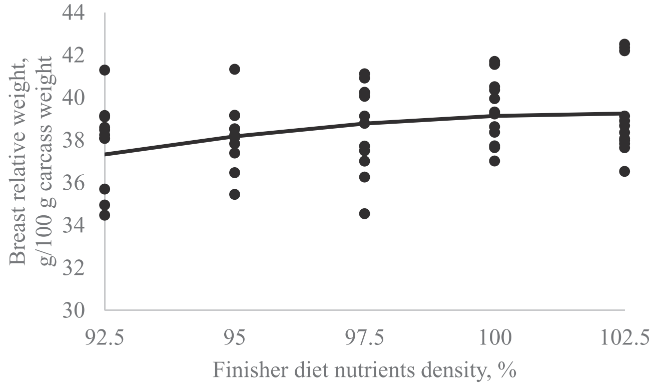

FIGURE 4 Fitted broken-line plot of breast relative weight (g/100 g of carcass weight) of male Cobb-500 broilers during the finisher period as a function of diet nutrients density (% of strain recommendation). $Y = -0.26 + 39.26\ (99.70–X) \times I$, $I = 1$ (if $X < 99.70$ or $I = 0$ (if $X > 99.70$), $p < 0.021$ and $R^2 = 0.13$, the break point occurred at 99.7 ± 3.51.

(2020), who found that FCR increased progressively with age, from 1.54 at day 30 to 2.35 at day 50 of age. On the contrary, delaying the SA from 38 to 46 days reflects a significant ($p < 0.02$) positive effect on YUA. SA changed YUA by about 23% and increased gradually from 36.32 kg/m^2 for the early SA group (38 days) to 44.67 kg for the late SA group (46 days), respectively.

4.2 | Energy and protein efficiency

Improving in the energy and protein efficiency is influenced by increasing in WG and FCR in response to fed dense diets. Diet's energy and nutrient level lead to change in growth rate, body fat and protein deposition. These changes in growth patterns cause modifications in the maintenance and gain requirements rate. Better knowledge of energy requirements and actual energy utilization efficiencies for protein and fat deposition is very important to formulate diets that promote reduction in body fat deposition (Sakomura et al., 2005). In addition, improving the energy and protein retention by increasing finisher diet ND can be the result of reducing physical and metabolic activity, especially GIT, which leads to reduced maintenance requirements (Carré & Méda, 2015; Kamran et al., 2008). It has been reported that the application of feed restriction increases the length of the rearing period to reach a certain weight and thus increases the maintenance requirements (Latshaw & Moritz, 2009). The energy and protein efficiency in the birds that were slaughtered at 38 days of age were 8% and 20% higher than those slaughtered at 46 days of age, respectively. In agree with the current study, it has been reported that protein and fat storage in the body decrease as age increases beyond 42 days (Sakomura et al., 2005). By decreasing finisher diet ND, the RFI has changed with a quadratic polynomial curve. The lowest RFI belonged to the birds fed finisher diet with ND equal to 97.5% of strain suggestion. The birds fed a finisher diet with ND of 97.5% had the lowest RFI, whereas the lowest FCR was shown by the birds fed the finisher diet with 102.5% ND.

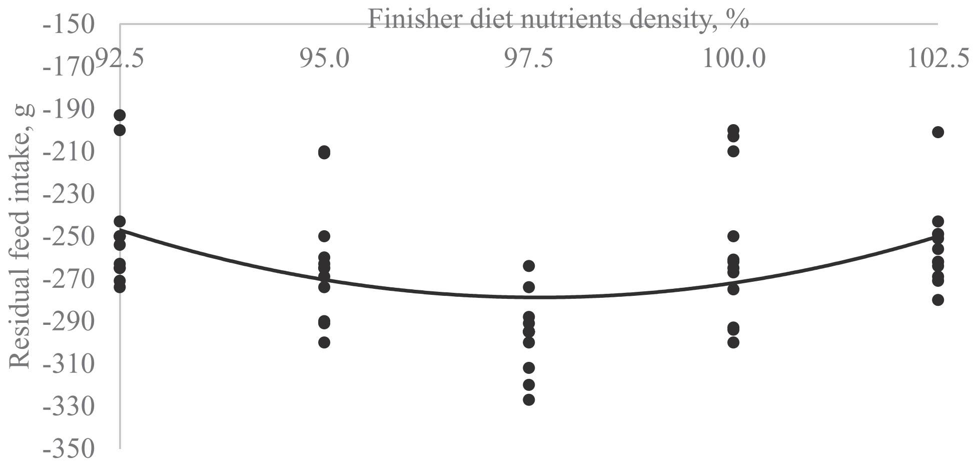

FIGURE 5 Fitted quadratic polynomial plot of residual feed intake (g) of male Cobb-500 broilers during the finisher period as a function of diet nutrients density (% of strain recommendation). $Y = 0.825X^2 - 160.9X + 7580$, $p < 0.021$ and $R^2 = 0.29$, the optimized point occurred at 97.5 ± 1.56.

This may be due to differences in the capability of FCR with RFI in estimating feed efficacy. The RFI is used to indicate the feed efficiency of growing animals. It is concluded as a function of LBW, body WG, gain composition, protein retention efficiency and diet composition (Carré & Méda, 2015). The RFI is the difference between the actual animal FI and its estimated FI determined by the growth rate and mean body weight. The FI of high RFI individuals is higher than that of low RFI individuals. Therefore, using the RFI as a trait is more likely to produce a condition with low FI and high productivity (Yi et al., 2018). The use of RFI index in feed efficiency tests can be more usefulness than FCR (Van der Werf, 2004).

4.3 | Carcass and cut-up parts

In agreement with the current experiment result, the reported relative carcass weight of broiler chicks was not influenced by dietary ND (Corduk et al., 2007; Onbaşılar et al., 2009). The finisher diet ND shows a significant effect on RBW, abdominal fat accumulation and relative GIT weight. In agreement with our result, reported GIT weight of broiler chicks was not influenced by dietary energy level (Rabie et al., 2017). In general, FI increases with the dilution of nutrient density. However, birds may have difficulty maintaining energy intake with high levels of dilution (Nielsen, 2004), which may adversely affect growth rate, and feeding a low-density diet during the finisher period leads to reduced abdominal fat accumulation (Washburn, 1990).

The current experiment data reveals a significant effect of chickens' age on their relative carcass parts weight ($p < 0.01$). Birds slaughtered at 46 days showed significantly higher relative legs (thigh + drumstick) and breast weight as a percentage of carcass weight than birds slaughtered at 38 days of age. In agreement with our result, reported SA affects broiler performance, carcass traits and carcass cut-up (Cobb-Vantress, 2019). Greater breast proportions with increasing the age of chicken were noticed by many authors (Abougabal & Taboosha, 2020; Baeza et al., 2012; Połtowicz & Doktor, 2012; Young et al., 2001). These results are compatible with the results drawn from the study of Abougabal and Taboosha (2020), who defined that SA had a positive and significant effect on the relative breast and edible parts weight.

Consumer habits have globally transformed into a strong preference for carcass cut-up (parts) and processed poultry meat. Subsequently, the market for carcass pieces has surpassed the whole carcass market. As more giant chicken provide larger breast, it has resulted in a late broilers SA for producing professional breast meat (Schmidt, 2008). Breast fillets are the most economically part of the carcass. Abdominal fat accumulation was higher in the birds slaughtered at 46 days than in birds slaughtered at 38 days of age. Similarly reported, the relative abdominal fat weight in the birds slaughtered an older age was higher than those a younger age (Połtowicz & Doktor, 2012; Young et al., 2001). Excessive fat in modern poultry strains has been one of the significant problems in the broiler industry (Zhou et al., 2006). The rearing broiler until later old and higher weight is associated with higher abdominal fat deposition (Lippens et al., 2000).

4.4 | Breast meat quality

The broiler meat market shifted towards attaining yield characteristics for increased breast weight (Young et al., 2001). Concerning to breast meat quality properties, by increasing finisher diet ND up to 75.7%, the WHC increased. WHC influences the sensory quality of meat because water loss during cooking can affect the juiciness and tenderness of meat (Abougabal & Taboosha, 2020). Therefore, meat with a low WHC that loses large amounts of fluid during cooking may taste dry (Sarica et al., 2019). In this study, the WHC of breast meat was significantly affected by the SA. Similar observations were also found by the previous researcher. They found that breast and thigh meat WHC values were significantly affected by SA (Abougabal & Taboosha, 2020; Sarica et al., 2019). CL and WHC will also be important meat quality characteristics affecting consumer preferences (Mikulski et al., 2011).

Data shows that the moisture in chicken breast meat decreased from 73.08% to 72.04% when the SA increased from 38 to 46 days of age. Muscle moisture directly affects the meat-eating quality as the tenderness and succulence. In agreement with our results, as found, the aged chicken had lower muscle moisture (Abougabal & Taboosha, 2020; Baeza et al., 2012; Yi-ping et al., 2016). In contrast with moisture, the ether extract content of chicken meat increased as the age of slaughter increased. Ether extract tended to be significantly higher in older than in younger chickens. These results are in with another researcher who reports that moisture content decreased, lipid content regularly increased for broiler breast, thigh and drumstick increased with their age (Abougabal & Taboosha, 2020; Baeza et al., 2012; Yi-ping et al., 2016).

The current study results showed that dietary ND and interaction effects between finisher diet ND and SA had no significant effect on breast meat colour ($p > 0.05$). These findings agree with those reported that dietary ND has no significant effect on meat colour (Fanatico et al., 2007; Mirshekar et al., 2013). The birds slaughtered at 46 days showed a positive sign of breast meat L^*, a^* and h^*. Birds slaughtered at 46 days typically had redder meat than those slaughtered at 39 days of age. Myoglobin content of the tissue is a major factor contributing to poultry meat colour and depends on species, muscle and age of the bird (Fanatico et al., 2007). Moreover, reported meat colour might be affected by fillet thickness (Fletcher, 2002) and the difference in muscle fibre type (Lonergan et al., 2003). Muscle fibre, biochemical and structural characteristics can be independently manipulated by intrinsic and extrinsic factors to improve meat quality (Listrat et al., 2016). These muscle fibres are distinguished by their morphological traits, metabolic and contractile properties (Joo et al., 2013).

4.5 | Estimated optimum finisher diet nutrient density

Based on the current study, predicted finisher diet ND for optimal growth performance traits was estimated at 97.5%–102.0% of strain recommendation. It has been confirmed in various kinds of research that the environmental conditions, genetic lines, FIs, dietary energy and nutrient levels, variant feed ingredients, bird's age and numerous estimation methods are all factors that can affect nutrient requirements (Leeson & Summers, 2001; Maharjan et al., 2020; Rao et al., 2011). The model proposed in this study includes the effect of finisher diet energy and nutrient composition, which affects body composition and energy utilization efficiencies of protein and fat deposition (Wang et al., 2017). This factor improves the accuracy of predicting energy and nutrient requirements. Modern commercial broilers have been genetically improved for increased final LBW, feed efficiency and relative breast muscle weight. Thus, it is necessary to update the nutrient requirements of broilers to produce the highest performance and meat production (Fouad & El-Senousey, 2014).

5 | CONCLUSIONS

In the current experiment, the finisher's diet nutrient density was investigated on growth performance, carcass parts and breast meat quality of broiler chickens. The result has shown that broilers during the finisher period have a relatively limited capability for increasing their feed consumption following diet dilution. Therefore, it is not allowed to reduce the concentration of dietary energy and nutrient concentration below a specific limit. The energy and protein efficiency and BEI were reduced when broilers were fed with diluted diet or the rearing period was prolonged. Nutrient density of diet did not affect meat quality traits. Formulation broiler chicken's finisher diet with nutrients concentration lowers than 97.5% of strain recommendation is unsuitable. RFI methodology can be a viable alternative to measure dietary energy efficiency.

AUTHOR CONTRIBUTIONS

Heydar Zarghi and Mahdie Nikbakhtzade designed and carried out the experimental trail. Mahdie Nikbakhtzade carried out the experimental trail lab analysis. Heydar Zarghi performed the statistics, tabulated the data, wrote the draft, and reviewed the manuscript. Abolghasem Golian reviewed the manuscript.

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CONFLICT OF INTEREST STATEMENT

No potential conflict of interest was reported by the authors.

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DECLARATIONS

The authors declare that all of the authors listed in the manuscript are employed at an academic or research institution where research or education is the primary function of the entity. Moreover, this manuscript is independently submitted by the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

The authors confirm that the ethical policies of the journal, as noted in the journal's author guidelines page, have been adhered to and the appropriate ethical review committee approval has been received. The authors confirm that they have followed EU standards for the protection of animals used for scientific purposes and feed legislation.

ORCID

Mahdie Nikbakhtzade https://orcid.org/0000-0002-1502-879X
Heydar Zarghi https://orcid.org/0000-0002-2739-2580
Abolghasem Golian https://orcid.org/0000-0001-9419-1175

PEER REVIEW

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