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Original Article

Performance and Egg Quality of Commercial Laying Hens Fed Diets Formulated Using Non-Linear Programming

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ABSTRACT

Feed formulation using linear programming consists of determining the mixture of feedstuffs required to meet pre-established animal nutritional requirements at the lowest cost. On the other hand, with the use of non-linear programming, it is possible to define nutritional requirements at the time of formulation, aiming at maximum profit. The objective of the present study was to compare feeds formulated using linear and non-linear programming in terms of live performance and internal and external egg quality of commercial laying hens. A total of 288 Hisex® White laying hens, 1.540 ± 0.128 g body weight, were evaluated from 33 to 45 weeks of age. Hens were distributed in a completely randomized block design, including six treatments with six replicates of eight birds each. Three treatments consisted of feeds formulated using linear programming and based on the nutritional requirements of Rostagno *et al.* (2011), of the genetic strain manual, or mathematical models to maximize performance. The other three treatments consisted of feeds formulated using non-linear programming considering typical, favorable, or unfavorable market scenarios. Data were submitted to analysis of variance, and in case of significance ($p<0.05$), means were grouped using the Scott-Knott test (5%).The treatments did not influence ($p>0.05$) Haugh unit, albumen height, or external egg quality parameters. Treatment effects ($p<0.05$) on yolk weight, albumen weight, yolk color, yolk percentage, albumen percentage, and performance parameters were described. In general, feeds formulated using linear programming and based on nutritional requirements obtained by mathematical models and the genetic strain manual promoted better performance results because the feeds were nutritionally denser. However, the treatments that maximized live performance did not result in higher profitability, which was obtained with the diet formulated for a favorable market scenario using non-linear programming.

INTRODUCTION

Feed cost is the most limiting factor of poultry production systems, and accounts for more than 60% of the total production cost. The feed formulation strategy adopted by the industry is that of least cost, using linear programming. This method combines different feedstuffs in order to meet the nutritional requirements pre-established by the nutritionist at the lowest possible cost (Saxena, 2011).

However, the nutrient levels required for profit maximization are lower than those required to obtain optimal animal performance (Eits *et al.*, 2005b). The use of non-linear programming allows establishing the nutritional requirement needed to maximize production profitability during feed formulation. Cerrate & Waldroup (2009), using non-linear programming, simulated changes in the nutritional density of the feed and observed that, when corn and chicken prices were high, dietary nutrient density also increased. However, when the prices of soybean meal and oil increased, dietary nutritional density decreased. Therefore, non-linear programming consists of a flexible feed formulation procedure that considers the market scenario without the need of pre-establishing the animal's nutritional requirements during feed formulation.

In order to apply the non-linear feed formulation, bird performance as function of dietary nutrient levels need to be predicted using mathematical models, which should preferably be obtained from more than one set of data (Eits *et al.*, 2005a). Those models may be obtained by meta-analytical procedures (ST-Pierre, 2007) and can be used in feed formulation using non-linear programming with acceptable results (Faria Filho *et al.*, 2008).

Guevara (2004) applied non-linear programming in broiler feed formulation, and was able to determine the metabolizable energy level required to maximize profit, depending on the market scenario. Gonçalves *et al.* (2015) employed mathematical models considering dietary metabolizable energy level, and broiler sex and age to formulate feeds using non-linear programming to maximize profit as a function of market scenarios. Dadalt *et al.* (2015) conducted an experiment comparing feeds formulated using linear and non-linear programming for male and female chickens housed at densities of 10 and 14 birds/m². Their results showed that non-linear programming resulted in worse feed conversion ratio, but in higher profit.

Few studies on non-linear programming for the formulation of commercial layer diets have been conducted. Afrouziyeh *et al.* (2010) and Afrouziyeh *et al.* (2011) utilized commercial laying hens from 24 to 32 weeks of age and from 32 to 44 weeks of age, respectively, and formulated feeds using non-linear programming, adjusting dietary metabolizable energy levels to maximize profit, according to feedstuff prices and prices paid per egg. In order to test their model, the authors increased and decreased egg, corn, and soybean meal prices by 25%, and the program corrected the ideal metabolizable energy for maximum profit, showing to be more profitable than linear programming.

The objective of the present experiment was to compare non-linear programming (maximum profit) with linear programming (minimum cost) for commercial layer feed formulation in terms of their economic and productive performance, as well as egg quality. A multiple polynomial mathematical model, which simultaneously considers metabolizable energy, crude protein content, calcium, available phosphorus, sodium, digestible methionine+cystine, digestible lysine, and digestible tryptophan, was applied.

MATERIAL AND METHODS

The experimental procedures were approved by the Ethics Committee for Animal Use of the School of Animal Science and Food Engineering of the University of São Paulo (FZEA/USP), in Pirassununga, São Paulo, Brazil, under protocol number 5048060215.

Birds, experimental design and management

The present study was carried out in the poultry sector of FZEA/USP. A total of 288 Hisex® White layers between 33 and 45 weeks old, with 1.540 ± 0.128 g average body weight, were used. Hens were distributed according to a completely randomized block design into six treatments with six replicates of eight birds each, totaling 36 experimental units. The randomized block design was applied in order to control differences in egg production between the plots at the beginning of the experiment.

Hens were housed in galvanized-wire cages (100-cm long x 40-cm wide x 45-cm high) placed in a masonry shed with clay tiles, and sides closed with galvanized-steel screens. Each cage was divided in four compartments of 1,000 cm² of floor area each, housing two hens each, resulting in a floor area of 500 cm²/hen. Therefore, the experimental unit consisted of a cage with four compartments, totaling eight hens each.

The shed was equipped with side curtains and ventilation fans, which were managed according to weather conditions to provide thermal comfort. Average maximum and minimum temperature and air relative humidity values recorded were 29.31°C and 16.21°C, and 62.46% and 27.23%, respectively. A lighting program of 16h30min of light per day was applied, and hens were offered water and feed *ad libitum*. Other management practices followed the strain manual (Hisex®, 2010).

Description of the treatments

The six experimental treatments consisted of: 1) minimum cost feed formulated according to the nutritional requirements proposed by Rostagno *et al.*

(2011); 2) minimum cost feed formulated according to the nutritional requirements recommended by the strain manual (Hisex®, 2010); 3) minimum cost feed formulated according to the nutritional requirements obtained by the average of the first partial derivative equal to zero of the mathematical models proposed by Faria Filho *et al.* (2015) for egg production, egg mass and feed conversion ratio (Table 1); 4) profit maximization feed formulated according to the typical market scenario; 5) profit maximization feed formulated according to a favorable market scenario, and 6) profit maximization feed formulated according to an unfavorable market scenario.

The minimum cost feeds (Treatments 1 to 3), were formulated using conventional feedstuffs and their prices in June, 2015, in the State of São Paulo, Brazil. The following prices were used: corn US$ 0.15/kg, soybean meal US$ 0.33/kg, soybean oil US$ 0.74/kg, dicalcium phosphate US$ 0.57/kg, calcitic limestone US$ 0.10/kg, common salt US$ 0.07/kg, DL-methionine US$ 5.72/kg, L-lysine US$ 3.56/kg, and vitamin-mineral premix US$ 2.56/kg. The simplex algorithm, a linear programming technique, was adopted to minimize the objective function, which was the feed price, established the following restrictions: i) non-negativity of the feedstuffs; ii)premix fixed at 0.3%; iii) 100% feedstuff sum, and (iv) accurate monitoring of metabolizable energy, crude protein, calcium, available phosphorus, sodium, digestible methionine+cystine, and lysine requirements, and compliance with the minimum digestible tryptophan requirement. The feeds were formulated using the Professional Plus 2013 version of Microsoft Excel®, aided by the Solver® supplement, in its default settings.

The mathematical models proposed by Faria Filho *et al.* (Table 1) were applied to determine the nutritional requirements in treatments 3 to 6. These are meta-analytical models and were developed based on 93 scientific articles published in Brazil and abroad, totaling 103 experiments. Egg production (%/bird/day), egg mass (g/bird/day), and feed conversion ratio (g/g) were used as the dependent variables of the models. The independent variables were laying cycle phase (phase 1 = up to 32 weeks; phase 2 = 33-45 weeks; phase 3 = 46-58 weeks, or phase 4 = 59 weeks until culling), egg variety (white or brown), electrolyte balance (55 to 257 meq/kg), metabolizable energy intake (178 to 373 kcal/day), calcium intake (1.96 to 6.30 g/day), available phosphorus intake (85 to 584 mg/day), sodium intake (85 to 321 mg/day), crude protein intake (5.74 to 22.92 g/day), digestible methionine+cystine intake (220 to 905 mg/day), digestible lysine intake (302 to 1.062 mg/day), and digestible tryptophan intake (73 to 269 mg/day). Each experiment entered the model as a random variable, and the independent variables were considered as fixed effects (St-Pierre, 2007). The models were adjusted using the SAS PROC MIXED program, and the parameters were estimated by the maximum likelihood method and maintained at $p<0.05$.

Regarding the formulation of maximum profit feeds, applied in treatments 4 to 6, the procedures described by Guevara (2004) were used. A spreadsheet was developed using the Professional Plus 2013 version of Microsoft Excel®, and the configurations of the Solver® supplement were: optimization method = non-linear GRG (; derivatives = central; initialization = multiple start, and other default options. The objective function to be maximized was the Profit function (P), calculated as the difference between the revenue (Egg x Egg_Price) and feed cost ((Feed x Feed_Price)/0.70), detailed as follows:

P (US$/bird/12weeks) = {(Eggx Egg_Price)–[(Feed x Feed_Price)/0.70]}

Where:

Egg = number of cartons of 30 dozen eggs produced in 12 weeks. This variable is calculated using the mathematical model proposed by Faria Filho *et al.* (2015) for egg production (Table 1), and, therefore, it is dependent on egg production phase, egg variety, and levels of nutrients that compose the model.

Egg_Price = price paid per carton of 30 dozen eggs (US$/30 dozen), dependent on the market scenario at the time of feed formulation.

Feed = feed intake per bird during 12 weeks (g/bird/12 weeks). This variable is calculated using the mathematical model proposed by Faria Filho *et al.* (2015) for feed intake (Table 1), and is, therefore, dependent on the phase, egg variety, and nutrient levels that compose the model.

Feed_price = price per kg of feed (US$/kg), dependent on the market scenario at the time of formulation, determined during the feed formulation process.

Throughout the feed formulation process, the decision variables were the feedstuffs and nutrients included in the mathematical models (Table 1) for egg production and feed intake. Thus, during the process, the nutritional levels that would maximize profit were defined, in addition of determining the feed formula. The following restrictions were imposed on the model: i) non-negativity of the feedstuffs; ii) premix fixed at 0.3%; iii) 100% feedstuff sum.

Table 1 – Regression parameters of meta-analytical models[1] for egg production, egg mass, and feed conversion ratio of laying hens.

	Egg production (%/hen/day)			Egg mass (g/hen/day)			Food conversion ratio(g/g)		
	Parameters	SEM[3]	*p*-value	Parameters	SEM	*p*-value	Parameters	SEM	*p*-value
Intercept	-75.99	8.535	<.0001	-58.47	5.925	<.0001	5.22	0.322	<.0001
Phase									
1 (18 to 32 weeks)	11.29	0.759	<.0001	2.30	0.567	<.0001	-0.123	0.0283	<.0001
2 (33 to 45 weeks)	10.29	0.614	<.0001	3.75	0.465	<.0001	-0.162	0.0234	<.0001
3 (46 to 58 weeks)	5.10	0.687	<.0001	1.91	0.511	0.0002	-0.099	0.0262	0.0002
4 (59 weeks to discard)	0	-	-	0	-	-	0	-	-
Egg color									
White	2.37	0.484	<.0001	-	-	NS	-0.0437	0.01869	0.0196
Brown	0	-	-	-	-	-	0	-	-
Linear effect[2]									
Metabolizable energy	0.3488	0.18500	<.0001	0.3883	0.05052	<.0001	-0.0160	0.00290	<.0001
Calcium	7.2869	2.71480	0.0074	-	-	NS	-	-	NS
Available phosphorus	0.0636	0.01095	<.0001	0.0372	0.00826	<.0001	-	-	NS
Sodium	-	-	NS	0.0654	0.02231	0.0035	-	-	NS
Electrolyte balance	0.0797	0.03985	0.0460	-	-	NS	-	-	NS
Crude protein	-	-	NS	-	-	NS	-0.1077	0.02141	<.0001
Digestible methionine+cysteine	0.0552	0.01444	<.0001	-	-	NS	-	-	NS
Digestible lysine	0.0502	0.02079	<.0001	-	-	NS	-	-	NS
Digestible tryptophan	0.1778	0.04550	<.0001	0.2380	0.02627	<.0001	-	-	NS
Quadratic effect[2]									
Metabolizable energy	-0.0005	0.00014	<.0001	-0.0005	0.00009	<.0001	0.00003	0.000001	<.0001
Calcium	-0.6935	0.31610	0.0286	-	-	NS	-	-	NS
Available phosphorus	-0.0001	0.00002	<.0001	-0.00006	0.000013	<.0001	-	-	NS
Sodium	-	-	NS	-0.00013	0.000056	0.0196	-	-	NS
Electrolyte balance	-0.00033	0.000131	0.012	-	-	NS	-	-	NS
Crude protein	-	-	NS	-	-	NS	0.00317	0.000687	<.0001
Digestible methionine+cysteine	-0.00003	0.000011	<.0001	-	-	NS	-	-	NS
Digestible lysine	-0.00003	0.000001	<.0001	-	-	NS	-	-	NS
Digestible tryptophan	-0.00048	0.000124	<.0001	-0.00056	0.000075	<.0001	-	-	NS

[1]Adaptedfrom Faria Filho et al. (2015).

[2]Metabolizable energy= 178 to 373 kcal/day; calcium = 1.96 to 6.30 g/day; available phosphorus = 85 to 584 mg/day; sodium = 85 to 321 mg/day; electrolyte balance = 55 to 257 meq/kg; Crude protein= 5.74 to 22.92 g/day; methionine+cysteine = 220 to 905 mg/day; lysine = 302 to 1,062 mg/day; tryptophan = 73 to 269 mg/day.

[3]SEM = Standard error of the mean.

NS = Not significant.

Feeds of treatments 4 to 6 included conventional feedstuffs, considering the previously-described market scenario for typical corn and soybean meal prices, and the price of US$ 18.15 per 30 dozen eggs. Regarding the favorable economic scenario, corn and soybean prices were reduced by 20% and the price paid per 30 dozen eggs was increased by 20%. For the unfavorable economic scenario, corn and soybean meal prices were increased by 20%, and the price paid per 30 dozen eggs was devalued by 20%. The experimental feeds are presented in Table 2.

Evaluated characteristics

Performance parameters and internal and external egg quality traits were evaluated at the end of each of the three 28-day cycles. The obtained results represent an average of the three cycles.

The evaluated performance parameters evaluated were feed intake (g/bird/day), egg production (%/bird/day), egg weight (g), egg mass (g/bird/day), and feed conversion ratio (g/g). Feed intake was calculated as the difference between feed offer at the beginning and feed residue at the end of the evaluation period. Egg production was measured by recording daily egg production and expressing the results as a percentage of the number of housed birds. Egg weight was measured on a precision scale (model AS5000C, Marte; 0.01-g accuracy), weighing the entire egg production on the evaluation day and calculating the mean per replicate. Egg mass was determined by multiplying egg

Table 2 – Experimental diets fed to 33- to 45-wek-oldlaying hens.

	Linear feed formulation			Non-linear feed formulation		
	Rostagno[1]	Hisex[2]	Model[3]	Typical[4]	Favorable[5]	Unfavorable[6]
Feedstuffs(g/kg^{-1})						
Corn	612.3	539.9	498.4	667.3	670.3	674.3
Soybean meal 45%	247.1	296.2	288.2	194.0	206.5	185.2
Soybean oil	25.3	40.6	58.6	10.0	10.0	10.0
Limestone	9.4.4	99.2	129.3	104.5	91.4	105.8
Dicalcium phostate	10.82	15.30	11.98	13.30	12.17	13.33
Sodium chloride	05.11	04.11	05.90	04.30	04.23	04.35
DL-methionine 98%	01.97	01.72	04.59	02.80	02.39	02.85
L-lysine HCl 78%	0	0	0.06	00.80	0	01.17
Premix[7]	3.00	3.00	03.00	03.00	03.00	03.00
Total (kg)	1000	1000	1000	1000	1000	1000
Calculated composition (as-fed basis)						
Metabolizable energy(kcal/kg)	2850	2850	2850	2782	2820	2785
Crude protein	160.0	176.5	169.6	140.3	146.2	136.9
Calcium	39.00	42.00	52.50	43.30	38.10	43.80
Available phosphorus	02.90	03.80	03.14	03.30	03.10	03.30
Sodium	02.20	01.80	02.50	01.90	01.90	01.90
Digestible lysine	07.51	08.64	08.40	06.91	06.62	06.95
Digestible methionine+cysteine	06.50	06.60	09.20	06.88	06.58	06.80
Digestible tryptophan	01.74	01.99	01.92	01.46	01.53	01.41
Price (USD/ton)	217.1	234.9	256.5	206.9	172.1	237.5

[1]Nutritional requirement according to Rostagno et al. (2011).

[2]Nutritional requirement according to the Hisex® Management Guide.

[3]Nutritional requirement obtained by the first partial derivative of the models (Table1).

[4]Market scenario in March, 2015 in São Paulo, Brazil, considering corn and soybean meal prices and price paid for 30 dozen eggs.

[5]Market scenario (20% better than Typical[4]).

[6]Market scenario (20% worse than Typical[4]).

[7]Levels per kg of product: vitamin A: 2333.33 IU; vitamin D_3: 666670 IU; vitamin E: 1666.67 IU; vitamin K_3: 533,330 mg; vitamin B_2: 1,000 mg; vitamin B_{12}: 2,666.67 mcg; niacin: 6,666.67 mg; choline: 78.120 g; pantothenic acid: 1,666.67 mg; copper: 2,666.7mg; iron:16.670 g; manganese: 23.330 g; zinc: 16.670 g; iodine: 400 mg; selenium: 66.670 mg; bacitracin zinc: 6,666.67mg.

production by egg weight. Lastly, feed conversion ratio was calculated as the ratio between feed intake and egg mass.

Internal egg quality was evaluated in four eggs per experimental unit using a Digital EggTester® device (model DET6000, Nabel, Japan) to determine egg weight (g), eggshell breaking strength (kgf), yolk color (YCF), albumen height (mm), and Haugh unit. Yolk and albumen were manually separated, weighed on a precision scale (model AS5000C, Marte, Brazil; accuracy of 0.01 g), and expressed as percentages of the fresh egg. Eggshell thickness (mm), eggshell percentage (% of the fresh egg), and egg specific gravity (g/mL) were also determined. In order to calculate eggshell percentage and thickness, the eggshell membranes were manually removed, left to dry at room temperature for 24 h, and measured using a micrometer (Mitutoyo, Japan; 0.001-mm accuracy). The specific gravity was obtained by immersing the eggs in 20-L buckets with specific gravity ranging from 1.060 to 1.100 at 0.005 intervals.

Statistical analysis

The data were checked for the presence of outliers, and then analyzed for error typicality (Cramer-Von-Mises test) and variance homogeneity (Brown-Forsythe test). After these assumptions were met, data were submitted to analysis of variance using the RStudio® program (R Core Team, 2015) and, in case of significance ($p<0.05$), the Scott-Knott test was applied (Scott & Knott, 1974).

RESULTS

The performance results are shown in Table 3. Lower feed intake and higher egg production ($p<0.05$) where obtained when hens were fed the Models treatment compared with the other treatments, which were not statistically different. The best egg mass, egg weight, and feed conversion ratio results ($p<0.05$) were determined with the Model treatment, followed by the Hisex® treatment, while no differences were detected among the other treatments. Lastly, the Favorable

Table 3 – Live and economic performance of laying hens fed with diets formulated using linear and non-linear programming, from 33 to 45 weeks of age.

Variables	Linear feed formulation			Non-linear feed formulation			SEM[7]	*p*-value	
	Rostagno[1]	Hisex[2]	Models[3]	Typical[4]	Favorable[5]	Unfavorable[6]		Treatment	Block
Feed intake (g)	109.4[a]	107.1[a]	103.5[b]	108.8[a]	110.5[a]	110.4[a]	0.557845	0.0005	0.5978
Egg production (%/hen/day)	95.2[b]	94.5[b]	97.6[a]	94.3[b]	95.5[b]	95.5[b]	0.290637	0.0167	0.8571
Egg weight (g)	60.1[c]	62.1[b]	64.1[a]	59.6[c]	60.4[c]	59.6[c]	0.361912	<.0001	0.4377
Egg mass (g/hen/day)	57.2[c]	58.7[b]	62.6[a]	56.2[c]	57.7[c]	56.9[c]	0.433881	<.0001	0.4041
Feed conversion	1.913[a]	1.825[b]	1.653[c]	1.936[a]	1.915[a]	1.940[a]	0.019651	<.0001	0.2008
Profit (US$/hen/12 weeks)	1.53[b]	1.40[c]	1.40[c]	1.59[b]	2.24[a]	1.01[d]	0.193704	<.0001	0.7595

[1]Nutritional requirement according to Rostagno et al. (2011).

[2]Nutritional requirement according to the Hisex® Management Guide.

[3]Nutritional requirement obtained by the first partial derivative of the models (Table1).

[4]Market scenario in March, 2015 in São Paulo, Brazil,regarding corn and soybean meal prices and price paid for 30 dozen eggs.

[5]Marketscenario (20% better than Typical[4]).

[6]Market scenario (20% worse than Typical[4]).

[a,b,c,d] Values within a row with different superscripts differ significantly at P<0.05 by the Scott-Knott test.

[7]SEM = Standard error of the mean.

treatment yielded the highest net income ($p<0.05$), followed by the Typical and the Rostagno treatments, then by the Hisex® and Models treatments, with the lowest value obtained with the Unfavorable treatment.

The internal and external egg quality results are shown in Table 4. Relative to internal egg quality, the highest yolk weight ($p<0.05$) was observed in hens fed the Models and Favorable treatments, but was not different among the other treatments. The highest albumen weight ($p<0.05$) were observed when the Model and Hisex® treatments, but no differences among the other treatments was determined. The three non-linear programming treatments displayed higher yolk color values ($p<0.05$) than the other treatments. The yolk percentage was higher ($p<0.05$) in the treatments using non-linear programming, whereas the percentage of albumen was higher ($p<0.05$) when using the linear programming treatments. Albumen height, Haugh

Table 4 – Egg quality of laying hens fed with diets formulated using linear and non-linear programming from 33 to 45 weeks of age.

Variables	Linear feed formulation			Non-linear feed formulation			SEM[7]	*p*-value	
	Rostagno[1]	Hisex[2]	Models[3]	Typical[4]	Favorable[5]	Unfavorable [6]		Treatment	Block
Internal quality									
Yolk weight (g)	15.98[b]	15.94[b]	16.73[a]	16.07[b]	16.35[a]	16.16[b]	0.075159	0.0247	0.8881
Albumen weight (g)	35.33[b]	36.90[a]	37.21[a]	34.06[b]	34.55[b]	33.93[b]	0.285353	0.00004	0.2647
Albumen height (mm)	7.71	8.03	8.33	7.91	8.03	7.75	0.061876	0.0500	0.4857
Yolk color	5.98[a]	5.40[b]	5.40[b]	6.14[a]	6.074[a]	6.15[a]	0.058726	<.0001	0.9756
Haugh unit	87.36	88.46	90.10	88.92	89.35	87.76	0.347468	0.2094	0.3787
Yolk (%)	26.21[b]	25.28[b]	25.77[b]	26.97[a]	26.96[a]	27.01[a]	0.149892	0.0004	0.3701
Albumen (%)	57.83[a]	58.37[a]	57.81[a]	56.94[b]	56.83[b]	56.61[b]	0.187978	0.0292	0.3734
External quality									
Specific gravity(g/cm^3)	1.089	1.088	1.088	1.087	1.088	1.089	0.000299	0.3879	0.4111
Eggshell weight (g)	9.87	10.11	9.66	9.35	9.04	9.31	0.175173	0.5571	0.5851
Eggshell thickness (mm)	0.407	0.400	0.408	0.405	0.403	0.406	0.001216	0.3864	0.2512
Eggshell resistance (kgf)	4.52	4.56	4.62	4.43	4.45	4.65	0.045433	0.5566	0.0383
Eggshell (%)	15.96	16.36	16.08	16.10	16.21	15.89	0.142193	0.9196	0.5427

[1]Nutritional requirement according to Rostagno et al. (2011).

[2]Nutritional requirement according to the Hisex® Management Guide.

[3]Nutritional requirement obtained by the first partial derivative of the models (Table1).

[4]Market scenario in March, 2015 in São Paulo/Brazil regarding prices of corn and soybean meal, and price paid for 30 dozen eggs.

[5]Market scenario (20% better than Typical[4]).

[6]Market scenario (20% worse than Typical[4]).

[a,b] Values within a row with different superscripts differ significantly at P<0.05 by the Scott-Knott test.

[7]SEM = Standard error of the mean.

units, and external egg quality parameters were not influenced by the experimental treatments ($p>0.05$).

DISCUSSION

A metabolizable energy level of 2,850 kcal/kg was established for the diets formulated by linear programming. However, when adjusted by non-linear programming to maximize profit, dietary metabolizable energy levels were lower than those generated by linear programming. Feed intake is influenced by dietary energy density: when the diet contains lower or higher energy levels than the animal's requirements, it increases or reduces its feed intake, respectively, in order to meet its requirements (Leeson *et al.*, 2001; Morris, 2004; Leeson & Summers, 2009). The lower feed intake observed when the Models treatment was applied may be explained by its high energy content (Leeson *et al.*, 2001), as well as by its high oil inclusion, as the presence of lipids in the duodenum promotes the perception of satiety (Ravindran *et al.*, 2016).

The higher production and egg mass achieved when using the Models treatment is mainly due to the greater nutritional contribution of this feed. These results are in agreement with those observed by Persio *et al.* (2015), who verified higher egg production and egg mass when dietary energy and nutrient density increased. The high protein level of the Models treatment possibly allowed greater albumen deposition (Leeson & Summers, 2009), which resulted in higher egg mass. The energy levels of the feeds formulated using linear programming were the same, although the amount of oil, included as an energy source, was higher in the Models treatment. It is known that lipids, due to their extra-caloric effect, enhance the utilization of dietary nutrients and energy (Leeson & Summers, 2009), which may explain the higher egg production obtained with this treatment.

The lower feed intake and higher egg mass observed in the Models treatment resulted in improved feed conversion ratio. However, optimal feed conversion ratio does not necessarily mean lower production costs (Dadalt *et al.*, 2015). The Favorable treatment resulted in worse feed conversion compared with the Models treatment, but generated higher profit. According to Eits *et al.* (2005b), the nutritional levels required to maximize profit do not always match those required for maximum performance, as observed in the feeds formulated using non-linear programming for maximum profits, which contained lower nutrient levels. According to Leeson *et al.* (2001) and Heydari (2014), low nutritional density feeds are cheaper. Although the Unfavorable treatment resulted in the lowest profit, the economic scenario considered was difficult, and therefore, better results were obtained with non-linear programming. In other words, although the Unfavorable treatment resulted in lower profitability, the inclusion of higher nutritional levels would have been even more detrimental to profit.

The results of the present study are consistent with those of Afrouziyeh *et al.* (2010) and Afrouziyeh *et al.* (2011), who obtained higher profitability with using non-linear programming to formulate diets for laying hens of 24 to 32 weeks of age and 32 to 44 weeks of age, respectively. In broilers, other authors (Heydari, 2014; Dadalt *et al.,* 2015; Gonçalves *et al.,* 2015), evaluating feed formulation for maximum profit, also observed that the better live performance provided by minimum cost feeds does not generate maximum profitability of the production system. This is due to the greater nutritional level flexibility provided by non-linear programming, which establishes the required nutritional levels to obtain the highest profit according to the economic scenario (Guevara, 2004; Eits *et al.,* 2005).Therefore, feed formulation using non-linear programming may be an alternative method to minimum cost feed formulation due to the program's ability to combine principles of precision nutrition (Cerrate & Waldroup, 2009; Gonçalves *et al.,* 2015).

Dietary nutritional density also influences egg weight (Wu *et al.,*2007). Chickens tend to lay larger eggs when they are supplied high levels of protein (Rizzo *et al.,* 2010; Persio *et al.,* 2015) and sulfur aminoacids (Pavan *et al.,* 2005; Kakhki *et al.,*2016). Also, egg weight gain is associated with dietary energy level and energy to protein ratio (Leeson & Summers, 2009; Persio *et al.,* 2015), and with the amount of energy that is harvested by the bird (Morris, 2004; Costa, 2004; Wu *et al.*2007). Methionine intake influences albumen weight, according to Kakhki *et al.* (2016), who reported a linear increase in egg weight as dietary methionine levels increased.

Costa *et al.* (2004) observed that albumen weight linearly increased as dietary protein and energy levels increased. The Models and Hisex® treatments, which feeds contained high crude protein levels, generated higher albumen weight compared with the other treatments. However, high albumen weight is also linked to dietary energy level, which favors protein deposition (Morris, 2004; Wu *et al.,* 2007; Leeson & Summers, 2009).

The better yolk color results obtained with the feeds formulated using non-linear programming may be justified by the higher inclusion of corn, resulting in higher dietary carotenoid concentrations. This may be the factor that most contributed to the deposition of xanthophylls in the egg yolk (Leeson & Summers, 2009), ensuring the deeper yolk color of the eggs laid by hens fed those diets.

External egg quality was not affected by the treatments. Considering that dietary calcium and available phosphorus levels exert significant influence on eggshell quality (Leeson & Summers, 2009; Hassan & Al Aqil, 2015), this indicates that the levels of these nutrients included in the diets formulated using non-linear programming, although lower than those typically used by the industry, were sufficient to provide optimal eggshell quality.

CONCLUSION

Feeds formulated using linear programming, according to the nutritional level pre-established by the nutritionist, promote better live performance. On the other hand, feeds formulated using non-linear programming, which nutrient levels vary according to the economic scenario, ensure the highest profit.

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