Effects of feeding rate and formula fineness degree of ring die pellet mill on mechanical property, physical quality, energy requirements, and production cost of poultry diets

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Abstract: The effect of a machine feeding rate (FR; 1, 1.5 and 2 Mg/h) and/or three levels of selected fineness degree (FD; 3, 5 and 7 mm) on machine performance, pellet physical parameters, required energy and production cost of three main types of broilers diets were examined in this experiment. The examined broiler diets were formulated to meet the Ross 308 strain requirements. A complete factorial design (3×3×3) was used to identify the effects of studied factors on the pellet mill machine and pellet production. The obtained results indicated that the pellet mill productivity significantly (p<0.001) improved through increased pellet mill feeding rate level. In addition, the machine pelleting efficiency was found to be significantly affected by all studied variables and their interactions. While the total power consumption of the machine showed no variations under the impact of the tested factors or with any of their combinations. Regarding the pellet physical quality indices, all broiler diets with all selected FD and lower FR had the maximum durability and bulk density levels. Furthermore, lower feeding rates were associated with higher hardness degrees. The lowest production costs were substantially correlated with high FR and intermediate FD (5 mm). Furthermore, production costs were determined to be reduced in finisher broiler diets under different feeding rates. Moreover, manufacturing costs of finisher broiler meals were observed to decrease in several feeding rates. Overall, these findings indicate the capabilities of producing high-quality pellets and reducing the needed production costs by optimizing feeding rates to 2 Mg/h and 2 mm fineness in broiler diets.

Keywords: feeding rate, fineness degree, broiler diets, pellet quality, production cost
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1 Introduction

Feed is widely recognized as the most expensive input element in the livestock production industry[1]. The sale of live or slaughtered birds defines an important company's profit margin in live production. However, enhanced profits may be increased through reduced diet formulation costs, promoted production efficiency, and decreased feed manufacturing costs[2,3]. To realize the higher benefits of diet manufacturing, it is vital to identify the optimal level of nutritional density and to develop production techniques that produce high-quality, highly digestible pellets while using the least amount of electricity[4,5]. Consequently, the scientists made great efforts to improve the efficiency and economy of livestock feeding by developing several methods of feed processing[6,7].

Until now, most types of broiler rations are offered in pelleted or crumbled[8,9]. Pelleting process is a costly procedure, but its usage is justified by performance enhancement[10]. Pellet feeding alone is not sufficient to promote the efficiency of the consumed diet and the performance of broilers[11,12]. The physical quality of the pellets, as well as their capability to tolerate handling pressures, must also be considered[13]. Several recent studies have demonstrated the advantages of feeding high-quality pellets to broilers[14-16]. In addition, healthy poultry needs an adequate amount of protein and carbohydrates, along with the necessary vitamins, dietary minerals,

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and a suitable supply of water[17,18]. The pelleting process may also result in partial protein denaturation, which has the potential to increase protein digestibility through inactivating protein enzyme inhibitors[19]. Thus, consideration should also be paid to the possible negative outcomes of techniques used to increase pellet physical quality on nutritional availability.

Pellets should have the desired degree of hardness and be resistant to abrasion during handling and transport[20]. Furthermore, pellet quality is heavily influenced by several factors, for instance, dietary protein, fiber and starch concentration, feedstuff particle size (fineness degree), conditioning time and temperature, ingredient moisture level, the pellet die compression rate (feeding rate), the gap between the pellet press roll and die, etc.[21] Furthermore, there may be interactions among these elements, resulting in outcomes that differ from those predicted when individual parameters are considered[22,23]. Although several previous studies separately examined the effects of protein level and ingredient fineness degree in the poultry industry[24,25], scarce information is available on the effects of ingredient feeding rate, fineness degree, and several broiler diets and their interaction on pellet quality and production cost. Therefore, the current experiment was conducted to study the effects of different feeding rates, ratio protein concentration (19%, 21%, and 23%), and selected fineness degree levels (3, 5, and 7 mm) on pellet mill process, pellet physical quality and production cost in broiler diets.

2 Material and methods

2.1 Experimental design

The current experiment was conducted at a private chicken feed factory located in the Saft-Elhena village, Abou-Hamad, Sharkia, Egypt. To investigate the research variables, a full factorial random design was used. The feeding rate was examined in three levels (1 Mg/h, 1.5 Mg/h, and 2 Mg/h). Each feed rate was tested using three broiler manufactured diets (19%, 21%, and 23% CP) at three different fineness levels (3 mm, 5 mm, and 7 mm). The broiler diets that were examined were designed to meet the Ross 308 strain requirements[26] for main nutrients (Table 1). Furthermore, all prepared diets were formulated to be isocaloric and isonitrogenous. After pelleting, a random sample of the experimental diets was collected in triplicate to determine pellet productivity, pellet efficiency, pellet bulk density, pellet durability, and pellet hardness. All diet samples were chemically analyzed to ensure that all manufactured diets had the amount of the required nutrients.

Table 1 Composition and calculated nutrient content of the tested diets

Ingredient	Diet/%		
	Starter	Grower	Finisher
Yellow maize	59.86	62.14	67.29
Soybean meal (44% CP)	30.99	28.59	24.47
Poultry by-product meal	3.00	2.00	1.00
Poultry oil	2.63	3.96	4.15
Dicalcium phosphate	1.40	1.27	1.20
Calcium carbonate	1.04	1.01	0.86
Sodium chloride	0.50	0.51	0.52
DL-Methionine	0.22	0.21	0.20
L-Lysine_HCl	0.04	–	–
Vitamin and mineral premix*	0.25	0.25	0.25
Copper sulfate	0.05	0.05	0.05
Zinc sulfate	0.01	0.01	0.01
Total	100	100	100
Calculated analysis			
CP/%	23.05	21.10	19.11
ME/kcal·kg^{-1}	3040	3160	3240
TSAA/%	0.92	0.85	0.79
Lysine/%	1.22	1.09	0.95
Calcium/%	0.90	0.80	0.70
Available phosphorus/%	0.45	0.40	0.35
Sodium/%	0.23	0.23	0.23
DM/%	87.9	88.3	88.1

Note: Vitamin and mineral premix includes per kilogram of diet: vitamin A (vitamin A acetate), 7716 IU; cholecalciferol, 2205 IU; vitamin E (source unspecified), 9.9 mg; menadione, 0.9 mg; B12, 0.01 mg; folic acid, 0.6 g: choline, 379 mg; Dpantothenic acid, 8.8 mg; riboflavin, 5.0 mg; niacin, 33 mg; thiamin, 1.0 mg; D-biotin, 0.06 mg; pyridoxine, 0.9 mg; ethoxyquin, 28 mg; manganese, 55 mg; zinc, 50 mg; iron, 28 mg; copper, 4 mg; iodine, 0.5 mg; selenium, 0.1 mg.

2.2 Pellet manufactured machine

In this experiment, the ring die pellet mill (Serviced Sprout-Waldron Acepellet Mill Bullrtin 5061) with a capacity of 3 Mg/h and equipped with a single conditioner to adjust the formula retention time combined with vapor was utilized. The horizontal ring die poultry feed pellet mill is made up of the following major components; pellet mill transfer gates, screw-feeding system, conditioning system, pelleting system, bearings, transmission system, and overload protection system. The screw-feeder (80 cm length and 20 cm diameter) was supplied by a 1.5 kW (2 hp) electric motor with the inverter to enable varied rotational speed ratios for running the feeding system and controlling the experiment' s different feed rates.

2.3 Pellet mill performance indicators

2.3.1 Pellet mill productivity

The productivity of the machine was measured as the mass of pellets collected per hour, during the experiments the pellets were collected for a time. The machine was operated for 10 min before taking any samples to have a steady experimental condition the pellet mill productivity was calculated according to the following formula:

$$\text{PMP} = \frac{W_p}{T} \times 3.6 \tag{1}$$

where, PMP is pellet mill productivity, kg/h; W_p is the total production of pellet, g; T is the consumed time, s.

2.3.2 Pelleting efficiency

Pelleting efficiency is the ratio of quantity of actual feed pellets obtained at the main pellet outlet after screening to the total feed input for a given unit of time. The feed mixture retained in the pelleting chamber was manually removed and weighed at the end of every experiment. The quantity of feed pelleted as well as retained, in comparison with the total mass of feed mixture fed to pelletizer, was used to calculate pelleting efficiency of the pelletizer. The efficiency of pelleting machine was determined by Shrinivasa et al.[27]

$$\text{PE} = \frac{W_p}{W_m} \times 100\% \tag{2}$$

where, PE is pelleting efficiency, %; W_m is total feed mass input, kg.

2.3.3 Total consumed power

The power factor of the inductive cycle drive motor was not measured directly. However, the motor specification stated a power factor of 0.817 under full load followed by Li et al. [28]:

$$\text{TCP} = \frac{\sqrt{3}IVPf}{1000} \tag{3}$$

where, TCP is total consumed power, kW; I is the line current, A; V is the line voltage, V; and Pf is the power factor.

2.3.4 Specific Energy Requirements

The mass flow rate of the pellets was estimated by monitoring pellet production under steady-state conditions to estimate the specific energy consumption per unit mass of pellets produced. The specific energy consumption was calculated by combining this data with the average overall power consumption recorded. Specific energy demand values were calculated using the following equation:

$$\mathrm{SER} = \frac{\mathrm{TCP}}{\mathrm{EP}} \tag{4}$$

where, SER is the specific energy requirement, kW/Mg·h; TCP is the total consumed power, kW; EP is extruder productivity, Mg/h.

2.4 Physical pellet quality indicators

2.4.1 Pellet bulk density

A container of known mass and volume, loosely filled with feed mixture to measure bulk density. The mixture was poured into the container from a height of 15 cm to facilitate the free flowing of the samples until the container overflowed. By striking a straight edge across the top, the excess material was removed. The weight of the material in the container was recorded. The net weight of the sample was obtained by subtracting the weight of the empty container. Pellet bulk density (PBD) was calculated by dividing the mass over the container volume as ascribed by the following equation:

$$\mathrm{PBD} = \frac{W_d}{V_d} \tag{5}$$

where, PBD is pellet bulk density, g/cm^3; W_d is the pellet sample mass, g; V_d is the pellet sample volume, cm^3.

2.4.2 Pellet durability

The durability of pellets was determined according to ASAE standard method[29]. To eliminate fines, the pellets were sieved through a suitable sieve. A sample mass of 500 g placed in the tumbling box or shaker device (consists of three cells; 14 mm× 13 mm×12 mm) rotated at a constant speed of 60 r/min and has 0.5 hp motor power) for tumbling for up to 10 min. Then, the sample will be removed, sieved and the percent of whole pellets calculated according to the following equation:

$$\mathrm{PD} = \frac{W_a}{W_b} \times 100\% \tag{6}$$

where, PD is pellet durability, %; W_a is pellet weight after shaker treatment, g; W_b is pellet weight before shaker treatment, g.

2.4.3 Pellet hardness

Before testing the uniform feed pellets, five pellets of about standard length (1.5 cm) from each batch were selected and tested by measuring the force of the initial fracture of individual pellets. Pellet hardness was tested using a SHIMPO digital force gauge (ELECTROMATIC Equip't Co., 175 Vincent Ave Lynbrook, NY 11563 USA) with an accuracy of 0.1 N and a conical head.

2.5 Pelleting production cost

The total cost of farm machinery had been divided into two main categories:

Ownership costs (fixed costs):

1) Depreciation is a cost resulting from wear, obsoles-cence, and age of a machine, before an estimate of annual depreciation can be calculated, an economic life for the machine and a salvage value at the end of the economic life needs to be specified, besides the remaining salvage value as a percent of new list price.

$$\text{Total depreciation} = \text{purchase price} - \text{salvage value}$$

$$\text{Remaining salvage value} = \text{current list price} \times \text{remaining value factor}$$

The economic life of a machine is the number of years over which costs are to be estimated (10 years). While the remaining salvage value is an estimate of the sale value of the machine at the end of its economic life. It is the amount you could expect to receive as a trade-in allowance, an estimate of the used market value if you expect to sell the machine outright, or zero if you plan to keep the machine until it is worn out. For the pellet mill, the salvage value after ten years is estimated as 35% of the new list price (purchase price = current list price)[30].

2) Interest on investment, housing, taxes and insurance, (IHTI): It was estimated 13.8 % of the remaining salvage value[31].

Operation costs (Variable costs):

1) Repairs and maintenance (R and M): Repair costs are very high in developing countries and contribute significantly to the total cost. It was estimated 50% of the initial value, spread over the life of the machine, has been taken[32];

2) Fuel (Power cost) consumption, L.E./h (1.15 L.E./kW);

3) Lubrication costs for a machine are equal to 10% of fuel cost;

4) Labor cost: The operator's salary is about 3500 L.E./month

$$\text{Total cost per hours(L.E./h)} = \text{Fixed cost(L.E./h)} + \text{Operating costs(L.E./h)}$$

Finally, the total production cost was calculated according to the following equations used by Mani et al.[33]:

$$\text{Production } c\text{ost} = \frac{\text{Total cost per hour}}{\text{Productivity}}$$

where, the unit of production cost is L.E./Mg; the unit of total cost per hour is L.E./h, the unit of productivity is Mg/h.

2.6 Statistical analysis

A full factorial design using SPSS V22 was used to analyze data in a completely randomized design. The Kolmogorov-Smirnov and Shapiro-Wilk tests were used to determine the normality and homogeneity of the data. All obtained data were displayed as mean±standard deviation mean (SDM). The significance of a difference was determined by p<0.05. Pearson's correlation coefficient test was used to calculate the correlation coefficient between all measurements. To evaluate the relationship between chosen variables, a linear regression model was applied.

3 Results

3.1 Machine operating parameters

The influence of pellet mill feeding rate (FR), ration protein percentage (PD, %), and fineness degree (FD) on pellet mill productivity, pelleting efficiency, and total consumed power are listed in Table 2. The pellet mill productivity significantly (p<0.001) was promoted by the highest pellet mill feeding rate level. While, the machine pelleting efficiency was found to be significantly affected by all studied variables (FR, PD, % and FD) and their interactions. Pelleting efficiency was higher in starting broiler diets with high FD (7 mm) and moderate FR (1.5 Mg/h). On the other hand, the total consumed power of the machine was shown to be significantly influenced by all evaluated factors, with no changes in any of their interactions.

3.2 Pellet quality measurements

The effect of pellet mill feeding rate (FR), ration protein percentage (PD, %), and fineness degree (FD) on the pellet quality parameters (pellet bulk density, durability, and hardness) are

Table 2 Effect of pellet mill feeding rate, ration protein, and fineness degree on pellet mill productivity, pelleting efficiency and total consumed power

FR/ $Mg \cdot h^{-1}$	RPC/ %	RFD/ mm	Measurements (n=3)		
			PMP/$Mg \cdot h^{-1}$	PE/%	TCP /kW
		3	0.95	94.63	18.99
	19	5	0.95	94.85	21.51
		7	0.86	94.46	24.02
		3	0.95	94.52	26.17
1.0	21	5	0.95	95.07	29.22
		7	0.96	95.63	32.80
		3	0.95	95.07	34.59
	23	5	0.95	94.53	37.64
		7	0.96	95.84	39.79
		3	1.45	96.48	23.66
	19	5	1.46	96.84	26.35
		7	1.46	96.91	28.50
		3	1.46	96.83	30.65
1.5	21	5	1.46	97.19	33.16
		7	1.47	97.82	37.28
		3	1.46	97.19	39.25
	23	5	1.47	97.82	42.12
		7	1.47	98.61	43.91
		3	1.93	96.32	27.24
	19	5	1.92	95.81	29.40
		7	1.95	97.33	32.26
		3	1.93	96.00	34.59
2.0	21	5	1.92	95.48	37.46
		7	1.94	96.62	41.41
		3	1.91	95.21	42.84
	23	5	1.94	96.61	45.88
		7	1.95	97.36	48.21
SDM			0.008	0.105	1.821
A full factorial design analysis (p value)					
	FR		<0.001	<0.001	<0.001
	RPC		0.181	<0.001	<0.001
	RFD		0.911	<0.001	<0.001
	FR×RPC		0.359	<0.001	0.991
	FR×RFD		0.180	<0.001	0.998
	RPC×RFD		0.318	<0.001	0.525
	FR×RPC×RFD		0.301	<0.001	1.000

Note: FR: Feeding Rate, Mg/h; RPC: Ration Protein Concentrate, %; RFD: Ration Fineness Degree, mm; PMP: Pellet Mill Productivity, Mg; PE: Pelleting Efficiency, %; TCP: Total Consumed Power, kW.

Table 3 Effect of pellet mill feeding rate, ration protein (%), and fineness degree on pellet bulk density, durability, and hardness

FR/ $Mg \cdot h^{-1}$	RPC/ %	RFD/ mm	Measurements (n=3)		
			PBD/$kg \cdot m^{-3}$	PD/%	pH/N
		3	750	90	122.7
	19	5	840	90	97.8
		7	830	91	93.2
		3	860	90.7	125.2
1.0	21	5	870	91.7	104.9
		7	905	90	98.4
		3	880	95	127.9
	23	**5**	850	93	103.3
		7	850	90	103.0
		3	752	83	97.8
	19	**5**	750	80	92.9
		7	790	80	88.2
		3	748	92	110.4
1.5	21	**5**	755	88	100.8
		7	805	82	98.2
		3	730	87	112.8
	23	**5**	860	85	105.1
		7	740	80	101.3
		3	715	80	85.8
	19	**5**	718	76	80.6
		7	719	75	75.9
		3	690	80	78.5
2.0	21	5	695	81	73.5
		7	680	79	76.1
		3	695	90	73.9
	23	5	680	92	71.3
		7	683	81	71.1
SDM			1.01	1.07	24.6
A full factorial design analysis (p value)					
	FR		<0.001	<0.001	<0.001
	RPC		<0.001	<0.001	0.818
	RFD		<0.001	<0.001	0.083
	FR×RPC		<0.001	<0.001	0.738
	FR×RFD		<0.001	<0.001	0.673
	RPC×RFD		<0.001	<0.001	1.000
	FR×RPC×RFD		<0.001	<0.001	1.000

Note: FR: Feeding Rate, Mg/h; RPC: Ration Protein Concentrate, %; RFD: Ration Fineness Degree, mm; PBD: Pellet Bulk Density, kg/m^3; PD: Pellet Durability, %; PH: Pellet Hardness, SDM, standard division mean.

presented in Table 3. The results showed that all of the factors tested and their interactions considerably improved pellet bulk density and pellet durability percentage. All tested broiler diets with all selected FD and lower FR had the highest pellet durability and bulk density levels. Conversely, the feeding rate was shown to be the only factor that significantly increased the hardness degree, whereas other factors had no influence. Lower feeding rates were shown to be related to increased hardness levels.

3.3 Pellet production energy requirement and cost

The influence of pellet mill feeding rate (FR), ration protein percentage (PD, %) and fineness degree (FD) on the specific energy requirement and hourly and production cost existing in Table 4. The obtained results indicated higher significant effects ($p<0.001$) in specific energy requirements and hourly and production costs. Furthermore, the interaction between feeding rate and varied protein ratios or fineness degrees improved specified energy demand levels and lowered production costs. The lowest production cost was shown to be highly associated with a high feeding rate and a medium fineness degree (5 mm). Besides, the production cost was found to be lower in finisher broiler diets under different feeding rates. Moreover, the production costs of finisher broiler diets were shown to be decreased in various feeding rates.

3.4 Statistical relation between measurements

Table 5 displays Pearson's correlation coefficients (r) between ring die pellet mill performance, physical pellet quality criteria, specific energy, and cost indices. The production cost positively significantly correlated with all pellet quality measurement (pellet bulk density, durability and hardness) and specific energy requirement. On the other hand, total power consumption was not statistically correlated to the cost of production of pellets. The machine operating parameters were negatively correlated with the cost of producing pellets.

Polynomial regressions analysis ($p<0.05$) between Feeding rate and Fiennes degree levels of poultry diets and pellet durability were

Table 4 Effect of pellet mill feeding rate, ration protein (%) and fineness degree on specific energy requirement and hourly and production cost

FR/ $Mg \cdot h^{-1}$	RPC/ %	RFD/ mm	Measurements (n=3)		
			SER /$kWh \cdot Mg^{-1}$	HC /$L.E. \cdot h^{-1}$	PC/ $L.E. \cdot Mg^{-1}$
1.0	19	3	20.0	44.6	47.0
		5	22.6	47.8	50.2
		7	29.3	51.0	61.9
	21	3	27.6	53.7	56.6
		5	30.6	57.5	60.3
		7	34.2	62.1	64.7
	23	3	36.3	64.3	67.5
		5	39.6	68.2	71.7
		7	41.4	70.9	73.8
1.5	19	3	16.3	50.5	34.9
		5	18.1	53.9	37.1
		7	19.6	56.6	38.9
	21	3	21.1	59.4	40.8
		5	22.7	62.5	42.8
		7	25.4	67.7	46.1
	23	3	26.9	70.2	48.1
		5	28.6	73.9	50.2
		7	29.9	76.1	51.8
2.0	19	3	14.1	55.1	28.5
		5	15.3	57.8	30.1
		7	16.5	61.4	31.5
	21	3	18.0	64.3	33.4
		5	19.6	68.0	35.5
		7	21.4	73.0	37.7
	23	3	22.4	74.8	39.1
		5	23.6	78.6	40.5
		7	24.7	81.6	41.8
SDM			1.611	2.285	2.244
A full factorial design analysis (p value)					
	FR		<0.001	<0.001	<0.001
	RPC		<0.001	<0.001	<0.001
	RFD		<0.001	<0.001	<0.001
	FR×RPC		0.001	0.990	0.050
	FR×RFD		0.057	0.998	0.097
	RPC×RFD		0.757	0.525	0.688
	FR×RPC×RFD		0.919	1.000	0.772

Note: FR: Feeding Rate, Mg/h; RPC: Ration Protein Concentrate, %; RFD: Ration Fineness Degree, mm; SER: Specific Energy Requirement, kWh/Mg; HC: Hourly Cost, L.E./h; PC: Production Cost, L.E./Mg

illustrated in Figure 1. According to the regression findings, 2 Mg/h FR and 2 mm FD provided good pellet durability. Also, Polynomial regression analysis (p<0.05) between Feeding rate and Fiennes degree levels of poultry diets, and pellet hardness were exemplified in Figure 2. Under a high feeding rate (2 Mg/h) and medium fineness degree (2 mm), the estimated equation derived from the regression analysis produced the optimal hardness level (Figure 3).

4 Discussion

The present study examined the effect of various feeding rates and graded levels of ingredient fineness degree using three different types of broiler diets on machine operating parameters, pellet physical quality, pellet manufacturing requirements, and production cost. According to the polynomial regressions used to estimate the relationship between pellet durability percentage or hardness degree with feeding rate levels and ingredient fineness degree, a 2 Mg/h FR and 2 mm FD are ideal for high pellet quality production in all types of broiler diets.

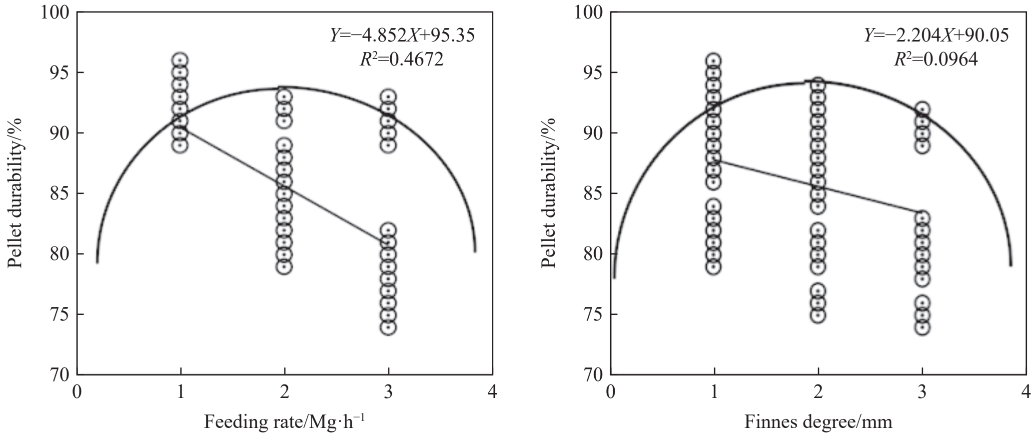
The most common type of broiler diet is pellets. When compared to mash diets, fed broiler on pelleted diets improves performance and feed efficiency[5]. However, productivity enhancements are reliant on pellet quality[34]. According to our study results, the machine operating measurements such as pelleting efficiency significantly improved in starting broiler diets under high FD (7 mm) and moderate FR (1.5 Mg/h). These results were in similarity to Abo-Habaga et al.[31] finding that the maximum value of pelleting machine productivity was recorded (40.220 kg/h) at die speed 190 r/min., 5 mm die holes' diameter, and 28% moisture content of feed mixture with gelatin as an adhesive ingredient in diet formula. In addition, the increments in production rate caused by raising the machine feeding rate from 200 to 400 kg/h may be attributed to increasing the mass of the formula between the rollers gap, which causes rollers to compress in time unit[35]. In general, increasing the level of feeding rate up to 500 kg/h was found to reduce machine productivity, which may be ascribed to an excess of mass in front of the rollers, causing the rollers to slide[31]. Therefore, it was shown that determining the optimal operational parameters, namely roller speed and feeding rate, may promote the performance of pelleting machines.

Improving pellet durability is an effective method of reducing fines. The pellet's durability may be affected by the diet composition[36]. Moreover, using raw materials with high binding ability, such as wheat, barley, and rape, was also shown to affect the durability percentage of the generated pellets[37]. While Feed rate levels will also affect pellet durability and may be less costly than

Table 5 Pearson's correlation coefficients (r) among ring die pellet mill performance, physical pellet quality parameters, specific energy and cost indices

	PMP	PE	TCP	SER	PBD	PD	PH	HC	PC
PMP	1	0.520**	0.446**	–0.657**	–0.870**	–0.689**	–0.506**	0.446**	–0.828**
PE		1	0.461**	–0.257*	–0.371**	–0.604**	–0.174NS	0.461**	–0.424**
TCP			1	0.340**	–0.289**	–0.708**	–0.241*	1.000**	0.081^{NS}
SER				1	0.683**	0.194^{NS}	0.307**	0.340**	0.962**
PBD					1	0.556**	0.428**	–0.289**	0.794**
PD						1	0.432**	–0.708**	0.392**
PH							1	–0.241*	0.389**
HC								1	0.081^{NS}
PC									1

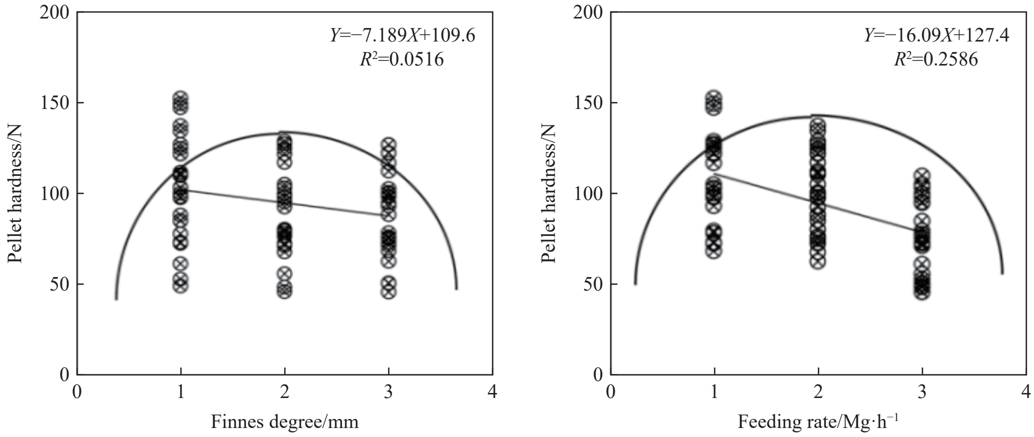
Note: PMP, Pellet Mill Productivity; PE, Pelleting Efficiency; TCP, Total Consumed Power; SER, Specific Energy Requirement; PBD, Pellet Bulk Density; PD, Pellet Durability; PH, Pellet Hardness; HC, Hourly Cost; PC, Production Cost. *: p<0.05, **: p<0.01, ***: p<0.001 and NS: Not significant



a. Feeding rate b. Fineness degree levels

Note: Values expressed as means±SD.

Figure 1 Polynomial regressions analysis (p<0.05) between feeding rate and fineness degree levels of poultry diets, and pellet durability



a. Feeding rate b. Fineness degree levels

Note: Values expressed as means±SD.

Figure 2 Polynomial regressions analysis (p<0.05) between feeding rate and fineness degree levels of poultry diets, and pellet hardness

a. Starter diet b. Grower diet c. Finisher diet

Figure 3 Higher quality of pellets and lower production costs achieved under 2 Mg/h feeding rates and 2 mm fineness degree in broiler diets

replacing raw ingredients or using pellet binders[38]. Our study results suggested that the best pellet durability, hardness, and bulk density levels could be obtained in all tested broiler diets under all tested FD and lower FR. These results were found to be in line with Abdel Wahab et al.[39] and Said et al.[40] finding. The improvement in pellet durability due to increased feeding rate and decreasing fineness degree may be ascribed to the larger compact of the formula within die holes, which reduces porosity between formula granules and produces un-fractured pellets with higher pellet resistance[35].

Morad and El-Maghawry[41] proved that specific mechanical energy values were reduced by rising ingredient fed rate up to 3.0 and 2.0 Mg/h for cattle and rabbit feed pellets, respectively. Any further increments in the machine feeding rate (3.0 Mg/h) could significantly increase the specific mechanical energy and production cost. According to our findings, the high feeding rate (1.5 Mg/h) and a medium fineness degree (5 mm) reduced the total production cost. Our study's findings were consistent with the results of Singh[42] and Domenech et al.[43]. The required consumption power increased as the feed rate increased owing to the higher ingredient flow through the extruder screw towards the die at the same time unit, creating a considerable strain on the screws haft and requiring more power[44]. Besides, higher formula feed rates than the optimum value (1.5 Mg/h for broiler feed pellets) tend to increase energy due to the substantial increase in power required relative to the higher in extruder productivity. Furthermore, friction force induced between formula particles under low fineness degrees tends to enlarge the required power, resulting in high specific mechanical energy[43].

5 Conclusions

Based on the research findings, it can be concluded that the optimum values of productivity, pelleting efficiency, pellet durability, specific mechanical energy, and pelleting cost could be achieved while pelleting broiler feed pellets at a feed rate of 1.5 Mg/h and a fineness degree of 5 mm.

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