Analysis of feed pelleting characteristics based on a single pellet press device

Fei Peng[1], Rui Xiang[1], Fang Fang[2,3*], Dan Liu[1]

(1. *School of Artificial Intelligence, Beijing Technology and Business University, Beijing 100048, China*;
2. *College of Chemical Engineering, Zhengzhou University, Zhengzhou 450001, China*;
3. *Key Laboratory of Environment Controlled Aquaculture, Ministry of Education, Dalian Ocean University, Dalian 116023, China*)

Abstract: Pelleting is the most extensively used thermal processing method in feed industry. In this article, a single pellet press device was developed to investigate the pelleting processing of animal feed. Effects of moisture content (10%-18% w.b.), preheating temperature (60 ℃-100 ℃) and maximum compression force (0.2-0.6 kN) on feed pellet were determined and analyzed, as well as energy consumption. The results showed that unit density, pellet hardness and energy consumption were 0.87-2.92 g/cm^3, 1.08-4.55 kg, and 3.27-12.66 J/g, respectively. Unit density was found to increase with the increase of preheating temperature and maximum compression force, but decrease with the increase of moisture content. Pellet hardness showed a first ascending then descending trend with the increase of moisture content, but exhibited a positive relationship with both preheating temperature and maximum compression force. Energy consumption increased with the increase of maximum compression force, but exhibited descending trends with the increase of moisture content and preheating temperature. Due to its features of low cost, high efficiency and easy control, the single pellet press device has a wide application prospect in feed processing.

Keywords: feed, pelleting, energy consumption, preheating temperature, experiments
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1 Introduction

Feed takes up to 60%-70% of the total cost in aquaculture and livestock breeding industries[1,2]. Feed processing (sieving, grinding, extrusion and pelleting) has contributed to increasing nutrient availability for animals. Pelleting is the most prevalent and widely used processing in feed production[3,4], aiming at combining ingredients particles by mechanical action in various conditions including moisture, pressure and temperature. It has been demonstrated that feed in pellet form can greatly improve feed intake and conversion ratio, resulting in easy weight gain of the animals[5,6]. Thus the increasing demand for pellet feed calls for further investigation and optimization of the parameters during pelletization process. Finding the optimum parameters will contribute to feed production with high efficiency and low consumption, as well as the stability of pellet form. However, the pelletization process is complex[7,8]. Currently, most feed pellets are produced in pellet mill with the roll-die structure[9]. Traditional research methods are primarily based on expensive and time-consuming “trial and error” experiments[10], which means a large scale pellet mill is used to study the effects of various process parameters on pelletizing characteristics and pellets quality. Moreover, some process parameters such as temperature and friction in channels of the die cannot be easily controlled because of their high speed rotation and the insular pelletizing chamber.

Compared with a large scale pellet mill, the single pellet press (SPP) with a press channel focuses on the compression and extrusion process, which could provide information about the material compressibility and estimate some pellet quality properties[11-13]. The SPP method has been used to test the compacting properties of materials, especially in the field of biomass. Among them, some research indicated the pelleting characteristics of single pellet press (SPP) can also be extrapolated to larger scale pellet mills[10]. However, several serious problems exist. The main component of animal feed is raw grain and there are obvious differences in processing parameters between animal feed and biomass. Besides, the processing parameters (moisture content, temperature and compression force) for animal feed are more strictly controlled than that in biomass. Therefore, this paper studied the effects of processing parameters on pellet feed using the single pelletizer specifically designed, which will be useful in understanding the interaction of feed raw materials and processing variables on the quality of pellet feed.

This research aims to develop an SPP machine for feed pelleting which consists of a precise loading device and a temperature feedback control device. Moreover, the effect of feedstuff moisture content (10%-18% w.b.), preheating temperature (60 ℃-100 ℃) and maximum compression force (0.2-0.6 kN) on the physical properties of pellet feed including unit density, pellet hardness and energy consumption, were studied and systematically analyzed.

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Biographies: **Fei Peng**, PhD, Associate Professor, research interests: agricultural products processing technology and equipment, Email: feipeng@btbu.edu.cn; **Rui Xiang**, Master candidate, research interests: food machinery, Email: 826499975@qq.com; **Dan Liu**, PhD, Associate Professor, research interests: agricultural science, Email: liudan@btbu.edu.cn.

*__Corresponding author__: **Fang Fang**, PhD, Associate Professor, research interests: agricultural science. College of Chemical Engineering, Zhengzhou University, Zhengzhou 450001, China. Tel: +86-371-67739781, Email: fangf1001@163.com.

2 Materials and methods

2.1 Materials

Based on the recommendation of the National Research Council (NRC)[14] and the actual situation in China, the diet formulation for piglet was used in the study. The composition of the basal diet is listed in Table 1. The initial moisture content of the basal diet was measured by Pl2002 electronic balance supplied by Shanghai Mettler Toledo Instrument Co., Ltd. and DHG-9240a electrothermal constant temperature blast drying oven supplied by Shanghai Jinghong Experimental Equipment Co., Ltd. The initial moisture content of the basal diet was 11.7%. Samples were adjusted to different moisture contents by a drying and water refilling method[15]. Samples at 10% were prepared by drying a known mass of basal diet at initial MC to the pre-calculated weight in a hot air oven. Samples at 12%, 14%, 16% and 18% were prepared by adding a calculated amount of distilled water, followed by kept in a tightly closed plastic bag. Finally, the samples were stored at 4℃ for several days to let them reach to the desired moisture content.

Table 1 Composition of the basal diet

Ingredients	Content/g kg^{-1}
Maize	490
Extruded maize	100
Extruded soybean meal	180
Wheat bran	100
DDGS (distiller dried grains with solubles)	40
Fish meal	20
Brewers dried yeast	20
Soybean oil	10
Premix	40
Dry matter	877
Crude protein	182.66
Calcium	9.01
N-Py-P	3.95
Crude ash	30.98
Crude fiber	29.31
Na	1.67

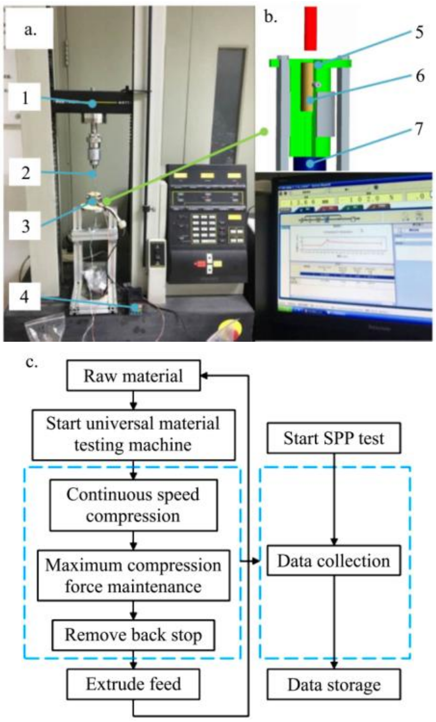
2.2 Experimental methods

2.2.1 Device design

The SPP device used in this study was designed and manufactured at China Agricultural University. As shown in Figures 1a and 1b, the device is mainly composed of four parts, namely a stainless steel mold including a cylindrical die of 8 mm diameter, a heating element with thermal insulation and a tightly fitted pressure bar driven by an universal material testing machine that could measure the compression force (P_x). The SPP device had a press channel of 20 mm in length and a chamfer angle of 45° at the entrance of channel. The die temperature is controlled by an electric heating ring connected to an intelligent temperature controller. The temperature of the feed material in the press channel was monitored by a temperature sensor and controlled based on the internal PID program algorithm by an intelligent temperature controller. The ambient temperature inside the die hole was recorded in real-time. The fixed backstop under the mold was to form a closed compressed space.

During the test, the SPP device was placed on the test platform of a universal material testing machine (instron-4411, Instron company). The upper end of the press bar was fixed with a movable module of the testing machine and the material was compressed by the vertical movement of the module. The compression procedures are illustrated in Figure 1c. After the sample was put in, the press bar moved at a constant speed of 40 mm/min. When reached the set maximum compression force, the press bar stopped moving and then held for 90 s to stabilize. Next, the resulted feed pellet was extruded out of the press channel. Finally, the press bar was returned to the initial position at a constant speed of 100 mm/min.

The SPP device, controlled by the intelligent temperature controller, could be heated to desired and steady temperature before the compression process. In this work, preheating temperature was adjusted and maintained to the desired value (60℃, 70℃, 80℃, 90℃, and 100℃, respectively). For each experimental run, 0.30 g sample that adjusted to desired moisture content was then put into the press channel; the sample was kept in the channel for 60 s to make the temperature achieve the preheating temperature value. Compressed by the press bar, the sample was compacted and then forced to pass through the press channel, thus the pellet was finally formed under the combined action of moisture content, preheating temperature and compression force. During the tests, the data will be collected in real-time and the force-displacement curve will be drawn automatically.



1. Movable module of the universal material testing machine 2. Press bar 3. Heating element with thermal insulation 4. Intelligent temperature controller 5. Cylindrical die 6. Raw material 7. Back stop

Figure 1 Typical composition of the test machine (a), magnified SPP unit (b) and flowchart of pelletization procedure (c)

2.2.2 Parameters

(1) Unit density

Assuming that pellet feed is of a perfectly cylindrical shape and the two ends of a single pellet were smoothed with sand paper (Figure 2). The unit density was obtained according to at least 10 samples.

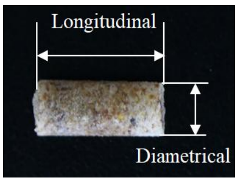


Figure 2 Diameter and length of a single pellet feed

(2) Moisture content

According to ASAE Standard S358.2[16] and ASAE Standard S269.4[17,18], the moisture content of the pellet feed was measured by drying at 60 ℃ for 72 h.

(3) Pellet hardness

Pellet hardness, which is the force that needed to break the pellet, was determined using a Kahl device (AMANDUS KAHL GmbH and Co. KG, Reinbek, Germany).

(4) Specific energy consumption

The raw materials were compressed to pellet form, during which energy was needed in order to overcome the friction between raw materials and the die hole. Thus, energy consumption means the work done by the force during the pelletizing process. In the compression and extrusion process of the feed pellet, force-displacement curves were recorded and the energy consumption can be obtained by integrating the force-displacement data by using the following equation[4]

$$E_m = \frac{\int_{s1}^{s2} F(x)\mathrm{d}x}{m} \tag{1}$$

where, E_m is the specific energy consumption, J/g; $F(x)$ is the compression pressure force, N; $s1$ and $s2$ are the initial and final position of the press bar, mm.

2.2.3 Experimental design

The Design-Expert 8.0.6 software (STAS-EASE Inc., Minneapolis, MN, USA) was employed for data analysis[19,20]. The lower and upper limits as well as coded levels of the above parameters (moisture content X_1, preheating temperature X_2 and maximum compression force X_3) were selected as the independent variables and listed in Table 2. Accordingly, unit density, pellet hardness and energy consumption were selected as evaluating indicators. The evaluation was carried out using the quadratic orthogonal rotation design.

Table 2 Actual and corresponding coded variables in the pelleting process

Independent variables	Symbol	Code variable levels				
		–2	–1	0	1	2
Moisture content/%	X_1	10	12	14	16	18
Preheating temperature/℃	X_2	60	70	80	90	100
Max compression force/kN	X_3	0.2	0.3	0.4	0.5	0.6

As shown in Table 3, 23 sets of experiments were generated using five levels of each variable. The effects of the independent variables on the evaluating indicators were discussed using a second-order polynomial equation:

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij} x_i x_j \tag{2}$$

where, y represents the response value (unit density, pellet hardness or specific energy consumption); x_i and x_j are independent factors (moisture content, preheating temperature and max compression force); b_0 is the intercept coefficient; b_i, b_{ii}, and b_{ij} are the linear, quadratic and interaction term, respectively; n is the number of independent factors.

3 Results and discussion

3.1 Results and analysis of combined tests

The results of unit density, pellet hardness and energy consumption determined in different process conditions are listed in Table 4. Ranges of unit density, pellet hardness and energy consumption were 0.87-2.92 g/cm^3, 1.08-4.55 kg and 3.27-12.66 J/g, respectively. As shown in Tables 5 and 6, all of the regression equations were statistically significant at p<0.01. Analysis of variance (ANOVA) indicated that the moisture content, preheating temperature and maximum compression force had significant effects on the evaluating indicators. By using the response surface models, 3D graphs were developed to understand the effects of these variables on the quality attributes (unit density, pellet hardness and energy consumption).

Table 3 Experimental design layout

Run	Coded variables			Actual variables		
	x_1	x_2	x_3	X_1/%	X_2/℃	X_3/kN
1	1	1	1	16	90	0.5
2	1	1	–1	16	90	0.3
3	1	–1	1	16	70	0.5
4	1	–1	–1	16	70	0.3
5	–1	1	1	12	90	0.5
6	–1	1	–1	12	90	0.3
7	–1	–1	1	12	70	0.5
8	–1	–1	–1	12	70	0.3
9	2	0	0	18	80	0.4
10	–2	0	0	10	80	0.4
11	0	2	0	14	100	0.4
12	0	–2	0	14	60	0.4
13	0	0	2	14	80	0.6
14	0	0	–2	14	80	0.2
15	0	0	0	14	80	0.4
16	0	0	0	14	80	0.4
17	0	0	0	14	80	0.4
18	0	0	0	14	80	0.4
19	0	0	0	14	80	0.4
20	0	0	0	14	80	0.4
21	0	0	0	14	80	0.4
22	0	0	0	14	80	0.4
23	0	0	0	14	80	0.4

Table 4 Experimental data measured in each run

Treatment	Unit density /g cm^{-3}	SD	Pellet hardness /kg	SD	Energy consumption /J g^{-1}	SD
1	1.72	0.24	4.33	0.18	7.36	0.19
2	1.06	0.11	2.85	0.15	5.11	0.22
3	1.45	0.07	2.19	0.03	8.73	0.51
4	0.88	0.06	1.46	0.05	5.95	0.72
5	1.95	0.10	4.55	0.10	8.70	0.65
6	1.33	0.02	2.97	0.06	6.41	0.08
7	1.61	0.05	2.25	0.02	9.50	0.44
8	1.25	0.01	1.51	0.01	6.88	0.83
9	1.48	0.04	1.08	0.02	3.27	0.43
10	1.65	0.08	1.45	0.16	9.16	0.50
11	1.77	0.10	2.68	0.11	5.13	0.08
12	1.41	0.02	2.13	0.03	12.66	0.65
13	2.92	0.01	3.82	0.25	11.81	0.31
14	0.87	0.03	1.55	0.06	3.51	0.24
15	1.28	0.09	3.12	0.13	6.74	0.80
16	1.34	0.04	3.26	0.14	6.50	0.36
17	1.31	0.01	3.19	0.30	6.55	0.24
18	1.33	0.22	3.35	0.12	6.36	0.38
19	1.25	0.04	3.15	0.05	6.71	0.10
20	1.22	0.03	3.34	0.12	6.60	0.57
21	1.31	0.05	3.22	0.06	6.14	0.08
22	1.29	0.05	3.05	0.17	6.52	0.05
23	1.33	0.03	3.24	0.05	6.80	0.40

Note: SD means standard deviation.

Table 5 Analysis of unit density and pellet hardness

Source	Unit density					Pellet hardness			
	df	SS	MS	*F*-value	*p*-value	SS	MS	*F*-value	*p*-value
Model	9	3.33	0.37	11.60	<0.0001	15.92	1.77	7.44	0.0007
X_1	1	0.12	0.12	3.68	0.0774	0.089	0.089	0.37	0.5523
X_2	1	0.16	0.16	4.95	0.0443	4.40	4.40	18.51	0.0009
X_3	1	2.49	2.49	78.02	<0.0001	5.14	5.14	21.63	0.0005
$X_1 X_2$	1	0.001	0.001	0.0035	0.9535	0.0066	0.0066	0.028	0.8701
$X_1 X_3$	1	0.008	0.008	0.24	0.6289	0.0015	0.0015	0.0064	0.9376
$X_2 X_3$	1	0.015	0.015	0.48	0.5006	0.32	0.32	1.33	0.2697
X_1^2	1	0.065	0.065	2.03	0.1781	5.64	5.64	23.63	0.0003
X_2^2	1	0.083	0.083	2.59	0.1215	0.74	0.74	3.10	0.1015
X_3^2	1	0.48	0.48	15.00	0.0019	0.24	0.24	1.00	0.3351
Residual	13	0.41	0.032	--	--	3.09	0.24	--	--
Lack of Fit	5	0.40	0.08	50.14	<0.0001	3.01	0.60	62.13	<0.0001
Pure Error	8	0.013	0.002	--	--	0.078	0.0097	--	--

Table 6 Analysis of energy consumption

Source	Energy consumption				
	df	SS	MS	*F*-value	*p*-value
Model	9	93.77	93.77	9.06	0.0003
X_1	1	16.24	16.24	14.12	0.0024
X_2	1	21.48	21.48	18.68	0.0008
X_3	1	44.02	44.02	38.28	<0.0001
$X_1 X_2$	1	0.11	0.11	0.09	0.7616
$X_1 X_3$	1	0.0018	0.0018	0.0016	0.9690
$X_2 X_3$	1	0.09	0.09	0.08	0.7812
X_1^2	1	0.19	0.19	0.17	0.6889
X_2^2	1	9.69	9.69	8.43	0.0123
X_3^2	1	2.18	2.18	1.89	0.1919
Residual	13	14.95	1.15	--	--
Lack of Fit	5	14.62	2.92	69.98	<0.0001
Pure Error	8	0.33	0.04	--	--

3.2 Unit density

The unit density, calculated as the mass per unit volume of the pellet, is an important index to evaluate the quality of the products. Higher unit density makes the pellets easier in transportation, storage and feeding. The response surface plotted in Figure 3 showed that unit density of pellet feed decreased with moisture content in range of 10%-18% w.b., but increased with preheating temperature, maximum compression force in range of 60℃-100℃ and 0.2-0.6 kN, respectively. These results are agreed with other studies on pelleting of ground wood chips[21] and maize stover[22]. The density was positively associated with the maximum compression force. The unit density sharply increased as the compression force increased from 0.2 to 0.6 kN. Increasing the compression force leads to plastic deformation of raw materials and consequently produces feed pellets with higher densities[23]. It has been found that when the moisture content is 10% w.b, the unit density decreased compared to pellets of other moisture content. The pelleting studies conducted by Guo et al.[19] on four biomass grinds (barley, oat, canola and wheat straw) at different moisture contents of 9%, 12%, and 15% w.b. indicated that pellets made at 9% w.b. had higher unit density as compared to pellets made at 15% w.b. This trend agreed with the present results that increased moisture content can lead to reduced density. This can be attributed to the fact that the void space between the raw material particles is occupied by water molecules. When the moisture content is relatively high, the water molecules cannot be expelled during the compression, which will result in increased volume and decreased density[20,23]. Therefore, during the feed processing especially for conditioning, the moisture content of feed raw materials should be reasonably controlled.

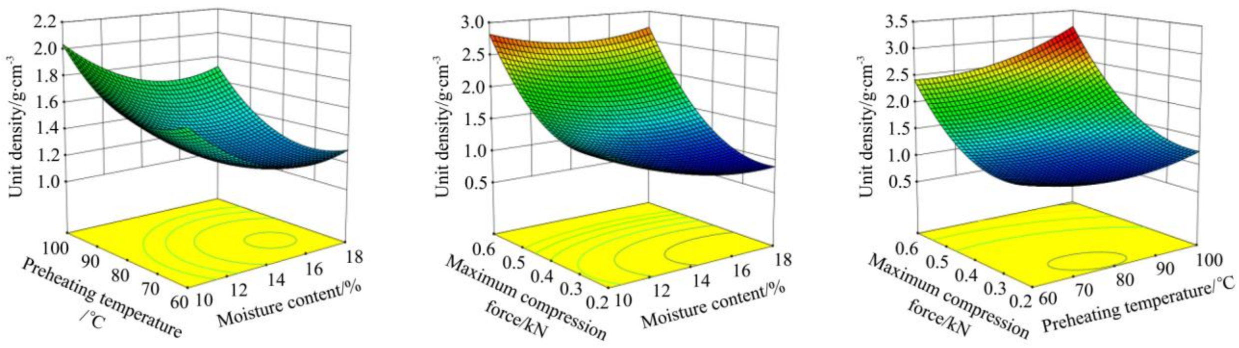
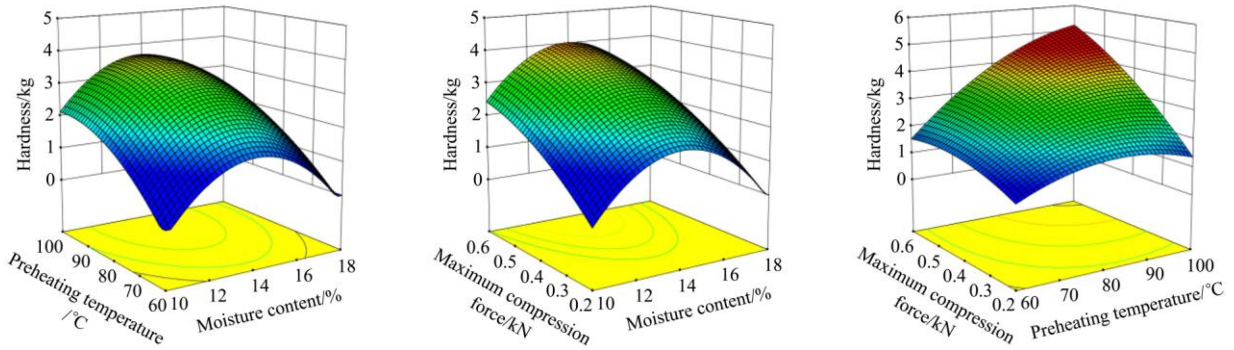


Figure 3 Response surface plots of unit density as a function of moisture content, preheating temperature and maximum compression force

3.3 Pellet hardness

Hardness is an important indicator of the pellet feed appearance quality and has obvious impact on animal production performance. If the pellets are too hard, the palatability of feed and the production performance of animals will be reduced. On the contrary, low hardness will lead to increased pulverization rate and waste, resulting in lower production performance of animals. The response surface plotted in Figure 4 manifested that pellet hardness increased with preheating temperature and maximum compression force. This can be attributed to the fact that high temperature favors gelatinization, thus hardness is in positive relationship with temperature. The results agreed with other researches[24,25]. Moisture content showed a trend of first increasing and then decreasing with hardness. This is because an increased moisture content (within range of 10%-14% w.b.) contributed to the improvement of gelatinization, but when the moisture content was beyond 16%, the excessive water content will reduce the mechanical strength.

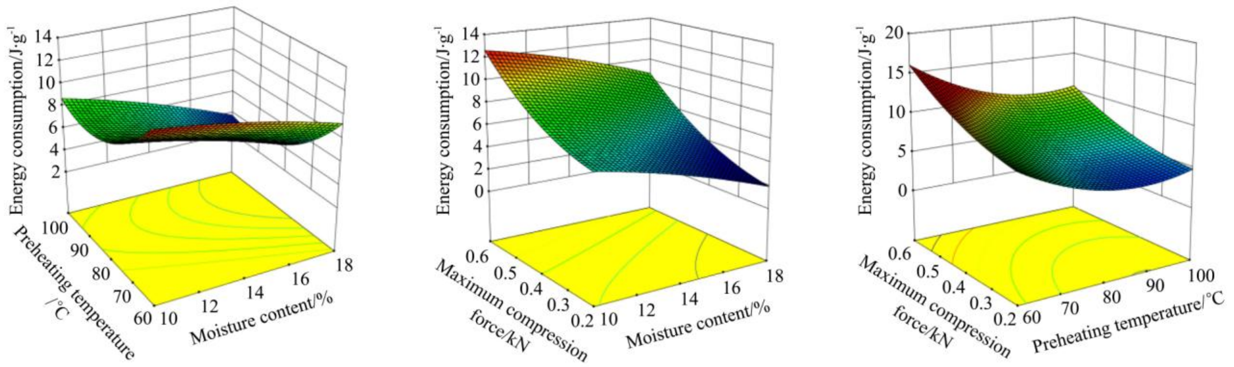


a. Maximum compression force was 0.4 kN b. Preheating temperature was 80 ℃ c. Moisture content was 14%

Figure 4 Response surface plots of pellet hardness as a function of moisture content, preheating temperature and maximum compression force

3.4 Energy consumption

Regression analyses showed that energy consumption was significantly (p<0.05) affected by linear and quadratic effects of moisture content (X_1), preheating temperature (X_2) and maximum compression force (X_3). The response surface plotted in Figure 5 showed that when the moisture content and preheating temperature were constants, the energy consumption increased with the increment of maximum compression force. Adapa et al.[3] described a similar bulk density compaction characteristic and energy consumption of barley, canola, oat and wheat straws. It is because when the maximum compression force increased, both the pressed force and compression displacement increased, resulting in a significant increase of specific energy consumption. The energy consumption decreased with the increase of moisture content and preheating temperature. Similar results were observed from other researches[21]. Increased moisture content is of benefit to the fluidity of raw materials and can reduce friction in the die holes. At elevated pelleting temperature, the materials showed greater plastic compression[12]. Due to the fact that forces dissipate with the plastic deformation, the plastic compression can decrease the radial stresses at the die walls, resulting in lower die friction and energy consumption. The regression model and statistical data are given in Table 7.



a. Maximum compression force was 0.4 kN b. Preheating temperature was 80 ℃ c. Moisture content was 14%

Figure 5 Response surface plots of energy consumption as a function of moisture content, preheating temperature and maximum compression force

Table 7 Final equations in terms of coded factors after excluding the insignificant terms for moisture content, preheating temperature and maximum compression force

Coded model equation	R^2	Adj R^2	Pred R^2	Adeq precision
$Y_{TD}=1.27+0.099T+0.39S+0.0038MT+0.13F^2$	0.89	0.81	0.12	14.00
$Y_H=3.26+0.52T-0.45M^2$	0.84	0.72	0.31	8.41
$Y_{EC}=6.55-1.01M-1.16T+0.59T^2$	0.86	0.77	0.12	10.94

Notes: M=Moisture content, T=Preheating temperature, F=Maximum compression force.

4 Conclusions

In the present study, a single pellet press device was developed for feed pelleting. The effects of moisture content (10%-18% w.b.), preheating temperature (60℃-100℃) and maximum compression force (0.2-0.6 kN) on unit density, pellet hardness and energy consumption of the extruded feed pellets were determined and analyzed. The following conclusions were drawn. The ranges of unit density, hardness and energy consumption of feed pellets were 0.87-2.92 g/cm^3, 1.08-4.55 kg and 3.27-12.66 J/g, respectively. Unit density was found to increase with the increase of preheating temperature and maximum compression force, but decrease with the increase of moisture content. The hardness showed a descending trend with moisture content, but exhibited an ascending trend with preheating temperature and maximum compression force. Energy consumption increased with the increase of maximum compression force, but negatively correlated with moisture content and preheating temperature. The comprehensive research will contribute to the production of feed pellets in various processing conditions.

Further studies should investigate the quality of the pellets affected by different formulations and physicochemical parameters, to build processing characteristics databases of raw material for animal feed.

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