EFFECT OF RAW MATERIAL PROPERTIES AND DIE GEOMETRY ON THE DENSITY OF BIOMASS PELLETS FROM COMPOSTED MUNICIPAL SOLID WASTE

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Densification of biomass feedstocks, such as pelletizing, can increase bulk density, improve storability, reduce transportation costs, and ease the handling of biomass using existing handling and storage equipment for grains. In order to study the pelletizing process, compost pellets were produced under controlled conditions. The aim of the work was to investigate the effect of raw material properties and the die geometry on the true density of formed pellets and also find the optimal conditions of the densification process for producing pellets with high density. Compost was extruded into cylindrical pellets utilizing open-end dies under axial stress from a vertical piston applied by a hydraulic press. The effects of independent variables, including the raw material moisture content (35 to 45% (wet basis)), hammer mill screen size (0.3 to 1.5 mm), speed of piston (2 to 10 mm/s), and die length (8 to 12 mm) on pellet density, were determined using response surface methodology. A quadratic model was proposed to predict the pellet density, which had high F and R^2 values along with a low p value, indicating the predictability of the model. Moisture content, speed of piston, and particle size significantly affected ($P < 0.01$) the density of pellets, while the influence of die length was negligible ($P > 0.05$).

Keywords: Solid waste; Compost pellet; Density; Die geometry; Raw material properties; Response surface methodology

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INTRODUCTION

Municipal solid waste (MSW) is produced in great quantity in Iran and its management has become a challenge, both economically and environmentally. More than 50% of the MSW generated by the Iranian population is organic waste (Mavaddati *et al*. 2010). Composting of MSW is considered a method of transferring organic waste materials from landfills to a product that is suitable for agricultural purposes at relatively low cost (Eriksen *et al*. 1999; Wolkowski 2003). Composting MSW reduces the volume of the waste, kills pathogens that may be present, decreases germination of weeds in agricultural fields, and destroys malodorous compounds (Jakobsen 1995). Converting the municipal waste to compost is very important, because useful materials like compost produced from waste has been widely used for agricultural and horticultural purposes (Mavaddati *et al*. 2010). Composting of MSW has the potential to become a beneficial recycling tool for waste management in Iran. One of the major barriers against the use of composts is their handling, application, and storage due to low density. Therefore, these bulky residues need to be densified into pellets.

Pelletizing is a method that increases the bulk density of biomass, which facilitates transportation and reduces the cost. Pellets have low moisture content for safe storage and a high bulk density for efficient transport and storage. The process of forming biomass into pellets depends upon the physical properties of ground particles and the process variables during pelletizing. The compaction (pelletization) process is a complex interaction between particles, their constituents, and forces. Tabil and Sokhansanj (1996) studied the effect of process parameters, such as steam conditioning, die geometry, L/D ratio, die speed, and particle sizes of the biomass, on quality of pellets. Mani *et al.* (2003) and Samson *et al.* (2005) reviewed the biomass pelletizing process and the effect of various process parameters on pellet density and durability. Tabil and Sokhansanj (1997) studied the bulk properties of alfalfa in relation to its compaction characteristics. Mani *et al.* (2006) studied the effects of compressive force, particle size, and moisture content on mechanical properties of biomass pellets from grasses. The results of their research showed that compressive force, particle size, and moisture content significantly affected the pellet density of barley straw, corn stover, and switchgrass. Also, Serrano *et al.* (2011) showed that there is an optimal range of moisture content to obtain straw pellets with high density. Tumuluru *et al.* (2010) studied the effect of process conditions, such as die temperature and moisture content of raw material, on the pellet properties. They observed that the physical properties of biomass pellets varied depending on the moisture content of the biomass and the die temperature. Knowledge of the fundamental compaction properties of particles of different biomass species, sizes, shapes, chemical compositions, bulk densities, and particle densities is essential to optimize densification processes (Tabil and Sokhansanj 1995; Tabil 1996; Thomas and van der Poel, 1996). It is also important to understand the compaction mechanisms in order to design energy-efficient compaction equipment and to quantify the effects of various process variables on pellet density and pellet durability. The objective of this study was to investigate the effects of moisture content, speed of piston, length of die, and particles size on the density of pellet from composted municipal solid waste.

EXPERIMENTAL

Sample Preparation

Compost samples were ground using a hammer mill with three different hammer mill screen sizes (0.3, 0.9, and 1.5 mm) in order to understand the influence of particle size on density. The ground feedstocks were stored at room temperature (25 ºC). The moisture content of the ground samples was determined following the procedure given in ASAE Standard S 269.4. The samples of compost were placed in an oven at 105±3ºC for 24 hours. The moisture content of the samples was determined by weighing and is expressed in percent wb. The moisture contents of ground feedstocks were adjusted to 35, 40, and 45% (w.b.) by adding water; they were equilibrated overnight to determine the effect of moisture content on pellet density.

Pellet Production

A hydraulic press and a single pelletizer were used to produce pellets (Fig. 1). The pelletizer consisted of a plunger and cylinder assembly. The cylinder had an internal diameter of 10 mm and a length of 100 mm. The dies placed at the end of the cylinder had a hole with a 6 mm diameter and different lengths. A hydraulic press was used to move the piston. This press had three important features: pressure control, piston speed control, and residence time control at the set pressure. The hydraulic press was equipped with a data recording system for displacement, force, and time. By moving the piston, material is compressed and converted to pellet form when emerging from the die. Produced pellets were dried at ambient temperature until their moisture content reached about 12% (wet basis).

Fig.1. The laboratory equipment used for producing pellets

Pellet Density

The density of each individual pellet (true density) was calculated by measuring the length and diameter of the pellet cylinder using an electronic caliper and by measuring the mass using an electronic balance with a precision of 0.01 g. To achieve a uniform length, the edges of the pellets were smoothed. Pellet density was calculated by dividing mass of individual pellets by their volume calculated from length and diameter (Shankar *et al*. 2007). Pellet density values are reported as an average of five measurements.

Experimental Design

A Box-Behnken design with four variables was used to study the response pattern and to understand the influence of moisture content (X1), speed of piston (X2), die length (X3), and particle size (X4) on density of pellets. The experimental design was developed using Design Expert 8.0.7.1, which resulted in 29 tests. The level values of each variable and code investigated in this study are presented in Table 1.

Table. 1. Experimental Range and Level of Independent Variables

Independent variable	Coded level and range		
	-1	0	1
Moisture Content, %	35	40	45
Speed of piston, mm/s	2	6	10
Length of die, mm	8	10	12
Particles size, mm	0.3	0.9	1.5

Statistical Analysis

A second order quadratic equation was used to describe the effect of independent variables in terms of linear, quadratic, and interactions. The proposed model for the response (ρ) was,

$$\rho = b_0 + \sum_{i=1}^{3} b_i X_i + \sum_{i=1}^{3} b_{ii} {X_i}^2 + \sum_{i=1}^{3} \sum_{j=i+1}^{4} b_{ij} X_i X_j + \varepsilon \qquad (1)$$

where ρ is the predicted response (density), b_0 is the interception coefficient, b_i , b_{ii} , and b_{ij} are the linear, quadratic, and interaction terms, ε is the random error, and X_i is the independent variables studied. The Design Expert 8.0.7.1 software was used for regression and graphical analysis of the data obtained. The significance of the statistical model was evaluated by the F-test analysis of variation (ANOVA).

RESULTS AND DISCUSSION

Effect of Independent Variables on Pellet Density

Table 2 shows the results of the single pellet tests carried out at three levels of moisture content, speed of piston, die length, and particle size. The measured and predicted densities are depicted in Fig. 2. Based on the experimental data, the developed quadratic models in terms of coded variables are given in Equation 2. This equation predicted the density well with a high R^2 and low probability.

$$\rho = +1120.87 + 9.4 X_1 - 26.57 X_2 - 21.79 X_4 - 9.4 X_2 X_3 - 14.9 X_1^2 - 21.85 X_4^2 \qquad (2)$$

The value of "Prob <F" less than 0.0001 revealed that the quadratic model of response variables is a reliable model. Also the model showed a high determination coefficient (R^2 = 0.95) and low lack of fit (Table 3). All the independent variables included in this study, except for die length, had significant effects on density of the pellets (Table 4). The particle size of the feedstock and the speed of piston showed a negative relationship with density. The increase of die length had a negligible effect on the increase of density. With an increase in moisture content, density initially increased and then decreased.

Table. 2. Experimental Design (actual and coded values) and Responses

Treat	Moisture (%)	Speed of Piston (mm/s)	Die length (mm)	Particles size (mm)	Diameter (mm)	Length (mm)	Weight (g)	Density (Kg/m^3)
1	35(-1)	2(-1)	10(0)	0.9(0)	5.69	16.17	0.46	1117
2	45(1)	2(-1)	10(0)	0.9(0)	5.6	17.54	0.49	1140.5
3	35(-1)	10(1)	10(0)	0.9(0)	5.73	17.65	0.49	1073.8
4	45(1)	10(1)	10(0)	0.9(0)	5.63	19.16	0.52	1082.6
5	40(0)	6(0)	8(-1)	0.3(-1)	5.28	11.14	0.27	1122.8
6	40(0)	6(0)	12(1)	0.3(-1)	5.42	24.83	0.65	1128.5
7	40(0)	6(0)	8(-1)	1.5(1)	5.71	13.32	0.36	1065.3
8	40(0)	6(0)	12(1)	1.5(1)	5.78	13.33	0.38	1076.3
9	35(-1)	6(0)	10(0)	0.3(-1)	5.59	18.18	0.49	1102.1
10	45(1)	6(0)	10(0)	0.3(-1)	5.22	17.7	0.42	1109.7
11	35(-1)	6(0)	10(0)	1.5(1)	5.82	22.08	0.62	1057.9
12	45(1)	6(0)	10(0)	1.5(1)	5.78	12.75	0.36	1080.7
13	40(0)	2(-1)	8(-1)	0.9(0)	5.89	11.45	0.35	1134.6
14	40(0)	10(1)	8(-1)	0.9(0)	5.55	20.35	0.54	1105.9
15	40(0)	2(-1)	12(1)	0.9(0)	5.21	14.81	0.36	1156
16	40(0)	10(1)	12(1)	0.9(0)	5.49	16.07	0.41	1089.7
17	35(-1)	6(0)	8(-1)	0.9(0)	5.89	19.02	0.56	1089.6
18	45(1)	6(0)	8(-1)	0.9(0)	5.43	17.82	0.46	1108.8
19	35(-1)	6(0)	12(1)	0.9(0)	5.58	16.64	0.44	1089.7
20	45(1)	6(0)	12(1)	0.9(0)	5.57	10.95	0.3	1120.6
21	40(0)	2(-1)	10(0)	0.3(-1)	5.54	21.59	0.59	1137.2
22	40(0)	10(1)	10(0)	0.3(-1)	5.43	19.11	0.48	1089.2
23	40(0)	2(-1)	10(0)	1.5(1)	5.69	14.57	0.41	1111.2
24	40(0)	10(1)	10(0)	1.5(1)	5.25	12.83	0.29	1036.5
25	40(0)	6(0)	10(0)	0.9(0)	5.76	16.52	0.48	1120.2
26	40(0)	6(0)	10(0)	0.9(0)	5.68	9.59	0.27	1126.8
27	40(0)	6(0)	10(0)	0.9(0)	5.55	12.26	0.33	1103.8
28	40(0)	6(0)	10(0)	0.9(0)	5.68	38.46	1.1	1124.5
29	40(0)	6(0)	10(0)	0.9(0)	5.61	17.09	0.48	1129.1

Table. 3. Analysis of Variation (ANOVA) of Fitted Model

Source	SS	DF	MS	F Value	Prob > F
Model	20141.11	14	1438.65	20.85916	< 0.0001
Residual	965.58	14	68.97		
Lack of Fit	555.96	10	55.60	0.542904	0.8025
Pure Error	409.62	4	102.40		
Cor Total	21106.68	28			
R^2 = 0.95;	Adgusted R^2 = 0.91				
Pred R^2 = 0.82;	Adeq Precision = 19.28				

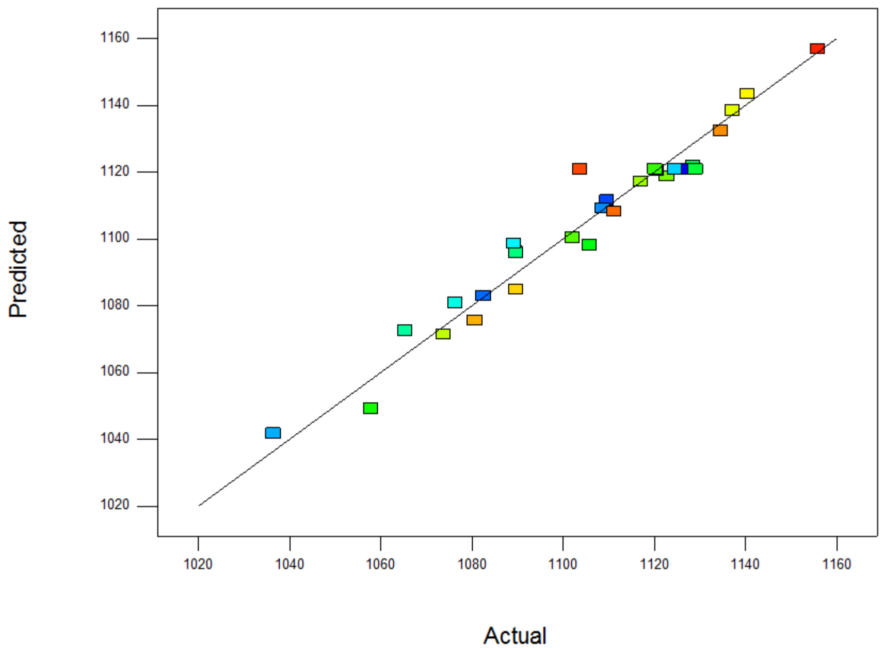

Fig. 2. Measured versus predicted density

Table. 4. Coefficient Values of the Fitted Model

Factor	Sum of Square	F Value	p-value Prob > F
Moisture, X_1	1060.13	15.37	0.0015
Speed of piston, X_2	8472.19	122.84	< 0.0001
Die length, X_3	94.71	1.37	0.2608
Particle size, X_4	5699.97	82.64	< 0.0001
X_1X_2	53.67	0.78	0.3926
X_1X_3	34.52	0.50	0.4909
X_1X_4	57.99	0.84	0.3747
X_2X_3	353.24	5.12	0.0401
X_2X_4	178.81	2.59	0.1297
X_3X_4	6.92	0.10	0.7560

Effect of Moisture Content

The feedstock moisture content exerted strong influence on density of pellets, as evidenced by the magnitude of linear terms in Equation (2) and in Table 3. Increasing the moisture content initially increased and then decreased unit density. In the densification process, water acts as a film-type binder by strengthening and promoting bonding via van der Waal's forces by increasing the contact area of the particles (Mani *et al.* 2003). According to the conducted research, the optimum moisture content for the densification process is different depending on the type of biomass and process conditions. The increase of moisture content from an optimal range reduces the intermolecular forces, and even much higher moisture content causes a biphasic mixture (liquid phase and solid phase) and disappear intermolecular forces entirely (Zafri and Kianmehr 2012).

Effect of Feedstock Particle Size

Feedstock particle size had a negative influence on pellet density. Density decreased with increasing particle size, which was in agreement with results from a study by Zhou *et al.* (2008). They showed that corn stover density decreased with an increase in particle size. The same trend of particle size–density relationship was also observed for wheat straw and switchgrass samples studied by Lam *et al*. (2008). In general, finer grinding produces higher-density pellets, since finer grinding yields a higher surface area of contact to form bonds or solid bridges during the compaction processes. However, this is not always the case, as conflicting results can be found in literature. The change in pellet density depends on the type of biomass. Payne (1978) reported that a proportion of fine to medium particles is required, but pellet quality and the efficiency of commercial pelletizers will suffer if coarse material is not present.

Effect of Die Geometry and Speed of Piston

To investigate the effect of die length on physical properties of biomass pellets, three dies with length of 8 mm, 10 mm, and 12 mm were used during the biomass pelletizing process. The use of a thicker die was found to enhance density of pellet. This result followed the same trend as the experimental result from the study by (Theerarattananoon *et al*. 2011). Results from the study by Behnke (1990) showed that the use of a thicker die increases pellets durability significantly. Kaliyan and Morey (2009) reported that the factors that increase pellet durability would also increase pellet density, although the relationship between durability and density of biomass pellets was still unknown. Speed of piston will influence flow rate and holding time of the feedstock in die. The results showed that the low speed of piston had significant effect on increasing the pellet density. Increasing in shear force resulted from increased friction between feedstock and die may be the reason for the increment of density. The results from this study were in agreement with results reported by Li and Liu (2000) for the processing of oak sawdust.

Response Surface for the Interactions of Moisture Content, Speed of Piston, Die Length, and Particle Size on Pellet Density

The regression coefficients, sum of square, F, and p values are shown in Table 4. All of the linear terms except the term of die length had significant effects on pellet density. All interaction terms except the interaction term of piston speed and die length did not significantly affect density, and the quadratic term of moisture content and particle size exhibited a negative effect on pellet density. Contrary to this study, Yunardi *et al*. (2011) reported that the interaction term of moisture content and particle size and quadratic term of particle size had significant effects on density of rice straw pellet. The results from this study were in agreement with results reported by Munoz-Hernandez*et al.* (2004). They determined optimal working parameters for the densification process for agricultural crop residues. In order to visualize the two factor interaction effects on pellet density, interaction response surfaces are shown in Fig. 3.

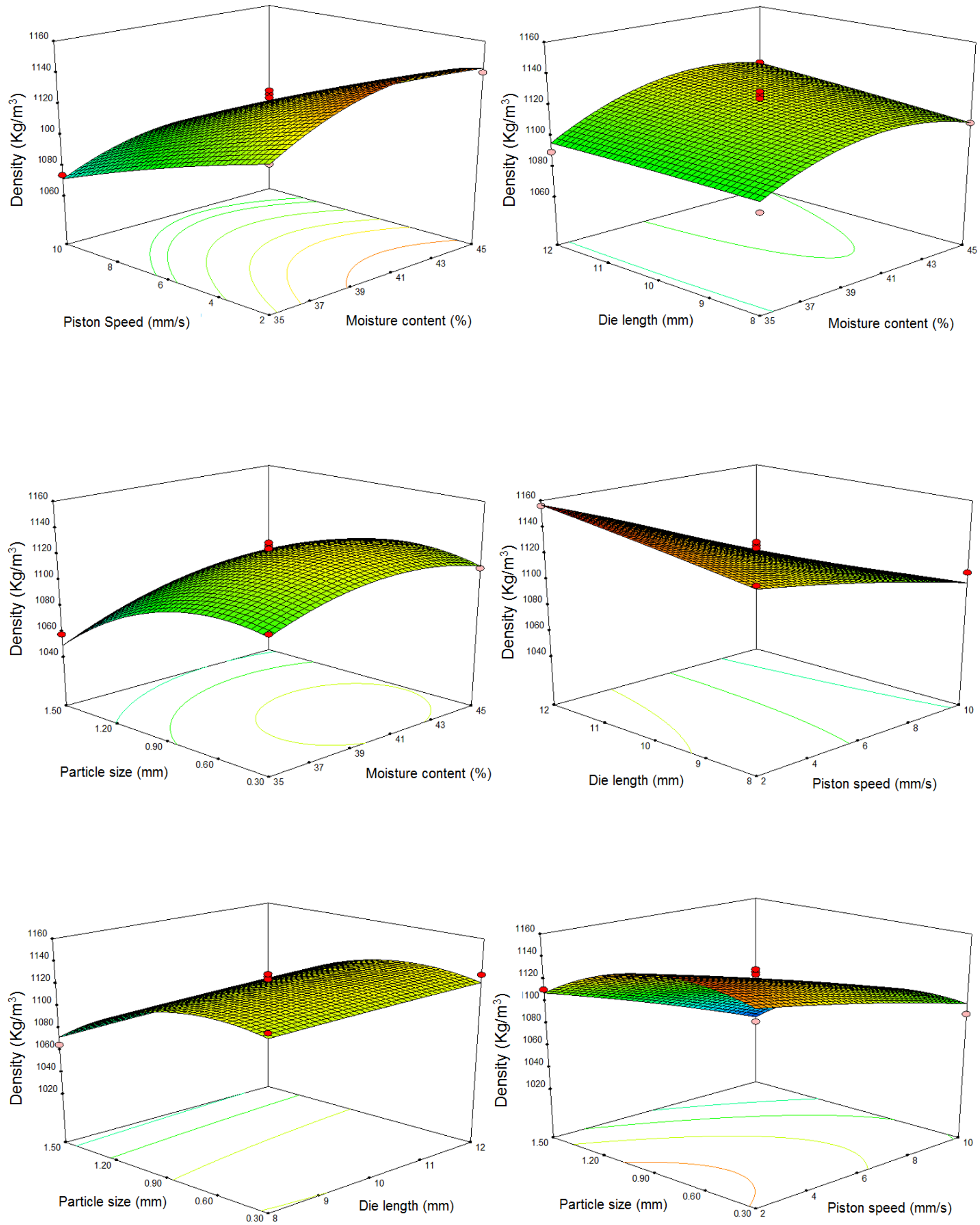

Fig. 3. Interaction effects of independent variables on pellet density (other variables are fixed at centre point)

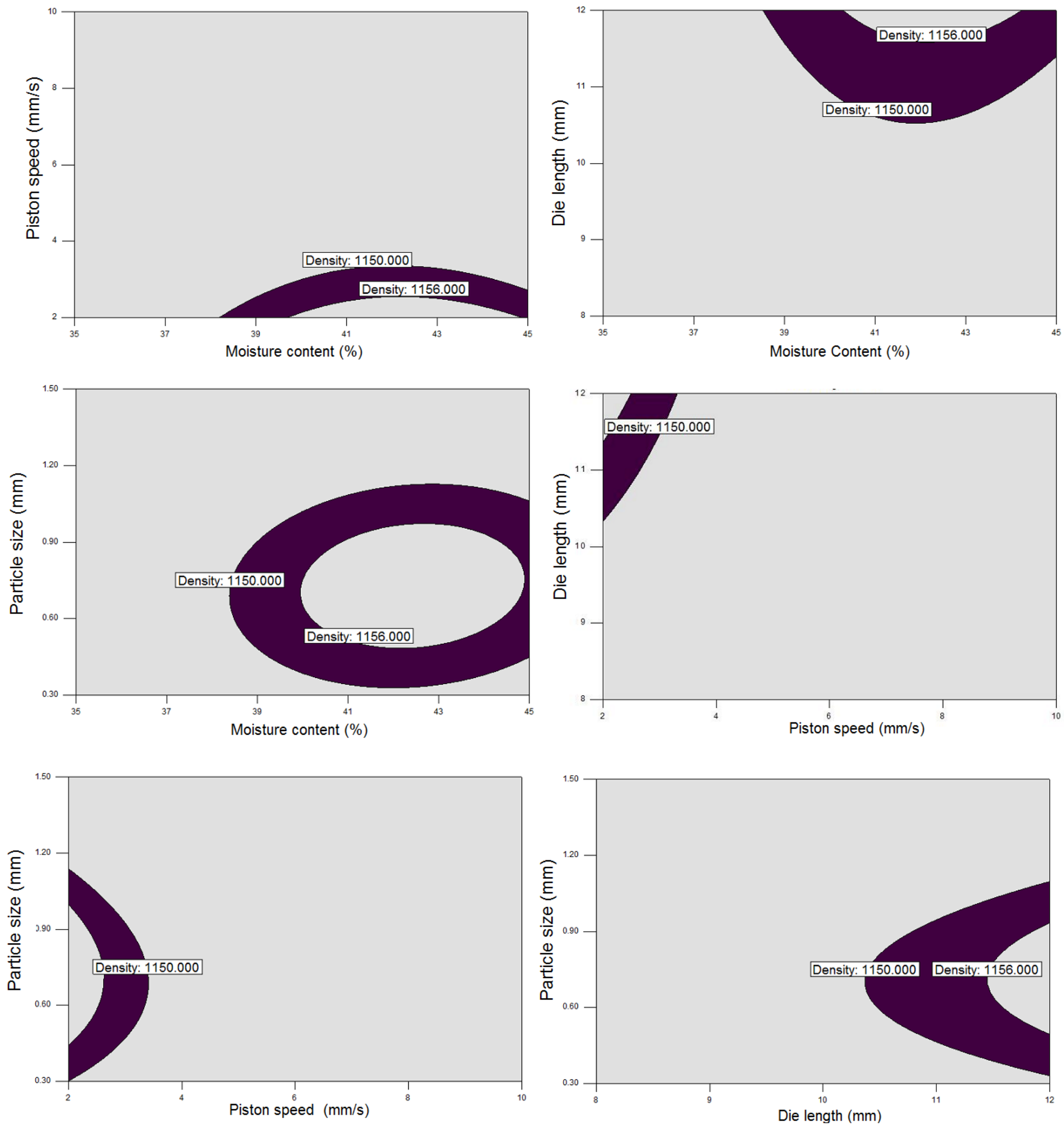

Fig. 4. Optimized range of density contour as affected by moisture content, piston speed, die length, and particle size

Optimization of Process Variable for Maximum Pellet Density

The main objective of this work was to find optimal conditions for the densification process for producing pellets from composted municipal solid waste. Accordingly, numerical and graphical optimization was performed using Design Experts 8.0.7.1 software. The optimized ranges of density contour are shown in Fig. 4. A variety of pretreatment conditions can be selected from the shaded regions in Fig. 4. Most of the region identified by the shaded area satisfied the maximum density. Six solutions among the most possible ones are shown in Table 5.

Table. 5. Solutions Such that the Constraints are Satisfied

Number	X_1	X_2	X_3	X_4	Density	Desirability
1	40.00	2	12.00	0.90	1156.84	1
2	41.95	2.44	11.59	0.61	1156.14	1
3	40.77	2.40	11.86	0.74	1157.14	0.992
4	41.95	2.16	11.82	0.82	1159.72	0.98
5	40.17	2.12	11.58	0.79	1156.03	0.971
6	44.06	2.01	11.28	0.71	1156.35	0.96

CONCLUSIONS

Composted municipal solid waste was extruded using a single pelletizer at various conditions based on a Box-Behnken experimental design to evaluate the effect of moisture content, speed of piston, die length, and particle size on pellet density and obtain maximum density.

1. Statistical analyses confirmed that the moisture content, speed of piston, and particle size significantly affected the pellet density.
2. The effect of the linear term of die length was negligible, but the interaction term of die length and speed of piston was significant relative to density.
3. Response surface methodology can be adopted to predict the pellets density.
4. It was found that higher density could be achieved at a moisture content of 40%, piston speed of 2 mm/s, die length of 12 mm, and hammer mill screen size of 0.9 mm.

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