Optimizing the single screw extruder die head to produce organic-based fertilizer pellet

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Abstract: Pellet production is an effective method for efficient use; reducing transportation costs and the improvement of economic efficiency for organic wastes such as vermicompost and municipal solid waste compost. Physical and rheological properties of the material are essential for the design of pellet machine accessories. In this study, the rheological parameters of yield stress (σ_0), shear stress (τ_0) and velocity factors (α and β) were determined by using a capillary rheometer. The number of holes of a single screw extruder die was also determined according to achieved results. The experiments on the materials at 45% moisture content resulted the values, σ_0 = 0.09 MPa, τ_0 = 0.009 MPa, α = 3.1 MPa sm^{-1} and β = 0.11 MPa sm^{-1} for paste compost and σ_0 = 0.506 MPa, τ_0 = 0.02498 MPa, α = 0.0357 MPa sm^{-1} and β = 0.00145 MPa sm^{-1} for vermicompost. The best results were achieved for single screw extruder with 10 holes for paste compost and with seven holes for vermicompost.

Keywords: rheology, capillary rheometer, compost, vermicompost, pellet, extruder, biomass

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1 Introduction

The term of biomass is used to describe any original biological material includes plant materials such as trees, grasses and crops and animal manure and municipal waste (sewage) (Crocker, 2010). High moister content and volume, high required conservation space, non-uniform constituent materials, creation of dust and pollution causeda limitation use of biomass materials, especially manure, vermicompost and urban waste compost (Mavaddati et al., 2010). Normally, transporting of these fertilizers to long distances is difficult and expensive due to the low density, so compression and providing pellets prepared one of the most effective ways to expend utilization and reduce transportation and usage costs of this type of materials (Adapa et al., 2003). According to the data from a research on a variety of pellets in the chemical industry and agricultural production, the quality of the resulting pellets can be optimized by controlling of the production process and modifying the configuration of the device and knowledge of the constituent materials formulation for use heating process in order to activate the natural adhesive compounds present in structure (Thomas et al., 1988). The quality of pellets is affected by machine variables such as die geometry, the time to pass the material through the barrel and pressure, inlet roller and process variables such as temperature, humidity and steam conditions (pressure and volume of steam used) and amount of material fed into the machine. However, there is an interesting point about this beneficial fertilizer especially vermicompost (McMahon, 1984). These materials are rich sources of beneficial bacteria called Plant Growth Promoting Rhizobacteria (PGPR) (Hoitink and Keener, 1993). Maintenance of these materials is very important issue during the pellets production process. Many of these bacteria could be bear to maximum 60°C because the beneficial bacteria will be lost at above this temperature level. Figure 1 shows the rate of temperature rise in pellet production of vermicompost at the end of the single screw extruder. According to the temperature-time curve

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for single screw extruder, it is expected that the temperature reach to 60°C in less than an hour. So, due to the continuous process, a refrigerant instead of dry steam or any other heating system and a temperature control system are needed to prevent temperature rising above 60°C (Bahram, 2012).

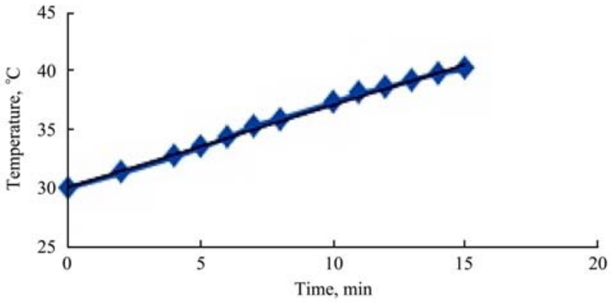

Figure 1 Temperature of the materials at the end of extruder for pelleting of vermicompost (Bahram, 2012)

Determining the physical and rheological properties of the materials is necessary to calculate the required power for extrusion process. Compost (municipal solid waste) and vermicompost without exception are viscoelastic and properties of these materials can be expressed by using rheological dashpot-spring models (Sitkey, 1986). Various devices are designed for determination the rheological properties, particularly liquid viscosity, semi-liquid and pasty materials which may have different working principles (Dobraszczyk and Morgenstern, 2003).

2 Materials and methods

In this study, a capillary rheometer was used for determining the rheological properties of municipal solid waste and vermicompost. So, the parameters of the σ_0 (yield stress in the entry die), τ_0 (shear stress in zero velocity at the die wall), α and β (speed factor) were determined and finally the number of holes in single-screw extruder (Figure 2) by method of Benbow and Bridgwater (1993) were used to determine the number of holes in the extruder for minerals.

Samples of vermicompost were collected from the wormy culture farm, College of Agriculture and Natural Resources, Karaj, Iran. The compost materials were prepared from the compost production factory (located in Tehran, Kahrizak) that uses the municipal solid waste for production. Figure 3 shows the schematic diagram of the capillary rheometer and its components that used in this study.

A hydraulic press apparatus was used to provide motion of the capillary rheometer. This set is composed of a fixed jaw (location rheometer) and a movable jaw (hydraulic cylinder) and a hydraulic jack to force the piston into the rheometer (Figure 4).

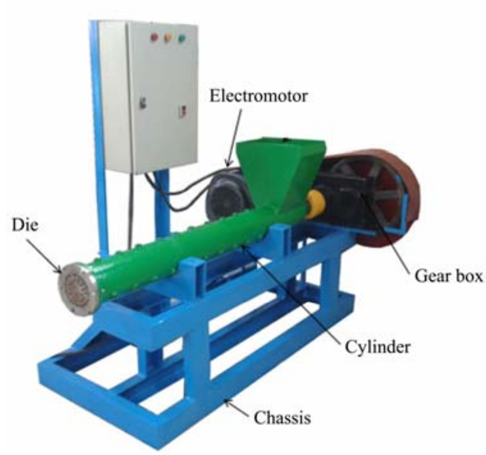

Figure 2 Single-screw extruder designed and manufactured in the University of Tehran

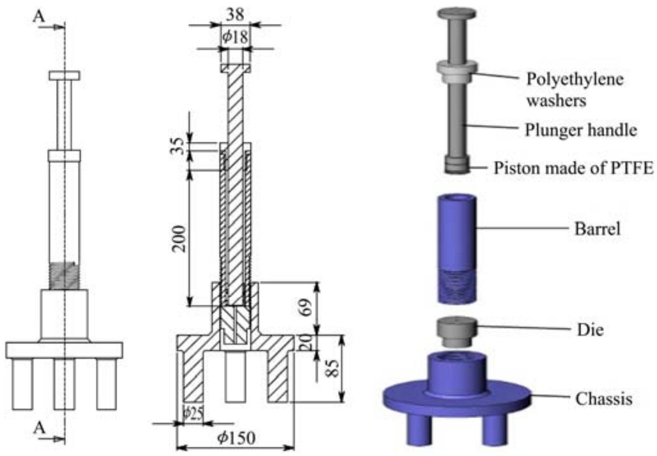

Figure 3 Schematic diagram and components of capillary rheometer

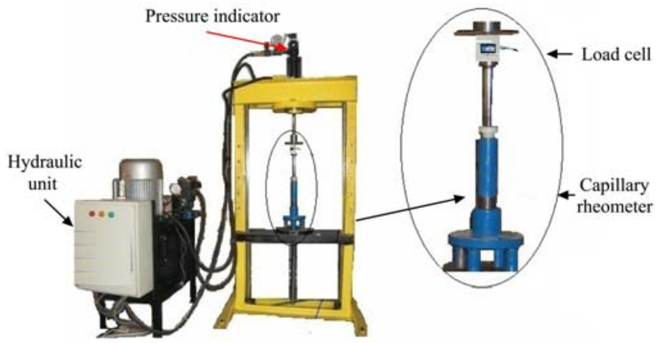

Figure 4 Capillary rheometer placements during the test

This set is capable to set the desired pressure for the passage or for setting the constant rate of applied force for passage the paste materials through the die of rheometer. Maximum pressure that the device is able to force to the piston is 250 Bar. The maximum force for extrusion in pelleting process can be determined by Equation (1):

$$F = P*A \tag{1}$$

where, A (mm^2) is the cross section of piston; F (N) is the force required for the passage of material through the die and P (kPa) is pressure applied to the rheometer piston.

2.1 Analysis of paste flow in open die

The Benbow-Bridgwater equation has provided a good first order model for axisymmetric extrusion and reasonable industrial design information, although the assumptions involved in the analysis make its precision low. The model is sometimes used to ascertain material constants for more general use. In this research this method was used for determining the rheological parameters of compost and vermicompost. When paste cross the barrel into the opens die, the piston must be overcome friction and shear stress of paste on the body of die. This method models the paste as a quasi-plastic material; the extrusion pressure required to extrude a paste from a circular barrel of diameter D through a concentric die of diameter D_o and length L at a die land velocity v as Equation (2):

$$P = 2(\sigma_0 + \alpha v)\ln\frac{D_o}{D} + 4(\tau_0 + \beta v)(\frac{L}{D}) \tag{2}$$

where, σ_0 is the initial yield stress (MPa); τ_0 is shear stress (MPa) at zero velocity zoon (the initial stress on the walls of the die's wall) and α, β are the parameters characterizing the effect of velocity on the die entry.

2.2 Determination of the parameters

According to the length and diameter of the die and the experimental results, the operational velocity diagram of the piston is shown in Figure 5.

According to the diagram the rheological parameters (α, σ_0, τ_0 and β) are calculated by using Equations (3), (4), (5) and (6) (Benbow and Bridgwater, 1993).

$$\alpha = \frac{OB - OA}{2(v_2 - v_1)\ln\frac{D}{D_0}} \tag{3}$$

$$\sigma_0 = \frac{OAv_2 - OBv_1}{2(v_2 - v_1)\ln\frac{D_0}{D}} \tag{4}$$

$$\tau_0 = \frac{v_2[(CJ) - (OA)] - v_1[(DJ) - (OB)]}{4(OJ)(v_2 - v_1)} \tag{5}$$

$$\beta = \frac{(DJ - OB) - (CJ - OA)}{4OJ(v_2 - v_1)} \tag{6}$$

It is notable that selection of velocity of press is based on the maximum pressure that the press can produce at this velocity level and this pressure is the same pressure that a single screw extruder can produce at different speeds near the die.

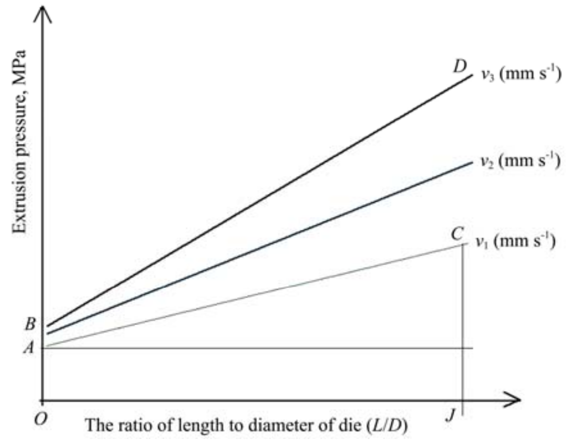

Figure 5 The extrusion pressure of the die versus the ratio of length to diameter at different velocity

2.3 Determination of the number of extrusion die holes

In the extrusion process, materials have to pass through more than one hole that is parallel to each other in the die. Pressure drop due to the flow paste through a barrel with diameter D_0 in to die land with diameter D expressed with the Equation 2. If the volumetric flow rate, Q passes uniformly from N number of holes with diameter D, the mean velocity (v) of material can be determined by Equation (7).

$$Q = \left(\frac{\pi}{4}\right)D^2 Nv \tag{7}$$

When the paste flows through a barrel with diameter of D and with N number of die holes, and if the paste passes from all holes, so the mean velocity (v) depended on $D_0/N^{0.5}$. By determining v from Equation (7) and inserting to extrusion pressure equation (Equation (2)), the overall pressure drop, due to passing paste from N number of hole will be determine by Equation (8), which is known as the Benbow-Bridgwater equation, Equation (8):

$$P = 2\left(\sigma_0 + \frac{4\alpha Q}{\pi D^2 N}\right)\ln\left(\frac{D_0}{DN^{1/2}}\right) + 4\left(\tau_0 + \frac{4\beta Q}{\pi D^2 N}\right)\left(\frac{L}{D}\right) \quad (8)$$

After calculating α, σ_0, τ_0 and β values from the Equations (3), (4), (5) and (6) respectively and replacing in Equation 8 and by having the values of pressure (P) and volumetric flow rate (Q) from rheometer experiments, and according to the known values of L, D and D_0 (die specification), only the number of holes (N) remains unknown that can be easily determined by the Equation 8.

3 Results and discussion

The result of the rheological behavior for compost during the loading test is expressed in Figure 6 as an example. The profile can be divided into three flow regions: compaction (oa), steady state (ab) and bottom of barrel (bc). The air entrained in the paste is expelled over the compaction region. As the paste is much less elastic than air, the extrusion pressure starts to rise very rapidly until it reaches a peak, at which point flow commences. There is a transient region, immediately after flow has commenced, where the flow pattern and extrusion pressure are unsteady (for this material this region is so small and negligible). After a short time, some optimal flow pattern is reached and the rest of the extrusion run proceeds under nominally steady state conditions. When the piston reaches to the end of the course, a sudden increase in pressure is obvious.

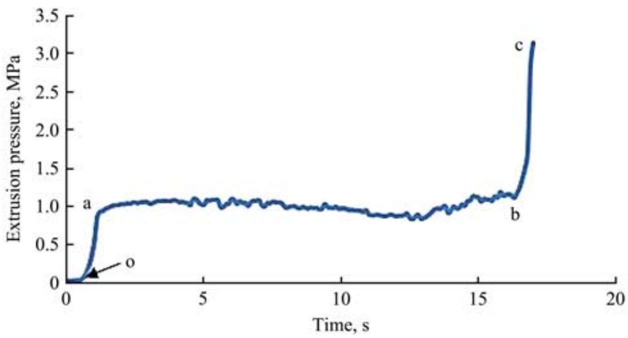

Figure 6 Piston force against time for Piston velocity = 10 mm s^{-1}, D = 3 mm, $L\ D^{-1}$ = 8. For compost paste by 45% moister content

The extrusion pressure diagrams are shown in Figure 7 for urban waste compost and in Figure 8 for vermicompost for the compost paste with 45% moisture content.

Considering the points of O, A, B, C, D and J points in Figure 5 and using the Equations (3), (4), (5) and (6), the characterization parameters (yield stresses σ_0 and τ_0 and velocity factors α and β) were calculated by non-linear regression using Matlab, which are represented in Table 1. It can be seen that vermicompost has a relatively large yield stress σ_0. This means that the contribution of the total extrusion works due to the deformation on entering the die land, described by the first term of Equation (8), can significantly greater than the shearing work in the dieland.

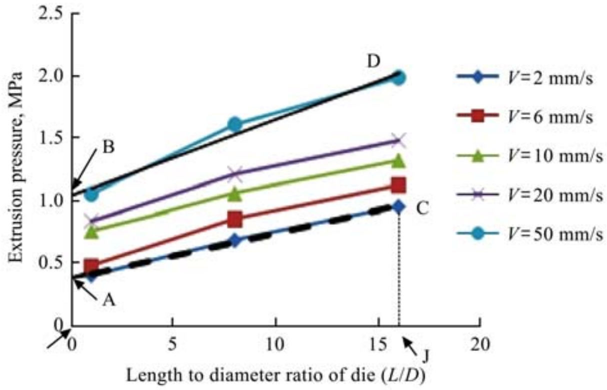

Figure 7 Extrusion pressure of different $L\ D^{-1}$ at different velocities for urban waste compost

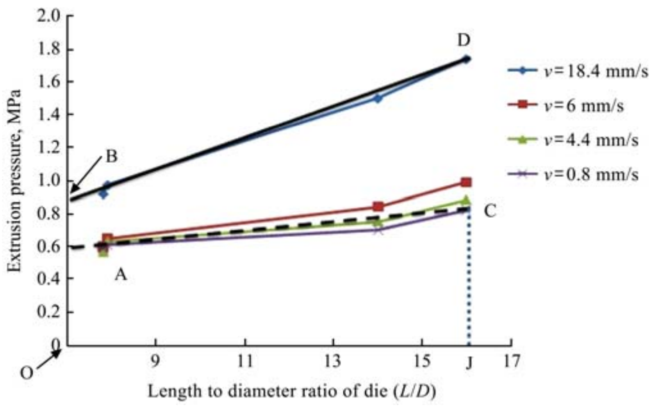

Figure 8 Extrusion pressure of different $L\ D^{-1}$ at different velocities for vermicompost

Table 1 Rheological parameters of urban waste compost and vermicompost paste

Rheological parameters	Vermicompost	Urban waste compost
σ_0 (MPa)	0.506	0.092
τ_0 (MPa)	0.025	0.009
α (MPa s m^{-1})	0.036	3.103
β (MPa s m^{-1})	0.00145	0.11240

The extrusion pressure values (MPa) of compost and vermicompost paste at different velocities, calculated by using Equation (2) and the data from experiments are represented in Table 2. The results show an acceptable correlation between experiment and computational dates.

So it can be claimed that Benbow-Bridgwater equation is suitable method for determining rheological property of compost and vermicompost for estimation of the number of extruder die holes.

Table 2 Calculated and experimental extrusion pressure values (MPa) of compost and vermicompost paste in length (*L*) to diameter (*D*) ratio of die equal to 1/16 at different velocity for *D*= 3 mm

Kind of compost	Extrusion pressure values, MPa								
	Urban waste compost					Vermicompost			
Velocity of material passing from die, mm s^{-1}	2	6	10	20	50	0.8	4.5	6	18.5
Calculated by Equation (2)	0.455	0.490	0.552	0.693	1.091	0.82	0.88	0.98	1.74
Experimental values	0.412	0.480	0.761	0.839	1.058	0.79	0.83	0.97	1.6

3.1 Calculating the number of holes in the extruder die

By using of the Equation 1 to 8, and considering the diameter die holes of 6 mm, the calculated numbers of die holes were 9.7 for urban waste compost and 6.49 for vermicompost**.** Based on the results, two dies with 10 and seven holes were design and constructed for pellet production by single screw extruder (Figure 9).

a. Vermicompost pellet b. Urban waste compost pellet

Figure 9 Produced pellet by using the design dies in the extruder for both pellets

4 Conclusions

The physical and rheological properties of the materials are essential for the design of pellet machine accessories such as the number of die holes in single screw extruder. The number of die holes (*N*) are determined by calculating the values of (σ_0, τ_0, α and β), pressure (*P*) and volumetric flow rate (*Q*) and replacing the values in the related equations. Therefore, seven and 10 holes were determined respectively for vermicompost and paste compost pelleting in the single screw extruder.

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