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Manufacturing and Evaluation of a Biochar Pelleting Machine

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ABSTRACT

Biochar is the solid product that remains when biomass is heated to temperatures typically between 300°C and 700°C while being completely or partially oxygen-free. Experiments were carried out through the year of 2022 at Department of Agricultural Engineering, Faculty of Agriculture, Damietta University, Egypt. In this study, four types of biochar were used (sawdust - rice straw - Bagasse – the discarded leaves of palm trees) along with two types of binders (molasses and starch) and three diameters of the extruder (20 mm, 30 mm, 40 mm). During the experiments, the results showed the highest compressive strength was 2170 N when using sawdust waste and molasses a binder at an extruder diameter of 20 mm, the highest shear force was 848 N when using starch and sugar cane waste at an extruder diameter of 40 mm. The maximum value of pelletizing efficiency and machine productivity were 80 % and 52.36 kg/h, respectively, when using sugar cane waste and starch at an extruder diameter of 40 mm, respectively. The lowest value of specific energy consumption was 0.04 Kw.h\kg when using sugar cane waste and starch at an extruder diameter of 40 mm. The lowest operational cost was 0.378 L.E\Kg when using sugar cane waste and starch at an extruder diameter of 40 mm.

1- INTRODUCTION

Hara (2001) added that there are two types of moulding (dis-molding) devices that form pellets of composted cattle manure. One type is the disc pelleter while the other is the extruder. He announced the discovery of a pelleting method for 5 mm-diameter composted cattle dung. If this is accomplished without the need for additional materials. **Lu et al., (2014)** reported that pellets were produced from wheat straw and binders (wood residue, pretreated wood residue, lignosulfonate, bentonite and crude glycerol) notice that the specific energy consumption for wheat straw pelletization significantly decreased. **Hu et al., (2015)** reported that when rice husk char was compressed into pellets with four types of binders . The compressive process and mechanical strength were examined to elucidate the effect of binders on the properties of biochar pellets. The results showed that the starch granules have good hydrophobicity, but low volume density and poor mechanical strength.

Ronsse *et al.*, (2013) and Kameyama *et al.*, (2016) indicated that biochar is produced from the residual biomasses such as crop residues, manure, wood residues, and forests and green wastes using modern pyrolysis technology. **Shaaban et *al.*, (2018)** mentioned that biochar made from wood-based biomass has a higher biodegradation resistance than biochar made from animal manures or crop leftovers. **Meier *et al.*, (2017)** said that the amount of carbon lost during biochar synthesis, as well as the physical and structural changes, are mostly determined by the pyrolysis temperature. Higher ash content results from larger production temperatures and residence durations, resulting in higher concentrations of nutrients like P, K, and Ca. At higher production temperatures, volatile nutrients like nitrogen tend to decrease. **Bonanomi *et al.*, (2017)** reported that Furthermore, adding biochar to the soil improved soil quality and helped plants retain nutrients, resulting in better plant growth. **Armah *et al.*, (2022)** reported that by lowering acidity and improving nutrient availability, biochar has been used to repair polluted agricultural soil and increase soil fertility. Thus, one of the finest practices for reducing biotic stress in soil and boosting crop yield, particularly in the agricultural sector, is the addition of biochar to soils. **Brown *et al.*, (2011)** mention that the dry waste obtained is simply cut into small pieces to less than 3 cm prior to use. The feedstock is heated either without oxygen or with little oxygen at the temperatures of 350–700°C (662–1292°F). **Zhu *et al.*, (2018)** reported that Biochar can be manufactured on a small scale using low-cost modified stoves or kilns or through large-scale, cost-intensive production, which utilizes larger pyrolysis plants and higher amounts of feed stocks. Biochar is produced from several biomass feedstocks through pyrolysis, generating oil and gases as by-products. **Rawat *et al.*, (2019)** indicated that the influence of biochar on physical properties of soil directly affects the growth of plants, since the depth of penetration and accessibility of air and water in the root zone is determined mainly by the physical composition of the soil horizons. This affects the soil's response to water, its aggregation, and work ability in soil preparation, dynamics, and permeability when swelling, as well as the ability to retain cations and response to changes at ambient temperature. The smaller the pores on biochar, the longer they can retain capillary soil water. The addition of biochar can reduce the effects of drought on crop productivity in drought-affected areas due to its moisture-retention capacity.

This study was conducted to manufacture a machine for compressing, mixing and pelletizing raw materials to produce biochar using different binders. So, the objectives of the present study may be summarized as follows:

1. Design and manufacturing a local pelleting machine for producing biochar
2. Use of cheap and readily available binders to facilitate biochar production.
3. Evaluate the performance of pelleting machine to produce high quality of biochar pellets.
4. Optimize some operating and engineering parameters (three extruder diameters, four types of raw biochar and two binders) affecting the performance of biochar pelleting machine.
5. Evaluate the performance of biochar pelleting machine from the cost point of view.

2- MATERIAL AND METHODS

Experiments were carried out through the year of 2022 at Department of Agricultural Engineering, Faculty of Agriculture, Damietta University, Egypt.

2.1. MATERIALS:

2.1.1. Raw materials:

The raw materials used in this study are (Rice straw - Date palm waste - Sawdust - Sugar cane waste) as shown in **Fig.1.** The following **Table1.** shows some characteristics and analysis of the biomass materials used in this study. Two types of bonds were used (molasses and starch).

Table 1. Characteristics and analysis of used biomass materials.

Analysis *	Rice straw	Date palm waste	Sawdust	Sugar cane waste
MC, %	11.9	7.9	2.5	4.9
Total N, g/kg	0.71	1.30	8.61	4.09
Total P, g/kg	0.48	0.04	0.17	0.29
Total K, g/kg	8.74	1.6	0.29	1.05
Total Ca, g/kg	16.58	0.75	0.53	0.19
Total Mg, g/kg	2.21	0.08		
Cellulose, %	48.16	32.7		
Hemicellulose, %	24.33	29.1		
Lignin , %	3.09	28.3		

*** Percentages are on a dry weight basis**

Figure .1. Raw materials rice straw, sugar cane waste, date palm waste and sawdust.

2.1.2. Biochar Pyrolysis Kiln:

The biomass was burned in an airless environment at a temperature ranging from 300-700°C. Using "El-Sheikha 2020" kiln as shown in the following **Fig.2.**

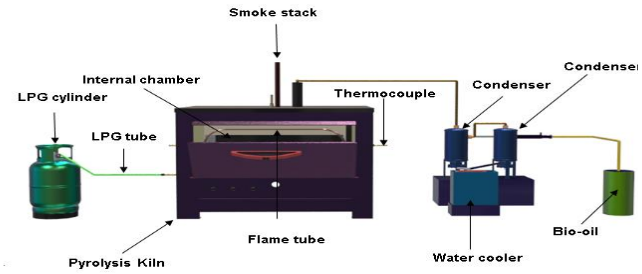


Figure .2. Pyrolysis set-up unit for biochar production.

2.2. The new manufactured machine:

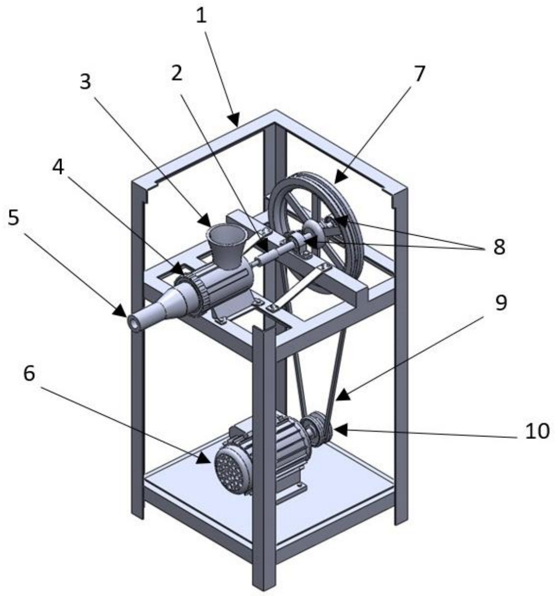
The pelleting machine of biochar was manufactured and evaluated technically. The main parts of the biochar pelleting machine are shown in **Fig. (3)**.

1. Main frame:

The chassis is made from iron which welded and manufactured locally. The fabricated machine has dimensions of 47×47×93 cm (length× width× height).

2. Feed hopper:

This is where the Biochar mixture with binder was fed into. The hopper was a funnel-shaped piece cut from a cylinder measuring 14 cm in diameter, 6 cm in height, and 2 cm in thickness. Made of stainless steel to prevent biochar from sticking to the feed hopper and to allow for easy cleaning. The maximum capacity of the feeding hopper was 0.5 kg.



No.	Part Name	No. of
1	Main frame	1
2	Coupling	1
3	Feed hopper	1
4	Lock nut	1
5	Extruder	1
6	Electric motor	1
7	Reduction pulley	1
8	Two bearing	2
9	Belt	1
10	Driver pulley	1

Figure .3. Schematic 3D drawing of the manufactured pelletizing machine.

3. The mixing unit:

At this stage, the biochar mixture is rotated and pushed by helical auger, which rotates in a clockwise direction to ensure obtaining a homogeneous mixture and transferring it to the pelleting stage.

4. Pelletizing unit:

The pelletizing unit is the last stage consists of a knife, lock nut, die and the extruder. After mixing the biochar with the binders for a moment inside the machine, the mixture is pushed through a helical auger into the holes of the die plate, and then the biochar is pressed, and the biochar pellets come out of the machine’s extruder with the appropriate diameter.

5. Power source:

An electrical motor [2 hp (2.2 kW), 5.5 A, 220V and 1400 rpm] was used. Power is transmitted from a pulley (10cm diameter) on the main motor shaft to a pulley (40cm diameter) on pelletizing unit shaft by main of v belt.

3. Experimental Method:

Practical studies have been carried out to evaluate the performance of biochar pelletilizing and optimize certain operating parameters affecting the efficiency of the pelletizing machine and the effect on the pellet quality of the biochar. All experiments were performed under the following variables:

1. Four types of raw biochar (Rice straw - Date palm waste - Sawdust - Sugar cane waste).
2. Three extruder diameters of (20, 30and 40 mm), (D_1,D_2, D_3).
3. Two binders (starch-molasses).

3.1. Preparation of Components and Start-up:

First, the biochar as well as the binders are weighed using a digital scale. First, starts by placing the biochar in the mixing bowl, then add the binder with water in the case of starch, or gradually add diluted molasses. Mixing occurs manually until a homogeneous mixture is obtained. When the mixing is finished, the machine is started, and then the mixture is placed in the hopper and pressed with an auxiliary manual tool, after that the mixture is pushed to the pelletizing unit and the pellets begin to come out. They are received directly on wooden boards, and then they are cut into equal lengths and transferred to trays until complete Drought.

3.1.1. Primary tests:

(A) Test 4 kg from component in the case of starch:

During testing of 4 kilograms of biochar and starch in a ratio of 1: 2 in the presence of suitable moisture content, the mixing was good, and a homogeneous mixture was obtained, which led to obtaining cohesive pellets.

(B)Test 4 kg from component in the case of molasses:

After doing trials, during testing of 4 kilograms of biochar and molasses diluted with water at a ratio of 1: 1, it was observed that the problems were solved, the mixing was good, and a homogeneous mixture was obtained, which resulted in obtaining coherent pellets.

3.1.2. Method for measuring the mechanical properties:

Mechanical properties were measured in Faculty of Agriculture, Al-Azhar University, Cairo using (Instron Universal Testing Machine/SMT-5).

(A) Shear force:

A metal vertical part is installed in the device from the top with two metal cylinders placed below them at a distance approximately equal to the length of the pellets, and the arm is moved to reach the vertical metal part in the middle of the pellets until the pellets are completely torn and collapsed, and the results are recorded on curves.

(B) Compression strength:

A small piston is installed on the top of the device and another piston at the bottom, and the distance between them is adjusted by the movable arm until reaching that the pellets are vertically balanced and in contact with both pistons, then the arms are moved until the sample collapses and the data is also recorded on curves and appears on the computer screen.

4. Measurements

In the performance evaluation of the pelleting machine efficiency, the following measurements were taken into account:

4.1. Chemical analysis:

(A) Moisture content:

The moisture content of each sample was calculated using the equation below **Bartolome *et al.*, (2021):**

$$M.\ C_{w.b.} = \frac{M_o - M_1}{M_o} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Where:

M. $C_{w.b.}$= Moisture content %, wet basis.

M_0 = Initial mass of the pellet samples, g.

W_1 = Dried mass of the pellet samples, g.

(B) Biochar yield:

The biochar yield was calculated as described by **Lynch and Joseph (2010)**, on air-dry weight basis of the raw material, as follows:

Biochar yield (%) = (W_1/W_0) x 100……………. (2)

Where:

W_0 = the weight of the raw feedstock on an air-dried basis (g).

W_1 = the weight of the produced biochar (g).

(C) Ash content:

Ash content was determined by the dry combustion for 1.00 g of the different feedstock or biochar samples at 700 °C for 12 hrs in an open porcelain crucible **(Samsuri *et al.*, 2014)**.

The percentage of the ash content was calculated according to **Lynch and Joseph (2010)** as follows:

Ash content (%) = (W_{ash} / W_{sample}) X 100…………. (3)

Where**:**

W_{ash} = the weight of ash (g)

W_{sample} = the weight of biochar (g).

4.2. Machine productivity:

Machine productivity (pelletizing capacity) (P, kg/h) was calculated as follows **(Regupathi, 2019).**

$$P = \frac{W_{out}}{t},\ \text{kg/h}\ \ldots\ldots\ldots\ldots\ldots\ldots\ (4)$$

Where:

W_{out}: Weight of output pelletized biochar, kg.

T: time of test duration h.

4.3. Pelletizing efficiency:

The pelletizing efficiency is the ratio between the quantity of biochar pelleted and the total feed input **(Okolie *et al.*, 2019)**. It was determined for 1 kg of biochar using the following relationship

$$(\eta p) = \frac{W_{out}}{W_{in}} \times 100\ldots\ldots\ldots\ (5)$$

Where:

W_{out}: Weight of output pelletized biochar, kg.

W_{in}= recovered weight after pelletizing (kg).

4.4. Consumed power:

The specific energy consumption of the machine as evaluated using

following equation **Orisaleye *et al.*, (2009)**:

Specific Energy Consumption (kWh\Kg) =

$$\frac{\text{Power of motor} \times \text{Time taken}}{\text{Mass production}}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (6)$$

4.5. Operating cost:

The operational cost required for the grinding operation was estimated using the following equation: **(Awady *et al.*, 1982).**

$$C_{op.} = \frac{C}{Mp},\quad \text{L.E/kg}\ \ldots\ldots\ldots\ (8)$$

Where:

Cop = operational cost, L.E/kg

MP = machine productivity, kg/h

C = Hourly cost, L.E/h

The hourly cost of grinding operation was determined using the following equation: **(Awady, 1978).**

$$C = \frac{P}{h}\left(\frac{1}{a} + \frac{i}{2} + t + r\right) + (W.e) + \frac{m}{144},\ \text{L.E/h}\ \ldots\ldots\ldots\ (9)$$

Where:

C = hourly cost, L.E/h

p = price of machine, L.E

h = yearly working hours, h/year

a = life expectancy, h

I = interest rate/year, %

t = taxes, over heads ratio, %

W = power of motor in, kW

r = repairs and maintenance ratio, %

3- RESULTS AND DISCUSSION

In order to select the appropriate operational parameters for the biochar Pelletizing process, it was necessary to determine the compression force ,shear force, deformation distance, Pelletizing efficiency, machine productivity and operational cost. These parameters varied with four wastes of biochar (sawdust - rice straw - sugar cane waste - palm waste) and two types of binders (molasses and starch) and three diameters of the extruder (20 - 30 - 40) mm.

3.1. Experimental Results of biochar produced from molasses:

The result of each sample passing through biochar extruder was tested. The experimental results were assigned for testing and analysis using Matlab software (R2015a) to study the effects of input parameters on biochar production , as shown in **Table.2.**

Table.2.Data of compression force and deformation distance of biochar using molasses as a binder:

Type of biochar	Extruder diameter, mm	Compression force, N	Deformation distance, mm
Sawdust	20	2170	2.75
	30	2084	1.58
	40	1558	2.21
Rice straw	20	597.5	2.21
	30	312.5	1.97
	40	2160	14.66

3.1.1. Effect of extruder diameter and type of biochar on compression force:

Fig. 4 showed that it was noticed that the highest value of compression force of 2170 N was obtained when using the sawdust, at extruder diameter 20 mm. In contrast, the lowest compression force of 313 N was obtained when using the rice straw waste at extruder diameter of 30 mm. It can be seen that using the sawdust showed a significant increase in compression force, when extruder diameter decrease from 40 to 20 mm. In contrast, using the rice straw waste showed an increase in compression force, when extruder diameter increase from 20 to 40 mm.

This result agrees with **Elsheikha *et al*., (2020)** there is a direct relationship in the case of using molasses as a binder with rice straw the larger extruder diameter, the highest compression force.while the results proved that there is an inverse relationship in the case of using molasses as a binder with sawdust as the diameter of the extruder decreases The compression force increased.

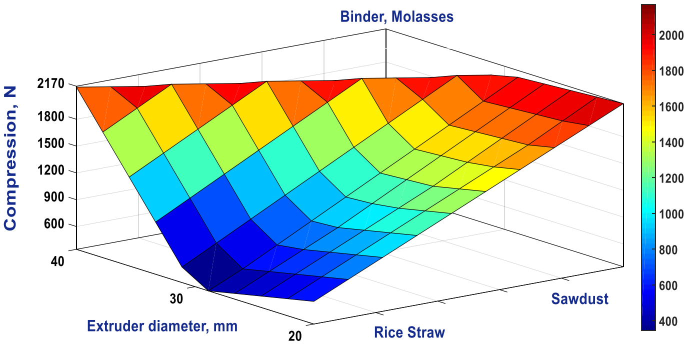


Figure .4.The 3D response surface for compression force of produced biochar using molasses as a binder.

3.1.2. Effect of extruder diameter and biochar type on shear force when using molasses as a binder:

Table.3 shows the actual results of the shear force and the deformation distance obtained through the experiment, as well as the inputs parameters , which are extruder diameter (20 - 30 - 40 mm) , the type of biochar (sawdust - rice straw) and the type of binder (molasses).

Table.3.Data of shear force and deformation distance of biochar using molasses as a binder:

Type of biochar	Extruder diameter,mm	Shear force,N	Deformation distance,mm
Sawdust	20	342.5	0.34
	30	583.8	0.40
	40	265	0.49
Rice straw	20	45	0.29
	30	140	0.75
	40	141.3	1.16

Fig.5 showed that It can be seen that the highest shear force of 584 N was obtained when using the sawdust at extruder diameter of 30 mm , while the lowest shear force of 45 N was obtained when using the rice straw waste at extruder diameter of 20 mm.

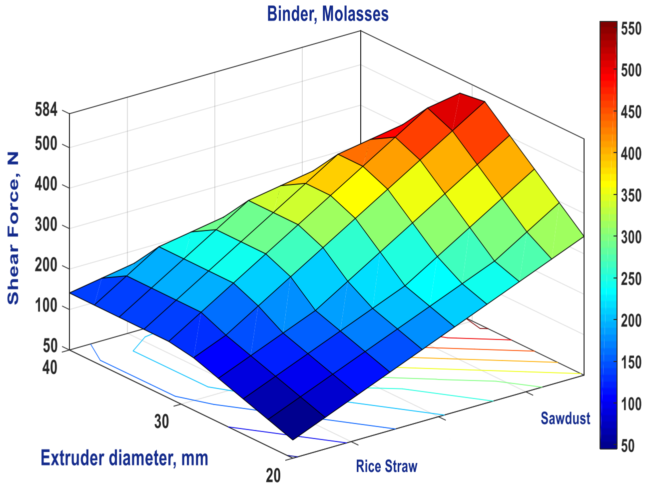


Figure .5. The 3D response surface for the shear force of produced biochar from the rice straw waste and sawdust using molasses as a binder.

This result agrees with **Niedzoilka *et al.*, (2015)**, he reported that the type of straw and the composition of its mixtures in most cases did not have a statistically significant effect on the mechanical strength of the produced pellets.

4. 2.Experimental Results of biochar produced from starch:

4.2.1. Effect of extruder diameter and type of biochar on compression force when using starch as a binder:

After conducting the experiment, the results of compression force and deformation distance were obtained, and they were recorded in **Table .4**.

Table.4.Data of compression force and deformation distance of biochar using starch as a binder:

Type of biochar	Extruder diameter, mm	Compression force,N	Deformation distance,mm
Sawdust	20	511.25	Mm
	30	432.5	1.63
	40	983.8	1.96
Rice straw	20	176.3	2.16
	30	512.5	1.82
	40	416.3	4.66
Sugar cane waste	20	1499	4.76
	30	1653	3.52
	40	1863	1.85
Date palm waste	20	297.5	5.41
	30	803.8	2.65
	40	1170	5.94

Fig.6 showed It was noticed that the increase in extruder diameter from 20 to 40 mm increases the compression force. Using the date palm waste showed a significant increase in compression force, where the compression force increase from 298 to 1170 N at increasing extruder diameter from 20 to 40 mm. It can be seen that the highest compression force of 1863 N was obtained when using the sugar cane waste at extruder diameter of 40 mm.

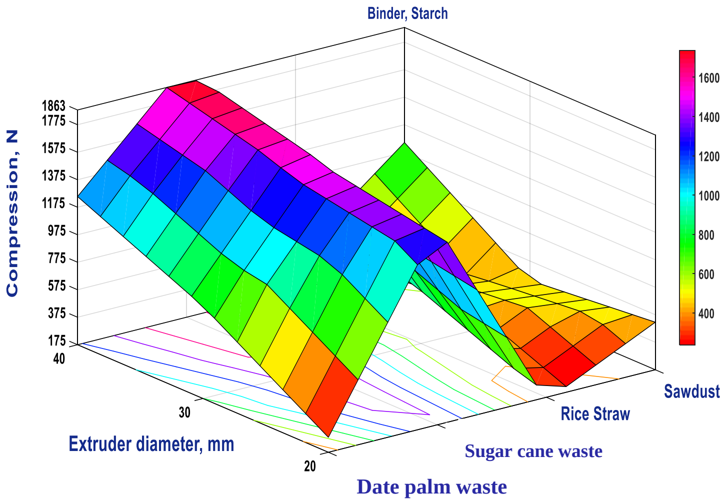


Figure .6. The 3D response surface for the compression force of produced biochar using starch as a binder.

This result agrees with **Hu et al., (2015)**, he proved that starch pellets had the worse strength properties and did not exhibit obvious energy saving advantages.

3.2.2. Effect of extruder diameter and type of biochar on shear force when using starch as a binder:

After conducting the experiment, the results of shear force and deformation distance were obtained, and they were recorded in **Table .5.**

Table.5.Data of shear force and deformation distance of biochar using starch as a binder:

Type of biochar	Extruder diameter, mm	Shear force, N	Deformation distance,mm
Sawdust	20	76.25	0.31
	30	50	0.35
	40	301.3	0.93
Rice straw	20	32.5	0.42
	30	80	0.65
	40	206.3	0.99
Sugar cane waste	20	163.8	0.53
	30	441.3	0.76
	40	847.5	1.98
Date palm waste	20	113.8	0.71
	30	235	0.70
	40	417.5	5.28

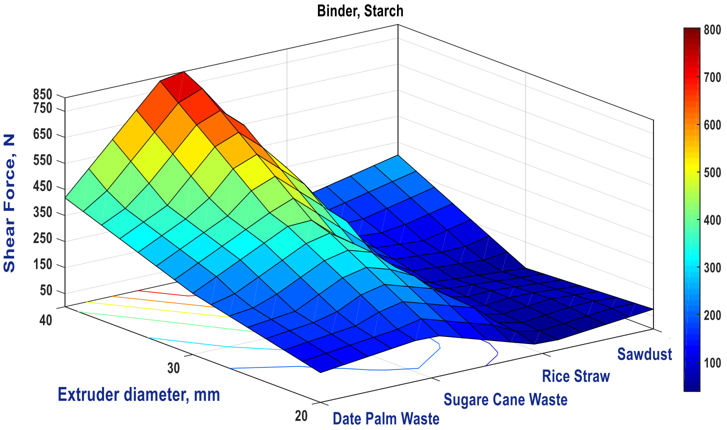


Figure .7. The 3D response surface for the shearing force of produced biochar using starch as a binder.

This result agrees with **Elsheikha *et al.*, (2020)** he indicated that there is a direct relationship between extruder diameter and shear force.

3.3. Effect of operating parameters on pelletizing efficiency using different binders:

Effect of produced biochar from the rice straw waste and sawdust using molasses as a binder and extruder diameter on pelletizing efficiency were presented in **Table .6** and **Fig.8.**

Table.6.Data of pelletizing efficiency of biochar using molasses as a binder:

Type of biochar, binder	Extruder diameter, mm	pelletizing efficiency,%	W_{In}, Kg	W_{out}, Kg
Sawdust, molasses	20	61	1	0.61
	30	63		0.63
	40	68		0.68
Rice straw, molasses	20	61	1	0.61
	30	67		0.67
	40	74		0.74

Fig.8 showed that the pelletizing efficiency values for the rice straw waste and sawdust are very close at the extruder diameters 20, 30 and 40 mm. Where using the rice straw waste showed an increase in pelletizing efficiency, where the pelletizing efficiency increases from 23.61 to 34 % at increasing extruder diameter from 20 to 40mm.

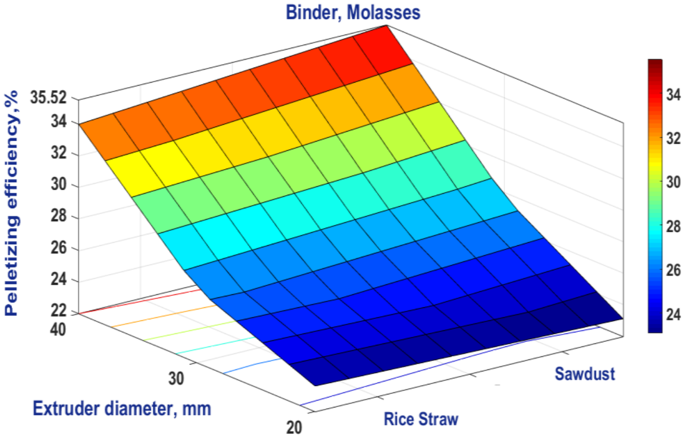


Figure .8. The 3D response surface for pelletizing efficiency of biochar pelletizing machine using molasses as a binder.

This result agrees with **Morad *et al.*, (2007)**, According to the obtained Figure it was found the reason of increasing the pelleting efficiency by increasing extruder diameter, can be due to the increase of the die output area that tend to decrease pressure in extrusion unit when using molasses as a binder.

After conducting the experiment, the results of pelletizing efficiency was obtained, and they was recorded in **Table .7**. The table shows the coefficients of extruder diameter (20-30-

40mm), the type of biochar (sawdust-rice straw- sugar cane waste- date palm waste) and the type of binder (starch).

Table.7.Data of pelletizing efficiency of biochar using starch as a binder:

Type of biochar, binder	Extruder diameter, mm	Pelletizing efficiency, %	W_{In} , Kg	W_{out} , Kg
Sawdust, starch	20	60	1	0.6
	30	65		0.65
	40	75		0.75
Rice straw, starch	20	55	1	0.55
	30	60		0.6
	40	65		0.65
Sugar cane waste, starch	20	65	1	0.65
	30	75		0.75
	40	80		0.8
Date palm waste, starch	20	59	1	0.59
	30	62		0.62
	40	70		0.7

Fig.9 showed that it was noticed that the increase in extruder diameter from 20 to 40 mm increases the pelletizing efficiency. It was noticed that using the sugar cane waste showed a significant increase in the pelletizing efficiency, where the highest pelletizing efficiency of 80% was obtained at extruder diameter of 40 mm.

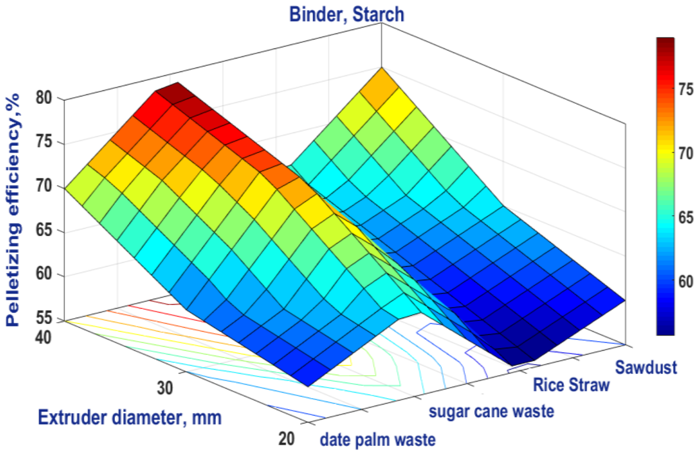


Figure .9. The 3D response surface for pelletizing efficiency of biochar pelletizing machine using starch as a binder.

As well as using the sawdust showed a slight increase in pelletizing efficiency, where the pelletizing efficiency increase from 60 to 75% at increasing extruder diameter from 20 to 40mm. This result agrees with **Bartolome et al., (2021)** According to the type of biochar used.

Effect of produced biochar from the rice straw waste and sawdust using molasses as a binder and extruder diameter on machine productivity were presented in the following table and figure .As shown in **Table .8.**

Table.8.Data of machine productivity of biochar using molasses as a binder:

Type of biochar	Extruder diameter, mm	Machine productivity, Kg/h	Time of pelletizing ,S	W_{out} , Kg
Sawdust	20	23.61	93	0.61
	30	26.68	85	0.63
	40	34	72	0.68
Rice straw	20	23.12	95	0.61
	30	27.72	87	0.67
	40	35.52	75	0.74

Fig.10 showed that The machine productivity values for the rice straw waste and sawdust are very close at the extruder diameters 20, 30 and 40 mm. Where using the rice straw waste showed an increase in machine productivity, where the pelletizing efficiency increase from 61 to 68 kg/h at increasing extruder diameter from 20 to 40mm. As well as using the sawdust showed an increase in machine productivity, where the machine productivity increase from 61 to 74 kg/h at increasing extruder diameter from 20 to 40 mm.

That's because of the same reason mentioned in the machine productivity when using starch as a binder.

Table .9 shows the results obtained through the experiment to produce biochar to determine the productivity of the machine.

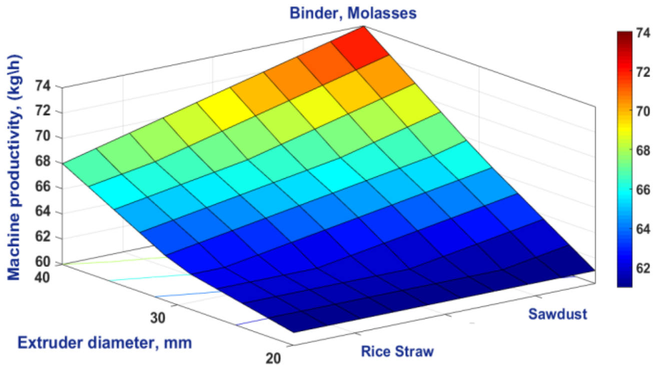


Figure .10. The 3D response surface for machine productivity of biochar pelletizing machine using molasses as a binder.

Table.9.Data of machine productivity of biochar using starch as a binder:

Type of biochar	Extruder diameter, mm	Machine productivity, Kg/h	Time of pelletizing ,S	W_{out}, Kg
Sawdust	**20**	**27**	**80**	**0.6**
	30	**33.43**	**70**	**0.65**
	40	**45**	**60**	**0.75**
Rice straw	**20**	**23.29**	**85**	**0.55**
	30	**27**	**80**	**0.6**
	40	**36**	**65**	**0.65**
Sugar cane waste	**20**	**26.29**	**89**	**0.65**
	30	**38.57**	**70**	**0.75**
	40	**52.36**	**55**	**0.8**
Date palm waste	**20**	**23.6**	**90**	**0.59**
	30	**27.9**	**80**	**0.62**
	40	**36**	**70**	**0.7**

Fig.11 showed that it was noticed that the increase in extruder diameter from 20 to 40 mm increases the machine productivity. It was noticed that using the sugar cane waste showed a significant increase in the machine productivity, where the highest machine productivity of 52.36 kg/h was obtained at extruder diameter of 40 mm. In contrast, using the rice straw waste showed a slight increase in machine productivity, where the lowest machine productivity of 23.29 kg/h was obtained at extruder diameter of 20 mm.

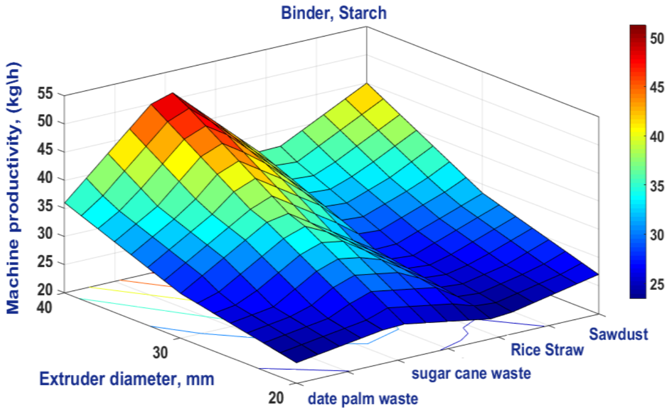


Figure .11. The 3D response surface for machine productivity of biochar pelletizing machine using starch as a binder.

This result agrees with **Morad et al., (2007)**, he reported that the increase in the productivity of the extruder by increasing the feed rate may be due to the increase in the quantities of food rations that passed through the extrusion unit and were expelled from the mold slots at the same time.

3.5. Effect of operating parameters on specific energy consumption using different binders:

Table.10 shows effect of extruder diameter and type of biochar on specific energy consumption using molasses as a binder were presented in the following table and figure.

Table.10.Data of specific energy consumption of biochar using molasses as a binder:

Type of biochar	Extruder diameter, mm	specific energy consumption, Kw.h/kg	Time of pelletizing ,S	W_{out}, Kg
Sawdust	**20**	**0.09**	**93**	**0.61**
	30	**0.08**	**85**	**0.63**
	40	**0.06**	**72**	**0.68**
Rice straw	**20**	**0.1**	**95**	**0.61**
	30	**0.08**	**87**	**0.67**
	40	**0.06**	**75**	**0.74**

Fig. 12 showed that the specific energy values for the rice straw waste and sawdust are very close at the extruder diameters 20, 30 and 40 mm. Where using the rice straw waste showed an increase in specific energy, where the

specific energy decrease from 0.1 to 0.06 Kw.h\kg at extruder diameter 20 and 40mm.

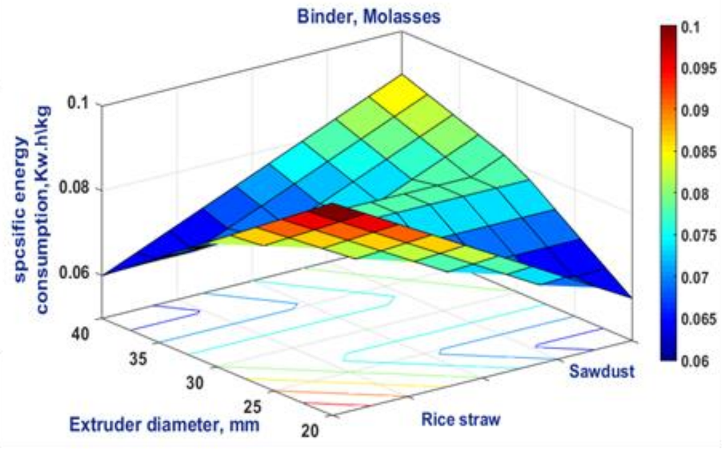


Figure .12. The 3D response surface for specific energy consumption of biochar pelletizing machine using molasses as a binder.

These results agree with **Kaddour et al., (2003)**, he reported that It was observed that increase in die diameter when other variables were kept constant led to decrease in the System Mechanical Energy of the machine.

Table .11 shows effect of extruder diameter and type of biochar on specific energy consumption using starch as a binder were presented in the following table and figure.

Table.11.Data of specific energy consumption of biochar using starch as a binder:

Type of biochar	Extruder diameter, mm	specific energy consumption, Kw.h/kg	Time of pelletizing ,S	W_{out} , Kg
Sawdust	20	0.08	80	0.6
	30	0.07	70	0.65
	40	0.05	60	0.75
Rice straw	20	0.09	85	0.55
	30	0.08	80	0.6
	40	0.06	65	0.65
Sugar cane waste	20	0.08	89	0.65
	30	0.06	70	0.75
	40	0.04	55	0.8
Date palm waste	20	0.09	90	0.59
	30	0.08	80	0.62
	40	0.06	70	0.7

Fig.13 showed that it was noticed that the increase in extruder diameter from 20 to 40 mm decreases the specific energy consumption. It was noticed that using the date palm waste and rice straw showed the same values of the specific energy consumption, where the specific energy consumption of 0.09 , 0.08 and 0.06 Kw.h\kg were obtained at extruder diameter of 20,30 and 40 mm. In contrast, using the sugar cane waste showed the lowest value of the specific energy consumption of 0.04 Kw.h\kg was obtained at extruder diameter of 40 mm.

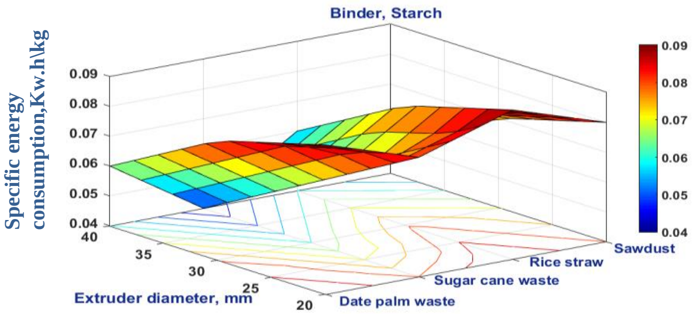


Figure .13.The 3D response surface for specific energy consumption of biochar pelletizing machine using starch as a binder.

This result agrees with **Orisaleye et al., (2009)** similar results were obtained for the specific energy consumption, 0.69 kW.h/kg, in the case of using starch as a binder.

3.6. Effect of operating parameters on operational cost using different binders:

As shown in **Table .12**, during the experiment, the best results were obtained for operational cost of the biochar pelletizing machine by calculating machine productivity and hourly cost.

Table.12.Data of Operational cost of biochar using molasses as a binder:

Type of biochar	Extruder diameter, mm	Operational cost, L.E/kg	Machine productivity, Kg/h
Sawdust	20	0.839	23.61
	30	0.742	26.68
	40	0.582	34
Rice straw	20	0.856	23.12
	30	0.714	27.72
	40	0.557	35.52

Fig.14 shows that the operational cost values for the rice straw waste and sawdust are very close at the extruder diameters 20, 30 and 40 mm. Where using the rice straw waste showed a decrease in operational cost, where the operational cost decrease from 0.856 to 0.557 L.E\Kg at extruder diameter 20 and 40 mm.

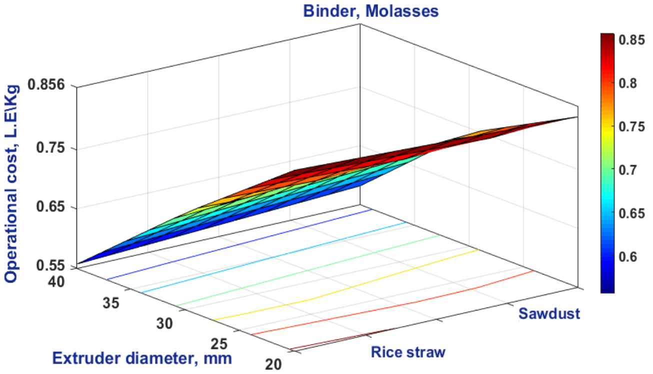


Figure .14. The 3D response surface for operational cost of biochar pelletizing machine using molasses as a binder

The results showed that there is an inverse relationship between increasing diameter of the extruder and decreasing the operational cost. The decrease in pelletizing costs may be by increasing the rate of feed when increasing extruder diameter.

Effect of extruder diameter and type of biochar on operational cost using starch as a binder were presented in the following table and figure . **Table .13** showed the actual results of the operational cost treatment obtained through the experiment.

Fig.15 shows that it was noticed that the increase in extruder diameter from 20 to 40 mm decreases the operational cost. It was noticed that using the highest operational cost was 0.85 L.E\Kg at extruder diameter of 20 mm and when using rice straw waste , the lowest operational cost was 0.378 L.E\Kg at extruder diameter of 40 mm and when using sugar cane waste.

Table.13.Data of Operational cost of biochar using starch as a binder:

Type of biochar	Extruder diameter, mm	Operational cost, L.E/kg	Machine productivity, Kg/h
Sawdust	20	0.733	27
	30	0.592	33.43
	40	0.44	45
Rice straw	20	0.85	23.29
	30	0.733	27
	40	0.55	36
Sugar cane waste	20	0.753	26.29
	30	0.513	38.57
	40	0.378	52.36
Date palm waste	20	0.839	23.6
	30	0.709	27.9
	40	0.55	36

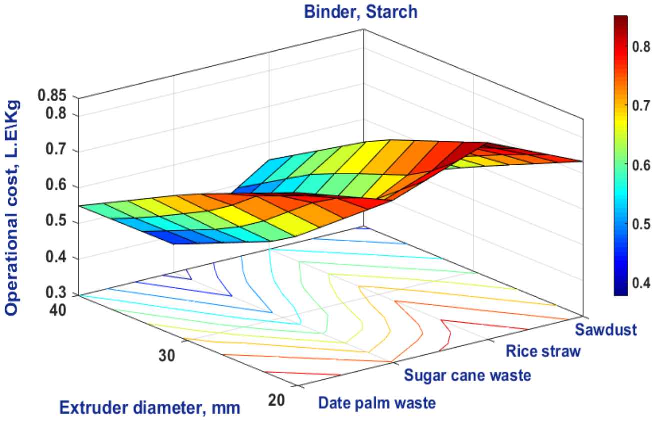


Figure .15. The 3D response surface for operational cost of biochar using starch as a binder.

This result agree with **El-Shal *et al.*, (2012)** results showed that the high decrease of operational cost by increasing feed rate could be due to the high increase in extruder productivity with low increase in extruder power consumed.

4- CONCLUSION

The important results as mentioned in the obtained data were summarized in the following:

The maximum value of pelletizing efficiency and machine productivity were 80 % and 52.36 kg/h, respectively when using sugar cane waste and starch at extruder diameter 40 mm, respectively. The lowest value of specific energy consumption was 0.04 Kw.h\kg when using sugar cane waste and starch at extruder diameter 40 mm. The lowest value of operational cost was 0.378 L.E\Kg when using sugar cane waste and starch at extruder diameter 40 mm.

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CONFLICT OF INTEREST:

The authors declare that they have no conflict of interest.

AUTHORS CONTRIBUTION

Elsheikha, A.M., Eissa, S.M., and Khafagy, S.N: developed the concept of the manuscript. Eissa wrote the manuscript. All authors checked and confirmed the final revised manuscript.

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الملخص العربى

تصنيع وتقييم آلة تكوير الفحم الحيوي

الفحم الحيوي هو عباره عن مادة ذات حبيبات دقيقه صلبة يتم الحصول عليها من خلال تفحم الكتلة الحيوية بمعزل او مع القليل من الاوكسجين . ويمكن إضافته الى التربة لتحسين خصائصها وزيادة جاهزية العناصر والحد من التلوث البيئي.

وتحددت أهداف الدراسة الرئيسية فيما:

- تصميم وتصنيع آلة محلية الصنع لتكويرو إنتاج الفحم الحيوي.
- استخدام مواد رابطة رخيصة ومتاحة بسهولة لتسهيل إنتاج الفحم الحيوي.
- تقييم أداء آلة التكوير لإنتاج حبيبات الفحم الحيوي عالية الجودة.
- تحسين بعض معاملات التشغيل(ثلاثة أقطارمن الطارد، وأربعة أنواع من الفحم الحيوي الخام واثنين من المواد الرابطة) التي تؤثر على أداء آلة تصبيع الفحم الحيوي.
- تقييم أداء آلة تصبيع الفحم الحيوي من حيث التكلفة و الانتاجية.

تم تنفيذ التجارب خلال عام 2022 بقسم الهندسة الزراعية بكلية الزراعة جامعة دمياط لتقييم أداء ماكينة تكوير الفحم الحيوي المصنعة.

المبادئ التوجيهية التالية ، بناءً على النتائج التي تم الحصول عليها في هذا العمل البحثي:

1. يوصى باستخدام آلة تصبيع الفحم الحيوي وذلك بسبب انخفاض استهلاك الطاقة والجودة العالية للكريات وانخفاض تكاليف التشغيل.
2. ينصح باستخدام الدبس والنشا كمواد رابطة لحبيبات الفحم الحيوي، وذلك لاحتوائها على عناصر غذائية مفيدة للنباتات والتربة.
3. يوصى بتشغيل الآلة عند محتوي رطوبي 25% للفحم الحيوي الخام، بقطر الطارد 40 مم عند استخدام مخلفات قصب السكر والنشا كمواد رابطة، وذلك للحصول على أفضل النتائج في جميع القياسات:
    - قوي الضغط ومسافة التشوه كانت 1863 نيوتن و5.41 مم.
    - قوي القص ومسافة التشوه كانت 848 نيوتن و1.98 مم.
    - كفاءة التصبيع 80%.
    - بلغت إنتاجية الماكينة 52.36 كجم/ساعة.
    - كان استهلاك الطاقة النوعي 0.04 كيلو وات.ساعة/كجم.
    - بلغت تكاليف التشغيل 0.378 جنيه مصري/كجم.
4. تعتبر آلة تكوير الفحم الحيوي المصنعة مناسبة جدًا للاستخدام في مصر نظرًا لصغر حجمها وكفاءتها العالية لتحقيق الهدف الرئيسي من الدراسة وقدرتها الاستهلاكية البسيطة وتكاليفها وسهولة التعامل معها ونقلها من مكان إلى آخر بسهولة، فضلا عن سهولة الصيانة والتنفيذ محليا.

الكلمات المفتاحية: ألة تكوير, مواد رابطة,الفحم النباتي ,الكتلة الحيوية.