Design, fabrication, and testing of biomass pelleting machine for coffee wastes

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Abstract A biomass pelletizer was designed and fabricated to produce pellets using coffee husks and spent coffee grounds. The pelletizer works on a principle of a rotating roller pellet mill in which power from the prime mover is transmitted to the rotating spindle at a reduced speed, and causes the roller dies to drift and press the pellet mixture through the thick perforated die plate. An unsharpened knife attached to the spindle facilitates easy detachment of pellets from the die plate upon extrusion and the perforated pellet chute separates the non-pelletized particles and fines from the pellets itself. The performance evaluation of the machine revealed an average pelleting capacity and efficiency of 1.50 kgh⁻¹ and 92.49 percent, respectively, suitable for small-scale pellet production and also a low percentage losses (5%). The physical characteristics of the pellets produced were found to have high uniformity with an average length of 9.86±0.63 mm, diameter of 5.71±0.41 mm, mass per pellet of 0.12 g, moisture content (dry basis) of 16.65 percent, and a bulk density of 850 kg m⁻³. The researchers recommend that the performance of the pelleting machine be optimized by attaching a feed controller on the hopper and manipulating the speed of the roller dies. Furthermore, it will also be best to analyze the thermochemical properties of the pellets including the proximate and ultimate composition employing standard test methods.

1. Introduction
There is a growing interest on the use of biomass for heat and energy generation with the need to reduce fossil fuel consumption, greenhouse gas emissions, and environmental degradation [1-2]. Among renewable energy alternatives, biomass has the major advantage of being available in large quantities from a variety of sources, and they can be utilized for sustainable heat and power production with significant environmental and socioeconomic benefits. Large volume of biomass comes from agricultural wastes, however, they lack the required density to be transported to the point of energy production causing expensive transportation cost [3]. Moreover, biomass in raw form, has lower volumetric energy content than traditional fossil fuel, low bulk density, high moisture content and hydrophobic character [2, 4, 5]. Agricultural residues and woody biomass have bulk densities ranging from 80-100 kgm⁻³ and 150-200 kgm⁻³, respectively, that can be densified up to 700 kgm⁻³ through pelletization [6]. Through this process, biomass materials are provided with uniform physical properties and improved combustion properties at low moisture content, and costs of handling, transportation, and storage are significantly cut down.
In general, a large percentage by weight of biomass feedstocks consist of cellulose (40-50%), followed by hemicellulose (20-40%), and lignin. Along with the relative percentage composition of biomass, key factors that determine the suitability as energy crops include the amount of moisture and ash, fixed carbon, calorific value, and alkali metal content [3, 7]. The main raw materials used in pelletization are wood residues like saw dust, wood shavings and chips, as well as agricultural residues, food industry wastes and fuel crops in which a pellet mill with ring roller dies are commonly employed in commercial facilities due to their high capacity and good pelletization properties [8-9]. The configuration and operation of the pellet mills greatly influence the efficiency of the operation and properties of the pellets produced in addition to the type of feedstock, additive or binders, and other machine parameters [10-11]. To maintain homogenous pellet products in the national and international markets, various quality standards have been prescribed [12]. Biomass pellets also generate lower emissions over their original form and other conventional biomass fuels [13-14]. In addition, its dimensional configuration and standard size allow a more compact storage, handling, and automatic feeding in large scale operations.

Depending on the kind of processing, coffee generates a significant amount of agro-waste. Coffee pulp and coffee husks are among the solid residues and currently have no profitable uses [15]. Coffee husks which is fibrous in nature, consist of organic-rich components (50% cellulose, 38% hemicelluloses, pectin, and lignin) that makes it an ideal feedstock for pellet production. Its composition is also similar to wood dust. Meanwhile, spent coffee grounds (SCG), is another major by-product of coffee processing and it was estimated that about 2 kg of SCG is produced per kilogram of instant coffee, generating several millions of tons of waste worldwide every year [16]. SCG is a solid residue that has high amount of moisture, acidic, and organic-rich, yet, its composition is very diverse, suggesting that it can be used for a variety of applications. SCG is composed of a huge amount of carbon-based compounds like the coffee husks, wherein, cellulose is the primary cause of volatile matter and lignin plays as a natural binder [17].

Studies on biomass pelletizing have been carried in different ranges from small to large-scale operations using various configurations of pelleting machines. On the other hand, biomass feedstocks are commonly blended to improve the properties of the pellets, but few studies have focused on using coffee wastes and pure biomass materials. There is also a limited availability of local pelleting machines that can be used in small-medium scale operations. Adoption of machines from foreign manufacturers may also pose problems or difficulties in maintenance and after-sales services. To resolve these issues, a locally-fabricated pellet machine suitable for small-medium scale operations was designed employing the principle of roller pellet mills. Various mixes of coffee husks and SCG was also used as pellet feedstock. Preliminary investigations focused on the efficiency and capacity of the pelleting machine and the uniformity of the properties of the pellets. It is deemed that this project will open up new applications of the coffee wastes while coming up with a locally-made, easy to operate, and economically-feasible agricultural machinery.

2. Materials and methods

2.1. Design criteria
The pelleting machine should convert the pellet mixture of coffee husks and spent coffee grounds into densified pellets. It follows the principle of a rotating roller pellet mill where power is transmitted from the electric motor to a shaft or spindle with a reduced speed, and urges the roller dies to drift and press the pellet mixture. The machine was designed such that at least one person is required to control its operation, materials for construction were low-cost and locally available, and the fabrication procedures should include basic machining operations such as drilling, boring, and milling for ease of machine manufacturing.

2.2. Design details and specifications
The pelleting machine (Figure 1) is a motor-operated machine powered by a single-phase 1.5-hp electric motor. The speed of the motor was reduced to approximately 30 rpm from 1800 rpm using a 1:60 speed reducer. It has an overall dimensions of 740 x 413 x 790 mm (L x W x H). High-tensile
Fasteners were used for assembly of the components to reduce risks of misalignment and breakage due to high pressure and temperature build-up during the pelleting operation.

**Figure 1.** Representation of the biomass pelleting machine

The machine consists of several major components that allow a highly efficient pelleting operation. The pellet mixture is loaded on a frustum-shaped hopper with dimensions of 215 x 245 mm (H x dia.) that directs the mixture to the pelleting chamber, with a holding capacity of 1 kg. The pelleting chamber facilitates mixing and pressing of the pellet mixture using two roller dies – one grooved type and one flat type. The grooved type roller die has 24 teeth and each tooth is 2 mm x 5.67 mm (H x W). The roller dies were made of cold-rolled steel 1080 and were attached to the shaft perpendicularly, allowed to freely rotate on its axis through deep-groove ball bearings. The pressed mixture is extruded into cylindrical-shaped solid pellets with approximately 6-mm diameter through the thick die plate, which is locked in position by bolts and nuts to prevent slippage during the operation. The thick die plate has 96 holes whose inlet and outlet diameters of each hole were 10 mm and 6 mm, respectively. The high pressure build-up inside the chamber increases its frictional forces and so its temperature. A knife attached to the shaft cut the produced pellets from the die plate to a desired length of 10 mm. Upon extrusion, pellets are discharged to an outlet chute, inclined at 30°, with 4-mm perforations to separate the non-pelleted particles and fines from pellets.

### 2.3. Testing and evaluation

Pelletting was carried out in three trials using 1 kg of pellet mixture in each trial. The mixture was composed of the following: 28.6 percent coffee husks, 28.6 percent spent coffee grounds, 14.2 percent starch, and 28.6 percent water. The performance characteristics of the components of the machine including the speed of prime mover shaft, spindle, and roller shaft, the noise level, and the input power of the machine were determined. The machine was also evaluated in terms of its pelleting capacity and efficiency with the procedure adopted from the Philippine Agricultural Engineering Standards for hammer mill (PAES 217:2004).
The pelleting capacity refers to the weight of pellets produced per unit of operating time (kgh$^{-1}$) while pelleting efficiency is the ratio of the weight of pellets produced on the pellet discharge chute to the total weight of biomass materials fed into the hopper (%), computed as follows:

\[
C_p = \frac{W_p}{T_p} \quad (1)
\]

\[
E_p = \frac{W_p}{W_i} \quad (2)
\]

where $C_p$ is the pelleting capacity (kgh$^{-1}$), $W_p$ is the weight of pellets produced (kg), $T_p$ is the total time of pelleting (h), $E_p$ is the pelleting efficiency, and $W_i$ is weight of input biomass mixture (kg).

2.4. Physical properties of pellets

The physical properties of the pellets were described in terms of pellet length, pellet diameter, pellet mass and bulk density. The dimensions of each of the 100 randomly selected pellet samples from each trial were measured.

In determining the moisture content, three 50-gram samples of pellets from each trial were oven-dried at 110°C for 24 hours or until constant weight. The moisture content of each sample was calculated using the equations below:

\[
\% \text{MC}_{\text{wet basis}} = \left( \frac{M_o - M_1}{M_o} \right) \times 100\% \quad (3)
\]

\[
\% \text{MC}_{\text{dry basis}} = \left( \frac{M_o - M_1}{M_1} \right) \times 100\% \quad (4)
\]

where $\%MC$ is the moisture content (wet basis and dry basis), $M_o$ is the initial mass of the pellet samples (g) and $M_1$ is the final mass of the oven dried pellet samples.

For the determination of the bulk density, cooled pellets were loaded into a funnel placed in a tared container with known volume. Pellets were allowed to free flow into the container. Excess pellets (above the top rim of the container) were removed by scraping off with a straight edge. The container and pellets were weighed and the weight per volume was reported as its bulk density.

3. Results

3.1. Preliminary testing observations and interventions

The performance of the pelleting machine varied with different mixtures of coffee husks, spent coffee grounds, binder, and water. Among the problems encountered were longer pelleting time primarily due to the congestion in the holes of the flat die plate, stacking up and hardening of the mixture, and occurrence of occasional stops when the spindle and roller dies operate. To overcome these problems, the large particle size of the coffee husks in the mixture were reduced to ease passage of pellets through the die plate. The amount of binder was also optimized to improve the firmness of the pellets and avoid cracking. This also helped reduce the chances of hardening of the mixture in the pelleting chamber. Lastly, to avoid congestion in the die plate, feeding of the pellet mixture was manually controlled.

3.2. Performance characteristics

The performance of the pelleting machine was characterized with and without load wherein, no significant difference was observed among parameters (Table 1). The average speed of the motor shaft was recorded at 1,799.0 rpm and the speed of the roller dies was 28.1 rpm. Noise levels were below the limit for agricultural machineries 26.5 db (<92 dB).

The evaluation of the pelleting capacity and pelleting efficiency revealed an average value of 1.50 kgh$^{-1}$ and 92.49 percent, respectively. At this rate, the percentage losses reached only 7.5 percent of the
total input mixture while 5.0 percent of mixture is lost during the pelleting operation. When compared with other pelleting machines, this average pelleting capacity of may be low primarily due to lower roller shaft speed that affects the rate of pelleting. Nonetheless, the recorded pelleting efficiency is a good indicator to the performance of the machine.

### 3.3. Physical properties of pellets and pellet uniformity

The average length and diameter of the pellets produced were 9.86±0.63 mm and 5.71±0.41 mm, respectively (Table 2). The machine was designed to produce pellets with average length of 10 mm and average diameter of 6 mm. Statistical analysis showed that the 75th percentile of the 300 pellet samples has length ≥10.39 mm and diameter of ≥5.82 mm. The average mass of each pellet was also almost uniform at 0.12±0.001 g.

In terms of the moisture content and the bulk density, the average moisture content in dry and wet basis of the pellets is 16.65 and 14.27 percent, while the bulk density is 850 kg m⁻³. Similar raw materials (spent coffee grounds) upon pelleting were also reported by earlier researchers. A density of 1058-1255 kg m⁻³ and 6.2-11.78% for moisture content were reported for pellet’s characteristics of spent coffee grounds [17-19]. However International Organization for Standardization standardized the fuel specifications for solid biofuels, a density higher than 500 kg m⁻³ and a moisture content lower than 10% for pellet must be achieved for its safe storage and efficient combustion [20]. This is supported by other research works stating that a density of 700 kg m⁻³ and a moisture content of 8-12% for pellets is a typical bulk densities and moisture contents of biomass pellets and a pellet’s density below 400 kg m⁻³ is a low density pellet for biomass making it difficult to store, transport and utilize [21-22].

| Performance Characteristic       | Mean  |
|----------------------------------|-------|
| Speed of the motor shaft         | 1799.0 rpm |
| Speed of the roller die(s)       | 28.1 rpm  |
| Noise level                      | 265. dB   |
| Power input                      | 2.0 kW     |
| Current drawn                    | 8.4 A      |
| Voltage supply                   | 238.3 V    |
| Total weight of input            | 1000.8 g  |
| Weight of pellets produced       | 925.7 g    |
| Weight of fines                  | 24.6 grams |
| Losses                           | 50.5 grams |
| Percentage Losses                | 5.0%       |
| Pelleting time                    | 0.6 hr     |
| Pelleting Capacity               | 1.5 kg h⁻¹ |
| Efficiency                       | 92.49%     |

*aDifference in the mean values is not significant.

Table 2. Analysis of the physical properties of 300 pellet samples in terms of length, diameter, and mass for uniformity assessment

| Parameter | Length | Physical Property | Mass |
|-----------|--------|-------------------|------|
| N         | Valid  | 300               | 300  |
|           | Missing| 0                 | 0    |
| Mean      | 9.8609 | 5.7053            | .1160|
| Variance  | .631   | .0410             | .001 |
| Minimum   | 5.06   | 4.7600            | .10  |
| Maximum   | 12.45  | 6.1700            | .20  |
| Percentiles| 25     | 9.3800            | .1000|
|           | 50     | 9.9000            | .1000|
4. Conclusion
The developed biomass pelleting machine can produce pellets from a mixture of coffee husks and spent coffee grounds at an acceptable pelleting capacity and high efficiency. The pellets produced have uniform physical characteristics and low moisture content that reflect the reliability of the machine. Suitable for small-scale pelleting operation, the machine can be easily manufactured using locally available materials. The pelleting capacity can be increased by optimizing the speed of the spindle and roller dies, coupled with controlled feeding. It is recommended for further studies to include the analysis of the calorific value of the pellets and their proximate and ultimate composition using standard methods. Furthermore, to assure that the pellets will be safe for long-term storage, air-drying is recommended to reduce its moisture content after processing.

5. References
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