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Design and Development of a Biochar Pelletizer

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ABSTRACT

Biochar's potential value as a soil amendment is in continuous demand. However, as-produced biochar comes in different forms and sizes making its application and distribution challenging. Because there is a limited commercialized biochar pelletizer machine in the Philippines, a biochar pelletizer was developed to meet the requirements of the end-user and to produce a relatively efficient and comparatively inexpensive machine. The developed pelletizer was fabricated in local shops. The pelleting mechanism was composed of a horizontal die and two rollers. Pellet rollers were designed to press the biochar against the die. As the mixture passed the holes, pellets were formed and then fell to the catchment. The developed pelletizer was tested using three (3) different feedstocks, namely: carbonized rice hull (CRH), carbonized coconut shell (CCS), and carbonized wood chips (CWC). Cassava paste was utilized as the binder in levels of 10%, 15%, and 20%, respectively. The pellets produced in the study were 13 mm long with a range of 6.60 to 7.79% moisture content. Particle and bulk densities were highest with CRH at 764.22 and 343.67 kg-m3, respectively. The hardness and durability were highest with CWC with 1272.75 Pa and 87.48%, respectively. The highest actual capacity was observed with the CRH at 678.22 kg/day. An analysis of variance showed that the mean machine efficiency ranged from 67.86% to 71.02%, irrespective of the binder level. On the other hand, the binder level had a significant effect on the pelleting recovery with the highest recovery of 98.50%was achieved with a binder level of 20%. CCS and CWC could hold water up to 101 to 104% of their weight and could resist up to 806.66 to 1559.6 Pa of pressure. The study recommends the testing of pellets with other feedstock materials and other binder types and formulations.

Keywords: *pelletizer, carbonized rice hull, pellets, biochar*

INTRODUCTION

When biomass is heated in a closed system under a limited supply of oxygen, a carbon-rich product known as biochar is obtained. Biochar can be produced from several thermochemical technologies such as pyrolysis, gasification, and hydrothermal conversion. Among these technologies, pyrolysis is the most commonly used process due to its easy operation and low cost. The commonly processed biochar is sourced from biomass such as rice, coconut, and sugarcane. Biochar has several uses such as being soil conditioners, water filters, insulators, and even as a replacement for pulverized coal as fuel (Zhang et al., 2019). As a soil amendment, biochar can increase water-holding capacity, reduce bulk density, provide additional cation exchange sites, and serve as a source of reduced carbon compounds that may benefit microbial populations - all of which promote plant growth. Biochar holds the plant nutrient and prevents them from leaching, thus helping the plants absorb the fertilizers. Aside from that, biochar also precludes groundwater and food contamination by absorbing and removing heavy metals from the soil.

Biochar is produced in a brittle powdery-like form with wide particle size distribution and low energy density, making its utilization of it less optimized. In particular, approximately 30% of loss is due to the wind during its handling, transportation, and application to the field (Husk and Major, 2008). Meanwhile, Major et al. (2010) reported a 53% loss of biochar incorporated into the soil due to surface runoff during intense rain events. Despite these minor concerns, its benefits outweigh its disadvantages leading to its increased production and utilization worldwide (Ugoamadi et al., 2012). Furthermore, the increase in its demand justifies the need for an appropriate solution for the concerns on its post-production process - such as storage, transportation, and field application.

When used as a soil amendment, biochar is usually applied to soil in either powder, granular, or as-produced forms. While these forms demonstrated positive effects as soil amendments, the problems with post-production processes (like losses due to wind and runoff) hinder its optimum utilization and reduce its potential as an efficient soil amendment. Given these identified problems, it is only necessary to transform biochar into a form known as a pellet to entail a regular shape, increase energy density, and enhance the ease of handling. One potential remedy is to transform biochar into pellet form. Pellets are produced under extrusion. Typically, they are a small rounded, compacted mass of substance produced through compression or extrusion.

Pelleting has been, and continues to be a popular processing technique in feed and fertilizer materials manufacturing. Pelleting also prevents waste considering this process increases the material's bulk density, which enhances its storage capabilities. In basic terms, pelleting transforms soft, often dusty raw material into dense, free-flowing agglomerates called pellets. This transformation is accomplished by compression, extrusion, and adhesion.

However, most of the commercially available pelletizers were developed for feeds. The study of Cha, et al (2018) developed a pelletizing system of fermented total mixed ration for pig feeding under a compression process. The machine capacity was 536 kg/hr and was found to be affected by rotation speed and feed moisture content. Mushiri, et al. (2017) fabricated a biomass pelletization machine, which aims to produce 900 kg of pellets per hr. Olugboji, et al. (2015) designed and fabricated a poultry feed pellet machine with locally available material that is electric power operated and has a capacity of 5 kg/hr.

The study aimed to design and develop a biochar pelletizer that could address the current limitations and challenges of the biochar production techniques such as handling, storage, and application and assess the physical properties of the biochar pellets. Different biochar feedstock and binder levels will be utilized to evaluate the performance of the biochar pelletizer in terms of efficiency scalability. A simple cost-benefit analysis was conducted to determine the economic viability of the biochar pelletizer and pellets and assess the potential cost savings and revenue generation that could be achieved through increased efficiency, reduced labor costs, and improved marketability of pelletized biochar products.

MATERIALS AND METHODS

Pelletizer design and fabrication

The design of the biochar pelletizer was based on multiple criteria to ensure it meets the end user's requirements and achieves enhanced efficiency at a cost-effective rate. Primarily, the machine was intended to be manufactured using locally available materials in local machine shops. The assembly process was intentionally simplified to facilitate easier maintenance and minimize repair expenses.

The dimensions of the machine were 1101.7 mm in length, 682.7 mm in width, and 1270 mm in height. It comprised several components, including a hopper, pelleting mechanism, power transmission system, outlet chute, and a main frame. The main frame played a crucial role in providing support and ensuring the integration and stability of all the machine parts.

The hopper served as a conical container where the mixture was poured and directed toward the pelleting mechanism. Its conical shape was intentionally designed to prevent the accumulation and adherence of feed materials along the hopper wall. Moreover, the hopper was optimized for a continuous and rapid feeding rate, eliminating the need for a feeding regulator.

Situated at the lower part of the hopper, the pelleting mechanism was encompassed by a cylindrical casing and comprised of a horizontal die and two rollers. The primary function of the pellet rollers was to exert pressure on the biochar against the die. The roller assembly was constructed with two (2) rollers connected to a single shaft. Each roller featured 16 milled teeth aligned parallel to the shaft. The horizontal dies were perforated using a 6 mm drill bit and designed to withstand the force applied by the pellet rollers during the pelleting process. As the mixture traversed the perforations, pellets were formed and subsequently collected in the catchment area.

The machine was powered by a 4.85kW (6.5 hp) gasoline engine, which supplied the necessary power. A belt-and-pulley drive system was employed to transfer the motor power to the differential transmission, enabling the transmission of perpendicular rotation. The smaller shaft of the differential transmission was connected to the pelleting mechanism, ensuring that the flat die rotated at a 7:1 ratio, thereby providing a substantial torque to the mechanism. The catchment area, which rotated along with the flat die, received the pellets from the pelleting mechanism.

To facilitate the movement of pellets, a blower was incorporated in the catchment area to propel them toward the outlet chute. The outlet chute was positioned diagonally to ensure a gradual descent of the pellets, preventing any potential damage or breakage during their transportation to the collecting bin. Other factors were taken into consideration, including the noise level and vibration produced by the machine, the arrangement of the assembly, the placement of controls, and the overall physical effort required to achieve the desired throughput capacity. Additionally, a focus was placed on ensuring operator comfort and safety during machine operation.

Pelletizer performance using different biochar feedstock

The machine's performance was tested using three (3) different carbonized materials and different binder levels. The carbonized materials were from rice hulls, coconut shells, and wood chips. The biomass materials were procured from the Laguna State Polytechnic University (LSPU), Siniloan, Laguna, Philippines. The biomass was converted into a carbonized material using LSPU's developed continuous feedstock carbonized for wood chips and coconut shells and open-type carbonized for the rice hull.

The binder levels were set at 10%, 15%, and 20%, respectively. Cassava paste was prepared by dissolving 250 g of cassava starch in 1250 ml tap water. Dissolved cassava starch was poured into 1L boiling water and was stirred constantly until its texture became denser. Materials were weighed with respect to the mixing ratio. The materials were mixed manually. Once the mixture could be compacted by hand, then it was set to be pelletized. A weighing scale was utilized to weigh the mixture for every testing of the machine.

The pre-test included the initiation of the biochar pelletizer without load and with a load of carbonized material. Adjustments were done before data gathering. The machine was cleaned every after a one-day trial to avoid the accumulation of mixture, thereby preventing damage to the machine. A timer was used to note the time of each operation. The amount of mixture and pellets formed after each test run was recorded.

The performance of the machine was tested in terms of actual capacity, theoretical capacity, machine efficiency, pelleting recovery, volume reduction, and fuel consumption.

$$Actual\ Capacity, kg/day = \frac{Weight\ of\ pellets\ (kg)}{Total\ Operating\ Time\ (day)}$$

Equation 1

Machine efficiency is the ratio of the actual capacity to the theoretical capacity of the machine. The machine can turn the mixture of biochar into pellets.

$$Machine\ Efficiency, \% = \frac{Actual\ Capacity\ (kg/day)}{Theoretical\ Capacity\ (kg/day)} x\ 100$$

Equation 2

Volume reduction of the biochar pellets is the ratio of the volume of biochar pellets to the volume of biochar.

$$Volume\ Reduction, \% = \frac{Volume\ of\ Pellets\ m^3}{Volume\ of\ Mixture\ m^3}\ x\ 100$$

Equation 3

Fuel consumption was determined as the amount of fuel consumed using a graduated cylinder for the fill method, for an hour of pelleting time expressed in L-hr$^{-1.}$

Biochar pellets characterization

The characteristics of biochar pellets determined in the study include length, moisture content, water-holding capacity, hardness, and durability. To determine the length of the pellets, 300 pieces of pellets were measured per treatment using a Vernier caliper. On the other hand, the moisture content of the biochar pellets was determined by drying 10 g of dried pellets in three (3) replicates per treatment at 105°C for 48 hours or until there were no significant changes in weight.

To establish the water-holding capacity of the pellets, 10 g of pellets in three (3) replicates from each treatment was saturated with water according to the procedure and equation of Raichle et al. (2013). Fifty (50) milliliters of water were slowly applied to each container having 10 g of pellets until excess water was observed. The pellets were then left to sit for 3 hours to assure homogeneity of water content throughout the pellets. After that, the pellets were drained through a 1 mm sieve. Plastic cups were then filled with wet pellet samples and the wet mass was noted using an analytical balance.

The hardness test was measured using a Kiya Seisakusho hardness tester model # 174886. It converted the kilograms in Pascals based on the 6mm diameter as a surface area. Pellets durability (Equation 4) was measured by placing 50 g of pellets into the Erlenmeyer flask attached to a rotator and was subjected to a durability test (Equation 4) for 20 mins at a speed of 70 rpm (Winowski, 1998).

$$Durability, \% = \frac{Pellet\ mass\ after\ tumbling}{Pellet\ mass\ before\ tumbling}\ x\ 100$$

Equation 4

Data analysis

Analysis of Variance (ANOVA) and Tukey's HSD was conducted on the performance of the pelletizer (actual capacity, machine efficiency, pelleting recovery, volume reduction, fuel consumption), and the characteristics of biochar pellets (length, moisture content, water-holding capacity, hardness, and durability). The software used was the Statistical Tool for Agricultural Research (STAR) Version 2.0.1 (International Rice Research Institute).

A cost analysis was conducted to determine the economic viability of operating the machine. The cost of fabrication is the sum of the cost of the following: all materials, labor costs, and the cost of a gasoline engine. Labor cost was assumed to be 40% of the material cost, based on fees charged by local fabricators.

The annual cost of operation is the sum of the fixed cost and variable costs. Fixed cost includes depreciation, interest on average investment, taxes, shelter, and insurance (TSI), and repair and maintenance (R&M) costs. Variable cost includes labor cost, the cost of materials that were used, and fuel consumption. Variable costs include labor cost, the cost of materials that were used, and fuel consumption. These respective costs were computed using Equations 6 to 8. Moreover, the assumptions to compute the annual cost of operation are shown in **Table 1**.

Annual production, in kg/yr = 188 days/year x Actual Capacity (kg/day)

Equation 5

Fuel cost = Fuel consumption (li) x Price/li (PhP/li)

Equation 6

Fixed cost = Depreciation + TSI + Interest + R&M

Equation 7

Annual cost = Fixed cost + Variable cost

Equation 8

It was assumed that the biochar pelletizer would operate for only 188 days a year, excluding Saturdays, Sundays, and legal holidays in the country. It was further assumed that 75% of the calculated 188 days per year was operational. The annual production of pelletized biochar based on actual machine capacity was computed using Equation 5.

Table 1. Assumptions on the cost of operation of the biochar pelletizer

ITEMS OF COST	DESCRIPTION/ VALUE
Machine Cost	Cost of fabrication and materials
Salvage Value	10% of the machine's cost
Machine Life	5 years
Interest Rate	25% of the machine's cost
Repair and Maintenance cost (R&M)	8% of Machine cost
Number of days of operation	188 days
Number of hours of operation per day	8
Number of operators	2
Wage rate	Php 450/day
Cost of Cassava starch	Php 40/day
Cost of Biochar	Php 50/kg
Fuel Cost	Php 50/Liter
Mark up	60%
TSI cost	2.25% of machine cost

Note: Biochar is assumed to be readily available.

Variable costs include labor cost, cost of fuel consumption, cost of biochar, and cost of cassava starch.

The annual cost of operation is the sum of fixed cost and variable cost (Equation 8).

The cost of biochar pellets per kilogram was determined by dividing the total annual cost by the annual production in kg per year. The viability of the operation of the machine at the designed custom rate was analyzed using the break-even point, payback period, and rate or return, respectively in Equations 9, 10 and 11.

$$\text{Breakeven point, kg} = \frac{\text{Fixed cost}}{\text{Custom cost - Variable cost}}$$

Equation 9

$$\text{Payback period, years} = \frac{\text{Annual cost of operation}}{\text{Net income}} \times 100$$

Equation 10

$$\text{Rate of return, \%} = \frac{\text{Net income}}{\text{Annual cost of operation}} \times 100$$

Equation 11

RESULTS AND DISCUSSION

The biochar pelletizer

Conforming to the design criteria, the biochar pelletizer (**Figure 1**) was fabricated in local shops out of locally available materials. The machine had an overall dimension of 1101.7 mm long, 682.7 mm wide, and 1270 mm high. It consisted of a hopper, pelleting mechanism, power transmission, outlet chute, and main frame. The main frame supported and held all the parts together. The hopper was a conical container in which the mixture was poured and was lead to the pelleting mechanism. It was made conical to prevent the sticking and resting of

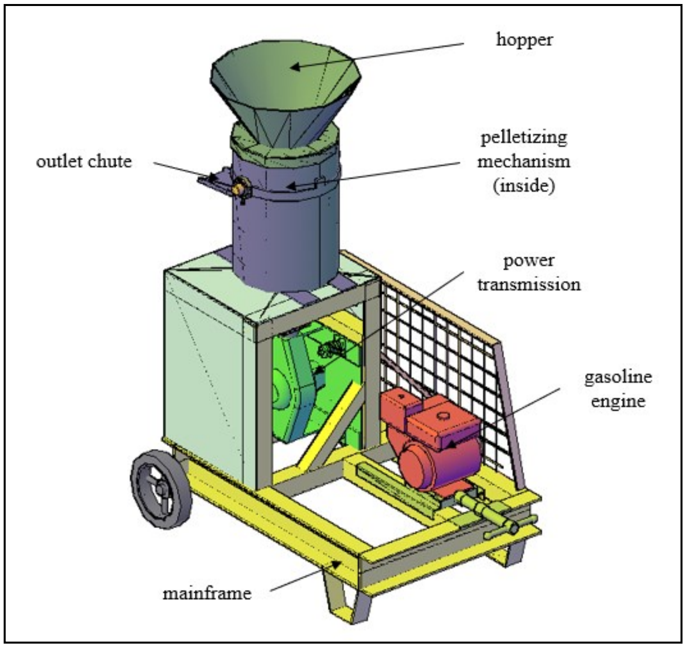

Figure 1. Schematic Drawing of the biochar pelletizer (Adrias, 2020)

feed materials into the hopper wall. The hopper had a capacity of 11 kg of mixture. It was designed for a continuous fast feeding rate that did not require a feeding regulator.

The pelleting mechanism was located at the bottom of the hopper and was enclosed with the cylinder case. The pelleting mechanism was composed of a horizontal die and two rollers. Pellet rollers were designed to press the biochar against the die. The roller assembly consisted of two rollers connected to a single shaft. Each roller had 16 milled straight teeth parallel to the shaft. The horizontal dies were perforated with a 6 mm drill bit and were designed to receive the force from the pellet rollers while pelleting. As the mixture passed the holes, pellets were formed and then fell to the catchment.

Power was supplied to the machine by a 4.85kW (6.5 hp) gasoline engine. A belt-and-pulley drive transmitted its motor power to the differential transmission to transmit a perpendicular rotation. The smaller shaft of the differential transmission was connected to the pelleting mechanism so that the flat die would rotate with a 7:1 ratio delivering a high torque to the mechanism.

The catchment area received pellets from the pelleting mechanism and rotated with the flat die. A blower was installed in the catchment area to blow the pellets that will lead them to the outlet chute. The outlet chute was installed diagonally so that pellets will fall slowly preventing damage or breaking whilst being transported to the collecting bin. The fabricated biochar pelletizer is shown in **Figure 2**.

Figure 2. The developed biochar pelletizer
(Adrias, 2020)

Machine performance using different biochar feedstock

The test on the performance of the machine included the actual capacity, machine efficiency, pelleting recovery, volume reduction, and fuel consumption (**Table 2**).

Actual capacity

The actual capacity of a machine serves as a quantifiable measure of its ability to convert biochar into pellets**. Table 2** displays noteworthy variations in the machine's actual capacity across different feedstocks and binder levels. Among the three feedstock and binder levels, the carbonized rice hull combined with 15% and 20% binder levels exhibited the highest capacity. This suggests that the capacity is influenced by both the specific feedstock material and the concentration of the binder. The observed disparities in capacity between the materials can be attributed to factors such as the size and shape of the carbonized particles. It is plausible that the carbonized rice hull possesses particle characteristics that align more favorably with this particular machine, resulting in a higher capacity when compared to the other materials. In consideration of the necessary downtime for adjustments and cleaning, the actual machine capacities were measured as 678.22 kg/day, 448.44 kg/day, and 412.44 kg/day for carbonized rice hull, carbonized coconut shell, and carbonized woodchips, respectively. These figures correspond to an annual production of biochar pellets amounting to 127, 84, and 77 tons per year, assuming an operational period of 250 days per year at 0.75% capacity utilization. Notably, this output significantly exceeds the reported capacity of 608 kg/day for a pelletizer used in animal feed production (Romallosa and Cabarles, 2009).

Machine efficiency

Machine efficiency was determined by calculating the ratio of the actual capacity to the theoretical capacity. The theoretical capacity represents the maximum output achievable by the machine under ideal conditions, while the actual capacity represents the measured output during practical operation. The results, presented in **Table 2** showed that machine efficiency (mean) ranged from 67.86% to 71.02%, irrespective of the binder level. However, significant differences in machine efficiency were observed among the different feedstocks, indicating that the machine's performance varied depending on the specific feedstock being processed.

Notably, carbonized wood chips displayed the highest machine efficiency among the three feedstocks. This suggests that carbonized wood chips are better suited for the machine, resulting in more efficient processing performance. In contrast, the observed lower efficiency in processing carbonized rice hull can be attributed to its physical characteristics before processing. Due to its loose and powdery nature, carbonized rice hull required longer mixing preparation, thereby affecting the overall processing time and subsequently reducing machine efficiency. These findings hold considerable importance for industries involved in feedstock processing, providing them with valuable insights for material selection and optimization of production processes. By considering the feedstock characteristics and their impact on machine efficiency, industries can make informed decisions to improve their production efficiency and output.

Pelleting recovery

As observed from **Table 2,** the binder level had a significant impact on the pelleting recovery, while the feedstock type did not show any significant effect. The highest pelleting recovery of 98.50% was achieved with a binder level of 20%. This indicates that for every kilogram of mixture loaded into the hopper, approximately 985 grams of biochar pellets were produced, resulting in a loss of about 15 grams of the mixture. The main factor behind this phenomenon is the strong influence of the binder on the formability of the pellets. Thus, regardless of the feedstock type, the machine's ability to transform the mixture into pellets remained unaffected. The observed pelleting recovery efficiency is comparable to that of a pelletizer used for ruminant feeds, as reported by Orden et al. (2013), which achieved a 98% efficiency. However, it is important to note that in the case of the ruminant feed pelletizer, pre-mixed materials based on feed formulation were pelletized without requiring any additional mixing steps. These findings highlight the significance of the binder level in determining pelleting recovery, while the feedstock type does not play a substantial role in this regard. Industries can utilize this information to optimize the pelleting process by carefully selecting and adjusting the binder level, thereby enhancing the efficiency and yield of biochar pellet production.

Volume reduction

Volume reduction is a crucial aspect that quantifies the size reduction achieved through the pelleting process. Pelleting plays a vital role in aggregating particles, thereby reducing bulk volume and minimizing the risk of particles being dispersed by wind during transportation and application. **Table 2** provides a comprehensive presentation of the volume reduction results. Regardless of the specific feedstock type and binder level, the as-produced biochar experienced a significant reduction in volume. The original size of the biochar was reduced to a range of approximately 46% to 47% of its initial volume. This indicates a substantial decrease in bulk, which is advantageous for handling, storage, and transport purposes. By

Table 2. Effects of the feedstock and binder level on the actual capacity (AC), machine efficiency, pelleting recovery, volume reduction, and fuel consumption of the Biochar Pelletizer

TREATMENT	ACTUAL CAPACITY kg-day^{-1}	MACHINE EFFICIENCY %	PELLETING RECOVERY %	VOLUME REDUCTION %	FUEL CONSUMPTION L-hr^{-1}
Feedstock					
Carbonized Rice Hull	678.22^{a}	64.89^{b}	95.3	46.58	2.30
Carbonized Coconut Shell	448.44^{b}	63.08^{b}	95.5	47.04	2.31
Carbonized Wood Chips	412.44^{b}	80.82^{a}	95.5	46.63	2.27
Binder Level					
10	455.11^{b}	69.89	92.8^{c}	46.75	2.29
15	520.00^{ab}	71.02	95.2^{b}	46.67	2.30
20	564.00^{a}	67.86	98.5^{a}	46.83	2.29
Cv	12.78	4.23	0.6624	2.21	1.90
Feedstock	<0.01	<0.01	0.8318	0.5975	0.2343
Binder Level	0.0085	0.0970	<0.01	0.9506	0.7164
Feedstock: Binder Level	0.7841	0.1338	0.4421	0.6877	0.6603

Significant means with ANOVA at 95% level of significance. This means with the common letter is not significantly different from Tukey's Honest Significant Difference (THSD) Test.

undergoing the pelleting process, the biochar particles effectively aggregate, resulting in a denser and more compact form. This compression significantly reduces the overall volume occupied by the biochar material. The size reduction is consistent across all tested feedstock types and binder levels, highlighting the robustness and effectiveness of the pelleting process in achieving volume reduction. The achieved volume reduction has practical implications for various industries involved in the production, distribution, and application of biochar. The reduced size enhances the efficiency of storage and transportation, as a larger quantity of biochar can be accommodated in a given space. Additionally, the compacted form contributes to easier handling and application, reducing the risk of particle dispersal during wind events.

Figure 3. Sample biochar pellets
(Adrias, 2020)

Fuel consumption

Fuel consumption is a measure of the amount of fuel utilized during the pelleting process. The data in **Table 2** reveals that the interaction between feedstock type and binder level did not have a significant impact on fuel consumption. Irrespective of the specific combination, the machine consistently consumed approximately 18.4 liters of fuel for a one-day operation. This fuel consumption rate translates to an average power consumption of 2.3 liters for each pelleting session. Comparing this to the animal feed pelletizer studied by Romallosa and Cabarles (2009), it is evident that power consumption differs significantly.

The aforementioned pelletizer consumed 15.78 watts per kilogram of pellets produced, which is 1.66 times greater than the power consumption of the pelletizer used in our study, considering both machines produced pellets of the same size. The consistent fuel consumption observed across various feedstock types and binder levels indicates that these factors do not substantially influence the energy requirements of the pelleting process. This implies that the machine's fuel consumption remains relatively stable, regardless of the specific feedstock or binder utilized. The findings underscore the efficiency and effectiveness of the pelleting machine in terms of fuel consumption. The relatively low fuel consumption rate observed in our study suggests that the machine operates in a highly efficient manner, ensuring optimal use of fuel resources. This has practical implications for industries involved in pellet production, as lower fuel consumption translates to reduced operational costs and improved sustainability.

Physical and mechanical characteristics of pelletized biochar

The test on the characteristics of biochar pellets (**Figure 3**) included the length of pellets, bulk and particle density, moisture content, water-holding capacity, hardness, and durability. The study's results on the physical and mechanical characteristics of the biochar pellets are presented in **Table 3**.

Length

The term "length" pertains to the initial height of the pellets, which was precisely measured using a vernier caliper. The collected data in **Table 3** demonstrates that the length of the biochar pellets displayed a narrow range, falling between 18.22 and 18.49 mm. This remarkable consistency in length indicates a high level of uniformity among the produced pellets. Intriguingly, despite variations in the feedstock type, cassava binder level, and their potential interaction, no noticeable impact on the length of the pellets was observed. The persistent and unchanging length of the pellets serves as a valuable indicator of the stability of the cutting scraper positioned beneath the pelleting flat die. This scraper plays a critical role in ensuring that the pellets are consistently cut to the desired height, resulting in the uniform length observed in the study. It is noteworthy that the dimensions of the pellets produced in this investigation align closely with those reported in prior research. For instance, Reza et al. (2014) conducted a study on pelletizing biochar derived from HTC wood and achieved pellets with lengths ranging from 8 to 10 mm and a diameter of 13 mm. Similarly, pellets designed for animal feeds, as reported by Romallosa and Cabarles (2009), exhibited a length of 11 mm and a diameter of 8 mm. The convergence of pellet dimensions across different studies underscores the consistent outcomes and reproducibility of pelletization processes. These findings provide valuable insights into the physical characteristics of biochar pellets and contribute to a growing body of knowledge in the field. Furthermore, the uniformity in pellet length enhances the practicality and efficiency of handling, transportation, and application of biochar pellets in various industries and agricultural practices.

Bulk density

Bulk density refers to the dry mass per unit volume of the bulk of biochar pellets, reflecting the space occupied by the pellets. The obtained data in **Table 3** demonstrates that bulk density was significantly influenced by the feedstock type, while no significant differences were observed in relation to the binder level and its interaction with the feedstock. Notably, biochar pellets derived from carbonized rice hull exhibited the highest bulk density, measuring 341.67 kg-m-^{3}. A higher bulk density indicates a more compact and heavier composition of the pellets. On the other hand, the remaining feedstock materials displayed lower bulk densities, ranging from 237.78 to 242.89 kg-m-^{3}. It is worth noting that other researchers have also explored the pelletization of wood biochar incorporating additional elements such as Nitrogen, Potassium, and Phosphorus. In their study, Johnson et al. (2013) achieved a significantly higher bulk density of 776 kg-m-3 for the resulting pellets. This disparity in bulk density can be attributed to variations in the composition and characteristics of the biochar feedstock, as well as the presence of additional elements or additives during the

Table 3. Effects of the feedstock and binder level on the length, bulk density, particle density, moisture content, and water holding capacity.

TREATMENT	LENGTH, mm	BULK DENSITY, kg-m^{-3}	PARTICLE DENSITY, kg-m^{-3}	MOISTURE CONTENT, %	WATER HOLDING CAPACITY, %
Feedstock					
Carbonized Rice Hull (CRH)	18.49	341.67^a	764.22^a	6.67^c	48.50^b
Carbonized Coconut Shell (CCH)	18.45	242.89^b	348.78^b	7.18^b	101.58^a
Carbonized Wood Chips (CWC)	18.22	237.78^b	342.00^b	7.50^a	103.52^a
Binder Level (BL)					
10	18.33	275.88	487.44	7.19	83.77
15	18.46	272.88	485.88	7.16	84.15
20	18.37	273.55	481.66	7.11	85.67
Cv	1.91	1.92	3.67	3.23	5.56
Feedstock	0.2296	<0.01	<0.01	<0.01	<0.01
Binder Level	0.7283	0.4621	0.7780	0.1523	0.6679
Feedstock: Binder Level	0.6563	0.1502	0.9910	0.1746	0.5975

Significant means with ANOVA at 95% level of significance. This means with the common letter is not significantly different from Tukey's Honest Significant Difference (THSD) Test.

pelletization process. The differences in bulk density observed among the various feedstocks and research studies highlight the influence of material properties, chemical composition, and processing techniques on the final density of biochar pellets. Understanding and manipulating bulk density are crucial factors in optimizing the storage, transportation, and application of biochar pellets in diverse industries and agricultural practices. By achieving a higher bulk density, biochar pellets can effectively reduce the storage space required and enhance handling efficiency, facilitating their widespread utilization in sustainable and environmentally friendly applications.

Particle density

Particle density refers to the measurement of dry mass per unit volume of an individual biochar pellet. The corresponding data in **Table 3** illustrates that pellets derived from carbonized rice hulls exhibited the highest particle density, reaching 764.22 kg-m-3. However, there were no significant differences observed in the means of the binder-level treatments and their interactions. Comparatively, the particle densities for carbonized coconut shell (CCS) and carbonized wood chips (CWS) were recorded at 348.78 kg-m-^{3} and 342 kg-m-^{3}, respectively. It is interesting to note that the particle density of biochar made from coconut shells, as reported by Mahimairaja & Shenbagavalli (2012), was observed to be 540 kg-m-^{3}, surpassing the particle density observed in the current study. This discrepancy can be attributed to the compaction of particles during the pelleting process, which leads to a reduction in the pore spaces between each particle. As a result, the particle density of the biochar increases. The variation in particle density among different feedstocks highlights the influence of the inherent properties and characteristics of the raw materials.

Factors such as particle size, shape, and composition can significantly affect the compactness and density of the resulting pellets. Understanding particle density is crucial for optimizing the production and utilization of biochar pellets in various applications, including agriculture, energy production, and environmental remediation. By achieving higher particle densities, the efficiency and effectiveness of biochar pellets can be enhanced, leading to improved performance and desired outcomes in their respective applications.

Moisture content

Moisture content refers to the quantity of moisture present within the biochar pellets. Before the pelleting process, the biochar material contained approximately 49% moisture. After subjecting the pellets to oven drying, their moisture content ranged from 6% to 7% on a dry weight basis, as indicated in **Table 3**. Interestingly, no significant variations in moisture content were observed among the different binder treatment means. However, the feedstock type exerted a significant influence on the moisture content of the pellets, with carbonized wood chips exhibiting the highest moisture content at 7.50%. Comparing these findings to those reported by Johnson et al. (2013), it is evident that the moisture content of the current study's pellets is notably higher. In Johnson et al. (2013) research, engineered pellets that incorporated nutrients such as K, Ca, Mg, N, P, and S, with lignin (Insulin AT, kraft pine lignin) as a binder, exhibited moisture content ranging from 0.3% to 1.10%.

The disparity in moisture content could be attributed to several factors, including the initial moisture content of the biochar material used and the level of binder employed during the pelleting process. Controlling moisture content in biochar pellets is crucial for their stability, durability, and effectiveness in various applications. Excessive moisture content can lead to issues such as pellet degradation, increased susceptibility to microbial growth, and reduced shelf life. On the other hand, insufficient moisture content may result in poor pellet formation and inadequate binding. Finding the optimal moisture content range is essential for ensuring the quality and performance of biochar pellets in their intended applications, such as soil amendment, carbon sequestration, and energy production.

Water holding capacity

Water-holding capacity refers to the maximum amount of water that biochar pellets can retain when saturated. This characteristic is significant as it indicates the pellets' ability to store water, which can be particularly valuable during dry periods. Higher water-holding capacity can offer solutions for irrigation and address water scarcity issues.

In **Table 3**, it is evident that the water-holding capacity varied among the different feedstock types, with carbonized coconut shells and carbonized wood chips displaying the highest values at about 100% to 104%. Conversely, carbonized rice hull exhibited the lowest water-holding capacity at 48%. This implies that pellets produced from carbonized coconut shells and carbonized wood chips can retain water over their weight. Interestingly, no significant differences were observed in the water-holding capacity regarding the binder level treatment means and their interaction with the feedstock type. This suggests that regardless of the binder level and its interaction, the pellets exhibit a consistent ability to retain moisture. This consistency in water-holding capacity is an advantageous characteristic as it ensures the pellets' reliability in retaining water for various applications. Comparing these findings to the research conducted by Johnson et al. (2013), it is evident that the water-holding capacity of the current study's pellets is higher. Johnson et al. reported a lower range of water-holding capacity for their pellets, at 35% to 69%. The disparity in water-holding capacity can be attributed to the pelleting process, which tends to reduce the pellets' ability to retain water compared to pure biochar.

Raichle et al. (2013) found the water-holding capacity of pure biochar to be 27%. On the other hand, Adrias and del Rosario (2017) reported higher water-holding capacities for specific feedstock materials, such as rice hull at 294.83%, twigs at 116.45%, and coconut fronds at 138.67%. The reduced water-holding capacity of biochar pellets can be attributed to the presence of binder particles, which fill the spaces between the compacted biochar particles. Despite this reduction, the pellets still exhibit a considerable capacity to retain water, offering potential benefits in terms of water management and conservation in various applications, including agriculture and environmental remediation.

Pellet hardness

The measurement of pellet hardness serves as an indicator of the physical integrity of the biochar pellets, ensuring that they are not excessively hard, which could limit their dissolvability when applied to the soil. Unlike tumblers that test hundreds of pellets simultaneously, in this study, pellet hardness was assessed on an individual pellet basis. This

Table 4. Effects of the feedstock and binder level on the hardness and durability.

TREATMENT	HARDNESS, Pa	DURABILITY, %
CRH: BL10	681.16[c]	61.91[c]
CCS: BL10	806.66[b]	74.70[b]
CWC: BL10	1183.10[b]	72.40[c]
CRH: BL15	896.33[b]	72.66[c]
CCS: BL15	1290.70[a]	82.16[b]
CWC: BL15	1290.70[a]	98.06[a]
CRH: BL20	1183.10[b]	72.23[c]
CCS: BL20	1469.93[a]	89.67[b]
CWC: BL20	1559.60[a]	92.00[a]
Cv	5.95	3.03
Feedstock	<0.01	<0.01
Binder Level	<0.01	<0.01
Feedstock: Binder Level	0.0405	<0.01

Significant means with ANOVA at 95% level of significance. This means with the common letter is not significantly different from Tukey's Honest Significant Difference (THSD) Test.

approach allows for a more precise evaluation of the pellets' strength. Significant differences were observed in pellet hardness among the different treatments and their interactions. Both the feedstock type and binder level were found to have an impact on the strength of the pellets. Specifically, pellets produced from carbonized coconut shells and carbonized wood chips feedstock, with binder levels of 15% and 20%, exhibited the highest hardness compared to the other treatments. The data presented in **Table 4** revealed that pellets from these specific treatments could withstand pressures ranging from 1000 to 1500 Pa before breaking. It is important to note that apart from the treatments, the strength of the pellets is also influenced by the specific part of the die where they were formed. The center of the die typically experiences a higher extrusion rate, shorter dwell time, and greater wear. As a result, pellets produced from this region tend to be harder and more durable. The findings on pellet hardness have practical implications for the application of biochar pellets. The ability of the pellets to withstand a certain level of pressure without breaking ensures their suitability for various soil-related applications. It guarantees that the pellets maintain their physical integrity during handling, transportation, and soil incorporation. Moreover, understanding the factors influencing pellet hardness allows for process optimization and the production of pellets with desired physical properties.

Durability

Durability, in this study, is defined as the percentage ratio of the mass of pellets retained on the sieve after tumbling to the initial mass of the pellets before tumbling. It serves as a measure of the pellets' ability to withstand mechanical stresses and is closely related to the effectiveness of densification. The analysis conducted revealed that the durability of the pellets was significantly influenced by the feedstock type, binder level, and the interaction between these two factors. Among the different treatments, pellets made from carbonized wood chips exhibited the highest durability, indicating their superior resistance to breakage compared to the other treatments. The feedstock type played a crucial role in determining pellet durability, at 15% binder level as carbonized wood chips yielded a durability value of 98.06%, which was significantly higher than that of carbonized coconut shell (82.66%) and carbonized rice hull (72.66%) (**Table 4**). The variation in durability can be attributed to the inherent characteristics of the different feedstocks used. Carbonized wood chips possess physical properties that contribute to their enhanced durability, such as greater strength and structural integrity. These properties enable the pellets to withstand the rigors associated with shipping, loading, and other handling-related functions. On the other hand, carbonized coconut shells and carbonized rice hull, although still exhibiting considerable durability, showed slightly lower values due to their specific material characteristics. The findings emphasize the importance of selecting an appropriate feedstock to achieve desired pellet durability. Understanding the factors influencing pellet durability can aid in the optimization of pellet production processes and material selection. By producing pellets with higher durability, the risk of breakage and deterioration during transportation and handling can be minimized, ensuring that the pellets maintain their structural integrity and effectiveness in their intended applications.

Simple Financial Analysis

The fabrication of the biochar pelletizer incurred a total material cost of PhP 32,426.50. Taking into account the estimated labor cost at 50% of the material cost, the total fabrication cost of the machine amounted to PhP 64,853.00. In the online market, locally fabricated pelletizers are available for purchase, ranging from PhP 95,000.00 to PhP 120,000.00, with capacities ranging from 60 kg/h to 150 kg/h (source: https://www.olx.ph). On the other hand, pelletizers manufactured abroad cost PhP 30,000 and offer a capacity range of 150 kg/h to 200 kg/h (source: https://www.alibaba.com).

Considering the reported average capacity of the biochar pelletizer, the cost of producing one kilogram of pellets is approximately PhP 301.18. In comparison, the cost of producing pellets (based on price and capacity) ranges from PhP 1,009.52 per kilogram on the Online Exchange Philippines to PhP 171.43 per kilogram on ALIBABA. However, it is important to note that the latter price does not include shipping costs.

Table 5. Cost and return analysis of the biochar pelletizer

PARTICULARS	RESULTS FOR CRH
Annual production (kg)	127,505.00
Cost per kilogram (PhP-kg^{-1})	52.89
Variable cost (PhP-kg^{-1})	52.68
Annual cost (Php)	6,744,264.00
Gross income (PhP-yr^{-1})	10,837,956.00
Net income PhP-yr^{-1})	4,093,692.00
BEP (Pellet kg)	835.85
Payback period (yr)	1.65
Rate of return (%)	60.70
Selling price at 60% markup (PhP-kg^{-1})	84.63
Selling price (PhP-kg^{-1})	85.00

Note: This analysis did not consider the expenses for storage for biochar, pellets, and other equipment and tools, water consumption, fuel for binder preparation, taxes on income, packaging, and other incidental expenses.

The fixed costs encompassed machine depreciation, interest on average investment, repair and maintenance (R&M) costs, and total service input (TSI) costs, amounting to PhP 26,835.67. These fixed costs remained the same regardless of the binder used. Variable costs accounted for PhP 6,717,428.00, resulting in a total annual cost of PhP 6,744,864.00. With an annual production of 12,7505 kg, the cost of production per kilogram was calculated at PhP 52.89. **Table 5** presents a detailed cost and return analysis of the biochar pelletizer**.** The selling price of the pellets was determined based on the annual cost per kilogram of biochar pellets, with a markup price of 60%. Biochar pellets produced from CRH were projected to be sold for PhP 85.00 per kilogram. Assuming a high demand and easy sale of biochar pellets, a gross income of PhP 10,837,956.00 per year is expected to be achieved.

CONCLUSION

A biochar pelletizer was fabricated in local shops using locally available materials. The developed biochar pelletizer was able to convert biochar into pellets. The designed and developed biochar pelletizer was tested on three feedstocks, namely, carbonized rice hull, carbonized coconut shell, and carbonized wood chips at different binder levels of 10, 15, and 20% of the feedstock weight. Among the three feedstock and binder levels, the carbonized rice hull combined with 15% and 20% binder levels exhibited the highest capacity. The machine efficiency ranged from 67.86% to 71.02%, irrespective of the binder level. The highest pelleting recovery of 98.50% was achieved with a binder level of 20%, regardless of the feedstock type.

The original size of the biochar was reduced to a range of approximately 46% to 47% of its initial volume. Irrespective of the specific treatment interaction, the machine consistently consumed approximately 2.3 liters for each pelleting session. The length of the biochar pellets displayed a narrow range, falling between 18.22 and 18.49 mm. Bulk and particle density were significantly influenced by the feedstock type, while no significant differences were observed in relation to the binder level and its interaction with the feedstock. Pellets derived from carbonized rice hull exhibited the highest bulk and particle density, measuring 341.67 kg-m-^{3} and 764.22 kg-m-3. The pellet's moisture content ranged from 6% to 7% on a dry weight basis. No significant variations in moisture content were observed among the different binder treatment means while carbonized wood chips exhibit the highest moisture content at 7.50% among feedstock. The water-holding capacity varied among the different feedstock types, with carbonized coconut shells and carbonized wood chips displaying the highest values at 100% to 104%.

Pellets produced from carbonized coconut shells and carbonized wood chips feedstock, with binder levels of 15% and 20%, exhibited the highest hardness compared to the other treatments. the durability of the pellets was significantly influenced by the feedstock type, binder level, and the interaction between these two factors. Among the different treatments, pellets made from carbonized wood chips exhibited the highest durability at 87%, which was significantly higher than that of carbonized coconut shell (82%) and carbonized rice hull (68%).

The financial analysis indicated that venturing into the pelletizing project using the biochar pelletizer would be profitable. The cost of the machine itself amounted to approximately PhP 64,853.00. Among the different types of pellets, those produced using carbonized rice hulls (CRH) incurred the highest annual cost of production, reaching Php 6,744,264.00. However, they also yielded the highest net income of PhP 4,093,698. This indicates the feasibility of the operation based on key financial indicators such as the breakeven point (BEP), payback period (PBP), and rate of return (ROR). The breakeven point represents the point at which the costs are recovered, and in this case, the cost of the machine will be recouped after approximately 1.65 years or 311 working days. In other words, the operation will start generating profits after producing approximately 836 kg of biochar pellets, which can be achieved within 2 working days. The rate of return (ROR) for this project is estimated at 60.70%, indicating a promising return on investment.

RECOMMENDATION

Based on the findings, it is recommended to further explore the potential of using other feedstock materials and different types of binders and formulations for pellet production. This could potentially expand the range of products and markets, enhancing the profitability and success of the venture.

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