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ENHANCING THE QUALITY OF MAIZE, WHEAT, RICE AND COTTON RESIDUE BRIQUETTES BY OPTIMIZING THE OPERATIONAL PARAMETERS

Hafiz M. Safdar[1,*], Abdul Nasir[1], Faizan-Ul-Haq Khan[1] and Riaz Ahmad[2]

[1]Department of Structures and Environmental Engineering, University of Agriculture Faisalabad-38040, Pakistan; [2]Department of Agronomy, University of Agriculture Faisalabad-38040, Pakistan.
[*]Correspondence author's e-mail: sarmsafdar@gmail.com

In this study briquettes prepared from four types of abundantly available crop residue (i.e., wheat straw, rice straw, maize straw and cotton sticks). These were optimized and tested to evaluate the enhancement in their properties including durability, bulk density, compression strength and calorific value. The briquettes were prepared using indigenously designed mechanical piston press briquettes forming machine. Briquettes formation was initially tested for three operational input material parameters i.e., moisture content, particle size and mould/die temperature from the four selected straws to find out their suitable ranges. Briquettes thus prepared were then statistically analyze using a 3-factor factorial design under CRD (completely randomized design) at three levels of three independent variables including moisture content (15, 20 and 25%), particle size (9, 12 and 15 mm) and temperature (200, 250 and 300°C) respectively. Ultimately, the best quality and economical briquettes were achieved at 20% moisture content, 12mm particle size and at 300 °C temperature from all types of crop residue. It was also noted that the best quality briquettes were achieved from maize straw while rice straw produce least quality. Considering the calorific value, study showed a range of 15.3 – 18.2 MJ/kg for selected briquettes. Ultimate results of the study can provide the guidelines to the farmers. So, they can set the input parameters according to crop residue type to obtain the best quality briquettes with enhanced economic benefits.

Keywords: Renewable energy, crop residue utilization, crop biomass, energy recovery, briquettes properties, briquettes quality, parametric optimization.

INTRODUCTION

Crop residue is defined as the leftover of crops in fields in the form of stalks, leaves, branches and roots after harvesting. It includes either dead or growing residues from almost all crops after getting the fruits (OECD, 2001). It may also refer as the byproduct of agriculture crops and forestry, which can be utilized as primary source of renewable energy (Daioglou*et al*., 2016). Pakistan is a country with promising crop residue availability due its agricultural based economy where 62% of its population resides in rural areas (World Bank, 2018). Pakistan's major crops include cotton, rice, wheat, sugar cane and maize. Pakistan is ranked fourth in cotton growing, fifth in sugar cane producing, eighth in wheat production, eleventh in rice production, and twenty fifth in maize crop production in the world according to a census carried out in 2014-15 (Butt *et al*., 2013). All these crops are a major residue source that is why enormous amount of crop residue is clustered in fields. A huge portion of which is used inadequately and in-efficiently i.e., either wasted or burnt without getting energy (Rehman *et al*., 2015).

Overall crop residue utilization is inefficient for domestic as well as for industrial purposes to extract energy without any modification to it. Direct use is also associated with many problems like low bulk density, less calorific value per unit volume, variation in quality and rapid burning. It is also difficult to collect, transport, store and handle in bulky form (Shukla and Savita, 2015). With efficient use of crop biomass in producing energy, Pakistan can meet a variety of energy needs including generating electricity, heating homes, and providing process heat for industrial facilities. The wastage of any type of energy acquiring opportunity, especially loss of crop residue is a great to an agricultural country. This not only affects the economy but also adds several environmental issues due to burning in open fields (Butt *et al*., 2013).

Crop waste to energy techniques has become popular in Asian countries like China, India and Pakistan and biomass conversion to suitable form is one of them. The crop biomass is an important feed stock due to massive agricultural base of these countries. There is only need for the efficient utilization of agricultural residue to overcome energy shortage (Tripathi, 1998). Waste crop residue can be utilized efficiently by producing biomass briquettes. These are the dense energy blocks made from agriculture or forest residue. In this way, low density biomass can be briquetted to about 1000 kg/m^3 or even more dense logs/ briquettes by applying pressure. It can easily be utilized for heat acquisition as well as in electricity generation. Biomass briquettes can also be used for small and large heating systems as a replacement of wood, coal and gas. Briquettes can replace conventional fuels from energy perspective, also, it results in significant reduction of emissions as compare to other fuels.

Ability of briquettes to be utilized as fuel depends on their physical properties and calorific value. Physical properties of briquettes are the indicator of their quality in terms of ability to withstand the crushing, fractural and load forces. As briquettes are to be transported, stored for long period of time their physical properties are vital to be considered. Important physical properties include density, durability and compressive strength of briquettes. However, these properties are influenced by nature of raw material (particle size, moisture content, mould temperature) and equipment utilized (type of briquettes forming machine). For briquettes production, these input material properties play a vital role in all processes of production i.e., shredding, mixing, feeding, and briquetting. For example, high level of moisture content in crop residue may chock shredder, feeding conveyer and compactor. It is also seen that too high moisture level may decrease the density of briquettes (Al-Shemmeri *et al*., 2015). Moreover, briquettes produced from fine sized particles were more durable, difficult to disintegrate and did not crumble during transportation (Kaliyan and Morey, 2009).

Main objective of briquettes formation is to increase density of agriculture, forest and processed residue from industry. Originally, these residues have very low density. Particularly, crop residue and grasses have density as low as in the range of 60-80 kg/m^3 and are difficult to utilize in straw form. To overcome these limitations, high density briquettes are prepared from this residue (Mitchell *et al*., 2007). Generally, durability of briquettes is determined in percentage and classified in three categories as high = (>80%), medium = (70 - 80%) and low = (<70%) (Adapa *et al*., 2003; Tabil, 1996). Karunanithy*et al*. (2012) used a piston press machine for the preparation of briquettes from different feed stocks (cotton stocks, pigeon pea, corn stove, switch grass, prairie cord grass and saw dust). They found the highest and lowest durability for corn stove and pigeon pea grass as 96.6 and 61%, respectively. Like durability, compressive strength of briquettes is an important physical property which indicates compressive stress due to the weight of the top layers of briquettes on the lowers during storage in bins or silos (Tabil and Sokhansanj, 1996). Calorific value should also be considered while discussing the quality of any fuel. It is the quantity of heat energy liberated during the complete combustion of unit mass of a fuel. Calorific value is the most important property of a fuel and helpful for setting up and to organize an energy plant (Singh *et al*., 2015).

The specific objectives of the study are to optimize and analyze the effect of three operational parameter (i.e., moisture content, particle size and mould temperature) based on three performance indicators of briquettes (i.e., durability, density and compressive strength) for selected four crop residues of wheat, rice, cotton and maize straw. Furthermore, three factor factorial design was applied for the parametric optimization based on the physical properties of briquettes plus calorific value and to analyze, compare the quality of different crop residue briquettes.

MATERIALS AND METHODS

In this study an indigenously developed mechanical piston press briquettes forming machine, available in University of Agriculture Faisalabad, was used to produce briquettes. Machine has the capacity to produce 300 kg/hr. Machine was tested and optimized for four selected crop residue i.e. wheat straw, rice straw, maize straw and cotton sticks those are abundantly available in surroundings. Crop's residue was collected from the fields of PARS (Post Graduate Agriculture Research Station), new campus, University of Agriculture, Faisalabad. It is impossible to prepare briquettes by directly inputting the crop residue (in the form of long straws) using this machine but it required some initial processing of raw material to be input to the machine. So, Material was shredded to required particle size and added to machine for the formation of briquettes.

***Determination of operational parameters*:** The properties of input raw material are very significant in the quality of briquettes formation. Important physical properties of raw material which control the quality of the final product include particle size of raw material, moisture content and mould temperature. First, a hammer mill was used to break the long-sized straws to the required particle size. It contains free moving hammers and a required sized bottom sieve. Raw crop biomass (wheat straw, cotton stalks, maize straw and rice husk) were putted into hammer mill in which hammers strike the straws repeatedly and reduced it into desired size which based on the size of sieve opening (Mani *et al*., 2002). Various particle sizes may thus be achieved by varying sieve size openings. These sieves are available in local market to get required particle size. Second, a digital moisture meter (TK100S) was used for the determination of grinned material's moisture level and thirdly, the temperature of mould was noted from heat sensors those were also installed to indicate temperature of the mould heaters. Any temperature value can be adjusted within the range of 0°C - 800°C (Fig. 1). Machine/instrument used to determine operational parameters A) shredder for required particle size, B) moisture meter to determine moisture content level C) electrical panel to note mould temperature (from right to left).

Figure 1. **Machine/instrument used to determine operational parameters; A) shredder for required particle size, B) moisture meter to determine moisture content level C) electrical panel to note mould temperature (from right to left).**

Figure 2. **Determination of physical properties of briquettes A & B) durability, C) density D) compressive strength (from right to left).**

Determination of physical properties of briquettes: Physical properties of briquettes are important to determine their quality. Physical properties of briquettes determined in this study are durability, density, and compressive strength. Firstly, Drop resistance test following the studies of (Al-Widyan and Al-Jalil, 2001; Mitchell et al., 2007; Li and Liu, 2000) was used for the determination of durability of briquettes. In drop resistance test, the weight of the briquette was noted, and it was dropped freely from a selected height of 1.85 m on a concrete floor. Some of the portion of briquette was shattered in small pieces. Weight retained by the largest piece of briquette to its initial weight in percentage is taken as durability. This test was performed for multiple briquettes and average value was quoted. Secondly, the density of briquettes was measured in two steps. Initially, the volume of an individual briquette was measured by water displacement method (Sengar et al., 2012). In this method, wax was coated on the surface of briquette to make it water proof. The weight of briquette was calculated before and after coating wax. Wax coated briquette was then submerged into a water containing cylinder and volume of water displaced by briquette was noted. Finally, density was measured by dividing initial weight of briquette before applying wax to the volume of briquette after subtracting the volume of wax (Sengar et al., 2012). This procedure was repeated on several different briquettes for three times to get an average value of density. Thirdly, a ton hydraulic press was used for the determination of compressive strength of briquettes. The smooth surfaces of briquette samples were placed on metal plate of the machine one by one. Machine was started and gradually reduced the space between the metal plate and sample surface. Load was applied at a constant rate until the test sample failed by cracking or breaking (Fig. 2). Determination of physical properties of briquettes A & B) durability, C) density D) compressive strength (from right to left).

Determination of calorific value of briquettes: Calorific value or higher heating value (HHV) was calculated by determining the percent volatile matter (PVM), percent fixed carbon (PFC) and percent ash content (PAC) using the method recommended in the studies of (Parker *et al*., 2004; Emerhi *et al*., 2011). PVM and PFC were determined by taking a sample of pulverized briquette having weight of 2g in crucible and placed in an electric oven until a stable weight was obtained. After achieving a constant weight of sample, it was placed in muffle furnace at 550 ^{0}Cfor 10 minutes (for PVM) and 4 hours (for PFC) and the weight was measured again after cooling in desiccator. PAC was calculated by subtracting PVM and PFC from a value of 100. Ultimately, the calorific value or higher heating value (HHV) was determined using the following formula.

$$\mathrm{HHV} = 0.3536\mathrm{PFC} + 0.1559\mathrm{PVM} + 0.078\mathrm{PAC}$$

RESULTS

Effect of pretreatments: First objective was to determine the effects of three most important parameters for example moisture level, particle size of input material and mould temperature. But, it was very difficult to deal with all parameters at once for all selected physical properties. So, these parameters were considered using a step wise pattern for the most important physical property i.e., durability. Initially, other parameters were selected as constant and effect of only one was checked to select its suitable range against the durability (Fig. 3 ABC). Ultimately, three levels within the specific range were selected for further optimization procedure. Figure 3. Effect of pretreatments on durability A= moisture content, B= particle size, C= mould temperature. Firstly, all crops showed almost similar trend against the variation in moisture content as shown in Figure

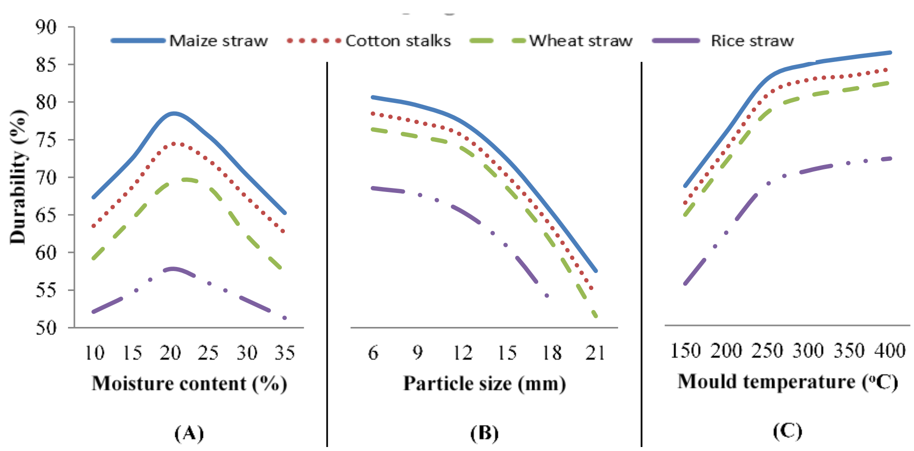

Figure 3. Effect of pretreatments on durability A= moisture content, B= particle size, C= mould temperature.

Figure 4. Preparation of briquettes using piston press briquettes machine.

3 A. All crops exhibited the lowest results of durability against the low and high values i.e., at 10 and 35% level of moisture content. Quality of briquettes for the rice straw briquettes was far lower as compared to other three. Maize straw briquettes showed highest results of durability. The best results of durability were found in middle values i.e. at 15 to 25% moisture content level from all types of crop residue. Secondly, with increase in particle size, durability was decreased for all types of selected briquettes shown in Figure 3 B. Decrease in durability became even faster as the particle size was increased from 12 mm. There was another observation regarding rice straw briquettes which showed no briquettes formation at 21 mm particle size. Thirdly, to check the impact of mould temperature on the quality of briquettes, temperature was varied from 0 to 400°C with 50°C temperature interval. Material was stocked at 0, 50 and 100°C while very low-quality briquettes at 150°C were found. Beyond 150°C, briquettes durability improved up to 300°C at faster rate but there was less variation above 300°C for all crop residues (Fig. 3 C). It shows once the upper surface of briquette is formed, more heat is utilized to penetrate towards the middle of briquettes, but this penetration is a very slow process as compare to traveling speed of briquette and does not have significant impact on strength of briquettes. Figure 4. Preparation of briquettes using piston press briquettes machine.

***Statistical approach to optimization of material properties*:** Keeping in view of results shown in Figure 3 ABC, a statistical analysis was done by selecting three levels of three independent variables including moisture content, particle size and mould temperature as (15, 20 and 25%), (9, 12 and 15 mm) and (200, 250 and 300°C), respectively. Here, dependent variables are durability, density and compression strength. These levels were selected keeping the view that briquettes should be more durable and economical i.e., having high value of physical properties at the low level of input material properties to reduce the cost of grinding, heat electricity cost etc. A statistical design of three factor factorial under CRD (completely randomized design) was used with triplet replicate to check the inter dependency of operational parameters. CRD design was used due to mix nature of sample base and all the experiments were conducted in lab conditions. Average results of all dependent variables for briquettes made from four selected crop residue

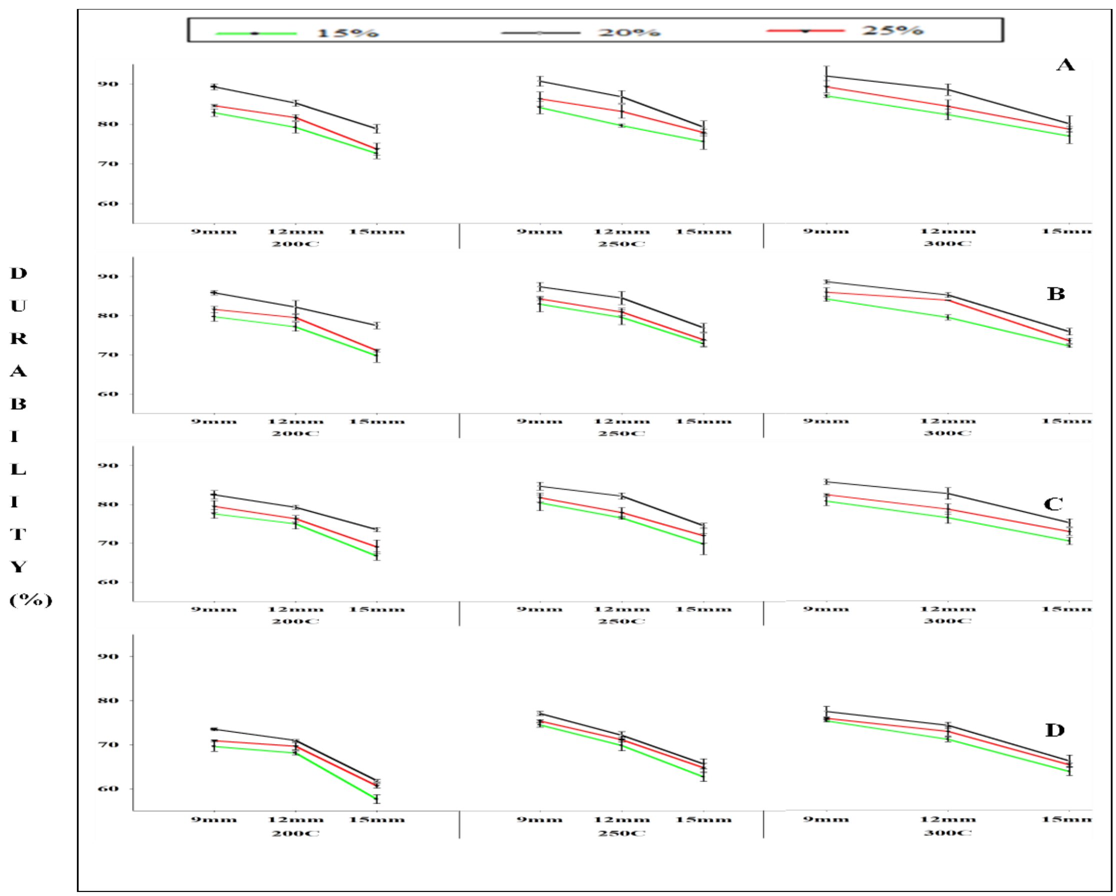

Figure 5. Durability of four selected crop residue briquettes (A= Maize straw, B= Cotton sticks C= Wheat Straw & D= Rice straw).

(wheat straw, cotton stalks, rice straw and maize straw) were drawn using a graphical software "Sigma Plot". Error bars in the form of standard deviation (shown for every individual average point).

Durability of selected crop residue briquettes: Figure 5 shows the inverse relationship with particle size and durability i.e., durability of briquettes made from maize straw, cotton sticks, wheat straw and rice straw were decreased to 12, 12.8, 10.6 and 11.2% as the particle size was increased from 9 mm to 15 mm at mould temperature 300°C and at 20% moisture level. Durability was increased with increase in temperature, but change was less as compare to moisture content variations i.e., durability of briquettes made from maize straw, cotton sticks, wheat straw and rice straw was increased to 2.7, 2.8, 3.3 and 4% as the mould temperature was increased from 200C to 300°C with 9 mm particle and at 20% moisture level. On the other hand, all types of crop residue gave more durable briquettes at 20% moisture content level (middle value) as compare to 15 and 25%, i.e. maize straw briquettes showed 92, 87 and 89.3% durability at 20, 25 and 15%, respectively. From Figure 5 it was also observed that the best durable briquettes were attained from maize straw at all combination points as compared to other type of crop residue. Cotton sticks, wheat straw and rice straw briquettes were at 2nd, 3rd and 4th respective positions. Maximum durability for maize straw (92%), cotton sticks (88.6%), wheat straw (85.7%) and rice straw (77.5%) was optimized at mould temperature 300°C

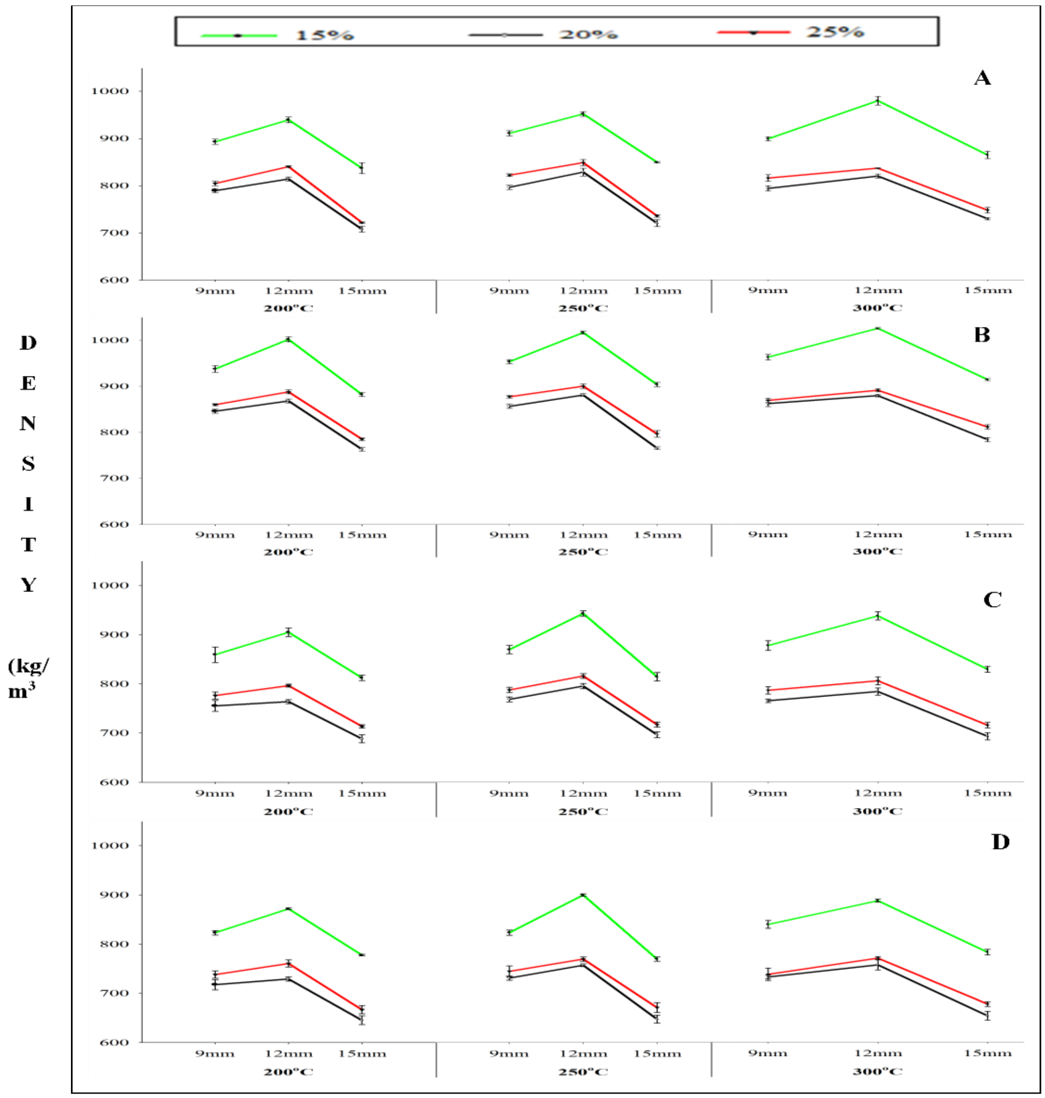

Figure 6. Density of four selected crop residue briquettes (A= Maize straw, B= Cotton sticks C= Wheat Straw & D= Rice straw)

with particle size of 9 mm and 20% moisture level.

Density of selected crop residue briquettes: Considering the density of briquettes, irregular behavior was shown by the briquettes against the change in particle size (Fig. 6). All types of crop residue produce more dense briquettes at 12 mm particle size as compare to 9 mm and 15 mm i.e. maize straw briquettes showed 939.7 kg/m^3, 893.1 kg/m^3 and 837.2 kg/m^3 density at 12 mm, 9 mm and 15 mm respectively at 15% moisture level and 200ºC. It was observed that density of all types was increased in a small amount as the particle size was increased from 9 mm to 12 mm i.e. 46.5 kg/m^3 on the other hand decrease was abrupt 102.5 kg/m^3 as the particle size was increased from 12 mm to 15 mm. Similarly, asymmetrical performance was shown by the briquettes against the change in moisture content. All types of crop residue produced more dense briquettes at lowest moisture content level i.e. 15% as compare to 20 and 25% i.e., maize straw briquettes showed 893.1, 939.7 and 837.2 kg/m^3 at 15, 20 and 25%, respectively. From the Figure 6 it was seen that density was far more at 15% moisture level as compared to 20 and 25%. While, 25% level shows more density as compared to 20% but the difference between 20 and 25% was not significant. In the end change in temperature shows no considerable amount of variation in density i.e., 893.1, 911.1 and 898.7 kg/m^3 at 200, 250 and 300°C, respectively when the particle size was 9 mm and moisture content level was 15% in maize straw briquettes. On an average the best compacted briquettes were attained from cotton sticks at all combination points as compared to other types of crop residue. Maize straw, wheat straw and rice straw briquettes were at 2nd, 3rd and 4th respective positions. Maximum density for cotton sticks (1025.3 kg/m^3), maize straw (979.7 kg/m^3), wheat straw (937.6 kg/m^3) and rice straw (899.7 kg/m^3) was optimized at mould temperature 300°C with

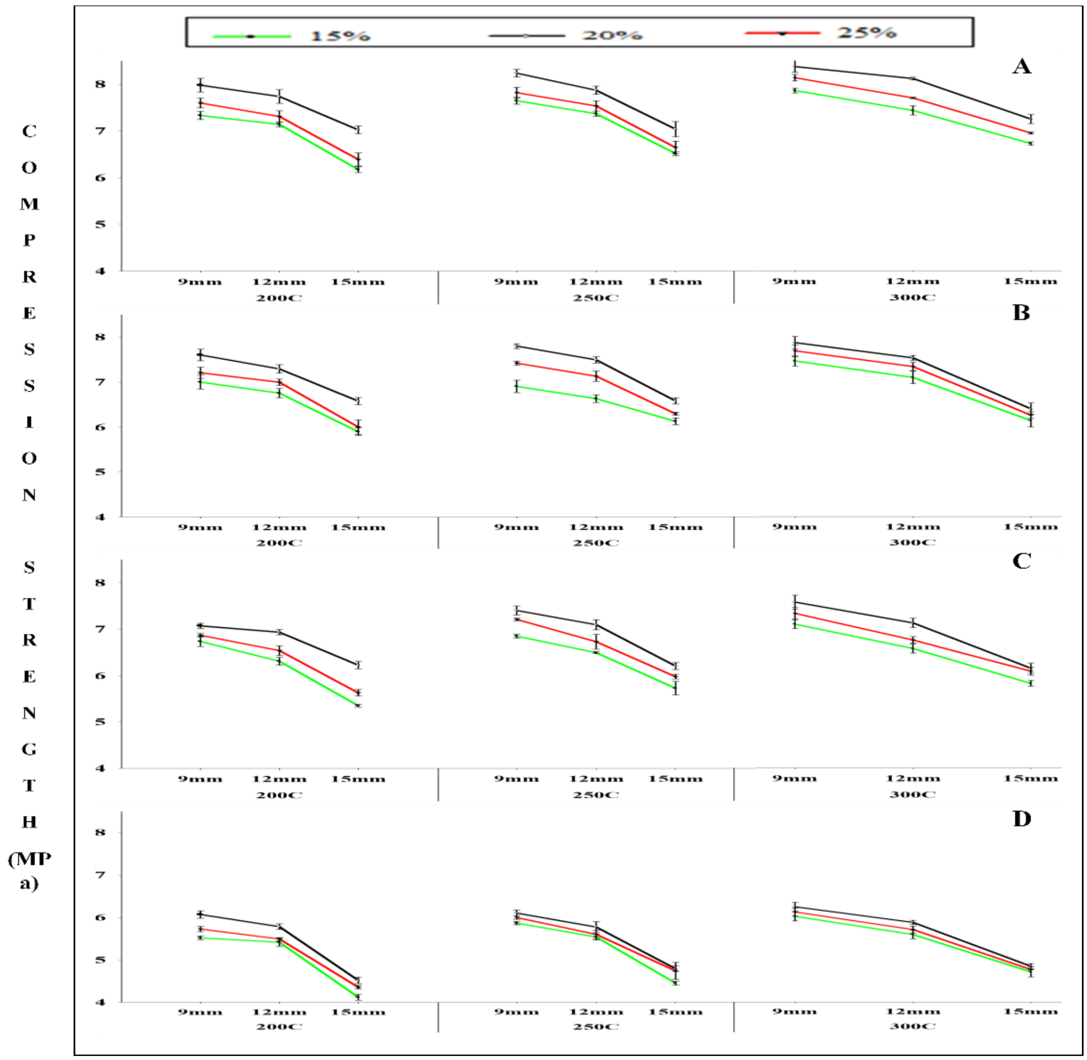

Figure 7. Compression strength of four selected crop residue briquettes (A= Maize straw, B= Cotton sticks C= Wheat Straw & D= Rice straw).

particle size of 12 mm particle size and 15% moisture level.

Compression strength of selected crop residue briquettes: Compression strength showed the inverse relationship with particle size like durability i.e. strength of briquettes made from maize straw, cotton sticks, wheat straw and rice straw were decreased to 1.13, 1.48, 1.43 and 1.41 MPa as the particle size was increased from 9 mm to 15 mm at mould temperature 300°C and at 20% moisture level (Fig. 7). Compression strength was also increased with increase in temperature but change was less as compare to moisture content variations i.e. compressive strength of briquettes made from maize straw, cotton sticks, wheat straw and rice straw was increased to 0.4, 0.27, 0.51 and 0.17 MPa as the mould temperature was increased from 200 to 300°C with 9 mm particle and at 20% moisture level. Irregular behavior was shown by the briquettes against the change in moisture content. All types of crop residue produce higher strength of briquettes at 20% moisture content level as compare to 15 and 25% i.e. maize straw briquettes showed 8.38, 7.86 and 8.13 MPa compressive strength at 20, 25 and 15%, respectively. The highest compressive strength briquettes were attained from maize straw at all combination points as compared to other type of crop residue. Cotton sticks, wheat straw and rice straw briquettes were at 2nd, 3rd and 4th respective positions. Maximum compression strength for maize straw (8.38 MPa), cotton sticks (7.87 MPa), wheat straw (7.58 MPa) and rice straw (6.24 MPa) was optimized at mould temperature 300 °C with particle size of 9 mm and 20% moisture level.

***Calorific value of selected crop residue briquettes*:** Calorific value/higher heating value for any fuel is the most important indicator because it determines the value of a fuel in terms of utilization, feasibility and efficiency (Fig. 8). The calorific value of all four optimal briquettes was determined in multiple experiments i.e., the procedure was repeated on several different briquettes for at least three times to get an average value of calorific value and averaged results are shown in Figure 8. Results of higher heating value in this study ranges from 15.3 – 18.2 MJ/kg for all crop residue briquettes. Maize straw showed highest value (18.2 MJ/Kg) while rice straw showed minimum value i.e., 15.3 MJ/Kg.

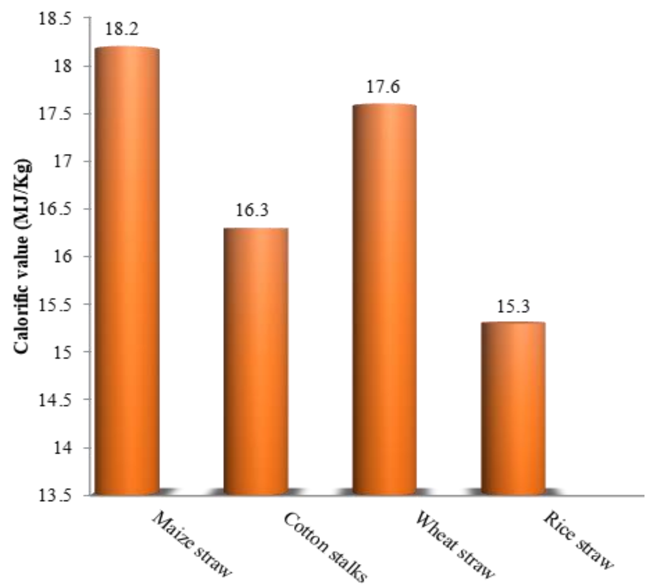

Figure 8. Calorific values for selected crop residue briquettes.

DISCUSSION

Durability and compressive strength showed the similar trend of results against the operational parameters because both qualities are the yard stick for the measurement of the strength of briquettes. While, density showed some anomalies in results which are discussed. Firstly, if we consider durability and compressive strength, it was seen that with increase in particle size both properties were decreased. In a study, Kaliyan and Morey (2006) indicated that fine particles produced good quality briquettes during compaction as they readily absorb moisture than large particles and thus undergo more conditioning. According to Karunanithy *et al*. (2012) in large particles there are more inter particle spaces and fissure points as compared to fine particles. These fissure points and spaces caused the cracks and produce fractures in compactness process. There is also inhomogeneous shrinking in case of large particle size, which would also lead to develop cracks. They suggested 8 mm particle size for good quality briquettes formation using piston press machine which are approximately close to particle size optimized in this study, i.e. 9 mm. Quality may increase for further smaller sized particles, however, to crush the straws at a very small particle size required a huge amount of power in the form of electricity which is not much feasible. Hence, 9 mm particle size was recommended as major outcome of this study. Secondly, durability and compressive strength were increased as the temperature of machine's mould/die was increased. According to Grover and Mishra, (1996) low temperature resulted in increased pressure and power consumption and lower production rate but high temperature assists in smooth operation by producing natural binding material (lignin) that firmly binds the particles together. Here, the increment in quality was very high from 150C to 300°C, but it produces very minute change for the further increment in temperature i.e. above > 300°C. So, we selected 300°C as the lowest acceptable level of temperature that generates the best quality product. Thirdly, durability and compressive strength were increased with increase in moisture content to some extent but further increase in moisture content resulted in declining trend. We found best results from all crop residues at the moisture content level of 20%. According to Erikson (1990) 15% moisture content level was recommended for piston press briquettes machines. Too low moisture content decreases the binding forces among the particle and cracks were produced in briquettes surface. While, too high level of moisture produces the briquettes those were unable to retain their shape and deformed at the time of preparation. The third physical property i.e., density showed the similar behavior against the temperature as was shown by durability and compressive strength (i.e., increased with increment in temperature) but it showed irregular behavior against the moisture content and particle size. Similarly, in a study, Mani *et al*. (2006) analyzed that the density of fuel from corn stove increased with decreasing moisture content. It showed the high density for less moisture content and large particle size because of heavy weight of bigger particles but due to small variation and quality of briquettes it was ignored. Conclusively, from results of the study and above discussion, operational parameters were selected as 20% moisture content, 9 mm particle size and 300°C mould temperature for all crop residues.

Considering the type of crop residue i.e., maize straw, wheat straw, rice straw and cotton sticks showed the similar trend of results for operational parameters against the selected physical properties like durability, density and compressive strength. Comparatively, maize straw residue resulted the highest quality of briquettes following the cotton sticks, wheat straw and rice straw. It was also observed that there was a big difference of quality (durability, density and compressive strength) between the rice straw briquettes to the other three types of briquettes. According to Adapa *et al*. (2003) and Tabil (1996) durability of briquettes is classified in three categories as high = (>80%), medium = (70% - 80%) and low = (<70%). So, three crop residue maize straw, cotton sticks and wheat straw lie in high quality class i.e., >80% of briquettes while rice straw briquettes lie in medium class category i.e., <80%. It was recommended to stack less height of rice briquettes during transportation.

There was not a great difference in calorific value among four i.e., only 2.9 MJ/Kg. That may be due to their similar nature of fuel i.e. crop residue. Calorific value was ranges from 15.3 MJ/Kg (highest for rice straw briquettes) to 18.2 MJ/Kg (lowest for maize straw briquettes). This range lies in the results reported by Gravalos *et al*. (2016) in their study as 14.3 to 25.4 MJ/Kg for a variety of crops and forest residue briquettes. The results of present study indicate that selected crop residue briquettes have a potential to be utilized as alternative energy options.

***Conclusions*:** The best durable, densified and high compressive strength briquettes were found at 20% moisture content, 9mm particle size and 300ºCmould temperature prepared from maize straw, wheat straw, cotton sticks and rice straw residue. Quality of briquettes prepared from maize straw was highest i.e., durability (92%), density (1025.3 kg/m^3), compression strength (8.83 MPa) and calorific value (18.2 MJ/Kg) at optimized level of operational parameters as compare to wheat straw, cotton sticks and rice straw. Rice straw briquettes showed lowest results i.e. durability (77.5%), density (899.7 kg/m^3), compression strength (6.24 MPa) and calorific value (15.3 MJ/Kg) at 20% moisture content, 9mm particle size and 300°C mould temperature. The results from this study show that physical properties of newly formed biomass residue briquettes can be significantly improved by carefully selecting basic parameters of crop residue and machine operation.

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