Investigation of Physical and Thermal Properties of Fuel Briquettes Made of Bagasse

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Biomass densification, which is also known as briquetting of sawdust and other agro residues, has been practiced for many years in several countries. The purpose of the present study was to produce fuel briquettes using heat-dried bagasse and to improve their physical properties and thermal value through using varying proportions of bagasse powder as the filler material and lignin as the natural binder. The results showed that lignin had a significant desirable effect on the entire properties of the prepared briquettes. In contrast, as a cellulose-based filler, bagasse powder was also able to significantly improve the thermal energy of the briquettes through increasing the briquettes' density and mitigating porosity and moisture content. On this basis, according to the obtained results it can be stated that the process of heat-drying, using lignin as the binding element, and using cellulose-based powders, such as bagasse, as the filler are all suitable alternatives to increase the energy yielded by briquettes biomasses.

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INTRODUCTION

Factors contributing to the development of non-renewable biomass energy include rapidly increasing global demand, declining fossil fuels, the negative effects of burning fossil fuels, and greenhouse gas emissions (Akay and Jordan 2011; Wang *et al.* 2017). According to investigations, global carbon emission is already putting the environment in a condition of instability; therefore, the global energy system needs to restrict global climate change before the year 2100 (Garrett-Peltier 2017). On this basis, renewable energies are considered as the main promising alternatives for mitigating the problems associated with the emission of pollutants.

According to Demirbas (2009), sustainable supply and the possibility to reduce the emission of greenhouse gases make biomass fuels the fourth main source of energy after coal, crude oil, and natural gas. Biomass is already supplying 10% of the global energy demand and is the only type of energy that can be substituted for fossil fuels in all fields of energy such as producing heat, electricity, and transportation fuel (Akay and Jordan 2011). Agricultural wastes are globally targeted as a potential source of energy, especially in countries pioneering in agricultural activities (Missagia *et al.* 2011). In general, there are two types of conversion technologies (autothermal (direct) and allothermal (indirect) gasification) that convert raw biomass into chemical materials with added value, fuels, heat, and power (Basu 2010).

However, using raw biomass is usually restricted due to issues such as high moisture content, shape and size irregularity, and low bulk density, which may cause problems in application, storage, transportation, and usage as fuel (Kaliyan and Morey 2009a). These problems can be solved through compression processes, which expand the usage of biomass in energy production. In the process of compression, pressure and heat are used to compress volumes of loose residues into briquettes or cubes of similar shape and dimensions. Compressed fuels have adequate quality, strength, and durability while facilitating subsequent operations such as application, storage, transportation, and feeding (Kaliyan and Morey 2009b).

Briquetting is a type of non-polluting technology that can prevent global warming as well as preserve forests. Briquetting is a high-pressure compression technology used to increase the density of biomass materials to enable for favorable energy production. The main constituents of agricultural waste biomass briquettes include hay, sugar cane bagasse, corn stem, coconut leaves, bran, peanut shells, and rice bran (Sharif *et al.* 2008). Once formed into briquettes, the density of biomass increases up to 900 to 1500 kg/m^3, making it easily usable in conversion and open space heating systems. Under the present circumstances, potential management of wastes can initiate and sustain new fuel commerce for local economies (Tumuluru *et al.* 2010, 2012; Panwar *et al.* 2011).

Mainly there are three types of commercial briquetting systems: 1) screw press; 2) hydraulic (Bramah) press; and 3) rolling press (Felfli *et al.* 2011; Gangil 2015). One difference between the hydraulic and rolling press systems in briquetting machines is that hydraulic presses apply pressure at a specified pressure, whereas screw presses continuously apply pressure. On this basis, hydraulic presses can be suitable options associated with less procedural costs for the production of biomass briquettes. Currently, both of these techniques are used in producing briquettes from biomass materials (Singh *et al.* 2008; Tumuluru *et al.* 2010). To produce high-quality fuels, it is necessary to grasp the binding mechanisms between biomass particles in compressed products. Solid bridges are of crucial importance in biomass materials. Due to the presence of lignin and hemicellulose in biomass compounds, polymers that detach from the cell wall interact with the surrounding particles. The extreme pressure and temperature created in the process of compression soften the lignin and make it flow. Therefore, wettability, intramolecular dispersion, and entanglement of polymer chains in the neighboring fibers are enhanced. This type of binding power is crucial for the strength of the compressed biomass (Stelte *et al.* 2012). Previous studies have shown that procedural variables, such as pressure, mold temperature, and mold geometry, play the most significant roles in the compression of biomass. Moreover, other important procedural variables include moisture content, particle dimensions and shapes, and the composition of materials such as cellulose, hemicellulose, and lignin (Li and Liu 2000; Shaw 2008; Tumuluru *et al.* 2010).

In addition to the mentioned factors, briquettes' quality is significantly affected by the time interval between biomass material feeding points in the compression system and the amount of time required to complete the compression process. Results of the study conducted by Al-Widyan *et al.* (2002) showed varying the processing time between 5 and 20 s does not have any significant effect on the quality and durability of biomass briquettes. In contrast, Li and Liu (2000) reported that the processing time has a much higher effect on the durability of briquettes at low pressures compared to higher pressures. They reported that at pressures above 138 MPa, the effect of processing time becomes negligible.

Processing times of longer than 40 s have negligible effects on the density of biomass briquettes, whereas a processing time of 10 s can result in a 5% increase in the density of briquettes. However, this effect may significantly dissolve for processing times longer than 20 s. In general, depending on a variety of factors including temperature, pressure, flow rate, *etc*., processing time leaves a significant effect on the density of biomass materials (Tumuluru *et al.* 2010).

Many studies have tried to improve the quality of briquettes by modifying the biomass, and one of the most well-known of these pretreatments is the process of roasting. Throughout the process of roasting, biomass materials will be exposed to temperatures between 200 to 300 °C to modify the properties of the biomass material and obtain higher-quality raw material to be used for energy production. This process is described as a form of pyrolysis in which elimination of volatiles is responsible for 80 to 90% of the overall heat-production of the materials while roughly 30% of the primary weight of the materials is lost during the roasting process (Al-Widyan *et al.* 2002). During the roasting process, active lignin zones become accessible, and the hemicellulose matrix decomposes to yield unsaturated compounds having better binding properties (Bates and Ghoniem 2012).

The moisture content of biomass is one of the most important factors effecting the performance of compression processes and energy conversion systems. Considering this, the moisture content of biomass must not exceed 15% (Chandak *et al.* 2015). For certain biomass materials, such as sugar cane bagasse, which is produced from highly moist sources, drying is a highly important phase that allows the use of the biomass as an energy source. Drying and dehumidification is a preprocessing phase required for heat-chemical conversion of biomass such as bagasse to a source of energy (Anukam *et al.* 2016a).

Selecting a proper raw material for energy production purposes depends on a variety of certain criteria such as per hectare potential efficiency, properties of the raw material, and application potentials (Kurian *et al.* 2013). Because sugarcane bagasse is potentially more available than it is used, it has become a target of interest. However, the value of bagasse as a fuel for energy production highly depends on its thermal value, which is in turn dependent on the composition of the used bagasse, its sucrose content, and especially its moisture content (Zafar 2014). A handful of studies have evaluated the pyrolysis behavior and combustion of bagasse, showing that during the pyrolysis process at the first phase, the decomposition of the hemicellulose component involves a rapid mass reduction in the bagasse; however, then lignin starts decomposing at a slower rate (Gani and Naruse 2007). The purpose of the present study was to produce fuel briquettes using heat-dried bagasse and to improve their physical properties and thermal value through using varying proportions of bagasse powder as the filler material and lignin as the natural binder.

EXPERIMENTAL

Materials

Bagasse

The present study used sugar cane bagasse supplied from the city of Ahvaz, Iran to produce sugarcane bagasse briquettes. Chemical compounds in bagasse included: cellulose: 45 to 55%, hemicellulose: 20 to 25%, lignin: 18 to 24%, ash: 1 to 4%, and waxes: < 1%. The length, width and thickness of the bagasse were respectively 15 cm, 4 cm, and 1 cm (Fig. 1).

Fig. 1. Bagasse used in this research

Cellulose filler

In order to improve the heating properties of the briquettes, in the present study cellulose filler material was used as a component in production of the briquettes. The bagasse powder was produced from bagasse using an industrial mill. Bagasse contains about 40 to 50% cellulose and 25 to 35% hemicellulose.

Binding element

In the present study, lignin was used as the binding element. It was prepared using the black liquor (black liquor is the by-product from the kraft process when digesting pulpwood into paper pulp removing lignin, some of the hemicelluloses, and extractives from the wood to free the cellulose).

Methods

Heat-drying the bagasse

In order to heat-dry the bagasse, the vacuum oven in the University of Agriculture and the Natural Resources of Gorgan, Iran was used. To this end, bagasse samples were prepared in 350-g packs and subsequently were placed in the vacuum oven at a temperature of 180 °C degrees for 30 min. Once the samples were cooled and their temperature reached room temperature, the heat-dried bagasse samples were stored in plastic bags.

Preparing Fuel Briquettes

Fuel briquettes were prepared using the handmade device operating in the University of Agriculture and Natural Resources of Gorgan, Iran. The 30-g briquettes were prepared using pure bagasse and heat-dried bagasse. To this end, bagasse powder was used as the cellulose filler to improve the bulk density and calorific properties of the briquettes. It is noteworthy that the filler was added to the pure and heat-dried bagasse samples in three proportions of 10, 15, and 20% of the briquettes' weight. In contrast, to enhance the binding properties between the composing particles of the briquettes, lignin compound was added to the pure and heat-dried bagasse samples in three proportions of 2, 5, and 10% of the briquettes' weight. To produce a briquette, predetermined percentages of materials were first mixed in a container. Then the mixture was poured into the briquetting machine's mold that was preheated before the process. Afterward, the briquettes were produced in six min under the temperature of 150 °C and pressure of 110 bars. Once the briquettes were produced, they were placed in an oven heated to 80 °C for 2 h to prevent them from cracking. Afterward, the samples were placed in zipper packs for further use in tests. It is worthy of mentioning that for each treatment, the samples were prepared in three replications.

Physical Tests

Bulk density

The samples' bulk density values were measured according to the ASAE S269.41991 (R2007) (2013) standard, and the data were used to calculate densities according to Eqs. 1 and 2,

$$V_{\mathrm{p}} = \pi d^2 L \tag{1}$$

$$\rho_{\mathrm{p}} = \frac{m_{\mathrm{p}}}{V_{\mathrm{p}}} \tag{2}$$

where V_{p} is denotes briquette density (cm^3), ρ_{p} denotes briquette density (g/cm^3), m_{p} denotes briquette mass (g), d denotes briquette diameter (cm), and L denotes briquette length (cm).

Mechanical Tests

Compressive strength

The compressive strength of briquettes was determined using a universal testing machine (INSTRON 3382) with a load cell capacity of 50 kN and a cross-head speed was 1mm/min in accordance with ASTM D2166-85.

Gross Calorific Value

Converting bagasse or any other biomass material in the presence of excess oxygen releases energy in the form of heat, and this is known as the thermal value or calorific value, which is usually measured using a calorimeter (Wazeer 2017). In the present study, the calorific value of the prepared briquettes was measured according to the ASTM E711-87 (2012) standard. It is noteworthy to mention that the calorific value of the prepared briquettes was measured using an Oxygen-Bomb calorimeter (6100 Compensated calorimeter; Parr Instrument Company, Moline, IL, USA) with a bowl pressure of 3000 kPa.

Ash Content

To this end, 2 g of each sample were placed in a furnace at a temperature of 575 ± 25 °C for 3 h. The ash test result is expressed as % ash. A magnified optical examination of the ash residue is performed to determine if the ash is glass, mineral, or a combination of both. The total ash content equals the weight of the ash divided by the weight of the original sample multiplied by 100%.

Percentage of Volatiles

To this end, 1 g of dry material was placed in a furnace at the temperature of 950 ± 20 °C for 7 min according to the ASTM method D3175-11. The amount of volatiles in the briquettes was calculated through the following formula:

$$\text{Volatiles\%} = ((\text{Primary weight} - \text{ash weight}) / \text{primary weight}) \times 100 \qquad (2)$$

Fixed Carbon

Fixed carbon is referred to as the combustible solid remaining of material after the extraction of volatiles. This property was calculated through the following formula:

$$\text{Fixed Carbon} = 100\% - (\text{Ash\%} + \text{Volatiles\%} + \text{Moisture\%}) \qquad (3)$$

Final Composition of the Treatments

Table 1 shows the final treatment compositions.

Table 1. The Final Compositions of the Treatments

No.	Treatments	No.	Treatments
1	Bagasse	17	Heat-dried bagasse
2	Bagasse + 2% lignin	18	Heat-dried bagasse + 2% lignin
3	Bagasse + 5% lignin	19	Heat-dried bagasse + 5% lignin
4	Bagasse + 10% lignin	20	Heat-dried bagasse + 10% lignin
5	Bagasse + 10% bagasse powder	21	Heat-dried bagasse + 10% bagasse powder
6	Bagasse + 10% bagasse powder + 2% lignin	22	Heat-dried bagasse + 10% bagasse powder + 2% lignin
7	Bagasse + 10% bagasse powder + 5% lignin	23	Heat-dried bagasse + 10% bagasse powder + 5% lignin
8	Bagasse + 10% bagasse powder + 10% lignin	24	Heat-dried bagasse + 10% bagasse powder + 10% lignin
9	Bagasse + 15% bagasse powder	25	Heat-dried bagasse + 15% bagasse powder
10	Bagasse + 15% bagasse powder + 2% lignin	26	Heat-dried bagasse + 15% bagasse powder + 2% lignin
11	Bagasse + 15% bagasse powder + 5% lignin	27	Heat-dried bagasse + 15% bagasse powder + 5% lignin
12	Bagasse + 15% bagasse powder + 10% lignin	28	Heat-dried bagasse + 15% bagasse powder + 10% lignin
13	Bagasse + 20% bagasse powder	29	Heat-dried bagasse + 20% bagasse powder
14	Bagasse + 20% bagasse powder + 2% lignin	30	Heat-dried bagasse + 20% bagasse powder + 2% lignin
15	Bagasse + 20% bagasse powder + 5% lignin	31	Heat-dried bagasse + 20% bagasse powder + 5% lignin
16	Bagasse + 20% bagasse powder + 10% lignin	32	Heat-dried bagasse + 20% bagasse powder + 10% lignin

Statistical Analyses

Evaluating the significance of average values obtained in the present study was completed using the Duncan test (95% confidence). To this end, the SPSS 16.0 software (SPSS, Chicago, IL, USA) was used. In this test, the effects of the above mentioned 32 different treatments (bagasse, heat-dried bagasse, bagasse combined with bagasse powder and lignin in three different proportions, and heat-dried bagasse combined with bagasse powder and lignin in three different proportions) were recorded and compared against a control sample.

RESULTS AND DISCUSSION

Physical Tests

Bulk density: Heat-dried bagasse vs. pure bagasse

Figure 2 shows the changes in the density of briquettes made out of bagasse and heat-dried bagasse mixed with varying amounts of bagasse powder and lignin. Results of statistical analysis (Table 1) show that the differences between the treatments were significant.

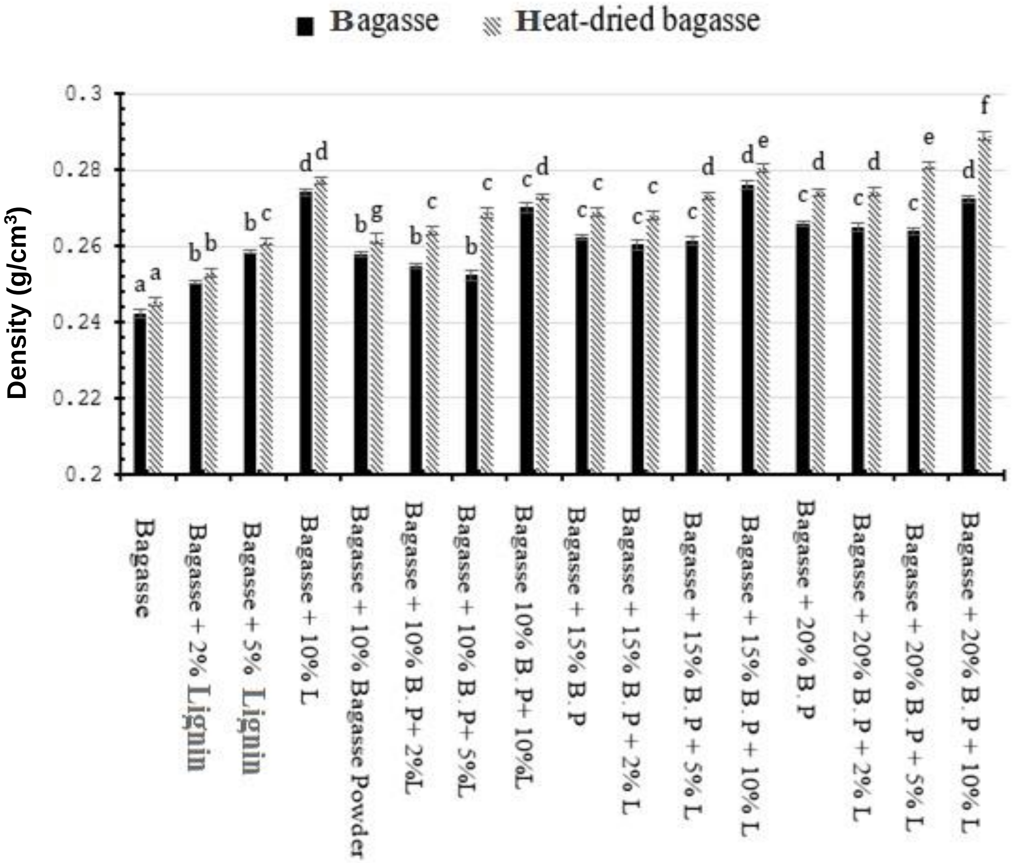

Fig. 2. Density changes in briquettes made out of bagasse and heat-dried bagasse (letters on each column indicate Duncan's grouping at the 99% level of confidence)

Table 2. Variance Analysis Pointing to Density Differences Between Different Briquettes

	Sum of Squares	df	Average Squares	F-value	Sig.
Intergroup	0.011	31	0.000	36.0679	0.000
Intragroup	0.000	64	0.000		
Total	0.011	95			

As shown in Fig. 2, roughly in all treatments involving heat-dried bagasse, the bulk density of the produced briquettes was higher. During the roasting phase, active lignin sites become accessible, and the hemicellulose matrix decomposes to form unsaturated compounds with better binding properties. This results in increased binding, and subsequently increases the density of the yielded briquettes (Wei *et al.* 2013). While investigating the effect of lignin on the bulk density of the briquettes, it was observed that for both types of used bagasse, as the percentage of added lignin increased from 0 to 10%, the bulk density of the produced briquettes increased significantly; this was also verified by the results of statistical analysis. In the present study, lignin was used as a binding element. Results showed that lignin is a suitable binder, resulting in increased density of the produced briquettes (Yank *et al.* 2016; Olugbade *et al.* 2019). The results of the present study were consistent with the findings of many other scholars including Muazu and Stegemann (2015). They reporting that increased lignin presence as the binding element results in increased bulk density of the resulting briquettes. In contrast, statistical findings have revealed that the presence of bagasse powder as the filler material in the construct of briquettes had significant effects on the briquettes’ bulk density. This finding was irrespective of the type of bagasse (pure and heat-dried). Thus, increased amount of bagasse powder will result in higher bulk density; however, the increase in heat-dried bagasse is more significant compared to normal bagasse. Moreover, milling causes some of the lignin material to decompose while also expanding the specific surface area and improving the particles’ binding properties. This increases the number of contact points that interconnect the particles through the process of compression, ultimately yielding higher-density briquettes (Anukam *et al.* 2014).

Moisture Content

Heat-dried bagasse vs. pure bagasse

Figure 3 illustrates the changes in different briquettes. As shown, the roasting process had a significant effect on the final moisture content of the prepared briquettes in a way that, the results of statistical analyses show that in almost all treatments, the moisture content of the briquettes made out of heat-dried bagasse was significantly lower than that of the briquettes made of pure bagasse (Table 3). During the process of roasting, the moisture content of the bagasse samples descended to values as low as 1%, which represents a roughly 3% difference relative to pure bagasse, which was a significant initial difference. In contrast, throughout the process of roasting at temperatures as high as 160 °C, thermal condensation involves certain chemical reactions. The hemicellulose content of the biomass is strongly affected by decomposition reactions that occur during roasting; therefore, it is clear that by preserving the cellulose and lignin, which is equal to preserving the majority of the energy of biomass, one can mitigate the wettability properties (Anukam *et al.* 2016b). These two reasons can account for the difference in the moisture content of briquettes made out of heat-dried bagasse and pure bagasse. Investigating the effect of lignin amount on the final moisture content of prepared briquettes showed that irrespective of the used bagasse type, as the amount of lignin increased the final moisture content of the briquettes increased as well in a way that, for briquettes made out of normal/pure bagasse a 10% increase in lignin amount caused the moisture content to leap from 4.4% to 5.6%; while for briquettes made out of heat-dried bagasse, an identical increase in the lignin amount caused a leap in moisture content from 3.3% to 4.8%. The results of this section of the present study are consistent with findings obtained by Kaliyan and Morey (2009a). Furthermore, Muazu and Stegemann (2015) reported that the increased presence of binders in the structure of briquettes results in increased porosity and moisture content. Figure 3 shows that adding 10% of bagasse powder to the construct of the briquettes as the filler material increased moisture content by 1%; however, increasing the amount of bagasse powder beyond this point did not result in any significant moisture content change. The reason for this observation can be bound to the fineness of the particles, which causes them to fill in the pores of the briquettes, thus decreasing their water-wettability.

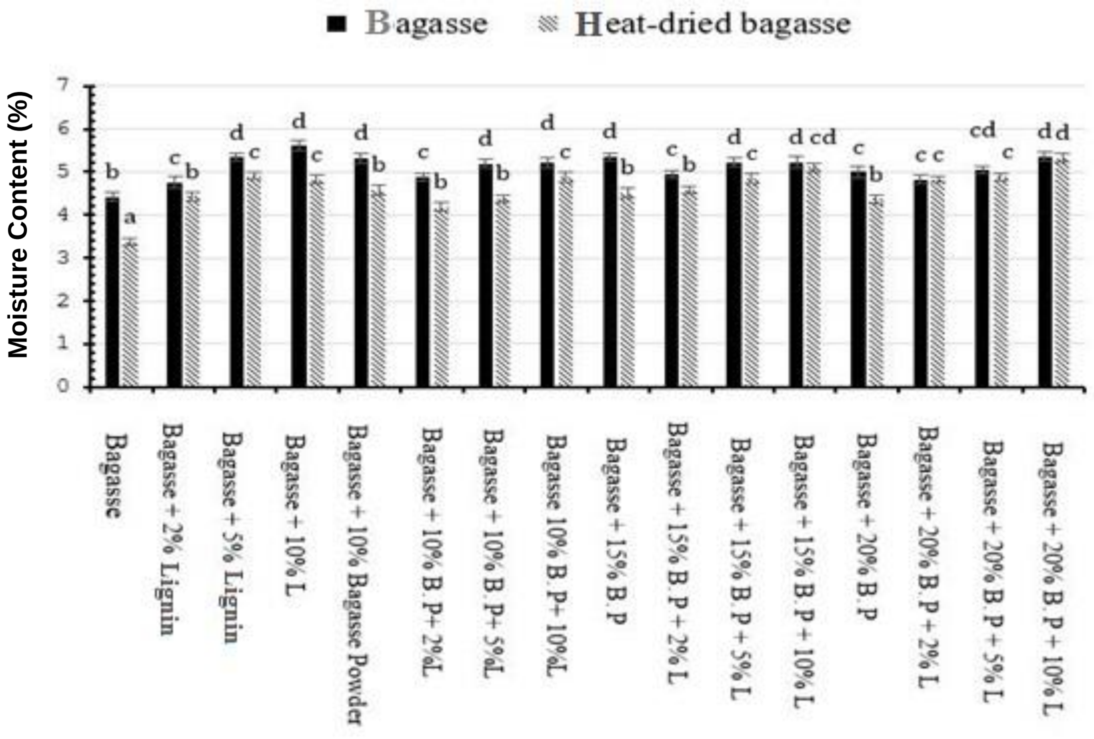

Fig. 3. Moisture content (%) of briquettes made out of bagasse and heat-dried bagasse (letters on each column indicate Duncan's grouping at the 99% level of confidence)

Table 3. Variance Analysis Pointing to Moisture Content Differences Between Different Briquettes

	Sum of Squares	df	Average Squares	F-value	Sig.
Intergroup	30.636	31	0.988	95.388	0.000
Intragroup	0.663	64	0.010		
Total	31.299	95			

Mechanical Tests

Compressive strength (%)- Heat-dried bagasse vs. pure bagasse

Figure 4 displays the results of comparing the compressive strength of briquettes made of heat-dried bagasse against that of briquettes made of the default (normal) bagasse. A glance at this figure makes it clear that the compressive strength of briquettes made out of normal bagasse under all treatments was higher than the compressive strength recorded for heat-dried bagasse. During roasting, the biomass loses its hardness due to the collapse of the hemicellulose matrix and depolarization, which results in a decrease in the length of fibers (Anukam *et al.* 2016a). In contrast, considering that during roasting, a significant number of OH groups present in the fibrous structure of bagasse get eliminated, resulting in a decrease in the number of bindings between the constituent particles. These two events, namely the shortening of cellulose chains and loss of ability to create hydrogen bonds, result in a decrease in the overall compressive strength of briquettes. Investigating the performance/efficiency of lignin as a binding element in the construct of briquettes concludes with results of statistical analyses, as shown in Table 4. It is apparent that the difference caused due to different lignin amounts was significant. Figure 4 shows that irrespective of the used bagasse type, as the percentage of lignin was increased, a subsequent increase was recorded in compressive strength in a way that, for briquettes made of normal bagasse, adding 2, 5, and 10% of lignin resulted in respectively 490, 540, and 590 KN/m^2 values for compressive strength. In contrast, for briquettes made of heat-dried bagasse, adding the same amount of lignin respectively resulted in 250, 360, and 460 KN/m^2 compressive strength values.

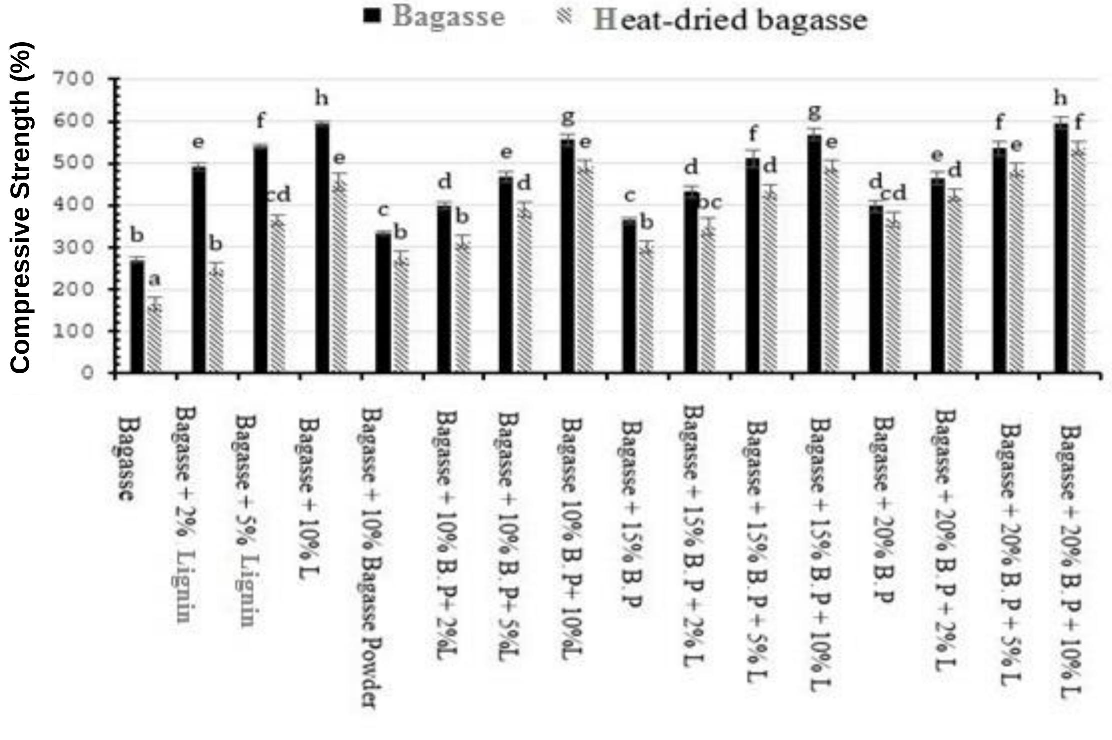

Fig. 4. Compressive strength of briquettes made out of bagasse and heat-dried bagasse (letters on each column indicate Duncan's grouping at the 99% level of confidence)

Table 4. Variance Analysis Pointing to Compressive Strength Differences Between Different Briquettes

	Sum of Squares	df	Average Squares	F-value	Sig.
Intergroup	1638553.948	31	52856.579	200.597	0.000
Intragroup	16863.784	64	263.497		
Total	1655417.732	95			

Results show that the effect on compressive strength left by lignin as a binding element is more desirable for proportions of 2 and 5% for normal bagasse; however, for the proportion of 10%, the effect was the same for both bagasse types. Lignin is an aromatic polymer lacking any crystal structure or any fixed melting point that starts to soften, melt, and liquefy at high temperatures. This plastic transformation in lignin accompanied by applying pressure causes the lignin and cellulose to bind and solidify (Sharif *et al.* 2008; Olugbade *et al.* 2019). Therefore, increasing the number of binding points within the fibrous structure of briquettes results in increased overall compressive strength.

Yet another variable in the present study was using bagasse powder as a filler material. In Fig. 4 it can be seen that using bagasse powder as a filler material in the formulation of briquettes significantly increased the overall compressive strength of the final briquettes. For briquettes made out of normal bagasse, adding 10% of bagasse powder caused a leap in compressive strength from 270 to 333 KN/m^2, showing a 63-unit increase. This was while adding 15% of bagasse powder did not result in significantly different results; however, adding 20% of bagasse powder further increased the compressive strength to 397 KN/m^2. The increase in compressive strength caused by bagasse powder can be on the one hand associated with increased available OH groups, which in turn results in more binding points, or on the other hand, associated with reduced porosity of briquette structure that in turn results in increased density. Results of statistical analyses showed that the increase in compressive strength achieved by adding bagasse powder to briquettes made of heat-dried bagasse was significantly higher than in briquettes made of normal bagasse. This finding can be attributed to an increase of OH groups, which in turn, results in more binding points in briquettes made of heat-dried bagasse against briquettes made of normal bagasse. In briquettes made of normal bagasse, a portion of the lignin was involved with bagasse production while another portion was engaged with the bagasse powder, while in briquettes made of heat-dried bagasse, a large portion of the added lignin engaged with the bagasse powder present in the composition of the briquette.

Calorific Value

Heat-dried bagasse vs. pure bagasse

The findings regarding the calorific value of the briquettes that are the most important characters are shown in Fig. 5. The results of statistical analyses, as shown in Table 5, indicate a significant difference in the calorific value of different briquettes. Figure 5 shows that for all treatments, the briquettes made of heat-dried bagasse had higher calorific values compared to briquettes made of normal bagasse. During the process of roasting, the formation of H_2O, CO, and CO_2 depleted the N_2 and H_2 content of the fibrous structure of bagasse, resultantly elevating the C content of heat-dried bagasse’s fibers against normal bagasse. Because a briquette’s calorific value is directly related to the carbon content of the fibrous structure of its constituent fibers, the calorific value, carbon content, and O_2 and H_2 number of briquettes made of heat-dried bagasse will be significantly higher than in briquettes made of normal bagasse (Tumuluru *et al.* 2010; Anukam *et al.* 2016a,b).

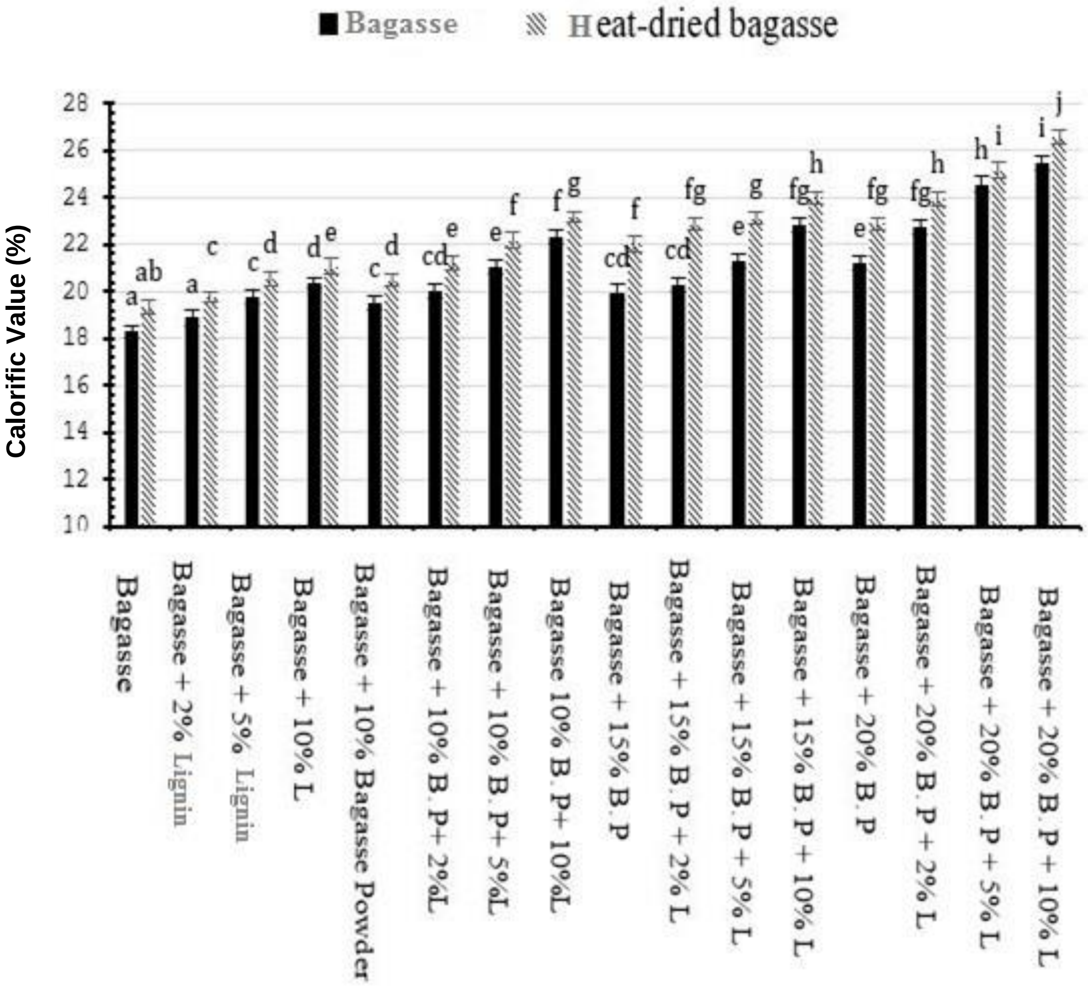

Fig. 5. Calorific value of briquettes made out of bagasse and heat-dried bagasse (letters on each column indicate Duncan's grouping at the 99% level of confidence)

Table 5. Variance Analysis Pointing to Calorific Value Differences Between Different Briquettes

	df	Sig.
Intergroup	31	0.000
Intragroup	64	0.000
Total	95	0.000

Investigating the effect of lignin on briquettes' calorific value revealed that as the percentage of lignin in the fibrous structure of the briquettes increased, the calorific value of briquettes made of both heat-dried and normal bagasse increased proportionally. In general, different studies report that binders increase briquettes' calorific value by increasing their density (Tamilvanan 2013). Results of statistical analyses show that the effect of lignin was almost similar for both types of briquettes, and as the lignin content increased, thermal value increased too. In addition to the positive effect of lignin on density, this increase can also be associated with the relatively high calorific value of lignin itself compared to cellulose and hemicellulose (Patil and Deshannavar 2017).

Figure 5 shows that using bagasse powder as a filler material was significantly effective relative to the calorific value of the final briquettes. As shown by the results, using 10, 15, and 20% of bagasse powder in briquettes made of normal bagasse, respectively resulted in 1.19, 1.66, and 3.56 MJ/kg increases in calorific value; whereas, adding the same amounts of bagasse powder to briquettes made of heat-dried bagasse led to respectively 1.16, 2.70, and 2.90 MJ/kg increases in calorific value. Therefore, it can be stated that the efficiency of bagasse powder in increasing the calorific value was much higher in briquettes made of heat-dried bagasse compared to ones made of normal bagasse. A briquette's calorific value is closely related to its density. Because bagasse powder particles are much finer than bagasse fibers and can fill the pores in the structure of briquettes, they effectively increase the briquettes' density. Moreover, in heat-dried bagasse, the lignin content is higher than cellulose and hemicellulose contents and resultantly the carbon content will be higher as well. All these characteristics coupled with each other will further increase the calorific value of briquettes made of heat-dried bagasse in a way that, concerning Fig. 5, the highest recorded calorific value of 26.6 MJ/kg pertains to the briquettes made of heat-dried bagasse and contained 20% bagasse powder and 10% lignin.

Ash Content

Heat-dried bagasse vs. pure bagasse

Figure 6 depicts the findings on the ash content of prepared briquettes. As shown in Table 6, the results of the statistical analyses showed that the difference in ash content of different briquettes was significant. As shown in Fig. 6, the ash content difference between briquettes made of heat-dried and normal bagasse was relatively high in a way that, for pure briquettes lacking additives, the ash content of briquettes made of normal bagasse was about 1% lower than briquettes made of heat-dried bagasse. In the roasting process, as the process temperature rises, the amount of ash will rise too, which is due to mass reduction at the time of the temperature increase. This leads to the accumulation of high densities of metallic elements. High ash content in biomass materials is usually associated with a high density of metallic elements in the biomass, and similarly, the density of mineral elements is also affected by thermal treatment of biomass (Xue *et al.* 2014). In the briquetting industry, ash content is an unwanted property because ashes will contain high amounts of unburned carbon, which not only bears disposal problems and emits additional pollutants, but also may trigger certain technical challenges such as accumulation, sedimentation, and surplus occurrence (Srivastava *et al.* 2006; Batra *et al.* 2008). Results show that adding lignin to briquettes' composition as a binding material also increases the ash content, and the increasing trend keeps consistent as more lignin is added. In fact, with a 10% addition of lignin to the composition, the ash content of normal and heat-dried bagasse samples increased 2.51 and 2.12%, respectively. Some studies report that among the main constituents of fibers, which are cellulose, hemicellulose, and lignin, lignin contains the highest ash content, and this could be the reason why the ash content was higher in briquettes containing lignin binders (Stefanidis *et al.* 2014; Zhao *et al.* 2017). In contrast, throughout the roasting process, the amount of lignin present in the fibers increases as a result of the depletion of cellulose and hemicellulose content of the fibers, which itself can be yet another reason for the high ash content of briquettes made of heat-dried bagasse, compared to ones made of normal bagasse. In Fig. 6 it can be seen that compared to the effect of lignin; bagasse powder has a way less significant effect on the ash content of briquettes. The results of statistical analyses show that adding 10% of bagasse powder did not leave any significant effect on the ash content of briquettes; however, adding 15 and 20% of bagasse powder did have a significant positive effect on the ash content of briquettes irrespective of their type. Based on the results, the highest ash content was recorded as 8.34% and was associated with the briquettes made of heat-dried bagasse and containing 20% of bagasse powder and 10% of lignin. Some studies report that an ash content higher than 6% of the total weight of biomass is not desirable, restricting its applicability, especially for gas production (Anukam *et al.* 2015). Therefore, this property can cause limitations on the use of lignin in briquetting as a binding element.

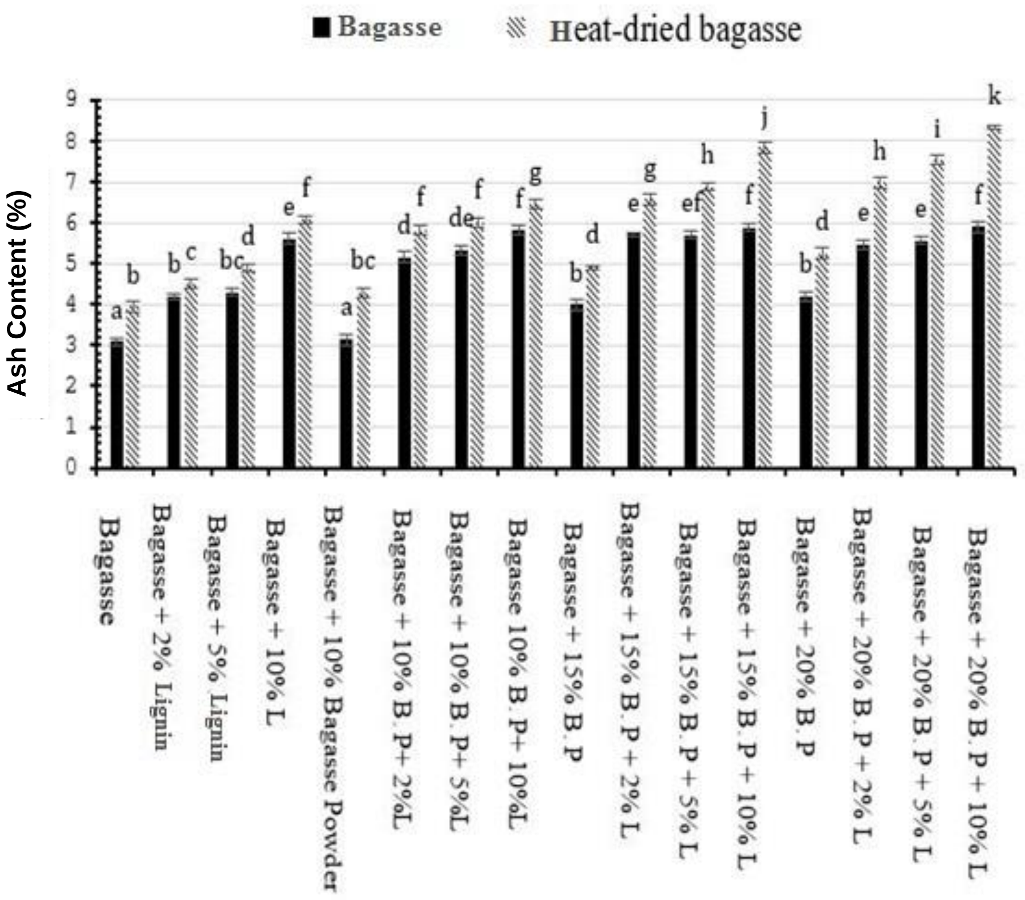

Fig. 6. Ash content of briquettes made out of bagasse and heat-dried bagasse in the face of different treatments (letters on each column indicate Duncan's grouping at the 99% level of confidence)

Table 6. Variance Analysis Pointing to Ash Content Differences Between Different Briquettes

	df	Sig.
Intergroup	31	0.000
Intragroup	64	0.000
Total	95	0.000

Volatile Matter Content

Heat-dried bagasse vs. pure bagasse

Figure 7 illustrates the amount of volatile content present in the prepared briquettes. As can be seen, the volatile matter content of briquettes varied, while statistical analyses have shown that these variations are statistically significant (Table 7). In Fig. 6 it can be seen that roasting reduced the volatile matter content of the briquettes in a way that, for briquettes made of heat-dried bagasse the volatile matter content was 12% lower than of the briquettes made of normal/pure bagasse. During the process of roasting, amounts of H_2 and O_2 present in the biomass were decreased significantly as a result of the formation of H_2O vapor. This reduction results in less smoke and steam formation, which ultimately reduces the volatile matter content of briquettes (Tumuluru *et al.* 2010).

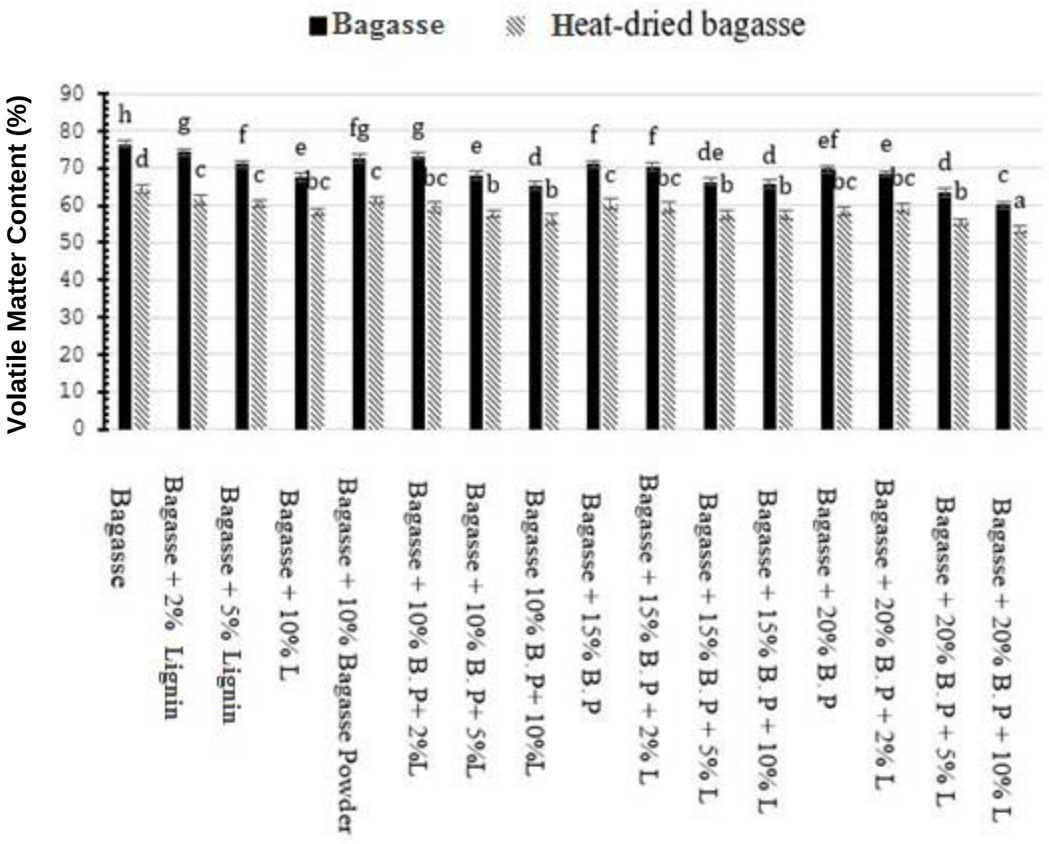

Fig. 7. Volatile matter content of briquettes made out of bagasse and heat-dried bagasse (letters on each column indicate Duncan's grouping at the 99% level of confidence)

Table 7. Variance Analysis Pointing to Volatile Matter Content Differences Between Different Briquettes

	df	Sig.
Intergroup	31	0.000
Intragroup	64	0.000
Total	95	0.000

Investigating the effect of lignin on volatile matter content shows that for briquettes made of normal bagasse, as the lignin content increased, the volatile matter content decreased; however, for heat-dried bagasse lignin did not leave any statistically significant effect on volatile matter content. One reason for this observation can be bound to the reduction of bagasse content of briquettes as a result of the substitution of lignin with bagasse. Some studies report that the presence of lignin as a binder material can reduce the briquettes' volatile matter content, and subsequently it can reduce the emission of pollutants through mitigating the sulfur content by chemical bonding process (Kim *et al.* 2002; Wang *et al.* 2017). Figure 7 shows that adding bagasse powder as the filler material had a tiny effect on the volatile matter content of the briquettes, reducing it slightly. Fillers reduced the volatile matter content of briquettes by reducing the porosity of briquettes which itself resulted in lower moisture content.

Fixed Carbon Content

Heat-dried bagasse vs. pure bagasse

Figure 8 shows the fixed carbon content of the briquettes. Based on the results, the fixed carbon content of the briquettes made of heat-dried bagasse was significantly higher than in briquettes made of normal bagasse. Through the process of briquetting, the moisture content of bagasse was reduced significantly, which resulted in briquettes with low moisture content as well. In contrast, as it was explained above regarding volatile matter content, during the process of roasting CO_2, CO, and H_2O gases are depleted and so the amounts of O and H atoms present in the fibrous structure of bagasse decrease.

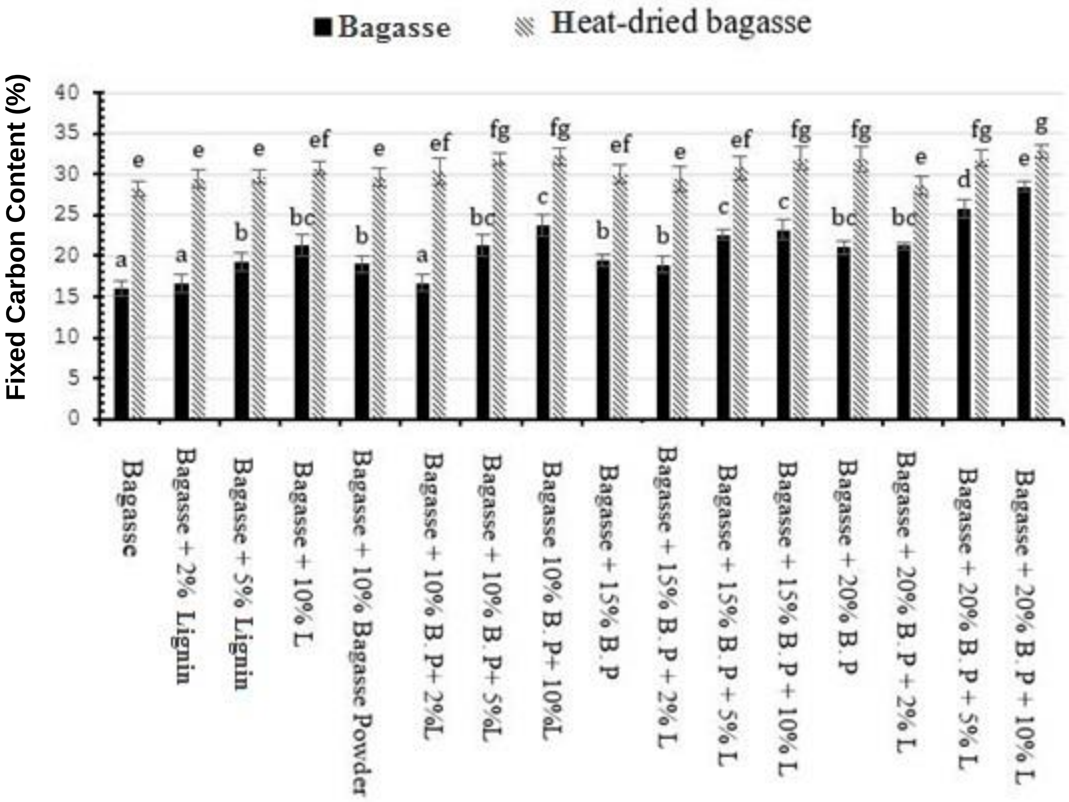

Fig. 8. Fixed carbon content of briquettes made out of bagasse and heat-dried bagasse (letters on each column indicate Duncan's grouping at the 99% level of confidence)

Table 8. Variance Analysis Pointing to Fixed Carbon Content Differences Between Different Briquettes

	df	Sig.
Intergroup	31	0.000
Intragroup	64	0.000
Total	95	0.000

Because of these events, the amount of carbon was higher in heat-dried biomass compared to normal, and so the briquettes made of heat-dried biomass contained higher fixed carbon content. The presence of lignin in the fibrous structure of the briquettes significantly reduced the moisture content (Fig. 3) and also strongly affects the volatile matter content of the briquettes (Fig. 5). Because the fixed carbon content measure was obtained by subtracting the moisture content, volatile matter content, and ash content from 100, any reduction in the amount of each of these elements results in a corresponding increase in the fixed carbon content (Anukam *et al.* 2015). Because this effectiveness was higher in briquettes made of heat-dried bagasse than in ones made of normal bagasse, the variations in the fixed carbon content of briquettes made of normal bagasse was higher than of briquettes made of heat-dried bagasse. Therefore, concerning the significant effects of heat-drying and lignin and bagasse powder addition on the fixed carbon content, it was concluded that the highest recorded fixed carbon content of 32.9% was associated with briquettes made of heat-dried bagasse and contained 20% bagasse powder and 10% lignin.

Ignition Time

Heat-dried bagasse vs. pure bagasse

Ignitability is an important property when making fuel briquettes out of biomass. Ignition times of briquettes made of different materials are reported in Fig. 9. Compared to briquette size, the effects of other variables were smaller, but still statistically significant. In Fig. 9, it is shown that roasting harmed the ignitability of bagasse in a way that, for all treatments, the briquettes made of heat-dried bagasse ignited after a long time compared to briquettes made of normal bagasse. This may be due to the volatile matter content of the briquettes. The most important factor affecting ignitability is the volatile matter content, and because during the roasting phase the volatile matter content of the biomass drops significantly, briquettes made of these compositions will have lower ignitability than those made of normal bagasse (Anukam *et al.* 2016b). While investigating the effect of lignin on the ignition time of briquettes, it was revealed that as the lignin amount increased, the ignition time of the briquettes increased as well; however, this increase was slight, causing the briquettes under study to fall under the same statistical category. While investigating the effect of bagasse powder on the ignitability of briquettes irrespective of their type, it was seen that similar to the effect of lignin, as the bagasse powder increased, the ignitability of the briquettes increased as well; however, this effect too was statistically insignificant, causing the briquettes under study to fall under the same statistical category. In general, because the volatile matter content of the briquettes decreased as a result of the presence of lignin and bagasse powder (Fig. 9), the ignition time of the briquettes increased. The sum of slight effects left by roasting, addition of lignin, and addition of bagasse powder made the briquettes made of heat-dried bagasse ignite roughly 250 s later than briquettes made of pure bagasse. This period was almost 1 min longer than for briquettes made of normal bagasse without any added binder or filler.

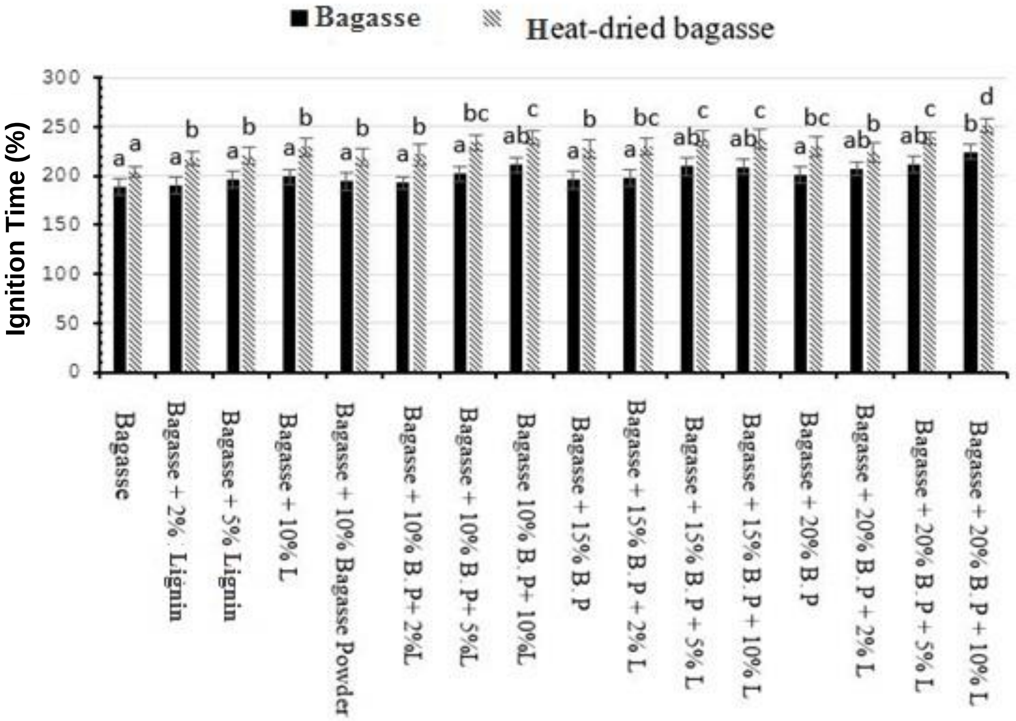

Fig. 9. Ignition time of briquettes made out of bagasse and heat-dried bagasse (letters on each column indicate Duncan's grouping at the 99% level of confidence)

Table 9. Variance Analysis Pointing to Ignition Time Differences Between Different Briquettes

	df	Sig.
Intergroup	31	0.000
Intragroup	64	0.000
Total	95	0.000

CONCLUSIONS

1. The moisture was lower in the case of briquettes that contained dried bagasse. Volatile content of the briquettes also was decreased.
2. With regard to the use of lignin as a natural binder for better formation of briquettes and also leaving positive effects on the volatile matter content and calorific value, results showed that the natural binder used in this study could leave a significant desirable effect on all the properties of prepared briquettes.
3. As a cellulose filler, bagasse powder was able to increase the density of the briquettes while also reducing their porosity and moisture content, which significantly increased the calorific value of the briquettes. The obtained results showed that the process of heat-drying, using lignin as a natural binder, and using cellulose powders, such as bagasse powder, as the filler material could be efficient ways to promote the output energy of biomass briquettes.

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