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Briquettes from maize cobs and *Ceiba pentandra* at room temperature and low compacting pressure without a binder

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Abstract

This paper reports the findings of densifying ground maize cobs and *Ceiba pentandra* sawdust at room temperature using low compacting pressure without a binder. The maize cobs were crushed using a hammer mill. Particle sizes of maize cobs and *C. pentandra* used for the study were ≤1 mm. The two materials were combined at mixing percentages of 90:10, 70:30 and 50:50 (*C. pentandra*/maize cobs). Briquettes were produced using a laboratory hydraulic press. Compacting pressure was varied from 20 to 50 MPa at an interval of 10 MPa. The results indicated that the relaxed density of briquettes produced from particles of maize cobs only ranged from 541 to 659 kg/m^3 whilst that made from a mixture of maize cobs and *C. pentandra* ranged from 565 to 774 kg/m^3. Compressive strength in cleft of briquettes produced from maize cobs only ranged from 0.12 to 0.54 N/mm whilst that produced from a combination of maize cobs and *C. pentandra* ranged from 7.72 to 59.22 N/mm. Additionally, at all compacting pressure levels, briquettes made from maize cobs only had an impact resistance index of 0%. Whilst those made from a combination of maize cobs and *C. pentandra* ranged from 115% to 500%. Thus, briquettes with adequate physical and mechanical characteristics could be produced from maize cobs at room temperature using low compacting pressure when maize cobs are combined with sawdust of *C. pentandra*. These findings could enhance the existing technology for densifying agricultural residues, for example, maize cobs, especially in rural communities.

Keywords: Briquettes; *Ceiba pentandra*; Compressive strength; Impact resistance index; Maize cobs; Relaxed density

Background

The solution to the current and future energy needs of Ghana requires diversifying the energy sources. Previous studies suggested that energy production methods should be best matched with the available natural resources in the region [1]. Ghana is an agricultural country and has an estimated workforce of over 60% employed by the agricultural sector [2]. This culminates into the cultivation of various crops such as millet, rice, maize, sugar cane and cocoa by farmers. This leads to the generation of large volumes of agricultural crop residues such as maize cobs, rice husk, millet stalks, baggasse and cocoa bean shells as presented in Table 1. These agricultural residues normally obtained from field and processing sites are often left to rot or burnt inefficiently in their loose form causing air pollution [3].

As shown in Table 1, by the end of the year 2010, about 1,872,000 tonnes of maize residue was generated in Ghana. This constitutes about 41% of the total agricultural crop residues generated. Maize cob, a residue of the maize crop, is a lignocellulosic biomass material which contains high amounts of organic constituents and energy. Therefore, it is recognised as a potential source of renewable energy [5]. However, its use as a domestic fuel presents its own challenges. Its structure is porous and has a low bulk density. The bulk density of a crushed maize cob is 227 kg/m^3 and it is more than double the bulk density of uncrushed cobs which is 104 kg/m^3 [6]. This low bulk density makes it difficult to handle, store and transport and also results in low energy density. Densification which employs high pressure to compress biomass raw materials in order to increase

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Table 1 Production of selected agricultural crops and estimated potential residues in Ghana in the year 2010

Crop	Residue	Residue-to-product ratio (tonnes/tonnes of crop)	Total crop production (tonnes)	Residue production (tonnes)
Maize	Cob	1.00	1,872,000	1,872,000
Millet	Stalk	3.00	219,000	657,000
Rice	Straw	1.50	429,000	643,500
Sugar cane	Bagasse	0.30	145,000	43,500
Coconut	Shell	0.60	298,000	178,800
Oil palm fruits	EFB	0.25	2,004,000	501,000
Cocoa	Pods, husk	1.00	632,000	632,000
Coffee	Husk	2.10	1200	2,520
Total			5,600,200	4,530,320

Source: [4,5].

their density could be used to mitigate these challenges. Densification of maize cobs will result in improved energy density, lower volume (higher bulk density), and better mechanical handling [7,8]. However, maize cobs, is noted to have low lignin content (5.6%), low water soluble carbohydrates (1.1%) and low protein (2.5%). These chemicals are largely responsible for forming solid bridge bonds during densification or briquetting [9,10]. Therefore, densification of maize cobs would require a high compacting pressure and/or an external binder. A considerable amount of research on briquetting technology on maize cobs has been conducted. Previous studies showed that pressing maize cob particles at a temperature of 25°C, using a compacting pressure of 150 MPa, resulted in the production of briquettes having a durability of 0% and a relaxed density of 940 kg/m^3 [9]. Further studies indicated that when maize cob particles were preheated to 85°C before pressing at 150 MPa, the durability and density were raised to 90% and above 1,100 kg/m^3, respectively [9]. Even though improved binding of maize cob particles due to preheating to 85°C is feasible, this could invariably increase production cost as a result of increased energy input therefore limiting its utilisation. Thus, it is imperative that one selects the most economic technology for densification or briquetting of maize cob particles to reduce the cost of the finished product. *Ceiba pentandra* is a low-density species (409.22 kg/m^3) with acid-insoluble lignin and alpha-cellulose content of 24.34% and 41.24%, respectively [11]. Briquettes produced from sawdust of *C. pentandra* at room temperature (28°C) and low compacting pressure (20 to 50 MPa) without a binder had adequate relaxed density, high compressive strength in cleft and high impact resistance index (IRI) [11,12]. Studies on densified fuels derived from blends of two biomass materials indicate that the mechanical strength of briquettes produced from only one type of biomass can be improved by blending that biomass with another biomass material [13]. Therefore, this study seeks to investigate the effect of combining maize cob particles and sawdust of *C. pentandra* on the relaxed density, compressive strength in cleft and impact resistance index of briquettes produced at room temperature using low compacting pressure.

Methods

Materials and material preparation

Sawdust of *C. pentandra* and maize cobs were used for the study. Both the maize cobs and sawdust were sun-dried at an average relative humidity and temperature of 75% and 28°C, respectively, for 5 to 7 days. The maize cobs were crushed using a hammer mill. Particle sizes of maize cobs and sawdust used for the study were 1 mm or less. The two materials were combined at mixing percentages of 90:10, 70:30 and 50:50 (*C. pentandra*/maize cobs).

Moisture content

The moisture content, on oven-dry basis, of the crushed maize cobs and sawdust was determined in accordance with [14]. Five samples of sawdust, maize cobs particles and their combination, each weighing 2 g were weighed and placed in a laboratory oven at a temperature of (103°C ± 2°C). Each sample was dried until the difference in mass between two successive weighings separated by an interval of 2 h was 0.01 g or less. The moisture content of the specimen was then computed as follows:

$$\text{Moisture content (\%)}\ db = \frac{M_1 - M_o}{M_o} \times 100, \quad (1)$$

where M_1 and M_o were masses (g) of test samples before drying and after oven drying, respectively. On the average, the moisture content of the maize cob particles, *C. pentandra* and the mixed samples were 9.00%, 13.27% and 9.21%, respectively.

Briquetting process

A 55.3-mm ID × 52.5-cm height cylindrical mould was used to produce the briquettes. Ninety grammes of each biomass material was weighed and filled into the mould. A manual hydraulic press with a gauge and piston was used to compress the biomass raw material without a binder to form the briquettes. A clearance of about 0.1 mm was provided between the piston and the inner wall of the mould to allow for air escape. The samples were then pressed using the following predetermined compacting pressure levels: 20, 30, 40 and 50 MPa. The dwelling time for each press was maintained at 10 s. This process was repeated for all the biomass materials.

Physical and mechanical properties of briquettes

The relaxed density, compressive strength in cleft and impact resistance index of the briquettes produced were investigated using standard testing methods.

Relaxed density

Relaxed density (RD) of the briquettes was determined 30 days after removal from the press in accordance with [15]. The mass of briquettes were determined using a laboratory electronic balance with an accuracy of 0.01 g. The diameter and length of a briquette were measured at three points with a digital vernier calliper. Relaxed density was then computed as follows:

$$\mathrm{RD}\left({}^{\mathrm{g}}/_{\mathrm{cm}^3}\right) = \frac{108000 \times M(\mathrm{g})}{\pi[d_1(\mathrm{mm}) + d_2(\mathrm{mm}) + d_3(\mathrm{mm})]^2 \times [l_1(\mathrm{mm}) + l_2(\mathrm{mm}) + l_3(\mathrm{mm})]}, \quad (2)$$

where d_1, d_2 and d_3 were diameters (mm) measured at three different points on the briquettes. L_1, L_2 and L_3 were lengths (mm) measured at three different points on the briquettes. M (g) is the mass of briquette.

Compressive strength

Compressive strength in cleft of briquettes was determined in accordance with [16] using an Instron universal strength testing machine (Norwood, MA, USA) with a load cell capacity of 100 kN. The crosshead speed was 0.305 mm/min. A sample of briquette to be tested was placed horizontally in the compression test fixture and a load was applied at a constant rate of 0.305 mm/min until the briquette failed by cracking. The compressive strength in cleft was then computed as follows:

$$\text{Compressive strength in cleft } \left({}^{\mathrm{N}}/_{\mathrm{mm}}\right) = \frac{3 \times \text{The load at fracture point (N)}}{[l_1(\mathrm{mm}) + l_2(\mathrm{mm}) + l_3(\mathrm{mm})]} \quad (3)$$

Impact resistance index

IRI of the briquettes produced was determined in accordance with [17], using the drop shatter test for coal. Five drops were set as the standard. Briquettes were released from a vertical height of 2 m and allowed to freely fall onto a concrete floor. After five drops, the broken pieces of briquettes as a result of the impact were collected and weighed using an electronic balance with an accuracy of 0.01 g. Only the number of pieces which weighed 5% or more of the initial weight was recorded for the purpose of calculating the impact resistance index. The impact resistance index was computed as follows:

$$\mathrm{IRI}(\%) = \frac{N}{n} \times 100, \quad (4)$$

where N is the number of drops and n is the number of pieces that weighed 5% or more of the initial weight of briquette after N drops.

Results and discussions

Relaxed density of briquettes produced from maize cob particles, *Ceiba pentandra* and their mixture

Relaxed density of briquettes produced from maize cobs, *C. pentandra* and their combined materials are presented in Table 2. Relaxed density of briquettes produced from only *C. pentandra* ranged from 523 to 716 kg/m^3 while that produced from maize cob particles only ranged from 541 to 659 kg/m^3.

Additionally, the relaxed density of briquettes obtained from a mixture of maize cob particles and *C. pentandra* ranged from 565 to 774 kg/m^3. The relaxed density of briquettes obtained from all the biomass materials used for the study could be considered adequate since they fall within the recommended values of relaxed density for briquette made using the hydraulic press. It has been previously reported that briquettes made from hydraulic piston press are usually less than 1,000 kg/m^3 and fall between 300 to 600 kg/m^3 [18,19]. It could be further inferred from this study that the relaxed density of all the briquettes produced from the combination of maize cobs and *C. pentandra* particles were higher than that of their corresponding values for the pure biomass materials. This may be due to the variations in the composition and structure of these two materials (*C. pentandra* and maize cob) which resulted in better rearrangement and densification when mixed together and pressed.

Correlation analysis between proportion of maize cob particles in the mixture and relaxed density of briquettes produced indicated that there was no significant correlation between the two parameters (Pearson's $r = 0.166$, p value = 0.102; $N = 60$, $\alpha = 0.05$; one-tailed). However, the compacting pressure was found to have a high significant positive correlation with the relaxed density of the briquettes produced from the mixture of *C. pentandra*

Table 2 Relaxed density (kg/m^3) of briquettes produced from maize cobs, *C. pentandra* and their combination

Biomass material	Mixing percentages	Compacting pressure			
	(weight basis)	20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs only	Pure (100%)	541	611	636	659
C. pentandra only	Pure (100%)	523	622	666	716
C. pentandra/Maize cobs	90:10	565	641	695	742
C. pentandra/Maize cobs	70:30	584	645	708	749
C. pentandra/Maize cobs	50:50	588	661	730	774

Source of data for *C. pentandra* only: [11,12].

and maize cob particles (Pearson's $r = 0.969$, p value = 0.000; $N = 60$, $\alpha = 0.05$; one-tailed). Increased compacting pressure level resulted in a reduction in intermolecular distance as well as increased crushed cell walls, therefore resulting in the formation of denser briquettes.

Analysis of variance (Table 3) on the effect of biomass raw material (maize cobs, *C. pentandra*, and their combination) and compacting pressure on relaxed density of briquettes produced indicated that at 5% level of significance, the biomass raw material, compacting pressure and their interactions have significant effect on the relaxed density of the briquettes produced (p value < 0.05). The multiple coefficient of determination (R^2) and root means square error of the ANOVA model were 0.9730 and 12.93, respectively. The R^2 value of 0.9730 indicates that the biomass raw material and compacting pressure could explain about 97.30% of the variance in the relaxed density of briquettes produced.

Compressive strength in cleft of briquettes produced from maize cobs, *Ceiba pentandra* and their combination

Table 4 shows the results of compressive strength in cleft of briquettes produced from sawdust of maize cob particles, *C. pentandra* and their combination. The result indicates that at all compacting pressure levels, the compressive strength in cleft of briquettes produced from maize cob particles only was very low, ranging from 0.12 to 0.54 N/mm. Compressive strength in cleft of briquettes produced from *C. pentandra* only, was very high and ranged from 29.23 to 44.58 N/mm. Furthermore, the compressive strength in cleft of briquettes produced from combination of maize cob particles and *C. pentandra* ranged from 7.72 to 59.22 N/mm.

This result suggest that briquettes produced only from maize cob particles at low compacting pressure and room temperature will not have adequate compressive strength in cleft for handling (compressive strength in cleft <19.6 N/mm). However, the compressive strength in cleft of briquettes produced from maize cob particles could be improved significantly when it is combined with sawdust from *C. pentandra*. According to Rahman et al. [20], the briquettes surface compressive strength (i.e. compressive strength in cleft) of 19.6 N/mm is reasonably adequate for handling or can be used as fuel for domestic purposes. With the exception of briquettes produced from the 70:30 mixing ratio and pressed at a compacting pressure of 20 MPa, all the briquettes produced from 90:10 and 70:30 mixing ratios had adequate compressive strength in cleft (compressive strength in cleft >19.6 N/mm). Additionally, briquettes produced from the 90:10 (*C. pentandra*/maize cobs) mixing ratio and pressed at 40 and 50 MPa had compressive strength in cleft higher than their corresponding values for *C. pentandra* only. Thus, the addition of 10% maize cob particles to sawdust of *C. pentandra* and pressed at compacting pressures of 40 and 50 MPa will significantly improve the compressive strength in cleft of briquettes produced from *C. pentandra*. This result confirms the research finding of other researchers who undertook a study on densified fuels derived from a blend of two biomass materials. Previous studies [13,21,22] indicated that the durability and mechanical strength of briquettes produced from only one type of biomass materials could be improved by blending that biomass with another biomass material. For instance, the durability of wheat straw briquette was enhanced by blending the straw with wood

Table 3 ANOVA of effect of biomass raw material and compacting pressure on the relaxed density of briquettes

Source	*df*	ANOVA SS	Mean square	*F* ratio	*p* value
Biomass raw material	4	76,341.54	19,085.3850	114.13	<0.0001*
CP	3	392,450.76	130,816.92	782.28	<0.0001*
Biomass material × CP	12	12,562.94	1,046.9117	6.26	<0.0001*
Error	80	13,378.00	167.225		

Briquettes are produced from maize cobs, *C. pentandra* and their combination. *Statistically significant at 0.05 level of significance. Legend: *df*, degree of freedom; CP, compacting pressure.

Table 4 Compressive strength in cleft (N/mm) of briquettes produced using compacting pressure levels from 20 to 50 MPa

Biomass material	Mixing percentages (weight basis)	Compacting pressure			
		20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs only	Pure (100%)	0.12	0.12	0.41	0.54
C. pentandra only	Pure (100%)	29.23	39.26	40.40	44.58
C. pentandra/Maize cobs	90:10	27.29	37.33	44.98	59.22
C. pentandra/Maize cobs	70:30	16.66	22.82	30.00	33.47
C. pentandra/Maize cobs	50:50	7.72	13.02	19.46	24.04

Briquettes are produced from maize cobs, *C. pentandra* and their combination. Source of data for *C. pentandra* only: [11,12].

waste [13]. Correlation analysis between proportions of maize cob particles in the mixing ratio and compressive strength in cleft of briquettes produced, indicated a strong negative correlation between the two parameters (Pearson's $r = -0.770$, p value = 0.000; $N = 60$, $\alpha = 0.05$; one-tailed). This implies that for the mixed biomass briquettes, an increase in proportion of maize cob particles in the mixture resulted in a decrease in compressive strength in cleft of briquettes produced. Compacting pressure was also found to have a high significant positive correlation with the compressive strength in cleft of briquettes produced from the combination of maize cob and *C. pentandra* particles (Pearson's $r = 0.582$, p value = 0.000; $N = 60$, $\alpha = 0.05$; one-tailed).

Two-way analysis of variance (Table 5) on the effect of biomass raw material and compacting pressure on the compressive strength in cleft of briquettes produced indicated that at 5% level of significance the biomass raw material, compacting pressure and their interaction had significant effect on compressive strength in cleft of briquettes produced (p value < 0.05).

The multiple coefficient of determination (R^2) and root mean square error of the ANOVA model were 0.9813 and 2.5939, respectively. Thus, about 98.13% of the variability in compressive strength in cleft of briquettes produced could be explained by the biomass raw material and compacting pressure.

Impact resistance index of briquettes produced from maize cobs, *Ceiba pentandra* and their combination

The impact resistance index of briquettes produced from maize cobs, *C. pentandra* and their combination is presented in Table 6. The results show that at all compacting pressure levels, briquettes produced from only maize cob particles had a very weak or no impact resistance index (%). This may be due to the low lignin content, low water soluble carbohydrates and low protein in the maize cobs. The impact resistance index of briquettes produced from the combination of maize cob and *C. pentandra* particles ranged from 115% to 500%. All the briquettes produced from this combination of biomass materials had adequate impact resistance index, that is, the impact resistance index greater than 100%, the minimum value set for this study.

According to the Italian standard for briquettes/pellets (CTI-R04/5) as cited in [23], briquette durability ≥97.7% is adequate. Additionally, the durability characteristics of briquettes is classified as high when impact resistance index is greater than 80% [24,25]. From the results obtained in this study, it was observed that when maize cob particles is combined with the sawdust of *C. pentandra*, the impact resistance index of the briquettes produced was significantly improved. Briquettes produced from the combination of *C. pentandra* and maize cob particles at 90:10 mixing ratio showed a very high impact resistance index than that produced from just the *C. pentandra* alone. The impact resistance index ranged from 200% to 500%. Furthermore, at the same mixing ratio of 90:10 and compacting pressure of 50 MPa, the briquettes produced did not show any disintegration after being dropped five times from a height of 2 m onto the ground. Correlation analysis between proportions of maize cobs in the mixing ratio and impact resistance index of briquettes produced indicated a strong negative correlation between the two

Table 5 ANOVA of effect of biomass raw material and compacting pressure on compressive strength in cleft of briquettes produced

Source	*df*	ANOVA SS	Mean square	*F* ratio	*p* value
Biomass raw material	4	23,287.04	5,821.76	865.24	<0.0001*
CP	3	3,530.87	1,176.96	174.92	<0.0001*
Biomass material × CP	12	1,437.39	119.78	17.80	<0.0001*
Error	80	538.28	6.73		

Briquettes are produced from maize cobs, *C. pentandra* and their combination. *Statistically significant at 0.05 level of significance. Legend: *df*, degree of freedom; CP, compacting pressure.

Table 6 Impact resistance index (%) of briquettes pressed using compacting pressure levels from 20–50 MPa

Biomass material	Mixing percentages (weight basis)	Compacting pressure			
		20 MPa	30 MPa	40 MPa	50 MPa
Maize cobs only	Pure (100%)	0	0	0	0
C. pentandra only	Pure (100%)	200	283	316	350
C. pentandra/Maize cobs	90:10	200	300	400	500
C. pentandra/Maize cobs	70:30	142	192	233	450
C. pentandra/Maize cobs	50:50	115	133	150	217

Briquettes are made from maize cobs, *C. pentandra* and their combination. Source of data for *C. pentandra* only: [11,12].

parameters (Pearson's $r = -0.577$, p value = 0.000; $N = 60$, $\alpha = 0.05$; one-tailed). Thus, for a mixture of *C. pentandra* and maize cob particles, increases in the proportions of maize cob particles in the mixture could result in a decrease in the impact resistance index of the briquettes produced. Additionally, compacting pressure was found to have a high significant positive correlation with the impact resistance index of briquettes produced from the combination of maize cob and *C. pentandra* particles (Pearson's $r = 0.614$, p value = 0.000; $N = 60$, $\alpha = 0.05$; one-tailed).

A two-way analysis of variance (Table 7) to determine the effect of biomass raw material and compacting pressure on impact resistance index of briquettes produced indicated that at 5% level of significance, the biomass raw material, compacting pressure and their interactions had significant effect on the impact resistance index of briquettes produced (p value < 0.05). The multiple coefficient of determination and root mean square error of the ANOVA model were 0.8152 and 77.42, respectively. Thus, about 81.52% of the variance in the impact resistance index of briquettes produced could be explained by the biomass raw material and compacting pressure. This result confirms that characteristics of the raw material used significantly have an effect on the quality of briquettes produced.

Conclusion

This study examined the characteristics of briquettes produced from a combination of maize cob particles and *C. pentandra* sawdust at room temperature and low compacting pressure without a binder. From the study, it can be concluded that

1. Briquettes produced from maize cob particles at room temperature using low compacting pressure does not have adequate compressive strength in cleft (compressive strength in cleft <19.6 N/mm) and impact resistance index (0%) for handling, storage and transporting. However, it has adequate relaxed density.
2. Combining *C. pentandra* and maize cob particles at mixing proportions 90:10 and 70:30 and pressed with compacting pressure 30 MPa or more at room temperature will produce briquettes with adequate compressive strength in cleft (compressive strength in cleft ≥19.6 N/mm).
3. Combining *C. pentandra* and maize cob particles at mixing proportions 90:10, 70:30 and 50:50 and pressed with compacting pressure 30 MPa or more at room temperature will produce briquettes with adequate impact resistance index (impact resistance index >100%).
4. The proportion of maize cob particles in a mixture of maize cobs and *C. pentandra* sawdust significantly affects the compressive strength in cleft and impact resistance index of briquettes produced.
5. The type of biomass material and compacting pressure has a significant effect on the relaxed density, compressive strength in cleft and impact resistance index of briquettes produced from maize cobs and sawdust of *C. pentandra*.

This study therefore reveals that it is possible to produce briquettes with adequate physical and mechanical properties from maize cobs when it is combined with sawdust of *C. pentandra*.

Table 7 ANOVA of effect of biomass raw material and compacting pressure on impact resistance index of briquettes

Source	*df*	ANOVA SS	Mean square	*F* ratio	*p* value
Biomass raw material	4	1,496,860.70	374,215.175	62.44	<0.0001*
CP	3	394,655.95	131,551.983	21.95	<0.0001*
Biomass material × CP	12	223,064.90	18,588.742	3.10	0.0012*
Error	80	479,451.20	5,993.140		

Briquettes are produced from maize cobs, *C. pentandra* and their combination. *Statistically significant at 0.05 level of significance. Legend: *df*, degree of freedom; *CP*, compacting pressure.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
SJM conceived of the study, participated in the design of the study, drafted the manuscript and participated in the sequence alignment. KFM and JOA participated in the design of the study and sequence alignment. NAD participated in the design of the study, performed the statistical analysis and participated in the sequence alignment. All authors read and approved the final manuscript.

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