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Characterization of Particleboard Produced from Residues of *Plantain pseudostem*, Cocoa Pod and Stem and *Ceiba*

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Abstract

This study investigated the possible use of four agro-forest residues generated in Ghana as an alternative raw material for particleboard manufacture using cassava starch and urea formaldehyde as adhesives. The particle size of the materials ranged from 0.5 mm to 1.5 mm. An industrial pressing machine was used to press the homogeneous single layer particleboard. Physical and mechanical properties were determined in accordance with ASTM D 1037-06a and ASTM D 7519-11. The results indicate that the density of the particleboards produced ranged from 421 kg/m^3 to 598 kg/m^3. The water absorption property of the particleboards also ranged from 7.66% to 22.41% and 18.17% to 59.46% for 2-hour and 24-hour immersions respectively. Additionally, the thickness swelling of the particleboards ranged from 3.38% to 5.03% and 9.37% to 21.49% for 2-hour, and 24-hour immersions respectively. The results further indicate that the modulus of elasticity, modulus of rupture, internal bond strength and hardness of the particleboards produced for both cassava starch and urea formaldehyde were adequate. Comparatively, for all the agro-forest materials used for this study, the physical and mechanical properties of the particleboards produced using urea formaldehyde as adhesive was better than those produced using cassava starch as adhesive. It could be concluded that the particleboards produced could be used for indoor applications or interior furnishings, under dry conditions. Additionally, it is recommended that further studies that combine cassava starch and urea formaldehyde as adhesives be conducted, as well as studies on combining *plantain pseudostem* and cocoa pod in particleboard production.

Keywords

Agro-Forest Residue, Cassava Starch, Particleboard, Physico-Mechanical Properties, Urea Formaldehyde

1. Introduction

Particleboard, an engineered wood product, dates back to the early 20th Century. It was developed during World War II to utilise inferior wood and wood waste when good quality wood was in short supply [1]. In the past, wood was the main raw material used for furniture and building applications, although the feasibility of non-wood alternatives had been investigated for many decades. Many factors including wood shortage as a result of the depletion of forest areas, environmental awareness and generation of large quantities of agro-forest residues which have disposal challenges have increased the need for the substitution of wood as a major raw material for the production of furniture and other wood products with particleboard. The demand for particleboard products has increased substantially throughout the world, representing 57% of the total consumption of wood-based panels, a percentage that is continuously growing at a rate of 2% - 5% annually. As a result of this, about 28.4 million m^3 of particleboards are produced in Europe each year mainly for furniture and building applications [2].

In recent times, most companies that produce particleboards have been substituting wood as a raw material with agricultural residues. This is because the volumes of timber harvested from the forest are being drastically reduced and less timber is available. On the contrary, farming operations with residual fibres are annually renewed, often in sustainable volumes that could supply for composite panel production. In 2005, at least 30 industrial plants all over the world integrated the use of non-wood lignocellulosic aggregates in the production of particleboards [3]. Today, although the technical feasibility of non-wood particleboards is generally accepted, further research is needed to fully understand how the intrinsic properties of the raw materials can contribute to enhancing the overall performance of the engineered materials [4].

Agricultural residue, that is, residual fibre, is one of the major solid residues produced in the world. Typically, such residues like wheat and barley straw, rice straw and husks, sugar cane bagasse, *plantain pseudostem*, and the pod, stem and husk of cocoa plant have little or no value. The management or disposal of these residues has become a questionable practice in many countries as they are often left to rot or burnt inefficiently in their loose form causing air pollution [5]. Besides, the burning of these residues is often detrimental to the soil and can cause health and related problems. The vast majority of examples of non-wood particleboard developments as indicated earlier are focused on the use of different kinds of natural fibres which comprise mainly agricultural residue. This is because the use of fibres makes an important contribution to the enhancement of the physical and mechanical properties of such boards through mechanical interlocking of particles [6]. Fibrous materials from crop plants are also preferred because of their availability and accessibility.

Plantain pseudostem (*Musa paradisiacal pseudostem*), a residue of plantain, is a lignocellulosic biomass material readily available on farmlands and in neighborhoods at no cost. Available data indicate that between 2000 and 2015, global production of plantain grew at a compound annual rate of 3.7 percent, reaching a record of 117.9 million tonnes in 2015, up from around 68.2 million tonnes in 2000 [7]. Ghana is the largest producer of plantain in West Africa and the third in Africa after Uganda and Rwanda [7]. It was estimated that at the end of the year 2016, about 7,184,842 tonnes of *plantain pseudostem* residue was generated in Ghana [7]. This constitutes about 59% of the total agricultural crop residues generated. *Plantain pseudostem* is one of the agricultural residues readily available in large quantities and has no special industrial application.

Another abundant agricultural waste generated in Ghana is the residue of cocoa (*Theobroma cocoa*). Ghana is second to Cote d'Ivoire, responsible for about 20% of global cocoa production. Cocoa prunings, pod, stem and shells are the main residue generated from cocoa production. Cocoa tree prunings and pods are normally left in the field as a kind of mulch while a small part may be used as domestic fuel. When cocoa pod decays on farm lands, the composts emit methane into the atmosphere which also affects the degradation of the ozone layer 25 times that of carbon dioxide [8] and it is also a carrier of botanical diseases such as black pod rot. The wood from trees cut during re-planting ends up as domestic fuel or is used for the construction of mud houses in the farming communities.

Ceiba (*Ceiba pentandra*) is a low-density species with density of about 409.22 kg/m^3 having acid-insoluble lignin and alpha-cellulose contents of 24.34% and 41.24% respectively [9]. It is noted to have long fibres. In a study conducted by Mitchual [9] which compared the fibre length of six (6) species of different particle sizes, ceiba was noted to have longer fibre length for each of the particle sizes. This characteristic makes it a suitable source of material for particleboard production.

Most of the previous studies conducted to explore alternative raw materials for production of particleboards have recognized agro-forest residues as a potential source for its manufacture. For most of such studies, urea formaldehyde was used as adhesive. The emission of carcinogenic formaldehyde in the production, and use of particleboards have generated a lot of discussions by researchers, some advocating for its substitution. Additionally, Rokiah *et al.* [10] noted that formaldehyde resins and other synthetic resins create waste disposal problems because they are non-biodegradable and also not recyclable. Thus, this study aimed at determining the physical and mechanical properties of particleboards produced from residues of *plantain pseudostem*, cocoa stem and pod, and ceiba sawdust using cassava starch and urea formaldehyde as adhesives.

2. Methodology

2.1. Materials and Material Preparation

2.1.1. Preparation of Particles of Biomass Material

Plantain pseudostem, cocoa stem and pod, ceiba sawdust, urea formaldehyde and cassava starch were used for the study. The *plantain pseudostem* was obtained from a farm land after harvesting. The water was extracted, and the fibres oven-dried before milling them into particles. Figure 1 shows the stages of preparation of *plantain pseudostem* particles.

Figure 2 and Figure 3 show the stages of conversion of cocoa stem and pod respectively into particles. Twenty-six (26) year-old cocoa trees were felled and then converted into sawdust by sawing. The fresh cocoa pods as shown in Figure 3(a) were first sun-dried and then crushed into particles using a hammer mill. Sawdust of ceiba was obtained from a timber processing company in Ghana.

2.1.2. Sieve Analysis and Grading of Particles

The particle size distribution of the agro-forest residues was determined in accordance with ASTM D6913-17 [11]. Two hundred grammes of each of the agro-forest materials was placed in a set of sieves with sizes: 4.75 mm, 3.15 mm, 2.00 mm, 1.00 mm, 0.60 mm, 0.425 mm, 0.30 mm, 0.15 mm and 0.063 mm and then mounted on automatic sieve shaker with serial number YGM15418/AZ/0260

(a) (b) (c)

Figure 1. Stages of processing *plantain pseudostem* into particles. (a) Fresh *plantain pseudostem*; (b) Water extraction from *plantain pseudostem*; (c) *Plantain pseudostem* particles.

(a) (b) (c)

Figure 2. Stages of processing cocoa stem into particles. (a) Cocoa plantation; (b) Cocoa stem; (c) Cocoa stem particle.

(a) (b) (c)

Figure 3. Stages of processing cocoa pod into particles. (a) Fresh cocoa pod; (b) Dried cocoa pod; (c) Cocoa pod particles.

and Model YGM15418. Shaking was done for 10 minutes. Thereafter, the weight of the materials retained on each sieve was determined using an electronic balance. The percentages of the materials retained on each sieve were computed and graphs of particle size distribution cumulative curves plotted.

2.1.3. Urea Formaldehyde

Urea formaldehyde (UF) resin with a ratio of 1:1, of 65% solid content, specific gravity of 1.266 g/cm^3 at 30˚C, viscosity of 2.3MPs at 30˚C, pH of 7.5 and a gel time of 65 seconds at 100˚C was used as the adhesive for making the particleboard.

2.1.4. Preparation of Cassava Starch

Fresh cassava tubers (**Figure 4**) were obtained, washed, peeled and milled to obtain cassava dough. The dough was diluted with clean water to form a solution. Thereafter, the solution was strained with 1 mm wire mesh and allowed to stand for 24 hours to allow the starch to settle. The water was decanted to obtain the cassava starch. The starch was air-dried for ten days and ground to obtain powdered starch as shown in **Figure 5**.

2.2. Bulk Density Determination

The bulk density of the loose biomass materials was determined in accordance with Hartmann *et al.* [12]. This was done by filling a 50-litre cylindrical container to the brim and weighing it. The volume of the cylinder was determined by measuring its height and internal diameter. The bulk density of the biomass materials was computed as shown in Equation (1).

$$\text{Bulk density}\left(\frac{\text{kg}}{\text{m}^3}\right)=\frac{M_{sp}}{V_c} \quad (1)$$

where:

M_{sp} = Mass of the biomass sample.

V_c = Volume of the cylindrical container.

2.3. Aspect Ratio

The particle width and length of one hundred and twenty particles of each specimen

Figure 4. Cassava tubers.

Figure 5. Cassava starch.

were measured with a digital LED compound light microscope of 10 × magnification and analyzed with ImageJ 1.51 Java 64-bit for determining the width and length. The aspect ratio was computed as shown in Equation (2).

$$AR = \frac{Pl}{Pw} \quad (2)$$

where:

AR = Aspect ratio.

Pl = Particle length.

Pw = Particle width.

2.4. Particleboard Manufacture

The bulk density of the biomass materials was: cocoa stem = 89.90 kg/m^3; ceiba = 94.41 kg/m^3; *plantain pseudostem* = 96.63 kg/m^3 and cocoa pod = 323.96 kg/m^3. The materials, particle size range 0.5 mm - 1.5 mm, were each dried to a moisture content of 4% and then thoroughly mixed with the adhesives. Ammonium chloride was added as a curing catalyst. The resinated particles were prepressed into an 80 mm single layer in 300 mm × 300 mm aluminium sheet mould. A 20 mm thick metal stopper was used to ensure that the boards produced had the same thickness. The mat was then pressed with the following conditions: temperature 170˚C; pressure 3.5 MPa; time 8 minutes; closing rate 3

- 4 mm/minutes; target thickness 20 mm; hardener 2%; adhesive UF and CS; and compacting time 15 minutes. The produced particleboards were then trimmed and conditioned for 6 days in a climate controlled room having a temperature of 20˚C ± 2˚C and a relative humidity of 62% ± 2% before they were sawn into various sizes for further studies.

2.5. Moisture Content

The moisture content on oven-dry basis of the particleboards was determined in accordance with the ASTM D 1037-06a [13]. Five samples of each of the particleboards with dimensions 50 mm × 50 mm × 20 mm were 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 two hours was 0.01 g or less. The moisture content of the specimen was then computed as shown in Equation (3).

$$\text{Moisture content } (\%)\, db = \frac{M_i - M_f}{M_f} \times 100 \quad (3)$$

where:

M_i = Initial mass (g) of the test sample before drying.

M_f = Final oven-drying mass (g) of the test sample.

2.6. Density

The density of the particleboards produced was determined in accordance with ASTM D-1037-06a [13]. Specimens of dimensions 20 mm × 20 mm × 30 mm was prepared from the particleboards produced and kept in a desiccator. The oven-dried mass of the specimen was determined using an electronic balance. The dimensions of the specimen: length, breadth and height were determined using a digital veneer calliper. Density of each specimen was then computed using Equation (4).

$$\text{Density}\left(\frac{kg}{m^3}\right) = \frac{\text{Mass}}{L \times W \times T} \quad (4)$$

where:

L = Length of specimen.

W = Width of specimen.

T = Thickness of specimen.

2.7. Thickness Swelling

The thickness swelling property of the particleboards was determined in accordance with ASTM D1037-06a [13]. A test specimen with dimension 20 mm × 76 mm × 152 mm was soaked in pure water at room temperature (27˚C) for 2 hours and 24 hours. The initial and the final thickness of the specimen after the period of submersion were determined with a digital veneer calliper. The thickness swelling for the 2-hour and 24-hour submersions was then computed using

Equation (5).

$$\text{Thickness swelling rate}(\%) = \frac{T_f - T_o}{T_o} \times 100 \quad (5)$$

where:

T_o = Initial thickness of test sample before soaking in distilled water.

T_f = Final thickness of test sample after soaking in water.

2.8. Water Absorption

The water absorption property of the particleboards was determined in accordance with ASTM D1037-06a [13]. A sample of dimension 20 mm × 76 mm × 152 mm was weighed and then submerged horizontally under 25 mm depth of pure water at room temperature (27˚C) for 2-hour and 24-hour. For each of them, the excess water on the surface of the sample was removed with hand paper towel and was immediately weighed. The 2-hour and 24-hour water absorption properties were then computed using Equation (6).

$$\text{Water absorption rate after 2 hours}(\%) = \frac{W_f - W_o}{W_o} \times 100 \quad (6)$$

where:

W_o = Initial weight of test sample before soaking.

W_f = Final weight of test sample after soaking.

2.9. Modulus of Elasticity and Modulus of Rupture

The modulus of elasticity (MOE) and modulus of rupture (MOR) of the particleboards were determined in accordance with the American Society for Testing and Materials Standard Methods ASTM D 1037-06a [13]. Specimen of size 20 mm × 50 mm × 250 mm was prepared from the particleboards produced. An Instron Universal Testing Machine (Model Inspekt 50-1) operated with a load cell capacity of 50 kN was used for the test. The loading rate applied to determine the bond strength was 4 mm/min.

2.10. Internal Bond (IB)

The test was conducted in accordance with ASTM D 7519-11 [14] and ASTM D 1037-06a [13]. Twenty four strips of particleboards (152 mm × 305 mm) with three replicates produced from each of the agro-forest residues using the two adhesives were subjected to the following exposure cycle: 16 hours of oven drying at a temperature of 70˚C, followed by a 3-hour soaking in water at a temperature of 20˚C. This was immediately followed by a 2-hour oven drying at a temperature of 70˚C, and immediately followed by a 3-hour soaking in water at 20˚C. After the third exposure cycle, the boards were dried for 16 hours in an oven at a temperature of 70˚C. Finally, four specimen blocks of dimension 50 mm × 50 mm were cut from each of the strips. Tension perpendicular to surface (Internal Bond) test was conducted according to the test method of ASTM D

1037-06a [13]. The internal bond of each specimen was calculated using Equation (7).

$$\text{Internal bond strength}\left(\frac{N}{\text{mm}^2}\right)=\frac{P_{\max}}{ab} \tag{7}$$

where:

$P_{\max}$ = Maximum load (N).

a = Width of the specimen (mm).

b = Length of the specimen (mm).

2.11. Hardness

The hardness of the particleboards was determined in accordance with the American Society for Testing and Materials standard methods ASTM D 1037-06a [13]. To conduct the hardness test the particleboards were laminated to obtain the given thickness and subsequently cut into 25 mm × 75 mm × 150 mm, as specified by the standard. Janka ball test was used for determining the hardness of the particleboards using universal testing machine model 4482, operating with a load cell capacity of 100 kN.

2.12. Ultra-Structure Analysis

Samples of the particleboard of size 5 mm × 10 mm × 10 mm were investigated using scanning electron microscope (SEM). The specimens were coated with a thin film of gold and mounted on aluminum stub using carbon tape and then analyzed with Phenom ProX desktop SEM with EID at 15 kV with a magnification range of 1300× to 1500×.

3. Results and Discussion

3.1. Aspect Ratio of Agro-Forest Residue

The results in Table 1 show that *plantain pseudostem* particles had the highest aspect ratio (135.03) followed by that of cocoa stem (61.60) with ceiba (60.54) being the least. Previous studies have indicated that the mechanical properties of particleboards positively correlate with the aspect ratio (particle geometry) of the biomass materials. This is because of the greater surface area it provides in terms of contact between particles [15] and [16]. Furthermore, Gozdecki *et al.*, [17]

Table 1. Aspect ratio of agro-forest residue.

Agro-forest residue	Number of samples	0.5 mm ≤ P < 1.5 mm		
		Aspect ratio	SD	Range
Ceiba	60	60.54	23.31	33.44 - 96.18
Plantain pseudostem	60	135.03	33.48	111.89 - 204.35
Cocoa pod	60	Parenchymatous cells (No fibres present)		
Cocoa stem	60	61.60	22.64	33.69 - 96.14

Legend: P = Particle size; SD = Standard deviation.

indicated that particles with a higher aspect ratio enhance stress transfer from the polymer matrix to the particles and ultimately improve the composite mechanical properties.

3.2. Particleboard Density

Density of particleboard is a measure of compactness of the individual particles in a board, and is dependent mainly on the density of the wood, the type of adhesive, and the pressure applied during pressing [18]. The density of the particleboards (**Table 2**) with cassava starch as an adhesive ranged from 497 kg/m^3 to 598 kg/m^3 whilst that of urea formaldehyde ranged from 421 kg/m^3 to 557 kg/m^3. According to ANSI A208.1 [19], such particleboards could be graded as low density. Additionally, particleboards produced compare favorably with those produced from medium density wood. Besides, similar results were observed by Melo and Stangerlin [20] in a study to determine the physical and mechanical properties of particleboards manufactured from wood, bamboo and rice husk.

The density of the particleboards produced from cocoa pod for both cassava starch and urea formaldehyde was significantly higher than those produced from the other biomass materials. This could be due to the exceptionally high bulk density of its biomass raw material. Furthermore, the particleboards produced using cassava starch as adhesive had higher densities than their corresponding values for urea formaldehyde.

3.3. Water Absorption

Understanding the water absorption property (WA) of particleboards is an important factor that needs to be evaluated in order to improve dimensional stability of composite [21]. **Table 3** shows the WA property of particleboards for 2-hour and 24-hour immersion in water. The WA property of the particleboards manufactured from cocoa pods was highest (worst) for the 2-hour immersion, having values of 22.41% and 14.98% for cassava starch and urea formaldehyde adhesives respectively. That of *plantain pseudostem* was the least for the 2-hour immersion, having values of 9.86% and 7.77% for cassava starch and urea formaldehyde adhesives respectively. The higher WA property of cocoa pod and ceiba particleboards could be due to the high content of silica and lower content

Table 2. Density of particleboard.

Biomass materials	Density (kg/m^3)	
	100% Cassava starch	100% Urea formaldehyde
Ceiba	536^a (11.69)	472^a (67.86)
Plantain pseudostem	543^a (32.25)	493^a (84.83)
Cocoa pod	598^b (34.31)	557^b (30.90)
Cocoa stem	497^a (26.24)	421^a (62.47)

Figures in columns with the same letters are not significantly different ($p > 0.05$).

Table 3. Water absorption (%) property of particleboards produced from agro-forest residue.

Agro-forest residue	Water absorption (%)			
	2-hour		24-hour	
	Cassava starch	UF	Cassava starch	UF
Ceiba	19.15^{c} (3.16)	13.07^{b} (1.82)	50.08^{d} (1.63)	30.97^{b} (1.07)
Plantain pseudostem	9.86^{a} (0.84)	7.66^{a} (1.49)	23.79^{a} (3.13)	18.17^{a} (1.58)
Cocoa pod	22.41^{c} (1.21)	14.98^{b} (1.57)	59.46^{d} (1.04)	43.80^{c} (5.09)
Cocoa stem	12.65^{b} (1.83)	8.10^{a} (1.32)	30.82^{b} (2.46)	22.08^{a} (1.64)

Figures with the same letters are not significantly different according to Tukey's multiple tests. UF = Urea formaldehyde.

of lignin present in these materials. Components such as silica interfere with the particles' adhesion and gluing processes [22] [23].

In all cases, 2-hour and 24-hour immersions, the particleboards produced using urea formaldehyde had lower (better) WA properties than their corresponding values for cassava starch. Cassava starch is hydrophilic, therefore, it tends to absorb more water, thus the bond formed between particles, particles-starch and starch-starch is easily broken [24] [25].

The WA property of the particleboards for the current study is similar to, or lower than, those obtained by other researchers who used wood species and agro-forest residues for particleboard production. In a study on the suitability of some fast-growing trees and date palm fronds for particleboard production using urea formaldehyde as an adhesive, Hegazy and Aref [26] indicated that the water absorption properties of boards produced ranged from 27.1% to 72.7% for 2-hour water immersion and 38.4% - 87% for 24-hour water immersion. The manufactured particleboards could be suitable for producing cabinet, cladding and other interior fittings likely to be used in an environment which will minimize its exposure to moisture.

3.4. Thickness Swelling

Thickness swelling is perhaps the most important factor when considering moisture effects on particleboards and it is affected by process variables such as the type of biomass raw material, particle geometry, board density, resin level, blending efficiency, and pressing conditions [27]. Using cassava starch as an adhesive, the thickness swelling of the particleboards as indicated in **Table 4** ranged from 3.51% to 6.31% for 2-hour immersion and 13.93% to 21.49% for 24-hour immersion. Additionally, the thickness swelling of the particleboards with urea formaldehyde as an adhesive ranged from 3.38% to 4.75% for 2-hour immersion and 9.37% to 16.17% for 24-hour immersion. For both the 2-hour and 24-hour immersions, the thickness swelling of the particleboards with cassava starch as an adhesive was significantly higher (worse) than those produced using urea formaldehyde. This could be due to the higher hydrogen polymer

Table 4. Thickness swelling of particleboards produced from agro-forest residue.

Agro-forest residue	Thickness swelling (%)			
	2 Hours		24 Hours	
	Cassava starch	UF	Cassava starch	UF
Ceiba	5.03[b] (1.04)	3.91[a] (0.05)	17.27[c] (2.23)	13.22[b] (2.62)
Plantain pseudostem	3.51[a] (0.31)	3.38[a] (0.28)	11.47[a] (4.52)	9.37[a] (1.03)
Cocoa pod	6.31[b] (1.15)	4.75[a] (0.77)	21.49[d] (2.57)	16.17[c] (1.14)
Cocoa stem	3.67[a] (1.34)	3.61[a] (0.53)	13.93[b] (3.42)	11.24[a] (2.11)

Figures with the same letters are not significantly different according to Tukey's multiple tests.UF = Urea formaldehyde.

chains of the cassava starch which resulted in higher absorption of water leading to higher thickness swelling [28].

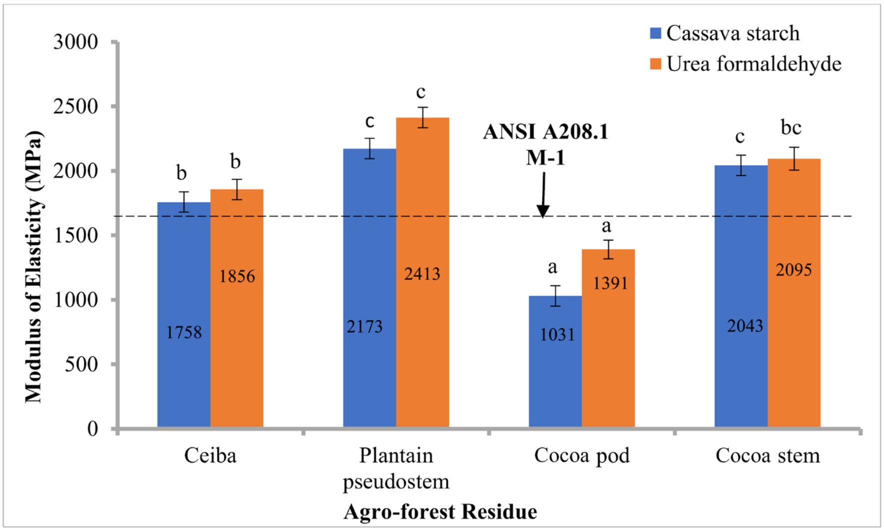
The results also indicate that for both 2-hour and 24-hour immersions, irrespective of the adhesive used, particleboards produced from cocoa pod had a relatively higher thickness swelling whilst those produced from *plantain pseudostem* showed minimum thickness swelling. The lower thickness swelling values of *plantain pseudostem* particles could be due to its low bulk density of 96.63 kg/m^3, which resulted in more compact boards, leading to better adhesion during hot pressing. Beside, the high bulk density of cocoa pod particles (323.96 kg/m^3) which could result in poor compaction, cocoa pod contains a high amount of parenchyma tissues which could lead to its greater affinity to absorb water [29] [30]. Kord *et al.* [31] indicated that the parenchyma tissues behaved like a sponge and also more hygroscopic compared to other cells. This therefore makes it easy for the panels to absorb water.

The thickness swelling of all the particleboards produced could be considered adequate since they were lower than that indicated in ANSI A208.1 [19] and EN 312-2005 [32]. According to ANSI A208.1 [19], particleboard for commercialization could have thickness swelling of up to 35% for 24-hour water immersion. Additionally, EN 312-2005 standards [32], indicate that particleboards should have a maximum thickness swelling of 8% and 15% for 2-hour and 24-hour water immersions respectively.

3.5. Modulus of Elasticity

The modulus of elasticity (MOE) obtained for the particleboards ranged from 1031 MPa to 2413 MPa (**Figure 6**). The highest MOE was obtained for particleboards produced from *plantain pseudostem* using urea formaldehyde as adhesive. The lowest MOE was obtained for particleboards produced from cocoa pod using cassava starch as adhesive.

With the exception of particleboards produced from cocoa pod, all the other particleboards had higher MOE than the minimum value required for particleboards by the America National Standard Institute ANSI A208.1 [19] which is 1550 MPa for general uses and furniture production.



NB: Bars with the same letter are not significantly different according to Turkey's multiple range tests

Figure 6. Modulus of elasticity of particleboards produced from agro-forest residue

The high MOE of the particleboards produced from *plantain pseudostem* particles could be attributed to its comparatively high aspect ratio which was more than twice that of the other materials. Bax and Mussig [15] indicated that the mechanical properties of particleboard positively correlate with the aspect ratio (particle geometry) of the biomass materials used for their production. The result (**Figure 6**) also indicates that for the same agro-forest residue there was no significant difference between the MOE of the particleboards produced using cassava starch as adhesive and that of urea formaldehyde. This suggests that cassava starch could be used to replace urea formaldehyde as an adhesive for producing particleboards.

3.6. Modulus of Rupture

Modulus of rupture (MOR) is a measure of the maximum load-carrying capacity of a member in bending and is proportional to maximum moment borne by the specimen. The MOR of the particleboards ranged from 4.95 MPa (cocoa pod) to 16.54 MPa (*Plantain pseudostem*) as indicated in **Figure 7**. With the exception of particleboards produced from cocoa pod using both cassava starch and urea formaldehyde adhesives all the other particleboards had MOR higher than the minimum value indicated by ANSI A208.1 [19] for MOR required for interior fitments (including furniture) which are 10 MPa.

Similar results were also stated for particleboards made using under utilized raw material as well as agricultural residues by Papadopoulos *et al.* [33], Tabarsa *et al.* [34], Azizi *et al.* [35], Khanjanzadeh *et al.* [36]. Similar to the result obtained for the MOE, all the particleboards produced using urea formaldehyde as an adhesive had higher MOR than their corresponding values which used cassava starch.

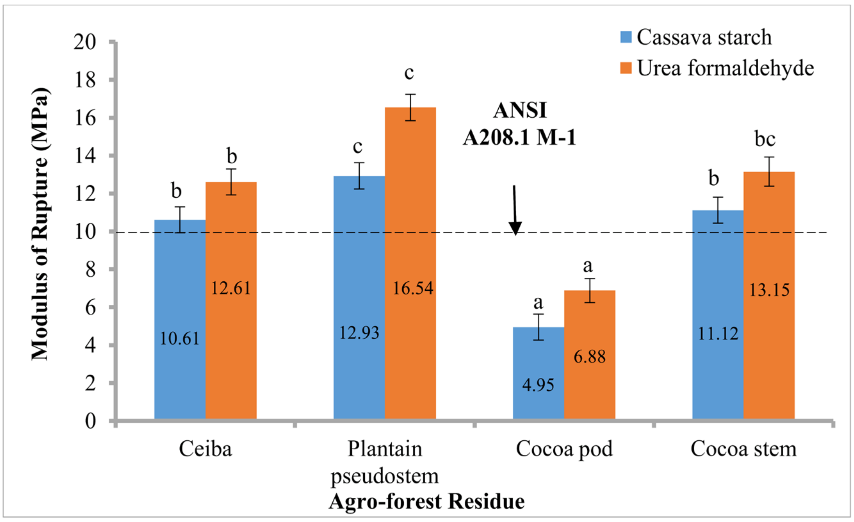
3.7. Internal Bond Strength

The internal bond (IB) of particleboards made with urea formaldehyde was higher than those produced with cassava starch (Table 5). *Plantain pseudostem* boards had the highest IB of 1.14 N/mm^2 and 0.97 N/mm^2 for both UF and cassava starch adhesives respectively, and boards from cocoa pods had the lowest IB of 0.63 N/mm^2.

This corresponds with the results of the aspect ratio of the particles of the agro-forest residues where *plantain pseudostem* had the highest aspect ratio of 135.03 and cocoa pods having no fibres. The boards with higher MOR and MOE had higher IB. The minimum value of internal bond required by ANSI A208.1 [19] is 0.5 N/mm^2 and according to EN 312 [32] is 0.40 N/mm^2 (for thickness of 6 - 13 mm). Therefore, the particleboards made comply with the standards.

3.8. Hardness

Figure 8 shows the hardness of particleboards produced and it indicates that the highest value which was 8.78 kN was obtained from *plantain pseudostem* boards



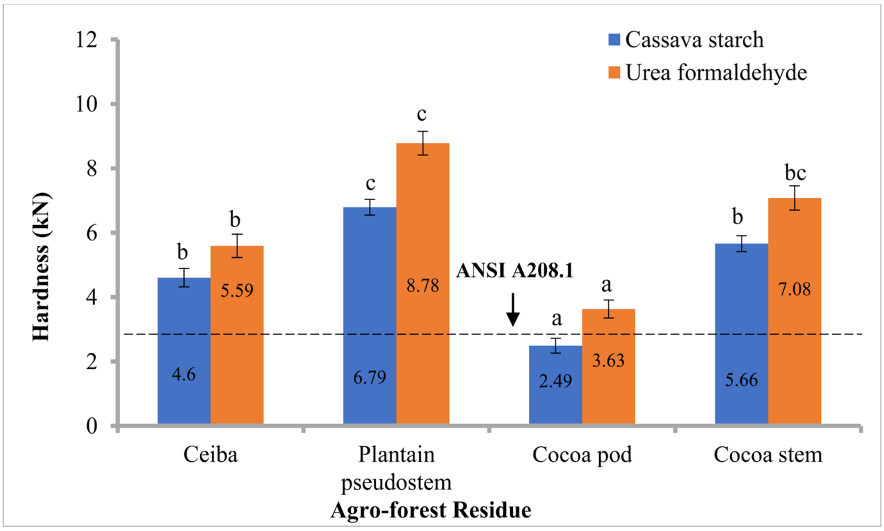
NB: Bars with the same letter are not significantly different according to Turkey's multiple range tests.

Figure 7. Modulus of rupture of particleboards produced from agro-forest residue.

Table 5. Internal bond strength of particleboards.

Agro-forest residue	Internal Bond (N/mm^2)	
	100% Cassava starch	100% Urea formaldehyde
Ceiba	0.76^a (0.09)	0.83^a (0.06)
Plantain pseudostem	0.97^b (0.05)	1.14^b (0.03)
Cocoa pod	0.58^c (0.03)	0.63^c (0.09)
Cocoa stem	0.70^a (0.04)	0.80^a (0.07)

Figures with the same letters are not significantly different according to Tukey's multiple tests. UF = Urea formaldehyde.



NB: Bars with the same letter are not significantly different according to Turkey's multiple range tests.

Figure 8. Hardness of particleboards produced from agro-forest residue.

using urea formaldehyde as an adhesive. The least hardness, 2.49 kN, was obtained for particleboards produced from cocoa pod using cassava starch as adhesive.

The results indicate that except for the particleboards produced from cocoa pods using cassava starch as adhesive, all the other particleboards produced had hardness higher than the ANSI A208.1 standard [19] for general purpose usage which is 2.8 kN. Therefore, *plantain pseudostem*, cocoa stem and ceiba sawdust \could be used to produce particleboards with adequate hardness for general purposes using cassava starch as adhesive. On the average, for the same agro-forest material the particleboard produced using urea formaldehyde was harder compared to those produced using cassava starch.

3.9. Scanning Electron Microscope (SEM) Analysis of the Manufactured Particleboards

The microstructural analysis of particleboards from cocoa pod using cassava starch and UF urea formaldehyde revealed major micro pores and loosed particles (**Figure 9(g)** and **Figure 9(h)**). It was observed that the particles were detached from the adhesives. The surface of the cocoa pod particleboard was very rough indicating that the bonding between the particles and the adhesive was poor. This could be as a result of high bulk density and low aspect ratio of the biomass material [37] [38].

On the contrary, specimen shown in **Figures 9(a)-(f)** indicated that the adhesives filled into the inter-particle spaces of the particleboards. This therefore led to better agglomeration and compaction of the particles and adhesives. This good interfacial bonding between the adhesive and the particles would result in improved mechanical strength [39].

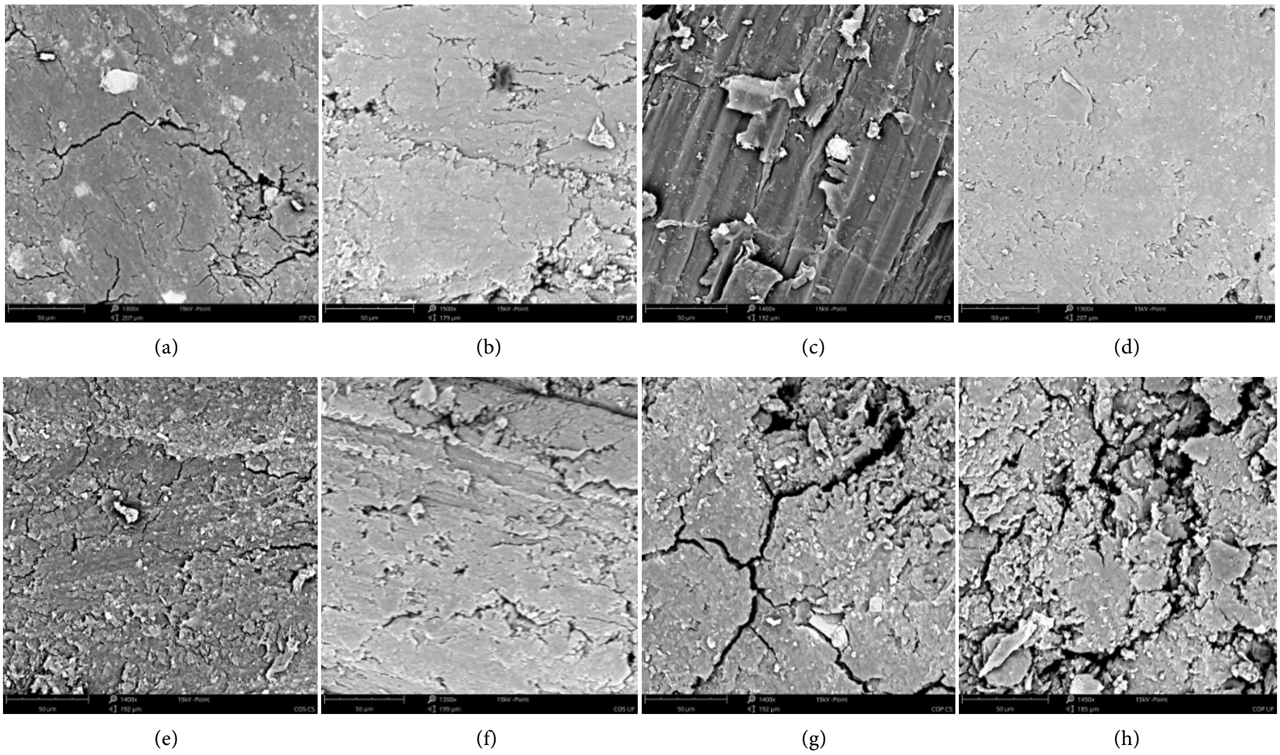


Figure 9. Show smooth surfaces indicating good compatibility between particles and adhesives. Figure 9(g) and Figure 9(h) show discontinuity of particles and adhesives, thus detached particles from adhesives surfaces. (a) C + CS; (b) C + UF; (c) PP + CS; (d) PP + UF; (e) CS + CS; (f) CS + UF; (g) CP + CS; (h) CP + UF. (**Legend**: C = Ceiba; PP = *Plantain pseudostem*; CP = Cocoa pod; CS = Cocoa stem; CS = Cassava starch: UF = Urea formaldehyde).

4. Conclusion

This study investigated the physical and mechanical properties of particleboards produced from cocoa stem and pod, *plantain pseudostem* and ceiba. The essence of this study was to investigate the suitability of the above mentioned agro-forest residues for making particleboards using cassava starch or urea formaldehyde as adhesive. It could be concluded from the study that with the exception of the particleboards produced from cocoa pod, those produced from all the other three agro-forest residues had characteristics that could allow them to be classified as low density composite boards. The physical and mechanical properties of the particleboards produced from cocoa stem, *plantain pseudostem* and ceiba were higher than that recommended by ANSI A208.1. Therefore, they could be used as a raw material for production of particleboards. Such composite boards so produced could be utilized for indoor applications and for general purposes under dry condition such as furniture manufacturing. It is recommended that a further study that seeks to blend cassava starch and urea formaldehyde as adhesive to produce particleboards be considered. Furthermore, it would be worthwhile considering a study that examines the effect of blending *plantain pseudostem* and cocoa pod on the physical and mechanical properties of particleboards produced.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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