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Production of Particleboard from Agricultural Waste - A Sustainable Approach to Waste Management

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Abstract

Large amounts of agricultural waste are left unutilized in Nigeria, resulting in detrimental environmental consequences. particleboard made from such trash would help to reduce deforestation and have a good impact on the environment. The characteristics of particleboard made from corncob (CC) and sugarcane bagasse (SB) with cassava starch and urea formaldehyde as separate binders were compared in this study. CC and SB mix proportions of 90:10, 70:30, and 50:50 percent (by volume) were used to make three layers of medium density particleboard. Manual mixing and blending of 25% and 10% by volume of the different binders and water respectively was done. The mixtures were compressed for 1 hour at 100 °C and 342 kg/m^2. The ASTM D. 1037-12 (2020) and EN 312 (2010) standards were used to evaluate the particleboard. However, particleboard produced from 90 % CC and 10 % SB with cassava starch binder had the greatest modulus of elasticity (MOE) of 444.65 N/mm^2 and modulus of rapture (MOR) of 10.59 N/mm^2. The MOR and MOE data from this investigation allowed researchers to draw the conclusion that while the mechanical qualities of the panels improved as the fraction of CC particles increased, the panels' physical characteristics remained subpar.

1. Introduction

Environmental Pollution generated by solid waste has become a massive source of concern worldwide as the amount of waste being released has become overwhelming [1]. Literature revealed that wastes such as kitchen, organic waste [2-5], metal, glass, plastic, and paper [6-8] can be converted into useful products/materials. These wastes can be categorized based on the degree of hazard they pose to the general human population [9-11] which includes radioactive waste material, inflammable material, and also materials that have fatal consequences when exposed to human beings [1].

The huge agricultural waste generated can be used to produce adsorbent [12], biogas [5,14], paper, pulp, and particle boards. Some variety of raw materials, in the form of tiny particles, are impregnated with resins or other reinforcement binders and pressed into particleboards [15-17]. Manufactured particleboards from Agricultural wastes are sustainable and affordable, as well as meeting today's comfort [18]. Agricultural products such as straw, cotton stalks, bagasse, corn stalk, rice husks, corn or maize cobs, coir, sunflower stalks, banana stalks, among others, have been identified as potential raw organic building materials [19,20].

The ratio of industrial waste generation has increased over the past five decades by 54 percent since 2005 [21]. The rate of deforestation, as well as its environmental effects, prompted manufacturers to look for alternative feedstock, especially in countries where wood is scarce compared to other cellulosic materials [22].

Furthermore, the global annual production of waste such as sawdust and agricultural residues is estimated at around 4 billion m^3, of which approximately 60 percent comes from agricultural residues and 40 percent from saw dust [22]. Burning waste items like corn cobs, sugarcane bagasse, etc. has resulted in significant environmental risks. According to data from [23], the biomass of corn burned increased by 57.6% between 2010 and 2017, while the biomass of sugarcane burned increased by almost 106%. This has resulted in a rise in the production of hazardous gases that contaminate the environment.

Particleboard is a panel constructed from lignocellulosic materials, most often wood, which has been composed of tiny particles or pieces and bound together with an adhesive using a hot press process where the adhesive helps to make the complete inter-particle bond [24,25]. Particleboard is among the most popular reassembled panel materials, and it's a great alternative to plywood. Over one hundred particleboard facilities are currently in operation around the world [26]. Several researchers have succeeded in making particleboards with a different binding agent. Research on the production of particleboard using rice husk, sawdust, and cement as a binder and came to the conclusion that the panels they produced might be utilized for non-structural uses such as partitions and ceilings [27]. Researcher implemented an experiment where urea formaldehyde and cassava starch were used separately as binders for particle boards and he reported that cassava starch may be utilized as a binder in the manufacturing of particleboards to replace the usage of urea formaldehyde adhesives, resulting in less indoor air pollution [12]. This means that different binding agents can be used as a replacement to decrease the over-dependence of urea formaldehyde resins and to minimize the amount of indoor pollution as tested in developing countries.

In the production of chipboards, they are produced in series. At the center is a hot press (stack or through-feed), which is used as the basis for all upstream and downstream processes. Chipboard – also sometimes referred to as Particle Board or Low-Density Fiberboard – is made by mixing small wood particles with epoxy resin, which are pressed together under intense heat and pressure to produce a rigid board, typically with a smooth surface. Chipboard, which is also called particle board in some places, is made from small pieces of timber obtained by shredding waste or recycled wood. The wood chips are mixed with a liquid plastic, which hardens when it is heated under pressure. The resulting sheets may be coated with wood veneer or another plastic.

The majority of peasant farmers in developing nations like Nigeria grow rice, maize/corn, palm trees, sugar cane, and a variety of other crops, followed by a substantial part of agricultural waste that is utilized as fuel or burned off in dumpsites, causing health problems [13]. Determination of the physical properties, mechanical properties, strength and extent of durability of particle board produced from maize cob and sugarcane bagasse particles using cassava starch and urea formaldehyde as an adhesive were studied in this work. Nevertheless, this study aims to investigate the physical and mechanical characteristics of particle boards produced from maize cobs and sugarcane bagasse using cassava starch and urea formaldehyde as a binding agent.

2. Materials and Method

The waste materials used in this study were Maize cob and Sugarcane bagasse. Fig. 1 shows the flow chart for the industrial setup for particle board production.

2.1 Research Design

Design of Experiment [DOE] was carried out because this research involves determining the impacts of two factors/variables: the species mix ratio (Corn cob & Sugarcane bagasse) and the binder (urea formaldehyde & cassava starch) on the particleboard's physical, mechanical, and durability properties. The study used a two-way factorial design with three treatments in a completely randomized manner. According to [18], when the researcher's goal is to establish a cause-and-effect link, a randomized experiment is the best study design.

2.2 Collection and Preparation of Corncob (CC)

Corncob residue was collected from a farm in Ota Ogun state Nigeria. The cobs were air dried for 3 days at room temperature (25-28 °C) [13]. Dried cobs were further oven dried to enhance milling. The air-dried particles were crushed with an Abrasion machine. The milled particles were sieved into two groups: <1mm and <4.75mm particle sizes, for core and face covering respectively. The sieve particles were batched as shown in Fig. 2.

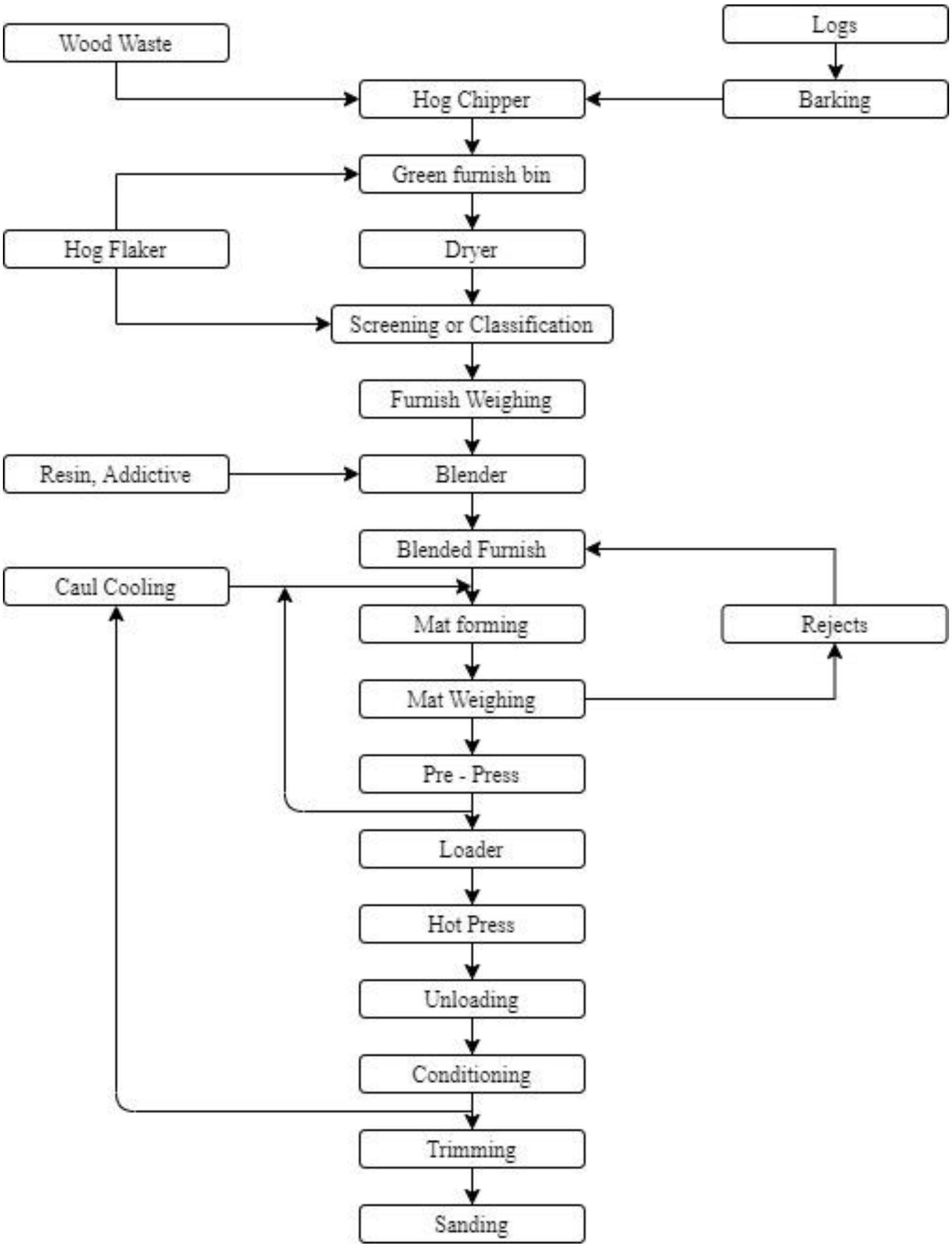

Fig. 1 *Flow chart for the industrial setup for particle board production [18]*

(a) (b) (c)

Fig. 2 *Corn cob particles; (a) CC ready to be crushed; (b) >1mm CC particles; (c) < 1mm CC particles*

2.3 Collection and Preparation of Sugarcane Bagasse (SB)

Sugarcane bagasse was obtained from the people of the Hausa tribe located in Ota, Ogun state. The sugarcane bagasse collected was then oven dried for 24 hours at 100°C to aid crushing. The oven dried particles were crushed with an Abrasion machine. The milled particles were sieved into two groups: < 1mm and < 4.75mm particle sizes, for core and surface covering respectively. The sieve particles were batched as shown in Fig. 3.

(a) (b) (c)

Fig. 3 *Sugarcane particles; (a) SB ready to be crushed; (b) >1mm SB particles; (c) < 1mm SB particles*

2.4 Preparation of Cassava Starch

Manihot Exculenta (specie of cassava) was obtained from Ota market, Ogun State, Nigeria and processed using the method of [28]. This starch was air dried for five days at an average humidity and temperature of 75% and 25 – 30°C respectively to obtain the powdered form of the cassava starch as shown in Fig. 4.

Fig. 4 *Cassava starch*

2.5 Mold Box Preparation

Aluminum composite panel and wood was used to make 6 mold boxes with inner dimensions of 26cm by 22.5cm by 2cm for the preparation of sample particleboard as shown in Fig. 5. The mold box was fabricated in the Foundry Department of Covenant University, Ota Ogun state.

Fig. 5 *Aluminium mold boxes for particleboard pressing*

2.6 Preparation of Moisture Content of Materials

The effect of binder and mix ratio of Maize cob and Sugarcane bagasse on quality of particle board produced were investigated. Maize cob and Sugarcane bagasse were prepared in the following ratios: 90:10, 70:30 and 50:50. The selection of the mix ratios was based on literature [12].

2.7 Determination of Moisture Content of Materials

Before mat formation, the moisture content of the graded particles was determined. This was carried out in compliance with ASTM guidelines. A sample of 2g of corn cob and Sugarcane bagasse particles was weighed into a grass disc and dried in a laboratory oven at a temperature of 100^{0}C for two hours. The specimen's oven-dry moisture content was calculated as follows:

$$Moisture\ Content\ (\%) = \frac{M_1 - M_0}{M_0} X\ 100 \tag{1}$$

Where, M_1 is mass of the test sample drying (g), and M_0 is oven-dry mass of the test sample (g).

2.8 Mat Forming and Pressing

For each sample of particleboard, the amounts of all the materials used are shown in Table 1.

Table 1 *Quantity of raw materials needed for particle board manufacturing*

Materials	Amount (cm^3)
Particles (Corn cob and Sugarcane bagasse	1212
Binder (Urea formaldehyde and cassava starch)	303
Water	121.2

The liquid adhesive (cassava starch powder and water) and the particles were mixed and blended together manually in a head pan with a hand trowel at the Highway and transportation lab in Civil engineering department, Covenant University. Three layers of particle boards were formed using the fabricated mold. Each surface layer comprises of 20% fine particles while in the core are concentrated the other 70% of coarse particles.

The mixture was evenly spread in 26cm by 22.5cm by 2cm box. The mats consisted of inserting the section of particles that correspond to one of the faces of the mold, followed by the core part and toping them to form the top layer with the second half of the tiny particles. This method was used to produce all the boards with their different mix ratios. The mattresses were cold pressed with a pressure of 342kg/m^2 for one hour. The pressure is then removed and the mat is placed in the oven at 100^{o}C for 24 hours to facilitate the bonding of the particles. The board is taken from the mat and air dried for 7 days at room temperature. Table 2 shows the pressing parameter of the boards produced.

Table 2 *Production parameters of particleboard*

Parameters	Value
Pressing Temperature (^{o} C)	130
Pressing Time (mins)	60
Press Pressure (kg/m^2)	342
Thickness (mm)	20
Target Density (kg/m^3)	800

2.9 Particleboard Finishing

After 7 days of air drying the particle boards, they were squared by cutting with a saw machine to obtain boards as shown in Fig. 6. The boards were then transferred to the Wood and Carpentry workshop in Civil Engineering Department, Covenant University, Ota. After 24 hours, the test samples were cut in accordance with ASTM, ANSI, and EN 252 for testing particleboard strength properties. These test samples were then taken for their respective tests.

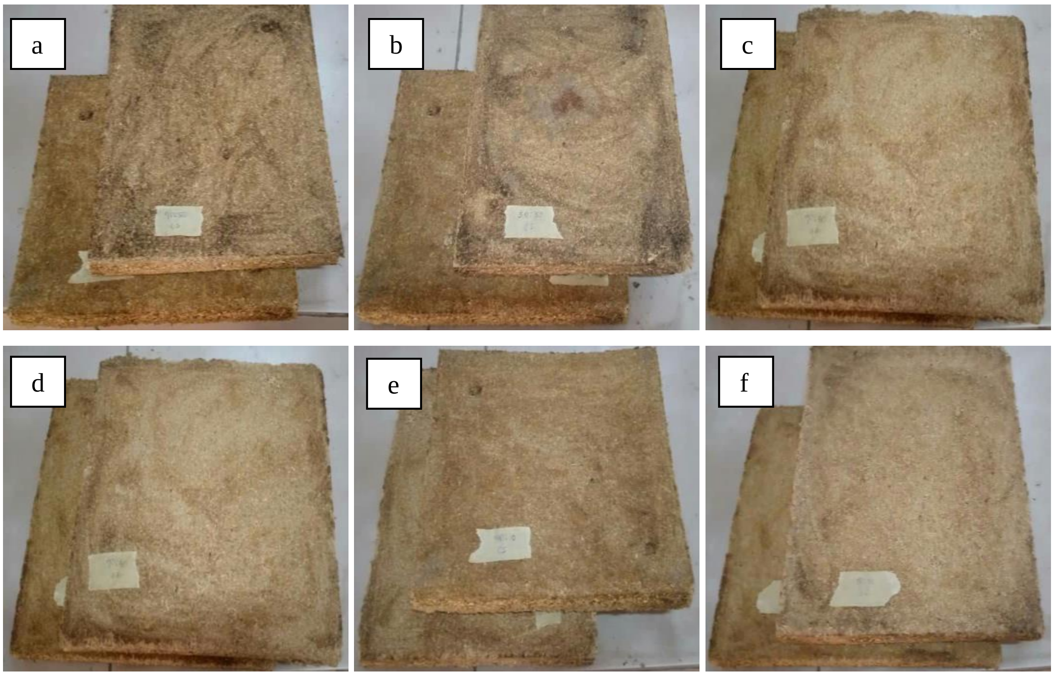

Fig. 6 *Particleboards produced and their ratios; (a) 90:10 mix ratio; cassava starch; (b) 70:30 mix ratio; cassava starch; (c) 50:50 mix ratio; cassava starch; (d) 90:10 mix ratio; urea formaldehyde; (e) 70:30 mix ratio; urea formaldehyde; and (f) 50:50 mix ratio; urea formaldehyde*

2.10 Determination of Physical and Mechanical Properties of the Particleboard

The following physical properties were examined: Density (D), water absorption (WA), moisture content (MC), and thickness swelling (TS). Mechanical properties such as modulus of rapture (MOR) and modulus of elasticity (MOE) were evaluated using the American Standard of Testing Materials (ASTM, 2020), ANSI (2009), and EN 312 standards (2010). Ten test specimens were cut from each mix ratio (90:10, 70:30, and 50:50 – sugarcane bagasse and corn cob, respectively) of particleboard of each binder (urea formaldehyde and cassava starch) for physical, mechanical, and durability testing. According to the standards of each test, the samples were sawn to 30mm x 20mm x 20mm for density and moisture content testing, 150mm x 50mm x 20mm for WA and TS testing, and 250mm x 20mm x 20mm for bending test (MOE & MOR). Table 3 shows the description of particleboard specimens.

Table 3 *Description of particleboard specimens*

Specimen	Materials Mix ratio		Binder
	Corn cobs (%)	Sugarcane bagasse (%)	
A	90	10	Cassava starch
B	70	30	Cassava starch
C	50	50	Cassava starch
D	90	10	Urea Formaldehyde
E	70	30	Urea Formaldehyde
F	50	50	Urea Formaldehyde

2.11 Determination of Density of Corn Cob and Sugarcane Bagasse Particleboard

The density of the pressed board was measured using ASTM D – 1037-96a. The specimens' oven dry masses were determined by weighing them with an electronic balance after they were placed in an oven to achieve a consistent weight. The density of each test sample was determined using the oven – dry method, which involves dividing the specimen's dry mass by its volume in the oven. After that, the density of each specimen was calculated as in Eq. 2, where the density of each test sample was measured and calculated for each mix ratio.

$$Density = \frac{oven\ dry\ mass}{Volume\ of\ the\ specimen} \quad (2)$$

2.12 Determination of Moisture Content of Corn Cob and Sugarcane Bagasse

The moisture content of the pressed boards was determined according to ASTM D – 1037-96a procedures. As indicated in Fig. 7, ten test samples (10) were sawn from each treatment beneath two parts with dimensions of 30mm x 20mm x 20mm. After weighing the specimens on the electronic balance, the initial weight of the test samples was recorded. After that, the specimens were dried in a laboratory oven at 100 °C for three days until a steady mass was reported after three repeated weightings. For calculating the oven dry moisture content of the specimen, the following formula was used:

$$Moisture\ Content\ [MC]\ (\%) = \frac{M_1 - M_0}{M_0}\ X\ 100 \tag{3}$$

Where; MC is moisture content, M1 is mass of the test sample drying (g), M_0 is oven-dry mass of the test sample (g), and every mix ratio was determined with the moisture content of the test sample.

Fig. 7 *Density and moisture content test samples*

2.13 Determination of Thickness Swelling of Corn Cob and Sugarcane Bagasse Particleboard

The particle board was tested for thickness swelling according to ASTM standards D. 1037 – 99 (ASTM, 2020) and American National Standards for particleboard (ANSI, 2009). To investigate the long-term water resistance qualities of the corn cob and sugarcane bagasse particleboard, rectangular test samples with dimensions of 150mm x 50mm x 20mm were soaked in water at room temperature (25–28^{o}C) for 24 hours (Fig. 8). The thickness of the specimens with a veneer caliper was measured before the soaking. The thickness of the samples was measured immediately after two hours and then again after 24 hours of soaking, in order to calculate the sample thickness of swelling. The TS was determined from the [26] formula:

$$TS_n = \frac{(t_n - t_0)}{t_0}\ X\ 100 \tag{4}$$

Where, TS_n is thickness swelling rate (%), t_0 is the initial thickness of test samples before soaking in water, t_n is the final thickness of test samples after soaking in water for n hours, n is no of hours, and the thickness swelling rate of the test sample was replicated eight times from each treatment.

Fig. 8 *Thickness swelling and water absorption test samples*

2.14 Determination of Water Absorption of Corn Cob and Sugarcane Bagasse Particleboard

The 24 hours water absorption (WA) test was carried out in accordance with ASTM D. 1037-99. Each WA specimen was constructed with 150mm x 50mm x 20mm dimensions and weighed (W_0) (Fig. 7). As shown in Fig. 7, the samples were next submerged in water at room temperature for 24 hours. The specimens were removed from the water after a 24-hour immersion process, and the surfaces were cleaned with a clean dry cloth. Within three minutes of taking the test samples from the water, they were reweighed to the nearest 0.01 g. The following formula to calculate the water absorption rate [12]:

$$WA_n = \frac{(W_n - W_0)}{W_0} X\ 100 \tag{5}$$

Where, WA_n is the water absorption rate (%), W_0 is an initial weight of test samples before soaking in water, W_n is the final weight of test samples after soaking in water for n hours, and n is no of hours. The water absorption rate of the test sample was replicated eight times from each mix ratio.

2.15 Mechanical Properties

Particleboards were finished and sliced into six test samples using ASTM techniques (D 1037 – 99) as shown in Fig. 9. The Modulus of Rapture (MOR) and Modulus of Elasticity (MOE) were determined using rectangular specimens of 225mm x 20mm x 20mm. MOE and MOR were evaluated using a Universal Testing Machine At 3.5mm/min, the crosshead moved. At 3.5mm/min the test samples (particleboard) had been loaded to fracture or break. The maximum force that caused the test sample to fracture was recorded in order to determine the outputs (MOE & MOR).

(a) (b)

Fig. 9 *Mechanical testing samples and test set-up; (a) MOR and MOE test samples. And (b) test setup*

2.16 Modulus of Elasticity (MOE)

The MOE of the samples were calculated according to ASTM standards Designation: 1037-99. Six test samples were tested and computed using the formula:

$$MOE = \frac{P'L^3}{4\Delta' b d^3} \tag{6}$$

Where, P is a load at limit of proportionality (N), L is a span or length of the test piece (mm), Δ is a deflection at mid length at limit of proportionality, b is a breadth of test sample, and d is a depth of the test sample. Modulus of elasticity test was replicated eight times from the experiment.

2.17 Modulus of Rupture (MOR)

The MOR of the test samples at given moisture content was computed at an adjustment of strength at 12% MC by the formula [29]:

$$MOR = \frac{3pl}{2bd^2} \tag{7}$$

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Where, P is the maximum load (N), l is a span of the specimen (mm), b is a width of the specimen (mm), and d is the depth of the specimen (mm). Modulus of rupture test was replicated eight times from the treatment.

3. Results and Discussion

3.1 Physical Properties of Sugarcane Bagasse and Corn Cob Particleboard Made with Urea Formaldehyde and Cassava Starch as Binder

3.1.1 Density

The densities of Particle board made from corn cob and sugarcane bagasse with the urea-formaldehyde binder or cassava starch as a binder is shown in Fig. 10. According to the findings, particleboard made from 90 percent corn cobs and 10 percent sugarcane bagasse using cassava starch as a binder had a maximum density of 634.4 kg/m^3. Using urea-formaldehyde as an adhesive, 50 percent maize cobs and 50% sugarcane bagasse particles were combined to produce the least dense particleboard (491.37 kg/m^3).

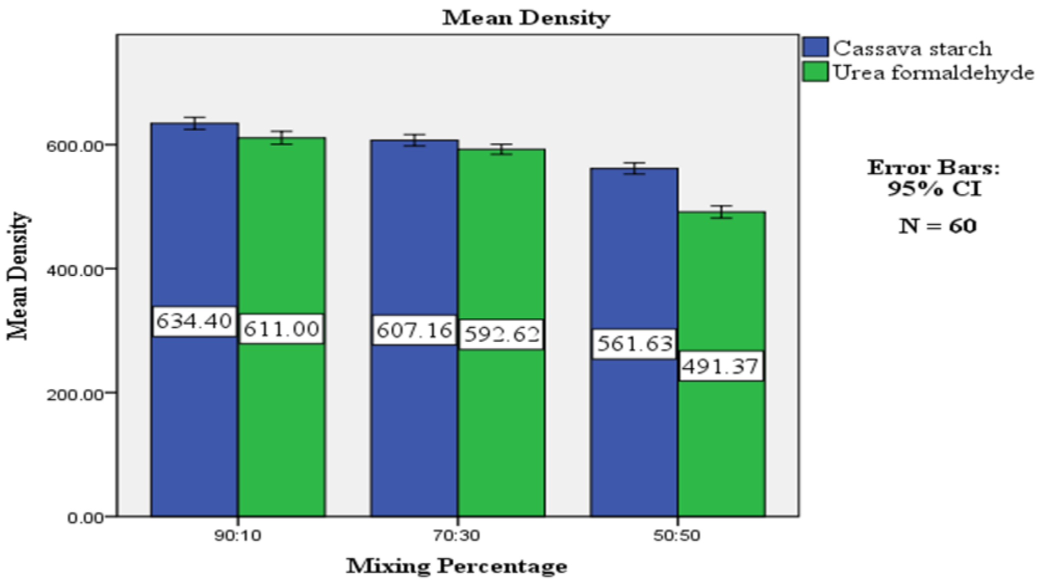

Fig. 10 *Mean density of particle boards produced in different ratios*

The densities of particleboards made with cassava starch as a binder were generally higher than those made with urea-formaldehyde adhesive. Furthermore, the density of particleboard produced increased as the quantity of maize cobs in the mixture increased for both binders. The density values obtained had a positive significant connection with the proportion of corn cobs mixture (Pearson's r = 0.817 P-value = <0.01, N = 60, 1-tailed a = 0.01).

The findings of a two-way ANOVA to investigate the influence of mixing percentage, Binder, and their interaction on the density of particleboard made from maize cobs and sugarcane bagasse are presented in Table 4. At a 5% level of significance, the results demonstrate that the mixing percentage, Binder, and their interaction had a significant effect on the density of the particleboard generated (P = 0.05).

Table 4 *ANOVA of the effects of mixing percentages, binder and their interactions on the density of particleboard*

Source	Sum of squares	DF	Mean square	F	Significance
Mixing percentage	101072.188	2	50536.094	295.088	0.0001-
Binder	19512.067	1	19512.067	113.934	0.0001-
Mixing percentage and binder	8965.129	2	4482.565	26.174	0.0001-
Total	129549.384	5			

- Statistically significant at 0.01 level of significance
DF = Degree of Freedom

The ANOVA model's multiple co-efficient of determination R^2 value is 0.933. As a result, the R^2 value of 0.933 indicates that the experimental factors analyzed could explain around 93.3 percent of the variance in particleboard density.

The Particle board produced has a density ranging from 491.37 kg/m³ to 634.4 kg/m³. According to ANSI (2009), medium-density particleboards range from 590 kg/m³ to 815 kg/m³ in density, while boards with low and high density have densities of less than 590 kg/m³ and more than 815 kg/m³, respectively. As a result, all particleboards produced meets the medium density particleboard certification, except for particleboards made from 50% Sugarcane bagasse and 50% maize cobs particles. (491.37 kg/m³ and 561.63 kg/m³). It was observed that the densities of particleboard produced using urea-formaldehyde were lower than their corresponding values for cassava starch adhesives. This implies that the type of adhesive used affects particleboard density. A study performed by [30] showed similar results. They explained that differences in the granular structure of the wood particles and the amount of Binder influence the density of the particleboard. This could be due to the carbohydrate functional group that developed during the sun drying of cassava starch. It has been reported that carbohydrate functional groups' presence was linked to the expansion performance during heating [31].

The particleboard density for both binders used increased with increasing corn cobs proportion in the mixture. [32] also reported similar results from 400 to 620 kg/m³ when evaluating the properties of particleboard made from varying proportions of corncobs and sugarcane bagasse. [34] also had similar findings when evaluating the density of pinewood and corncob particleboards. The density values they recorded increased from 630 kg/m³ (100:0 pinewood: corncob) to 680 kg/m³ (25:75 pinewoods: corncob). The particleboards were produced with constant pressure; an increased pressure could have increased the densities of the resulting particleboards produced to meet the requirements of the medium density particleboard certifications. [32] discovered that increasing the pressure of the press reduces the voids in the mat and compacts the particles better, hence, increasing the particleboard density.

3.1.2 Moisture Content and Statistical Analysis

The moisture content of Particleboard made by mixing maize cob and sugarcane bagasse particles with urea formaldehyde or cassava starch as a binder is shown in Fig. 11. The highest moisture content of 17.29 percent was attained from 10 percent maize cob and 10 percent sugarcane bagasse with urea formaldehyde as Binder. The particleboard with the lowest moisture content (11.4%) was made from 50 percent maize cob and 50% sugarcane bagasse, with cassava starch as a binder. Particleboard moisture content was found to range from 11.53 percent to 17.29 percent. The moisture content of particleboard made with cassava starch as a binder was generally lower than the moisture content of particleboard made with urea formaldehyde adhesives.

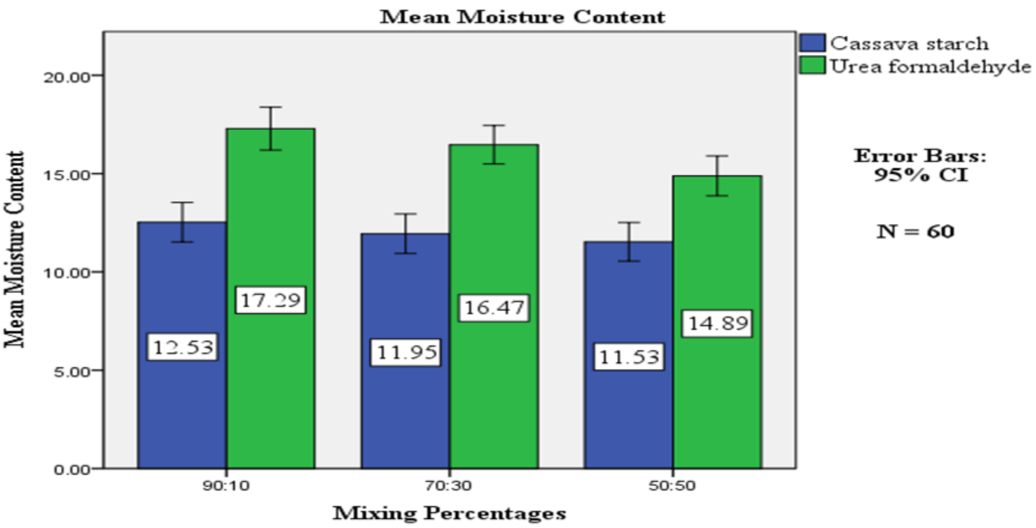

Fig. 11 *Mean moisture content of particle boards produced in different ratios*

The moisture content of particleboard made with both binders dropped as the quantity of maize cobs in the mixture decreased. A positive significant association was found between the amount of corn cobs in the mixture and the moisture content values (Pearson's r = 0.266, P-value = <0.05, N = 60, 1-tailed a = 0.05).

The outcomes of a two-way analysis of variance (ANOVA) were used to assess the influence of mixing percentages, Binder, and their interaction on the moisture content of the particleboard produced, as shown in Table 5. The results show that mixing percentage and Binder had significant influence on the moisture content of particleboard generated (P-value 0.05) at a 5% level of significance but their interactions are not statistically significant (0.255) at that level of significance.

Table 5 *ANOVA of the effects of mixing percentages, binder and their interactions on the moisture content of particleboard*

Source	Sum of squares	DF	Mean square	F	Significance
Mixing percentage	29.216	2	14.608	7.271	0.002-
Binder	266.325	1	266.325	132.561	0.0001-
Mixing percentage and binder	5.634	2	2.817	1.402	0.255+
Total	12348.701	60			

- Statistically significant at 0.01 level of significance, + Not statistically significant at 0.01 level of significance
DF = Degree of Freedom

The ANOVA model's multiple co-efficient of determination R^2 value is 0.735. As a result, the R^2 value of 0.735 indicates that the experimental factors analyzed could explain around 73.5 percent of the variance in particleboard density.

The moisture content of a particleboard is a fundamental parameter that influences its dimensional changes both in the plane and thickness of the board. The percentage moisture content of the particle boards produced ranged from 11.53% to 17.29%. The American Standards National institute (ANSI) state that the moisture content of medium density particleboards should not exceed 10%, therefore all the particleboards produced using both binders met the certifications of low-density particleboard (ANSI, 2009). This moisture content percentage can be ascribed to the press temperature of the particleboard. [34] is of the opinion that particleboard can be produced at high temperature to achieve low moisture content to conform ANSI standards. They explained this theory when they produced particleboard using rubber wood at high temperature of 200 °C to achieve moisture content of 4% to 6%. Nonetheless, the percentage moisture content of the particleboards produced with cassava starch as Binder were lower than the corresponding particleboard mix ratios using urea formaldehyde as an adhesive. This could be associated with the gel time of urea formaldehyde. At 100 °C, cassava starch hardens faster than urea formaldehyde as an adhesive. This means that cassava starch particles dry and solidify faster at a press temperature of 130 °C, effectively concealing particleboard pores.

The moisture content of particleboard made with both binders increased as the percentage of maize cob particles in the combination increased. This could be traced to the chemical components (extractives) of corn cob. The moisture content is inversely proportional to the extractives content; the higher the extractives content, the lower the moisture content [35]. The removal of chemical substances such as extractives from the species caused an increase in the moisture content of the particleboard produced, according to [36]. According to the results, particleboards should be pressed at a higher temperature and pressure with a combination of 50 percent corncob and 50 percent sugarcane bagasse to meet the ANSI criteria for medium density particleboard certification.

3.1.3 Thickness Swelling and Statistical Analysis

Fig. 12 shows the results of a test to determine the thickness swelling rate of particleboard made from corn cob and sugarcane bagasse particles using urea formaldehyde adhesives or cassava starch as a binder after 24 hours. particleboard generated has a thickness swelling rate ranging from 11.90 percent to 15.98 percent. particleboard made from 90 percent maize cob and 10 percent sugarcane bagasse and bonded with urea formaldehyde adhesives had the maximum thickness swelling rate of 15.98%. The particleboard with the lowest thickness swelling rate (11.90%) was made by blending 50 percent maize cob and 50 percent sugarcane bagasse particles with cassava starch as a binder. The lesser the thickness swelling, the more suitable it is for humid conditions.

The thickness swelling rate of particleboard made with cassava starch as a binder was, on average, lower than that of urea formaldehydes adhesives. Furthermore, the thickness swelling rate of particleboard rose with increasing corn cob proportion in the mixture for both binders. The amount of corn cobs in the mixture had a positive correlation with the thickness swelling values [Pearson's r = 0.759, P-value = <0.01, N = 48, 1-tailed test = 0.01].

The outcomes of a two-way analysis of variance (ANOVA) were used to assess the influence of mixing percentages, binder, and their interaction on the thickness swelling of the particleboard produced, as shown in Table 6. The results show that mixing percentage and binder had significant influence on the thickness swelling of particleboard generated (P-value 0.05) at a 5% level of significance but the interaction between mixing percentages and Binder are not statistically significant (0.434) at that level of significance.

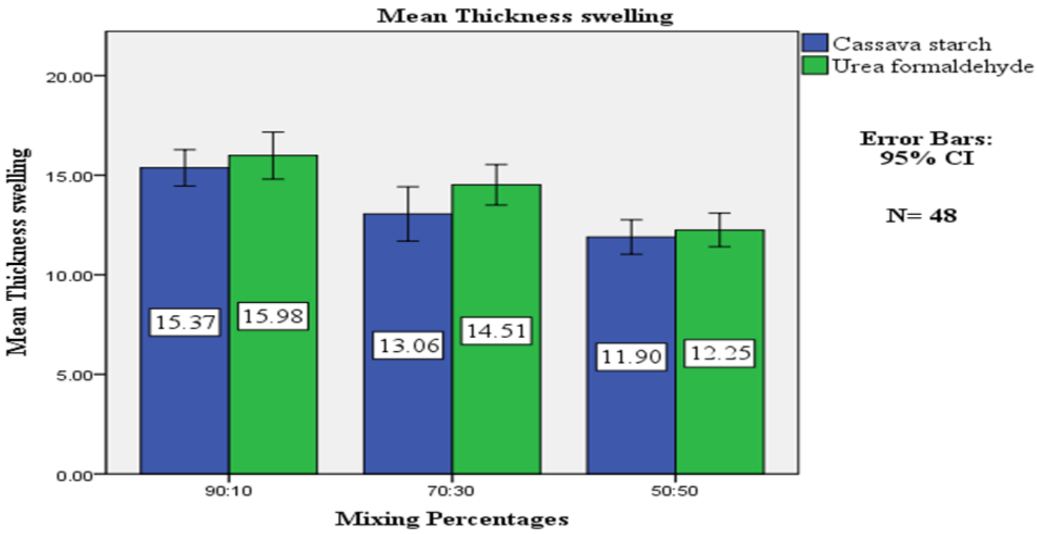

Fig. 12 *Mean thickness swelling of particle boards produced in different ratios*

Table 6 *ANOVA of the effects of mixing percentages, binder and their interactions on the moisture content of particleboard*

Source	Sum of squares	DF	Mean square	F	Significance
Mixing percentage	104.055	2	52.0.27	33.254	0.0001-
Binder	7.865	1	7.865	5.027	0.030*
Mixing percentage and binder	2.666	2	1.333	0.852	0.434+
Total	9380.299	48			

- Statistically significant at 0.01 level of significance, * statistically significant at 0.05 level of significance, + Not statistically significant at 0.05 level of significance
DF = Degree of Freedom

The ANOVA model's multiple co-efficient of determination R^2 value is 0.636. As a result, the R^2 value of 0.636 indicates that the experimental factors analyzed could explain around 63.6 percent of the variance in particleboard swelling rate.

Thickness swelling is the act of wood particles expanding or inflating when submerged in water for an extended period of time. The swelling rate determines the particles' ability to resist expansion; the lower the swelling rate, the better the board's dimensional stability. Particleboard thickness swelling rates ranged from 8.89 percent to 11.97 percent after two hours of soaking and 11.90 percent to 15.98 percent after 24 hours of immersion in water The maximum thickness swelling requirement for 2- and 24-hours water immersion are 8% and 15%, according to European Standards (EN 312, 2010) for medium density particleboard.

As a result, any particleboard made with both binders (urea formaldehyde and cassava starch) did not certify the specifications of medium density particleboard. This could be attributed to the fact that the board was not automatically hot pressed as it was supposed to so the compacting and bonding of the boards did not occur evenly. [32] reported similar values as the particleboard they produced was heated in the oven rather than automatically hot pressed. They reported thickness swelling values between 21.5 percent and 12.5 percent. Also, the high thickness welling values could also be attributed to the quantity of Binder used. An increase in the binder percentage could cause the thickness swelling rate to reduce. [37], obtained similar correlation when testing for thickness swelling of particleboards made from coffee waste and increasing quantities of urea formaldehyde.

The thickness swelling rate values of particleboard made with cassava starch as a binder were, on average, lower than those of urea formaldehyde adhesives. Furthermore, as the quantity of corn cobs particles in the combination rose, the thickness swelling rate increased for both binders. This could be due to the pith from the corn cob, which was used to make the particleboard. Pith is made up of parenchyma cells, which are softer than the rest of the cells, naturally spongy, and have a large expansion capacity [38,39]. [32] also reported increase in the 24-hour thickness swelling values from 12.5% to 21.5% as the percentage of corncobs increased from 0 to 100%.

3.1.4 Water Absorption and Statistical Analysis

Fig. 13 shows the results of a test to determine the water absorption rate of particleboard made from corn cob and sugarcane bagasse particles using urea formaldehyde adhesives or cassava starch as a binder after 24 hours. particleboard generated has a water absorption rate ranging from 48.89 percent to 71.53 percent. Particleboard made from 90 percent maize cob and 10 percent sugarcane bagasse and bonded with urea formaldehyde adhesives had the maximum water absorption rate of 71.53%. The particleboard with the lowest water absorption rate (48.89%) was made by blending 50 percent maize cob and 50 percent sugarcane bagasse particles with cassava starch as a binder. The lesser the water absorption, the more suitable it is for humid conditions.

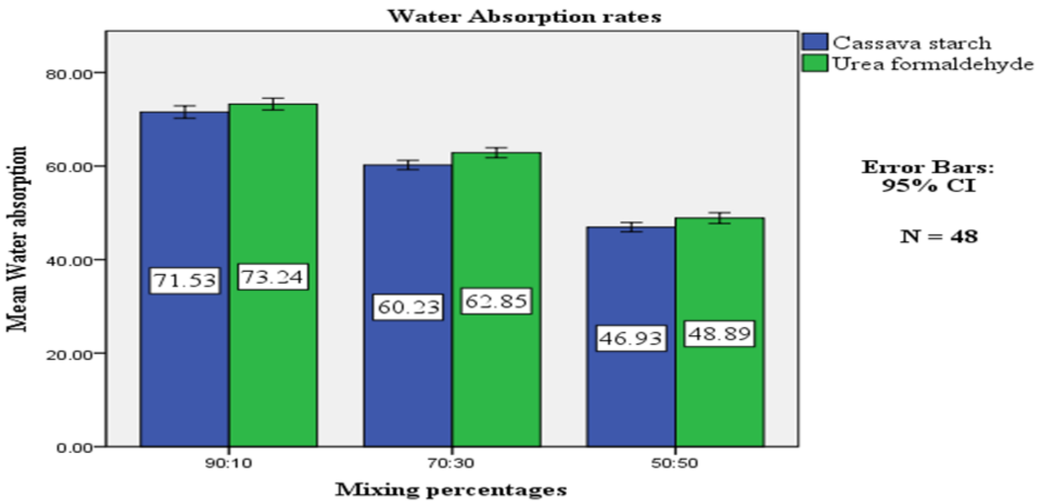

Fig. 13 *Mean water absorption of particle boards produced in different ratios*

The water absorption rate of particleboard made with cassava starch as a binder was, on average, lower than that of urea formaldehydes adhesives. Furthermore, the water absorption rate of particleboard rose with increasing corn cob proportion in the mixture for both binders. The amount of corn cobs in the mixture had a positive correlation with the water absorption values [Pearson's r = 0.984, P-value = <0.01, N = 48, 1-tailed test = 0.01].

The outcomes of a two-way analysis of variance (ANOVA) were used to assess the influence of mixing percentages, Binder, and their interaction on the water absorption of the particleboard produced, as shown in Table 7. The results show that mixing percentage and Binder had significant influence on the water absorption of particleboard generated (P-value 0.01) at a 1% level of significance but the interaction between mixing percentages and Binder was not statistically significant (0.624) at that level of significance.

Table 7 *ANOVA of the effects of mixing percentages, binder and their interactions on the water absorption of particleboard*

Source	Sum of squares	DF	Mean square	F	Significance
Mixing percentage	52.878	1	52.878	28.439	0.0001$^-$
Binder	4814.884	2	2407.442	1294.765	0.0001$^-$
Mixing percentage and binder	1.777	2	0.888	0.478	0.624$^+$
Total	181291.215	48			

$^-$ Statistically significant at 0.01 level of significance, $^+$ Not statistically significant at 0.01 level of significance
DF = Degree of Freedom

The ANOVA model's multiple co-efficient of determination R^2 value is 0.984. As a result, the R^2 value of 0.984 indicates that the experimental factors analyzed could explain around 98.4 percent of the variance in particleboard water absorption rate.

After 2 hours of immersion, the water absorption rate varied from 45 percent to 50.15 percent while after 24 hours of water immersion, the water absorption rates varied from 46.93 percent to 73.24 percent. In general, particleboard made with cassava starch as a binder had lower water absorption rates than particleboard made with urea formaldehyde adhesives. However, the binding values obtained correlate with those found by [40] when testing particleboard panels made from castor husk with a density of 700kg/m^3 and a 10% urea formaldehyde adhesive. They discovered that the rate of water absorption has increased from 56 percent to 68 percent. When coffee husk and eucalyptus particles were combined, [41] achieved the maximum water absorption rate of 96 percent.

The water absorption rate of particleboard made with both binders rose as the quantity of maize cobs in the mixture increased. Water had adequate time to permeate through the entire particleboard structure during the 24-hour soaking, and because corn cob is a low-density residue, it absorbed more water than sugarcane bagasse particles. When analyzing the physical features of particleboard manufactured from maize cob and pinewood, [33] found a similar growing propensity for water absorption after 24 hours particleboard immersion. Thickness swelling rates of 73 percent [particleboard constructed from 75 percent pinewood and 25 percent maize cob] and 82 percent [board built from 25 percent pinewood and 75 percent maize cob] were recorded.

Apart from the mixing percentages of wood particles and agricultural residue, other factors such as temperature, according to [42] could influence the water absorption rate. The particle geometry, which provided a bigger surface area, is another aspect that could impact a higher water absorption rate. Because it produces a larger contact area and lowers the availability of adhesive per particle, a larger superficial area allows for greater water absorption [43]. The hydrophilic character of both particles, according to [43] could potentially account for the greater water absorption rate. They are both porous hydrophilic composites made up of cellulose, lignin, and hemicellulose polymers containing functional groups such as hydroxyls that hydrogen bind easily with water molecules [22]. Because lignin is a natural wood binder, water absorption values of particleboards constructed from high lignin content materials are lower due to enhanced bond formation between particles during the forming process, according to [44]. Based on the findings, the particleboards best blend is 70% corncobs and 30% sugarcane bagasse particles with cassava starch as a binder.

3.2 Mechanical Properties

3.2.1 Modulus of Elasticity (MOE) and Statistical Analysis

Fig. 14 shows the modulus of elasticity of particleboard made from corn cob and sugarcane bagasse with urea formaldehyde or cassava starch as a binder in this section of the study. Particleboard's modulus of elasticity ranges from 444.53 N/mm^2 to 231.33 N/mm^2. The particleboard with the highest modulus of elasticity (444.53 N/mm^2) was made from 90% corn cob and 10% sugarcane bagasse, with cassava starch as a binder. The particleboard with the lowest modulus of elasticity, 231.33 N/mm^2, was made by blending 50 percent corncob and 50 percent sugarcane bagasse particles with urea formaldehyde adhesive.

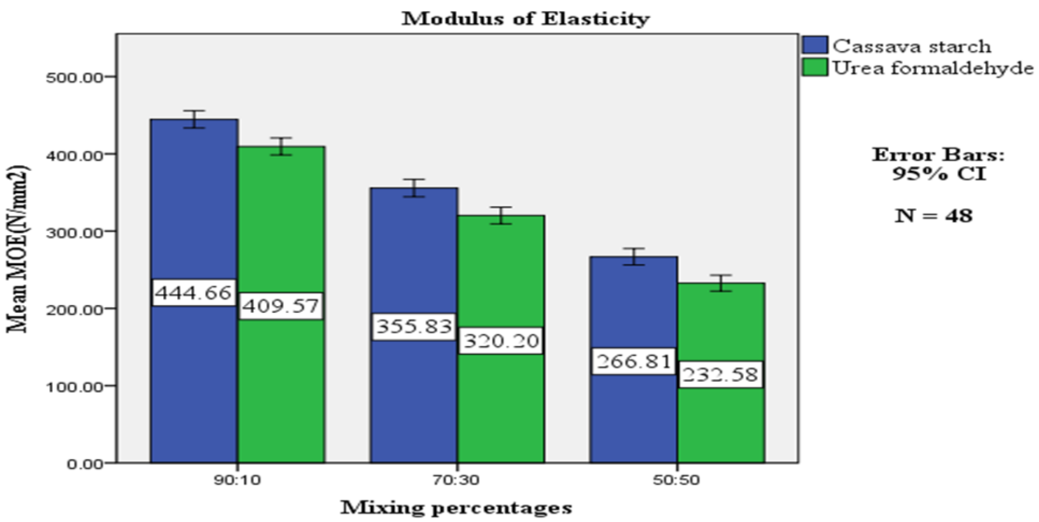

Fig. 14 *Mean MOE of particle boards produced in different ratios*

Furthermore, when the amount of corn cob in the combination grew, the value of the modulus of elasticity of particleboard produced increased for both binders. The amount of corn cobs in the combination had a positive significant association with the modulus of elasticity values obtained (Pearson's r = 0.959, p-value = 0.001, N = 48).

The findings of a two-way ANOVA to investigate the influence of mixing percentages, Binder, and their interaction on the modulus of elasticity of particleboard made from maize cobs and sugarcane bagasse are shown in Table 8. The results show that mixing percentage and Binder had a significant effect on the modulus of elasticity value of the particleboard generated (P-value 0.001) at a 1% level of significance. However, at a 5%

level of significance, the interaction between binder and mixing percentage had no effect on the particleboard's modulus of elasticity.

Table 8 *ANOVA of the effects of mixing percentages, binder and their interactions on the MOE of particleboard*

Source	Sum of squares	DF	Mean square	F	Significance
Mixing percentage	251817.398	2	125908.699	745.483	0.0001-
Binder	14683.555	1	14683.555	86.939	0.0001-
Mixing percentage and binder	3.973	2	1.987	0.012	0.988+
Total	5766230.600	48			

- Statistically significant at 0.01 level of significance, + Not statistically significant at 0.01 level of significance
DF = Degree of Freedom

The multiple coefficients of determination R^2 value of the ANOVA model was 0.974 respectively. Thus, the R^2 value of 0.974 means that about 97.4% of the variance in modulus of elasticity of particleboard produced could be explained by the experimental factors considered. The obtained modulus of elasticity for particleboard ranges from 232.58 N/mm^2 to 444.66 N/mm^2. According to ANSI (2009), which specifies 550 N/mm^2 as the minimum criterion for medium density particleboard, all particleboards manufactured with both binders did not meet the medium density particleboard certification requirements. This means that the particleboard generated can be utilized for only indoor applications in a dry less-humid environment, such as kitchen cabinets, ceilings, and partitions. Researchers have observed similar findings when using waste agricultural residues to make panels [32,45-47].

Particleboard made with cassava starch as a binder has a higher modulus of elasticity than particleboard made with urea formaldehyde adhesives. The gel time and expansion of the binders are two facts that have been observed and may have contributed to the high modulus of elasticity values. According to the literature, cassava starch binder has the fastest gel time and expands its volume after heating to give a thicker bond than urea formaldehyde adhesives. The modulus of elasticity of particleboard made with 90% Corn cobs and 10% sugarcane bagasse particles and both binders was higher than that of other mixing percentages (70:30 & 50:50). This suggests that increasing the proportion of corn cobs in the mix raised the modulus of elasticity values significantly. When looking at the values of modulus of elasticity as a function of increasing percentages of corncobs in the particleboard panels generated, [32] noticed an increased inclination to increased quantity of corncobs in the mixture. The modulus of elasticity was found to have increased from 11.28 N/mm^2 to 21.34 N/mm^2. When [40], investigated the characteristics of particleboard panels manufactured from eucalyptus and rice husks, they found similar results. For eucalyptus panels and rice husks, they measured 1225 MPa and 196 MPa, respectively.

Chemical features of the species, such as ash and lignin concentration, may have contributed to diminishing particleboard mechanical strength as the number of maize cobs in the mixture increased. An ash content of more than 0.5 percent, according to [49] has an impact on adhesive bond performance. The ash content of the corn cob, however, was 1.0 percent which may have influenced the bonding strength [33]. The presence of lignin encourages particle compaction and connection [50], Sugarcane species contained more lignin (21%) than maize cobs, according to the literature (14.7 %).

The results in Fig. 13 and Fig. 14 show that particleboard with a lower density has a higher modulus of elasticity. When evaluating the characteristics of flake boards made of hardwood, [51] found comparable results. [42] discovered that lower-density hardwoods have higher modulus of elasticity values than higher-density hardwoods. This means that when the density fell, the compaction ratio rose.

Panels designed for structural uses with densities more than the minimum requirement of 420 kg/m^3 were also needed to have minimum MOR and MOE values of 5 N/mm^2 and 400 N/mm^2, respectively, according to EN 312 (2010). Although not all of the panels manufactured had MOE values that satisfied the minimal requirement, the 90:10 CC:SB panel had MOE value of 444.66 N/mm^2, which is reasonably close to the minimum requirement. As a result, the panels are unlikely to be employed for structural or load-bearing purposes. [32] investigated the properties of particleboards made from of corn cob and sugarcane bagasse and found mean MOE values ranging from 11.28 to 21.14 N/mm^2, respectively, which is similar to the MOE result obtained in this study, but the result obtained in this study is significantly better.

3.2.2 Modulus of Rupture (MOR) and Statistical Analysis

Fig. 15 shows the modulus of rupture of particleboard made from corn cob and sugarcane bagasse with urea formaldehyde or cassava starch as a binder in this section of the study. Particleboard's modulus of elasticity ranges from 10.59 N/mm^2 to 5.53 N/mm^2. The particleboard with the highest modulus of elasticity (10.59 N/mm^2) was made from 90% corn cob and 10% sugarcane bagasse, with cassava starch as a binder. The particleboard with the lowest modulus of elasticity, 5.53 N/mm^2, was made by blending 50 percent corncob and 50 percent sugarcane bagasse particles with urea formaldehyde adhesives.

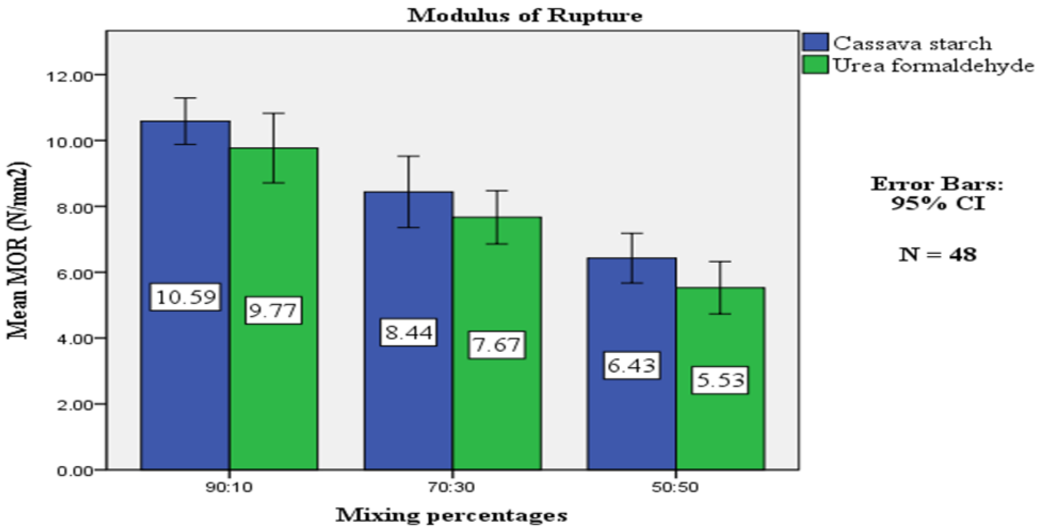

Fig. 15 *Mean MOR of particle boards produced in different ratios*

Furthermore, when the amount of corn cob in the combination grew, the value of the modulus of elasticity of particleboard produced increased for both binders. The amount of corn cobs in the combination had a positive significant association with the modulus of elasticity values obtained (Pearson's r = 0.849, p-value = 0.001, N = 48).

The findings of a two-way ANOVA to investigate the influence of mixing percentages, Binder, and their interaction on the modulus of rupture of particleboard made from maize cobs and sugarcane bagasse are shown in Table 9. The results show that mixing percentage and Binder had a significant effect on the modulus of elasticity value of the particleboard generated (P-value 0.01) at a 1% level of significance. However, at a 5% level of significance, the interaction between binder and mixing percentage had no effect on the particleboard's modulus of rupture value.

Table 9 *ANOVA of the effects of mixing percentages, binder and their interactions on the MOR of particleboard*

Source	Sum of squares	DF	Mean square	F	Significance
Mixing percentage	141.129	2	70.564	63.761	0.0001$^-$
Binder	8.234	1	8.234	7.440	0.009$^-$
Mixing percentage and binder	0.034	2	0.017	0.015	0.985$^+$
Total	3321.515	48			

$^-$ Statistically significant at 0.01 level of significance, $^+$ Not statistically significant at 0.01 level of significance
DF = Degree of Freedom

The multiple co-efficient of determination R^2 values of the ANOVA model were 0.763 respectively. Thus, the R^2 value of 0.763 means that about 76.3% of the variance in modulus of rupture of particleboard produced could be explained by the experimental factors considered.

Particleboard generated has MOR values ranging from 5.53 N/mm^2 to 10.59 N/mm^2. Most of the particleboard manufactured met the National Standard for medium density particleboard certification (7.6 N/mm^2 to 15 N/mm^2), according to the National Standard. This means that the particleboard produced can be utilized for a variety of applications, including coffee tables, wardrobes, office desks, ceilings, cladding, and so on. The modulus of rapture of particleboard made using cassava starch as a binder, on the other hand, was higher than that of urea formaldehyde adhesives. The MOR and density values were positively related, implying that the density and strength of the particleboard created were positively correlated. This could be due to the fact that maize cobs have lower ash content than sugarcane bagasse. According to [45], adhesive bond performance is affected by ash levels greater than 0.5 percent. Another finding could be linked to the higher lignin content found in maize cobs, which promotes more compaction and particle attachment [45].

The lignin level of corn cobs is 21 percent, compared to 16 to 19 percent in solid timbers [42]. Lignin is expected to play a significant role in particleboard derived from lignocellulosic sources in terms of strength and durability. The modulus of rapture of particleboard made from 90 percent corn cob and 10% sugarcane bagasse particles was higher than that of the other mixing percentages [70:30 & 50:50]. This means that increasing the number of maize cobs in the mix increased the modulus of rapture values. When maize cobs were added to sugarcane bagasse, [32] discovered an increase in MOR values from 1.9N/mm^2 to 4.4N/mm^2.

The chemical components (ash and lignin content) found in corn cobs as compared to sugarcane bagasse could be linked to an increasing tendency of modulus of rapture values when introducing high percentages of agricultural leftovers such as maize cob to wood species. According to [46], lesser ash concentration results in a more effective and stronger adhesive bond that can withstand stress. According to [47], higher lignin content promotes high compaction and particle attachment rates. When [40] evaluated the qualities of particleboard panels made with peanut husk and varied amounts of urea formaldehyde in the faces (10%) and core (10%), they came to the same conclusion (8 percent). They found that the modulus of rapture had increased from 9.3 MPa to 11 MPa. Table 10 shows the comparison of chemical composition of sugarcane bagasse, corn cob, paulownia, hardwoods and cotton stalk.

Table 10 *Comparison of chemical composition of sugarcane bagasse, corn cob, paulownia, hardwoods and cotton stalk*

Lignocellulosic material	Hemicellulose (%)	Cellulose (%)	Lignin (%)	Reference
Sugarcane bagasse	71	44	29	----
Corn cob	77	46	24	----
Cotton stalk	78	49	21	53
Paulownia	79	48	22	53
Hard wood	73	47	33	53

4. Conclusion

The possibility for using agricultural waste, such as corn cobs and sugarcane bagasse, in the manufacture of medium density particleboard as an environmentally acceptable alternative is highlighted by this study's result. According to the research, it is possible to produce particleboards using only a few pieces of basic machinery and still have them have acceptable physical qualities. With this achievement, the issue of disposing of agricultural waste in Nigeria is addressed in a way that has the potential to lessen negative environmental effects and stop deforestation. The study's conclusions highlight the benefits of utilizing cassava starch as a binder rather than urea formaldehyde since it not only lowers indoor air pollution but also encourages sustainable production methods. With a high modulus of elasticity (MOE) of 444.65 N/mm2 and a low modulus of rupture (MOR) of 10.59 N/mm2, the particleboards created from a blend of 90% corn cobs and 10% sugarcane bagasse had exceptional mechanical properties. These excellent qualities imply that these particleboards can be used with confidence for structural reasons. In conclusion, this research not only addresses the urgent problem of managing agricultural waste, but also offers a workable and environmentally responsible answer by presenting a novel method of producing particleboard. These discoveries could have a big impact on Nigeria's and other countries' attempts to save the environment and practice sustainable forestry.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** M.E. Ojewumi, F.O. Oladapo; **data collection:** F.O. Oladapo; **analysis and interpretation of results:** O.I. Oresegun, K.J. Jolayemi; **draft manuscript preparation:** O.R. Obanla. All authors reviewed the results and approved the final version of the manuscript.*

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