REVISTA MATÉRIA V.28 N.2
ISSN 1517-7076 articles e20230027, 2023

Durability and resistance of eco-friendly particleboards produced from agroforestry residues

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ABSTRACT

The aim to evaluate the raw material (agroforestry residues) for particleboard manufacture from the: pseudostem of *Musa paradisiaca*; the stem and pods of *Theobroma cacao*; and the sawdust of *Ceiba pentandra*. The particleboards produced from these cellulosic residues are mixed with cassava starch's natural adhesive and urea formaldehyde's synthetic adhesive. The results indicate that lignin, α-cellulose, hemicellulose, and extractives ranged from 6.2–19.0%, 41.4–50.2%, 24.4–31.5%, and 6.8–18.8% respectively and they were significantly different from each other. Additionally, tannins, alkaloids, saponins, flavonoids, phenols, glycosides, and sterols were the phytochemicals present in biomass materials in different quantities. Also, carbon, oxygen, nitrogen, and boron were the elementals significantly present in the manufactured particleboards in the range of 35.3–52.8, 30.2–43.0, 4.2–24.0, and 3.2–9.9 percentage concentration respectively. As for the mechanical properties, it was verified that the cellulose content influenced 96.5% of the variability of the modulus of rupture (MOR) values. Understanding the distribution, functional properties, and impact of biomass organic, phytochemicals and elemental constitutions is an impetus to the improvement of processes with higher retention of these constitutions in the utilization of agroforest residues in the particleboard industry. These chemical compositions of the residues under study contributed largely to the characteristics of the manufactured particleboards.

Keywords: Organic compounds; lignocellulosic materials; biodeterioration; sustainability.

1. INTRODUCTION

A future aimed at the development of a bioeconomy in which renewable resources can replace materials and products derived from petroleum can be an alternative to address factors related to environmental, social, and economic issues aligned with sustainable development [1]. Lignocellulosic biomass is among the most abundant renewable resources on the planet, being found mainly in agricultural residues: such as corn and wheat straw and sugarcane bagasse; in forest materials and residues, such as wood, bark, and tree branches; and crops aimed at the energy sector, such as elephant grass, miscanthus, and switchgrass [2].

Wood processing is associated with lots of bio-waste at all stages of production. Similarly, agricultural practices like post-harvest operations are associated with large volumes of reusable biomaterials. Cultivated in deciduous forests located in eastern and western India, *Ceiba pentandra* is a tree with a wide variety of applications, with its root, gum, and leaf widely used in medicinal applications, and the cotton extracted from the fruit is used for making mattresses and pillows. However, the husks generated by the fruit are considered agricultural waste with no added economic value [3]. Other waste-generating biomasses are *Musa paradisiaca* and *Theobroma cacao* are cultivated for their fruits, after which the plants are locally used for low-value applications or left to waste despite the global increasing attention on the bioeconomy and circular economy [4].

Seeking applications that promote the reduction of agroforestry residues produced, many kinds of research have been carried out using the biomass of *Musa paradisiaca*, *Theobroma cacao*, and *Ceiba pentandra* in the

Corresponding Author: Rafael Rodolfo de Melo Received on 26/01/2023 Accepted on 15/03/2023

DOI: https://doi.org/10.1590/1517-7076-RMAT-2023-0027

production of materials for the characterization of the properties. Evaluating the influence of cocoa residues on Medium Density Particleboards (MDPs), VELOSO *et al.* [5] verified that the addition of 21% of cocoa residues, replacing pine wood, promotes standardization in the physical-mechanical properties of the panels, enabling the material to be used in the construction of furniture used indoors. In their research with composite materials with type C gelatin matrix and glycerin reinforced with *Musa Paradisiaca* fibers, MARTÍNEZ *et al.* [6] verified that the presence of elements such as hemicellulose and lignin promoted good mechanical properties to the produced biodegradable material, with a tensile strength of 3.5 MPa and a Shore hardness of 82 on the A scale. His research analyzing the properties of briquettes/composites with sawdust particles from *Ceiba pentandra* wood, ANTWI-BOASIAKO and ACHEAMPONG [7], noted a high resistance to compression and shattering, pointing to good resistance to gravitational deterioration.

Biorefining is an essential strategy used in a circular economy, which according to MANZANARES [8], works to close the cycle of gross biomass, promoting the reuse of waste generated in agricultural, forestry, processing, and post-consumption activities as well as in the processes of water, carbon, and minerals. Biorefineries implement a circular bioeconomy, promoting secondary product valorization [8]. The method of recycling and using natural fibers as reinforcements and fillers in the manufacture of biodegradable, renewable, and low-cost materials can be a viable alternative in reducing the waste produced [9].

Biomass materials are resources of the organic, phytochemical, and elemental constitution. The role those chemical constituents of biomaterials play in manufactured particleboards is well recognized [10, 11]. Organic compounds like α-cellulose, hemicellulose, lignin, and extractives have been found to improve the rheological and heat transfer in the matrix during hot pressing, thus ensuring better bonding and mechanical properties of the panel [11, 12]. Among these compounds, lignin can promote rigidity in plant biomass's structure and protect against external biotic elements [2]. According to LÊ *et al.* [13], lignin also can influence the degree of aggregation and elasticity of the gel network present in nanocellulose, increasing structural elasticity and improving water release capacity. It is a material capable of thermally deforming during a hot-pressing process of the fibers. Due to its adhesive properties, it can be an alternative to producing low-cost lignocellulosic composites [14]. The major groups of phenolic compounds are simple phenolic acid, flavonoids, coumarins, stilbenes, tannins, and lignin [15]. Literature indicates that these compounds have a high affinity with the o adhesive and greatly contribute the to bonding ability of biomass materials. Various types of phytochemicals such as tannin, alkaloid, saponin, flavonoid, glycoside, phenol, and sterol have been found to contribute to the durability, physical and mechanical properties of the manufactured particleboards [16, 17].

The identification and characterization of active chemicals in agroforest residues are essential for integration and utilization. Efficiently, the scientific and beneficial use of such agroforest waste in particleboard manufacturing by industries has been acknowledged [18]. Several studies on the mechanical and physical properties of manufactured particleboards indicate that these properties are improved by biomass materials with high quantities of phenolic compounds [19, 20]. The authors also emphasized that these compounds are largely responsible for forming solid bridge bonds during the pressing of the particleboards. The use of adhesive, additives and the chemical constituents of individual biomass material in the manufacture of the particleboards predicts that various chemical reactions could occur.

These reactions may produce some other chemical elementals which could impact the properties of the manufactured particleboards. For instance, NATH *et al.* [17], noted that tannin-based adhesive produces particleboards with a higher modulus of rupture (MOR) and modulus of elasticity (MOE).

The development of this research will bring significant contributions to the industries producing particleboard panels, as it presents characteristics and properties of low-cost agroforestry residues, which can be used as a renewable raw material in making eco-friendly panels. In this context, the present study aims to determine the organic, chemical, and elemental properties of residues from the pseudostem of *Musa paradisiaca*, the stem and pods of *Theobroma cacao*, and the sawdust of *Ceiba pentandra* and characterized particleboard produced from these cellulosic residues together with the natural adhesive from cassava starch and the synthetic glue from urea formaldehyde.

2. MATERIAL AND METHODS

2.1. Materials and materials preparation

Musa paradisiaca pseudostem, *Theobroma cacao* stems, and *Theobroma cacao* pods under consideration were collected from reserved forests at Humjibre (2° 15' 57.780" W and 6° 9' 11.873" N), Sefwi-Bibiani Bekwai, Western Region, Ghana (Figure 1a, 1b e 1c). Saw materials of *Ceiba pentandra* were collected from a company

Figure 1: Materials collected for production and characterization of particulate panels. *Musa paradisiaca* pseudostem (a); *Theobroma cacao* stems (b); *Theobroma cacao* pods (c); *Ceiba pentandra* wood (d).

Figure 2: Powdered specimens of the biomass materials for organic composition and phytochemical test. *Ceiba pentandra* sawdust (a); particles of the *Musa paradisiaca* pseudostem (b); particles of *Theobroma cacao* stems (c); particles from *Theobroma cacao* pods (d).

(Evans Timbers Limited) at Abofour (2° 39' 36.000" W and 6° 9' 0.000" N) in the Offinso in Ashanti Region, Ghana (Figure 1d).

After collection, the fibers were extracted from the pseudostem of the *Musa paradisiaca* pseudostem, and a cleaning process was carried out, in which the fibers were washed in running water at a temperature of 25 ± 2 °C and subsequently dried in an oven with forced circulation, at a temperature of 104 ± 2 °C. Then the fibers were crushed in a knife mill, and the particles were sieved with sieves until a granulometry was between 0.5 and 1.5 mm.

The stem and pods of *Theobroma cacao* stem were washed, dried in the sun, and then crushed in knife mills. The particles were sieved until reaching a granulometry like those obtained for the fibers of *Musa paradisiaca*. Sawdust from the *Ceiba pentandra* tree was obtained as particles in sawmills in Ghana. The particles of this material also went through the sieving process to reach the grain pattern of the other materials studied in work.

For *Ceiba pentandra* and *Theobroma cacao*, the stem saw dust, unwanted particles were removed. Some tests (fixed oils and volatile oils) needed fresh or solid samples others (while flavonoids, saponins, triterpenoids, etc.) required powdered samples (Figure 2). The biomass particles were placed in the sun for drying at a humidity of 75% and a temperature of 28 ± 2 °C for four weeks. Then the particles were placed in a solar dryer at a temperature of 70 ± 5 °C until reaching a humidity of 3%. Subsequently, the biomass particles were sent to determine the organic composition, phytochemical analysis, and production of the panels.

2.2. Determination of chemical composition

Based on oven-dried mass, the extractive constitution of the biomass materials was determined according to ASTM D 1105 [21]. Hence, the percentage of lignin, cellulose, and hemicellulose wase was determined using the extractive-free specimen of each biomass material. The extracts were determined using the standard methods as described and used by ROOPASHREE *et al.* [22] and EJIKEME and EZEONU [23].

The essential phytochemicals constituents in the materials, namely: saponins, sterols, tannins, alkaloids, glycosides, flavonoids, triterpenoids, coumarins, phenols, mucilage, fixed oils, and volatile oils were determined. Saponins, sterols, and tannins were determined by the standard method reported by EJIKEME *et al.* [23] and EZEONU and EJIKEME [24]. Alkaloids and glycosides tests were conducted by the method reported by HIKINO *et al.* [25], flavonoids were analyzed using the method reported by HARBORNE [26], triterpenoids were determined by the method reported by EJIKEME and EZEONU [23], fixed and volatile oils were determined by a streak of the liquid content of the samples onto a filter paper and exposing the filter paper to light to dry off the wet paper, a permanent translucent stain after exposure to light indicates the presence of fixed volatile oils [27]. Following the parameters established by the ASTM D1110 standard [28], tests were carried out to determine the solubility of the material in cold water at a temperature of 23 ± 2 °C for 48 hours at constant agitation and solubility in hot water at a temperature of 100 ± 2 °C for 3 hours.

The elementary chemical composition of the manufactured particleboards was determined using a fully automated high-performance desktop Phenom ProX Scanning Electron Microscope (SEM) with model number 721-20000-00-0104, fully integrated with Elemental Identification analyzer (EID), Energy Dispersive Spectrometer (EDS). This is the most extended and effective solution for EID Particleboards specimens of 10 × 10 × 5 mm, which were fixed onto specimen holders with adhesive tape and coated with platinum to make them conductive, using JFC-1600 sputter auto fine coater. The concentration fraction of each element in the specimens was calculated automatically by the EID with an acceleration voltage of 15 kV and expressed in percentage concentration weight. Based on the analyses, an attempt was made to identify the presence of the elements with the most significant amount in the materials, such as carbon, oxygen, nitrogen, and boron.

2.3. Manufacturing particleboard

Biomass particles with granulometry between 0.5 and 1.5 mm at 3% humidity were mixed with the natural adhesive made from cassava starch and spread manually in the mold to manufacture the panels. To the performance of the resins, particleboards were also manufactured with biomass particles mixed with the urea-formaldehyde adhesive with the following properties: 65% solids content, a relative density of 1.27 $g.cm^{-3}$, viscosity of 2.5 MPs at 30 °C, and gel time of 1.05 minutes at 100 °C. The concentrations of adhesives used for the dry weight of the particles were 8%.

Ammonium chloride was used as a hardener. The furnish was pressed in 300 × 300 × 80 mm aluminum sheet mold with a pressing time of 8 minutes, a temperature of 170 °C, at a pressure of 3.5 MPa, and a target density was 600 kg/m^3. Eight different compositions were evaluated for the evaluation of the chemical properties of the panels (Table 1). The manufactured particleboards were trimmed off using a circular bench saw to square the edges and prevent edge defects. The final product was conditioned in a climate control room with a temperature of 20 ± 2 °C and a relative humidity of 62 ± 2% for 6 days, to reach equilibrium moisture content.

2.4. Determination of mechanical properties

Modulus of Rupture (MOR), Modulus of Elasticity (MOE), and Hardness were determined according to ASTM D 1037 [29]. With specimens' dimensions of 250 × 50 × 20 mm, MOR and MOE were determined using the universal testing machine (UTM-Instron model Inspekt 50-1), operating with a load cell capacity of 50 kN at room temperature. Whereas the hardness test was conducted using the universal testing machine (UTM-Instron model 4482), operating with a load cell capacity of 100 kN at room temperature, with specimens' dimensions of 150 × 75 × 25 mm. The internal bonding strength (IBs) test was conducted by ASTM D 1037 [29] and ASTM D 7519 [30].

Table 1: Different compositions for the particleboards produced from agroforestry residues.

IDENTIFICATION	COMPONENTS OF PARTICLEBOARDS (RESIDUES + ADHESIVE)
CP + CS	*Ceiba pentandra* + Cassava starch
CP + UF	*Ceiba pentandra* + Urea formaldehyde
MPP + CS	*Musa paradisiaca* pseudostem + Cassava starch
MPP + UF	*Musa paradisiaca* pseudostem + Urea formaldehyde
TCP + CS	*Theobroma cacao* pod + Cassava starch
TCP + UF	*Theobroma cacao* pod + Urea formaldehyde
TCS + CS	*Theobroma cacao* stem + Cassava starch
TCS + UF	*Theobroma cacao* stem + Urea formaldehyde

2.5. Statistical analysis

Data were given in mean and standard deviation (SD) obtained from 5 independent replicates. From the data obtained, correlation with probability levels of ($p > 0.01$) and ($p > 0.01$).

3. RESULTS

The results showed that all biomasses had a higher solubility in hot water, with emphasis on *T. cacao* pod, which showed the highest value, 38.5% (Table 2). Also verified, it shows the four main organic compositions of study materials. The results presented in Table 2 demonstrated that the studied biomasses presented variations in design. Evaluating the lignin and hemicellulose contents verified that the highest values were 19.0% and 31.5%, indicated by the biomass of *Ceiba pentandra*. The highest value for the cellulose content was 50.2%, indicated by *Musa paradisiaca* pseudostem. As for the extractive content, the highest value was 18.8%, presented by the *Theobroma cacao* pod.

Phytochemical screening reveals that the agroforest residues contain alkaloids, tannins, flavonoids, triterpenoids, coumarins, sterols, and phenol. Whereas, glycoside, fixed oils Volatile oils, and mucilage were present in only *M. paradisiaca* pseudostem. However, both *T. cacao* pod and *T. cacao* stem show the absence of glycosides, fixed oils, volatile oils, and mucilage, as shown in Table 3. The qualitative analysis of the results verified the presence of high amounts of tannin in all the agro-industrial residues examined, with the highest value of 827.22 mg.100 g^{-1} presented by *Ceiba pentandra* (Figure 3a). The results also show that *Musa paradisiaca* pseudostem had the highest percentages of alkaloids and flavonoids, with values of 8.17 and 4.03%, respectively (Figure 3b).

It is evident from Table 4 that the cellulose and the lignin contents directly correlate significantly with all the mechanical properties tested (MOE, MOR, Hardness, Internal bonding) and durability at the significant level of 1%. The hemicellulose content does not correlate significantly with all the mechanical and durability

Table 2: Chemical composition of agro-residues evaluated.

CHEMICAL COMPONENT (%)	*M. paradisiaca* pseudostem	*T. cacao* pod	*T. cacao* stem	*C. pentandra*
Solubility in cold water	13.0	29.0	8.6	3.1
Solubility in hot water	16.8	38.5	9.9	5.2
Lignin	11.2	6.2	16.0	19.0
α-Cellulose	50.2	46.4	42.1	41.4
Hemicellulose	24.4	28.3	31.2	31.5
Extractives	13.7	18.8	9.2	6.8

Table 3: Qualitative analyses of the phytochemicals or extractives components in *Musa paradisiaca* pseudostem, *Theobroma cacao* pod, *Theobroma cacao* stem, and *Ceiba Pentandra*.

PHYTOCHEMICALS	BIOMASS MATERIALS			
	C. pentandra	*M. paradisiaca* pseudostem	*T. cacao* pod	*T. cacao* stem
Tannins	√	√	√	√
Mucilage	χ	√	χ	χ
Saponins	√	√	√	√
Alkaloids	√	√	√	√
Flavonoids	√	√	√	√
Glycosides	χ	√	χ	χ
Fixed Oils	χ	√	χ	χ
Volatile oils	χ	√	χ	χ
Triterpenoids	√	√	√	√
Coumarins	√	√	√	√
Sterols	√	√	√	√
Phenols	√	√	√	√

Legend: √ = present, χ = absent.

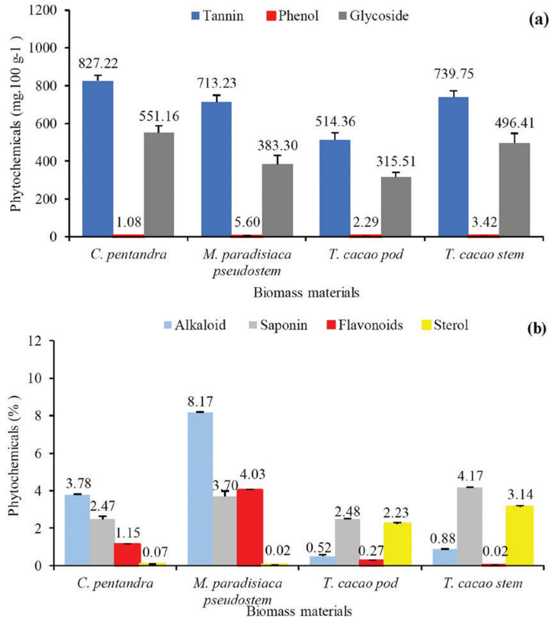

Figure 3: Quantitative phytochemicals in the test specimens. Tannin, phenol, and glycoside (a); Alkaloid, saponin, flavonoids and sterol (b).

Table 4: Correlation coefficient array of the effect of organic composition on the mechanical strength properties of particleboard manufactured from biomass materials.

MECHANICAL PROPERTIES	α-CELLULOSE	HEMICELLULOSE	LIGNIN	EXTRACTIVE
MOR	0.809**	0.117^{NS}	–0.415**	–0.132*
MOE	0.799**	0.060^{NS}	–0.644**	–0.056*
Hardness	0.722**	0.181^{NS}	–0.736**	–0.049*
Internal bonding	0.857**	0.177^{NS}	–0.532**	–0.391*
Decay resistance	0.563**	-0.078^{NS}	0.528**	–0.064*

NS = Not Significant; **Correlation is significant at the (p < 0.01) level of probability; *Correlation is significant at the (p < 0.05) level of probability; N = 40; 2-tailed.

properties tested. The variation in the chemical composition of the particles might explain the difference between the manufactured particleboards. The significant effect of cellulose means that increasing the cellulose content of agroforest residues will result in increasing the mechanical properties of the particleboard manufactured. Thus, the relationship between MOR and cellulose content, indicates that about 96.5% of the total variability in MOR values was attributed to the cellulose content. The same relationship exists for MOE, Hardness, and Internal bond with a cellulose content of which percentage variabilities of 98.6%, 97.4%, and 86.8% respectively are estimated. Also, 86.8% of the variability in internal bonding was attributed to the cellulose, lignin, and extractive content of the biomass materials.

The results in Table 5 show the correlation coefficients matrix of the phytochemical constituents of study materials and MOE, MOR, hardness, internal bond strength (IB), and the decay resistance properties of the homogeneous single-layer particleboard. It is verified from Table 5 that the tannins, alkaloids, saponins, flavonoids, and phenols strongly and significantly correlated with all the mechanical properties tested, while glycosides exhibited inverse correlations to MOE, hardness, and IB. This means that increasing other phytochemical content of biomass materials and decreasing glycoside content would result in increasing the MOE, hardness, and IB properties of the particleboard. On the other hand, sterols exhibited an inverse correlation to MOR and IB. Hence, increasing other phytochemical content of biomass materials and decreasing sterols content could result in increasing the MOR and IB properties of the particleboard produced. Whereas tannins, alkaloids, saponins, flavonoids, and phenols are inversely correlated with decay resistance. Thus, a decrease in these phytochemicals could increase the decay resistance properties of the particleboards. The results indicate that larger proportions of the phytochemicals in the respective biomass materials could significantly improve the mechanical properties of the manufactured particleboards.

Table 5: Correlation coefficient array of the effect of phytochemical constituents of the biomass materials on the mechanical strength and durability properties of the manufactured particleboard.

MECHANICAL PROPERTIES	PHYTOCHEMICALS IN THE TEST SPECIMENS						
	TANNINS	ALKALOIDS	SAPONINS	FLAVONOIDS	PHENOLS	GLYCOSIDES	STEROLS
MOR	0.612**	0.688**	0.588**	0.613**	0.430**	0.007^{NS}	–0.421**
MOE	0.742**	0.688**	0.771**	0.654**	0.670**	$–0.261^{NS}$	$–0.278^{NS}$
Hardness	0.744**	0.606**	0.848**	0.601**	0.763**	–0.414**	$–0.139^{NS}$
IB	0.791**	0.830**	0.443**	0.807**	0.552**	$–0.154^{NS}$	–0.566**
Decay resistance	–0.574**	–0.502**	–0.556**	–0.497**	–0.529**	0.268^{NS}	0.194^{NS}

NS = Not Significant; **Correlation is significant at the (p < 0.01) level of probability; N = 40; 2-tailed.

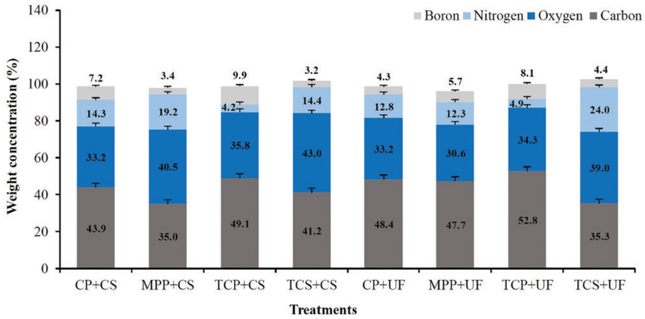

Figure 4: Percentage of elementary constituents in manufactured particleboards. CP = *Ceiba pentandra*; MPP = *Musa paradisiaca* pseudostem; TCP = *Theobroma cacao* pod; TCS = *Theobroma cacao* stem; CS = Cassava starch; UF = Urea-formaldehyde.

It is verified that the major elementary constituents in the tested specimens of particleboards manufactured with agroforest residues blended with cassava starch and urea formaldehyde were carbon and oxygen, followed by nitrogen and boron (Figure 4). *T. cacao* pod particleboard specimens blended with UF had the highest percentage of carbon 52.8%, and *M. paradisiaca* pseudostem particleboard specimens blended with CS had a lesser carbon of 35.0%. The high carbon content of these biomass relates to the major constituents of lignocellulose materials which are cellulose, lignin, and hemicellulose, plus minor amounts of other materials including compounds containing nitrogen.

It is confirmed that the most prominent elementals present in the manufactured particleboards were carbon, oxygen, nitrogen, and boron. The fungicidal and insecticidal properties of boron could contribute to the durability of the manufactured particleboards. Indicated in Figure 4 are other elementals present in the manufactured particleboards. Also, the test recorded traces of elements in very small quantities. These include silicon, aluminum, potassium, iron, chlorine, calcium, and iron. Most of these contribute to the durability of the particleboards.

4. DISCUSSION

4.1. Organic composition

Carrying out solubilization in lignocellulosic materials using cold water can extract different substances, such as gums, tannins, dyes, and sugars. On the other hand, solubilization using hot water can pull, in addition to the previously mentioned substances, it can remove starches [31]. According to ROFFAEL [32], wood extractives have physical-chemical properties encompassing a wide range of solubility in water and in different organic solvents. LI *et al.* [33] expose that hot water promotes chemical and structural changes due to cellulose's depolymerization, hemicellulose removal, and modification of lignin present in the cell wall, generating a contribution to increased access to biomass and a decrease in recalcitrance.

The organic composition of agroforest residues is one of the most essential properties that affect the mechanical properties of particleboards [34, 35]. Evaluating the influence of lignin content in plywood panels, LUBIS *et al.* [36] noticed that adding this constituent promoted a reduction in the solids content, decreasing the average viscosity of the adhesive used in the process. He also verified that a formulation containing 15% lignin in the bond provided more extraordinary thermomechanical properties when compared to percentages of 10 and

20% [36]. When lignin is used to replace phenol, it promotes practical improvements in the characteristics and performance of phenolic adhesives [37].

Cellulose and hemicellulose are crucial in water uptake in lignocellulosic material, hence increasing the hydrophilicity of the particles [11]. This improves the rheological and heat transfer in the matrix during hot pressing, thus ensuring better bonding. Furthermore, these compounds are hydrolyzed into simple sugar compounds and furan. The potential chemical constituents in promoting self-bonding between particles [38]. Besides, ÖRS and KESKIN [12] emphasized that cellulose is the skeleton of lignocellulose materials and that a high amount of cellulose improves the mechanical properties of particleboards. Contrary, a higher content of extractives in biomass materials causes lower values of mechanical properties because the extractives adversely affect the strength of the adhesive bond [39]. Extractives create air bubbles during hot pressing which weakens glue bonds. Also, the low mechanical properties values of *T. cacao* pod particleboard could be caused by a high content of extractives (18.8%).

Using wood particles and coconut fibers as reinforcement in cementitious composites, SOUZA *et al.* [40] found that extractives can significantly interfere with the properties of the panels produced. This influence may be due to free sugars, which reduce the bond between the cellulosic reinforcement and the cementitious matrix [32]. The characteristics of hydrophobicity presented by cellulosic biomasses are directly related to the amounts of extractives and lignins, which are non-polar molecular compounds [41]. When wood is glued with adhesives of synthetic origin, the extractives directly influence its surface wettability [32].

The polysaccharides components of the biomass cell wall particularly hemicelluloses are highly hydrophilic, whereas extractives and lignin are more hydrophobic [39]. Many research investigations have confirmed wood extractives as the main mechanism for wood decay resistance. The systemic poisons volatilizing from wood were suggested to kill termites in test chambers.

Lignin is composed of three p-hydro-xycinnamyl alcohol precursors: p-coumarin, coniferyl, and sinapyl alcohols [42]. Lignin has a highly complex 3D randomized structure linked to hemicelluloses. It functions as a biological barrier and as a binder holding together hemicelluloses and cellulose. Profiting from its unique structure in nature, lignin has significant potential to acquire added value to produce phenolic chemicals. Thus, lignin's capability to produce high-added-value phenolic compounds has recently attracted a great deal of interest from the scientific community [42]. Many lignin has been used in the development of adhesives, such as miscanthus lignin, wheat straw, and sugar maple [43, 44]. The mixture of phenol formaldehyde (PF) and urea formaldehyde (UF) with up to 40% lignin or lignin derivatives improves the cure and mechanical properties of the final composite. Also, several types of lignin have been studied as PF substitutes. KOCH and GRÜNWALD [45] noted that if the lignin is methylated, or ultrafiltration, or otherwise chemically modified, up to 70% of the PF may be replaced.

FENGEL and WEGNER [34] have reported, that high cellulose content decreases the brittleness of manufactured particleboard, whereas high lignin content increases its brittleness, which was supported by the findings of NASSER [35]. However, NEMLI *et al.* [20], concluded that increasing the concentration of the extractives decreased the mechanical properties of the particleboards. YALINKILIC *et al.* [46] emphasized that extractives act as natural toxicants that gradually but steadily increase the resistance of biomass materials to the deteriorating activities of fungi on manufactured particleboards.

4.2. Phytochemical constituents of the biomass materials

The tannin content presented by the agroforestry residues addressed in the research is a factor that can positively contribute to the properties of the manufactured panels. According to RHAZI *et al.* [47], biological and mechanical studies demonstrate that the relations between tannin, lignin, temperature, and pressure promote excellent mechanical properties to manufactured plywood panels. Their research also confirmed that panels manufactured with 75% mimosa tannin and 25% glyoxylate lignin manufactured at a pressure of 12 bar and temperature of 150 °C for 4 minutes presented an excellent performance. Based on their research with particle boards, CUI *et al.* [48] verified excellent mechanical properties for adhesives made from pinus pinaster tannins with 2% cellulose nanofibrils. Tannin-based polymeric adhesives have properties such as a high degree of in-plane flexion and low viscosity, factors that provide excellent wetting during the manufacture of particle boards [49].

In the work by NATH *et al.* [17] on tannin-based adhesives to produce particleboard, it was observed that the adhesive formulation containing 100% tannin showed the highest viscosity, solid content, and the best pH values. In addition, the highest (MOE) and (MOR) were found for particleboards fabricated with 100% tannin-based adhesive. Many studies have confirmed that phytochemicals improve the properties of manufactured particleboards including durability. Also, these phenolic compounds reduce the formaldehyde emission levels significantly, cure faster, and result in composite with better water and moisture resistance when compared with UF [16].

Flavonoids are found to be effective antimicrobial substances against a wide range of microorganisms. Phenols and phenolic compounds are known to be toxic to microorganisms. The ability of tannins to inactivate microbial adhesins and enzymes makes them antimicrobial active. *Musa paradisiaca* pseudostem is known to possess alkaloids, glycosides, flavonoids, phenols, tannins, and saponins (Figure 3), which either individually or in combination exert antibacterial activity. The more significant presence of these phytochemical constituents can promote improvements in the properties of panels reinforced with particles from *Musa paradisiaca* pseudostem since, according to SÁNCHEZ *et al.* [50], the use of flavinoids can improve the performance of universal adhesives. Molecules of flavinoids also can interact and form bonds with molecules of synthetic formaldehyde adhesives [51].

In their research evaluating the physical and chemical properties of Phyllanthus discoideus, Sacoglottis gabonenses, and Pycnanthus angolensis woods, EJIKEME *et al.* [52] expose that industries can use the tannins present in lignocellulosic materials for applications in leather, production of paints, production of adhesives for wood and other products developed by pharmaceutical industries. The research also pointed out the presence of alkaloids, flavonoids, and saponins, indicating antimicrobial properties inside the forest and antioxidant, and anti-inflammatory properties, among others.

In the presence of Phenols may also decrease the rate of thickness swelling because they will not dissolve when getting in contact with water [10]. The industrial board-making process, better polymerization is brought to completion in the press with the addition of phenols to the formaldehyde-based adhesive to form methyl phenol which helps to improve the viscosity of the adhesive. Thus, enhancing the rheological behavior of the furnish mix. In a study on biological, physical, and mechanical properties of particleboard manufactured from waste tea leaves, YALINKILIC *et al.* [46], observed that phenolic extractives act as natural toxicants that gradually but steadily increase the resistance of the particleboard during exposure to *Tyromyces palustris* and *Coriolus versicolor*, respectively.

4.3. Elementary chemical composition

In all the treatments evaluated in the research, carbon was the element that had the highest percentages in the manufactured panels. In their study using polymeric composites reinforced with residues of coconut husk and barley husk, BLEDZKI *et al.* [53] also found higher amounts of carbon, attributing this behavior to many hydrocarbons present in the waxy extracts on the surface of the fibers, and the presence of lignin.

Carbon content in wood is closely linked with the specific gravity and the mechanical properties of wood [54]. Furthermore, the use of cassava starch increased the carbon and oxygen content of the specimens which might be due to the chemical composition of cassava starch which has been reported to consist of two major molecular components, amylose, and amylopectin, which can be differentiated by their chemical structure. The linear α-(1→4) linked glucan is called amylase while an α-(1→4) linked glucan with 4.2%–5.9% α-(1→6) branch linkages is amylopectin. Starch has an excellent affinity towards polar materials such as cellulose, because of the many hydroxyl groups, forming strong adhesive bonds. It is extensively used in the form of binders, sizing materials, glues, and pastes [55]. Starch which is currently used in particleboard production involves a combination of synthetic adhesives, such as isocyanates and urea-formaldehyde resins [56]. The high resistance of particleboards manufactured with rice husk to termites was also verified by MELO *et al.* [57], who attributed this performance to the high content of carbon and inorganic components in the rice husk, a material that is difficult to digest termites.

The phytochemical and elemental constituents of the manufactured particleboards such as silica and some phenolics have been reported to have significant effects on improving the mechanical, water resistance and decay properties of particleboards [20]. The comparative high values of mechanical, physical, and durability properties of the manufactured particleboards from the agroforest residues may be due to their comparative high content of individual organic chemicals, phytochemicals, and elemental constitutions. These chemicals are largely responsible for forming solid bridge bonds during the pressing of the particleboards [9]. However, SOUZA *et al.* [41] expose that the technological performance of particleboards produced from agro-industrial waste depends on several factors and will sometimes show different behavior than those made only with wood.

The literature considers that all carbon content in wood returns to the atmosphere now of forest harvesting by instant oxidation. In this sense, the carbon stock in wood and non-wood products has been widely analyzed and studied by different researchers from numerous countries and their findings have been accounted for in different studies [58]. Information on carbon stocks of wood products would be useful in evaluating their potential for greenhouse gas (GHG) mitigation [59].

Although wood and non-wood but cellulosic forest products alone are not a solution to the problem of the concentration of greenhouse gases (GHG) in the atmosphere, their role should not be ignored in their reduction. Therefore, the desirability of wood and non-wood products accounts for national balances emission

[60]. Moreover, it is convenient to underline the positive consequences that the accounting of carbon storage in wood and non-wood products has in forest management, production, or trade of wood products. Thus, it may give a new added value to the forest industry. It's a traditional sector whose sustainability depends increasingly on new sources of competitiveness and the proper valuation of its products [61].

The results obtained in the research verified that the agroforestry residues of *Ceiba pentandra*, *Musa paradisiaca* pseudostem, *Theobroma cacao* pod, and *Theobroma cacao* stem present a potential to produce eco-friendly particle boards for applications such as dividing walls and furniture indoors. Using these sustainable materials can promote environmental, social, and economic benefits for humanity. BLEDZKI *et al.* [53] explain that agricultural residues present morphology, chemical composition, and complicated cellular geometry. These materials are cheap, available, and environmentally friendly, and their use will positively contribute to responsible waste management and the development of more inexpensive materials and products [53].

5. CONCLUSION

It can be concluded that the selected agroforestry residues contain essential organics, chemicals, and elementals that contribute mainly to the durability and resistance of the particleboards. The ability of these biomass materials to contribute to the improvement of various properties of the manufactured particleboards in this study may be attributed to the various active chemical components present in them, which, due to their individual or synergistic action, exhibit these characteristics. Hence, these research results have established that they have potential in industries, particularly for particleboard production.

This work can serve as fundamental scientific information for using these agroforestry residues in producing particleboards. Aim at improving the properties and new applications for particleboards, future studies to characterize other physical, mechanical, and thermal properties.

6. ACKNOWLEDGMENTS

The authors acknowledge the assistance of Mrs. Fredrica Mensah for financial support. Appreciation goes to Mr. Samuel Antwi and Mr. Adjei Asumadu for their kind assistance. The authors are grateful to the Wood Industry and Utilization Division of CSIR-FORIG for making their wood workshop and laboratory available for the study. Special thanks go from the authors to Mr. Benjamin Kwame Agyapong of the Department of Pharmacognosy Faculty of Pharmacy and Pharmaceutical Sciences of the Kwame Nkrumah University of Science and Technology, for providing some laboratory support for the study. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

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