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Review Article

Particleboard from biomass wastes: A review of production techniques, properties, and future trends

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Abstract

The availability of various biomass wastes and the stringent rules against deforestation have led to the increased utilization of waste biomass in particleboard development. These biomass wastes become environmental pollutants when not properly managed. Hence, their utilization in developing particleboards helps attain a sustainable environment, one of the United Nations Sustainable Development Goals. This study reviews some of the production techniques of particleboards from biomass wastes such as rice husk, sawdust, corn cob, sugarcane bagasse, oat hulls, coconut fibers, Areca nuts, rye straw, tomato stalk, hazelnuts, and castor husk. The properties (physical, mechanical, chemical, and thermal) and microstructures of the developed particleboards using a scanning electron microscope were critically reviewed. The density values were used to classify the particleboards into low-density, medium-density, and high-density particleboards. The particleboard's durability, storability, and dimensional stability are determined using the water absorption and thickness swelling values. The modulus of elasticity and modulus of rupture help to determine the quality and applicability of the particleboards following the appropriate standards. Lower thermal conductivity indicates better insulation properties. The challenges and prospects of particleboard production and utilization were stated. The utilization of waste biomass for particleboard production is sustainable to prevent environmental pollution and deforestation.

1. Introduction

Wood is a type of biomass that contains constituents like cellulose, hemicellulose, and lignin content. The various percentages of these constituents determine how structurally stable the wood will be during its utilization as a renewable energy source. The utilization of wood in the world grows on a timely basis to attain developmental needs such as furniture, building construction, and household appliances [1]. The huge impact of deforestation on the abundance of wood particles (wood shavings, sawdust) on the environment cannot be overemphasized. The availability of different sawmills in Nigeria has led to an increase in the wood particles in various sawmills across the nation. The sawdust and wood shavings are most times burnt in the open air; hence, causing environmental pollution and also adding to the depletion of the ozone layer [2]. The wood wastes are sometimes used in cooking, poultry farms, and so on.

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The all-round development of people can be linked to the correct utilization of available resources. For several decades, one of the important resources used by mankind was wood-based products. However, due to seeking better environmental conditions, coupled with the recycling of environmental wastes and global warming challenges, the utilization of non-wood resources has grown [3]. Non-wood resources including sunflower stalks, pepper stalks, rice straw, wheat straw, rice husks, sugarcane bagasse, cotton stalks, rapeseed, and many more, have found utilization in particleboard production [3 - 7]. For many years, forest products have been used in the production of particleboard. However, due to the reduction in the availability of these raw materials (forest products) with more demand for particleboard products, agricultural-based materials have been the new research focus in this regard because of their built-in insulation, low-cost production, and characteristic sound suppression [8, 9]. Some of the agro-waste (biomass) products that have been used are displayed in Fig. 1.

Fig. 1. Agro-waste utilized for particleboard manufacture (a) Areca nut fiber, (b) Coconut fiber, (c) Rye straw, (d) Sugarcane bagasse, (e) Rice husk, (f) Sawdust, (g) Corncob, (h) Oat hulls

Particleboard is the composition of wood elements with adhesive bonding and is produced under heat and pressure [10, 11]. In the production of particleboard, softwoods, and lower-density hardwoods are commonly utilized. The utilization of lower-density wood helps in the production of lower-density particleboards with the maintenance of their strength and stiffness [8]. Several adhesives have been used in the production of particleboards. For instance, citric acid and tapioca starch were used as adhesives in the particleboard produced using oil palm fronds, oil palm trunks, and empty fruit bunch [12]. The adhesives were utilized at different mixing ratios and the results of the particleboards bonded with the citric acid and tapioca starch showed better properties when compared with particleboards bonded by urea-formaldehyde. It is noteworthy that urea-formaldehyde (UF) is the most commonly utilized adhesive in producing particleboards [6, 9, 11]. Some of the various biomasses with the different adhesives that have been utilized in the production of particleboards are displayed in Table 1. A typical example of a particleboard is shown in Fig. 2.

Table 1. Particleboard produced from different biomass and adhesives

S/N	Biomass used	Parts utilized for particleboard production	Adhesive used	Ref.
1.	Areca nuts	Fiber	Tapioca adhesive	[13]
2.	Coconuts	Pit and Fiber	UF and green binders (BST00 and BST20)	[14]
3.	Hazelnuts with shell	Shell	Melamine-UF or polyurethane	[15]
4.	Rye	Straw	Polymeric diphenylmethane diisocyanate (pMDI)	[16]
5.	Sugarcane	Bagasse	UF	[11]
6.	Tomatoes	Stalk	UF	[9]
7.	Cashew nuts with shell	Shell	Isocyanate resin, UF resin	[17]
8.	Rice, Wood	Husk, Sawdust	UF and gelatinous starch	[6]
9.	Dates	Palm branches	Vermiculite	[18]

Lee et al. [19] presented the worldwide production quantity of particleboard to have reached 96.01 million m^3 in the year 2020 with a disparity of about 4 million m^3 from the preceding year 2019. Among the world-renowned leading producers of particleboards are China, Italy, Germany, Austria, France, and Poland, as displayed in Fig. 3. Of all the continents in the world, Asia was found to be the largest producer of particleboards while Europe, the Americas, Africa, and Oceania were not left behind. It is also important to state that with 54.43%, the European countries are the largest importers of particleboards.

Fig. 2. Typical particleboard

The other percentages are Asia (26.51%), America (15.89%), Africa (2.89%), and Oceania (0.34%) [19]. Concerning the exportation of particleboard, European countries such as Austria, Russia, Germany, France, Belarus, Belgium, and Romania, are among the highest exporters, while Thailand is recognized as the key exporter of particleboard in the year 2020 [19]. The Food and Agriculture Organization (FAO) data for the exportation quantities of particleboards in the year 2022 for some selected countries is presented in Fig. 4.

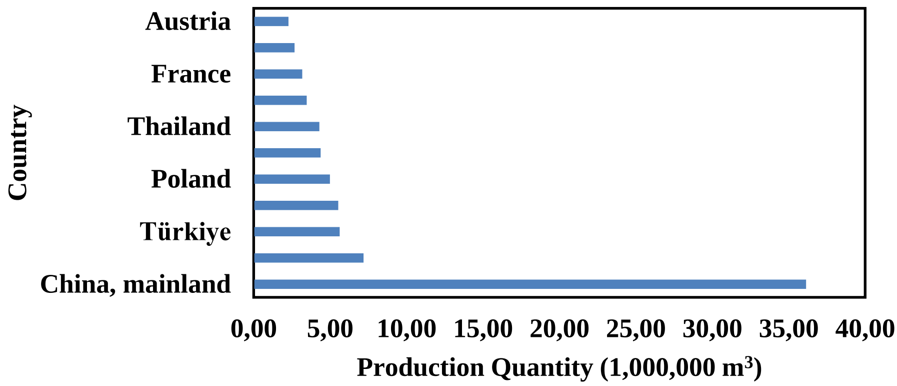

Fig. 3. Particleboard production quantity (m^3) per country in 2022 [20]

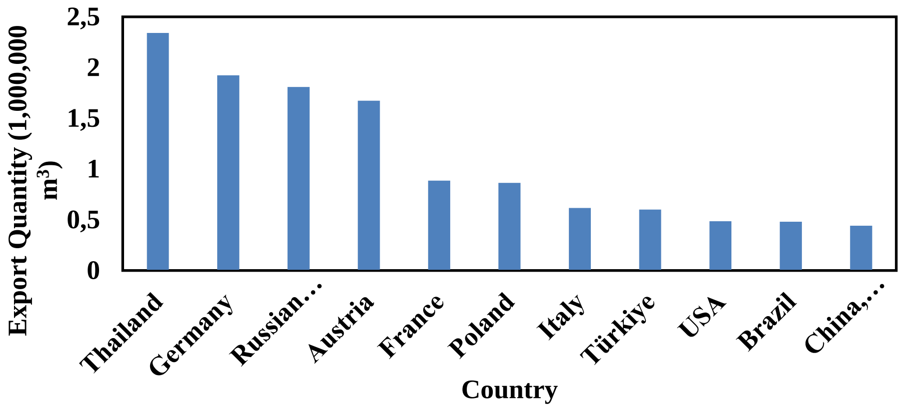

Fig. 4. Particleboard exportation quantity (in m^3) per country in 2022 [20]

The wood-based panel industry has suffered a setback in terms of the supply of wood due to the new legislative rules on wood usage in some countries, growing environmental challenges, and its global demand for wood raw materials. Hence, to replace wood in the production of particleboard due to the challenges earlier mentioned, an alternative search of naturally abundant feedstocks from renewable agricultural residues and wood by-products is a great measure of lowering the adverse environmental effects. The agricultural residues, considered biomass resources, have been greatly exploited and converted into different useful products such as energy utilization as densified biomass [21 – 25], biogas generation [26 – 28], particleboard production [6, 29], and many more. These utilizations have been reported to reduce environmental concerns and enhance environmental pollution control. In this current study, the utilization of agricultural residues for the production of particleboards was the focus and was not for other utilizations earlier mentioned. Hence, the application of agricultural residues in particleboard production should be made economically practicable and profitable. For the profitability of the particleboards made from agricultural residues, the manufactured boards are expected to meet or exceed the required technical standard of usage [19].

Within 5 – 6 years, it has been projected that there will be around a 6.1% increase in the global particleboard market. This is because of the increase in building activities around the world as well as the target market growth worldwide. Interestingly, due to increased urbanization, many urban settlers have the desire to beautify the interior of their building which could cause a boost in the global particleboard market [19]. The cost of particleboard compared to other wood products including plywood is a driver of the global particleboard market. More so, its extraordinary capability to absorb sound has made it find applications in recording studios and music halls. The aesthetic features of particleboard can be enhanced through coating, painting, or the application of beautiful wallpaper; leading to more demand for particleboards in modern offices and other similar sectors. More innovative and acceptable particleboards from natural fibers are gradually being introduced to the global particleboard market.

The utilization of biomass waste for the production of particleboard is to address and tackle environmental challenges and also to support responsible biomass waste resource management for sustainable ventures. The utilization of biomass wastes in the development of particleboard could result in several advantages. These include the cost-effectiveness of the biomass residue serving as an alternative to traditional wood chips. Production costs of the particleboards are reduced due to the utilization of these alternatives. The usage of biomass waste for particleboard production could also promote a circular economy where resources are efficiently re-used for the production of other sustainable products. Hence, the transformation of waste materials into viable particleboards helps to achieve sustainable urban development. With sustainable urban actualization through the use of waste materials for particleboard development, deforestation is reduced, the natural ecosystem is preserved, affordable housing is achievable, and environmental harm is minimized [19, 30 – 35].

This study focused on the review of the production techniques, properties, and future trends of particleboard from different biomass wastes. The physical, mechanical, chemical, and thermal properties of the particleboards were discussed as well and the internal microstructural arrangement was highlighted. The future trends in particleboard developments for continuous utilization were also discussed.

2. Method of Particleboard Production

Different production methods of particleboards have been employed in different studies. The most commonly used method of producing particleboard is the compression molding. The schematic diagram in Fig. 5 displays the overview of the step-by-step method involved in producing particleboards from various biomass or agro-waste materials using the compression molding technique.

In Fig. 5, the raw materials biomass residues such as sawdust, rice husk, and corncob) are locally sourced. They are sundried for some days to remove moisture inherent in them and sorted to remove unwanted foreign materials. They are screened to the required particle size of between 1 mm and 4 mm. The raw materials are later mixed at the desired mixing ratios or proportions while resins are added as adhesives. The mixtures are properly mixed either manually or mechanically to ensure a homogeneous distribution of the raw materials. Forming and pre-pressing are done by hand-filling the mixture in a created mold and manually pressing the mixture. The final compression can be either done using the hydraulic hot-pressing technique or the compression molding technique. The compressed mixture is allowed to stay for about 4 h before removing from the machine. The panel products are then ready for stacking and further usage [36 – 38].

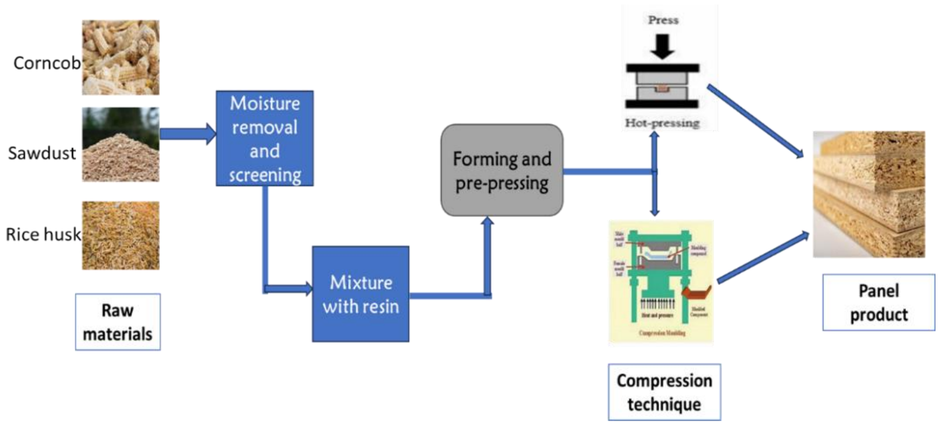

Fig. 5. Schematic presentation of particleboard production

Another method of producing particleboard is the extrusion method. In this method, the raw material particles are blended with bonding agents and other additives. A uniform thickness of the blended mixture is used to form the mat. The mat is then forced through a heated die to form the board. The board is passed through a heating zone to complete the resin curing. After, the board is allowed to cool before cutting to the desired size [39, 40]. In the steam-injection molding method, saturated steam is injected into the mat of particles during pressing. This is done through small holes or channels in the press platens. Through conduction, the steam heats the particles and binder. Through heat and pressure, the binder is cured. After, the steam is vented from the press via a vacuum system. The desired density and thickness are achieved through the continued pressure application to the mat. The board is allowed to cool before removal from the press for finishing operations [41 – 43].

Another technique of producing particleboard is the emulsion-based method. This method is commonly used for the development of particleboards with improved moisture resistance and durability. A water-based polymer (polyvinyl acetate (PVA) or acrylic emulsion) is the typical emulsion-based binding agent that is normally utilized. A stable and durable bond is created when this emulsion-based binding agent is mixed with the biomass particles. Typically, in this method, biomass particles are mixed with polymer emulsion binding and other additives. The blended mixture is used to form a uniform-thickness mat. Then, the mat is pressed to ensure the removal of excess water and achieve the desired density. The board is allowed to cure in a controlled environment (heated room or under ultraviolet light). The board is later cut to size and finishing treatments are applied on it [44, 45].

Studies have revealed the impact of resin contents on the mechanical properties of particleboards. The higher the resin contents in a particleboard, the better the mechanical properties. For instance, the effects of resin content on the mechanical properties of particleboard produced using *Neolamarckia* and *Leucaena* particles were evaluated by Abd Rahman et al. [46]. The resin used for the particleboard production was melamine urea formaldehyde at three different resin contents of 10, 12, and 14%. It was reported that mechanical properties such as internal bonding (IB), modulus of elasticity (MOE), and modulus of rupture (MOR) increased with an increase in resin content. The increase in MOE and MOR due to resin content increase could be linked to the increase in surface contact between the particle and the resin; thereby resulting in improved bonding properties. Ashori and Nourbakhsh [47] also reported an increase in mechanical properties of the particleboards produced using UF resin contents of 9, 10, and 11%. This implies that the resin-wood polymerization produced better properties at 11% resin addition. Also, using phenol-formaldehyde in the production of particleboards from oil palm fronds, the MOR, MOE, and IB values increased with increased resin contents from 9 to 11% [48]. Table 2 highlights some of the methods used by different studies. The methods of compression molding and hot-pressing machines were common in the study. However, various pressing pressure, temperature, and time were employed in the studies.

Table 2. Particleboard production method

S/N	Method of production	Ref.
1.	Three-layer composition board was produced using a hot-press machine at 160°C temperature for 5 min and a pressure of 3 N/mm^2.	[36]
2.	Urea formaldehyde was synthesized and added to a constant weight of the sawdust, and thoroughly mixed using an electric mixer. The mixture was molded using a compression molding machine at a pressure of 10 tonnes and a temperature of 150°C for 15 minutes.	[37]
3.	Binderless particleboards were produced at different pressing temperatures (180, 200, and 220°C), pressing times (15, 30, and 45 min), and pressure between 4 and 6 MPa. The particles were hand-formed into a particle mat using a forming box. After, the particleboards were hot-pressed and water-cooled.	[49]
4.	The pre-treated feedstock (wood chip) was mixed with adhesive and placed in a mat-forming box. Pre-pressing at 0.78 N/mm^2 of the particleboards was done using a manual pressing machine. Then, a hydraulic press was used to press the box for 8 minutes at 1.23 $\times 10^6$ N/mm^2 to produce the board.	][50]
5.	Leather shavings and waste papers were manually mixed at varied blend ratios using polyester resin as a binder and 2% methyl ethyl peroxide as a catalyst to produce a single-layer particleboard. A modified compression molding method was utilized by employing a hydraulic press of 50 kN load. Curing of the particleboard was done at room temperature for 4 h.	[51]
6.	12% UF resin content was used to adhere the particles together and were manually formed into a mat in a frame. Hot-pressing process using open hydraulic laboratory press using pressure of 2.5 N/mm^2, temperature of 180°C, and pressing time 20 s/mm.	[34]
7.	Corncob-sawdust particleboard was made from homogeneously mixed particles with adhesives. It was placed in a mold and compressed using a hydraulic compressing machine for 10 min. It was then oven-dried for 1 h at 80°C and allowed to cool. The panel was then removed from the mold and re-placed in the oven for 3 h at 130°C. The panel was allowed to cool before stacking.	[38]

3. Physical and Mechanical Properties of Particleboards

3.1 Density of Particleboard

The density of particleboards is determined to properly classify the boards into low-density, medium-density, and high-density boards [6]. It is usually evaluated using the ratio of mass (kg) and volume (m^3). It is a measure of how compact the particleboard is considering its particle. The particleboard's density depends on the wood's density, the adhesive used, and the applied pressure during compaction [52]. The density of the particleboards produced using plantain pseudostem, cocoa stem and pod, and Ceiba sawdust with either cassava or urea-formaldehyde (UF) were obtained to be classified as medium-density particleboards according to ANSI A208.1 standard [53]. Particleboards are classified as medium-density when the density is between 400 and 800 kg/m^3. The range of density values of particleboards with cassava starch adhesive was between 497 and 598 kg/m^3 while that of UF adhesive was from 421 to 557 kg/m^3 [52]. It can be deduced that there is more compaction of the particles of the raw materials of the board when cassava starch is used. The higher density when cassava starch was used could be due to the cassava adhesive properties which create strong bonds between the biomass particles leading to a denser structure. In addition, during the curing of the particleboard, cassava starch displays self-expansion properties. During the curing, the adhesive expands to effectively fill the gaps between the wood particles. Hence, the particleboard density is enhanced with this self-expansion property. It was, however, revealed that the high bulk density of cocoa pod over other raw materials like cocoa stem, plantain pseudostem, and Ceiba sawdust gave its particleboard superior density over other particleboards produced.

Table 3 presents the density of particleboards made from different materials and adhesives. The density values for the particleboards produced in the study of Iswanto et al. [36] ranged from 0.53 to 0.61 g/cm^3 which was less than 0.75 g/cm^3 target value. The density of the boards attained the JIS standard (0.40 – 0.90 g/cm^3) [54]. 8% isocyanate resin was used as the binder. Srichan and Raongjant [55] produced particleboards from bamboo shoot sheaths. The adhesive used in the production was diphenylmethane diisocyanate (MDI) resins. The obtained density values at 0.6 mm and 0.5 mm particle sizes varied from 554 to 836 kg/m^3, and 475 to 889 kg/m^3, respectively. In cement-bonded particleboard produced by Odeyemi et al. [56], all the boards produced met the minimum requirement as stipulated by ISO 8335, IS14276, and JIS A 5908 standards [54, 57, 58], which are respectively 1000, 1250, and 800 kg/m^3. The value of density of the particleboards ranged from 1281.10 to 1766.40 kg/m^3. The particleboards produced are classified as high-density particleboards. The presence of cement in the composition caused the density of the particleboards to be high, unlike those particleboards produced with cement as seen in some studies [6]. It is paramount to optimize the process involved to achieve an optimum density that would be useful in achieving the desired utilization.

3.2 Water absorption and Thickness swelling

A water absorption test is important to determine the hydrophilic or hydrophobic tendency of the particleboard. It is usually done after 2 and 24 h of water immersion. Water absorption has a direct link with thickness swelling. Thickness swelling occurs when the particleboard has absorbed water. The durability of the particleboard during storage can be assessed through a water absorption test.

In a study by Hartono et al. [78], elephant dung and wood shavings in the ratios of 100/0, 90/10, 80/20, 70/30, 60/40, and 50/50 (%w/w) were the materials used in the production of the particleboards after pre-treatment. The adhesive used was 7% isocyanate resin. The range of values for water absorption of the particleboard produced ranged from 58.32% (50/50 ratio) to 67.74% (100/0 ratio). These values indicate the lowest and highest water absorption, respectively. Water absorption in the particleboard produced reduced when wood shavings increased in the mix proportion. The low density of the particles of elephant dung led to higher water absorption. Particleboard's water absorption is affected by the size of the particles of the raw materials. Smaller particle sizes could lead to a larger surface area/contact area. However, the thickness swelling (TS) value significantly decreased with the increase of the wood shavings proportion. The value of TS ranged from 20.69% (100/0 ratio) to 36.5% (50/50 ratio). The reduction of TS value with increased wood shaving over elephant dung was linked to higher specific gravity possessed by the wood shaving than the elephant dung.

According to Odeyemi et al. [56], the dimensional stability of particleboards is mostly revealed by water absorption (WA) and thickness swelling. With the IS 14276 standard [58], the maximum WA recommended value should be 13% and 25% at 2 h and 24 h of immersion, respectively. From the study of Odeyemi et al. [56], WA was increased due to an increase in sawdust and cement percentage, whereas WA reduced with an increased percentage of periwinkle shell. Just like the WA, TS increased with a percentage increase in cement and sawdust while a reduction of TS was observed when periwinkle shell increased. The recommended standard TS as stipulated by ANSI A 208.1 standard is 8% [53]. This value was fulfilled by all samples produced.

In Ghana, Mitchual et al. [52] used four biomass residues (plantain pseudostem, cocoa stem and pod, and ceiba sawdust) for particleboard development using two different adhesives (UF and cassava starch). The particle size of the materials was within 0.5 to 1.5 mm. The WA properties were evaluated at 2 and 24 h of water immersion using ASTM D1037-06a standard. At 2 h immersion, the plantain pseudostem gave the least WA of 9.86% (with cassava starch adhesive) and 7.77% (with UF adhesives), while the highest WA was from cocoa pods with 22.41% (with cassava starch adhesive) and 14.98% (with UF adhesive). It was reported that the higher WA property of cocoa pod and ceiba particleboards could be associated with the high content of silica and decreased lignin present in the materials. When UF and cassava starch were used as adhesives in the production of particleboards, lower and better WA was achieved [52]. This could be linked to the hydrophilic nature of cassava starch which tends to absorb water [79].

Particleboards produced using cassava starch adhesive gave significantly higher but worse TS values than the particleboards produced using UF. For instance, at 2 h immersion, TS for Ceiba particleboard with cassava starch adhesive was 5.83% while that of UF adhesive was 3.91%. At 24 h immersion, TS for Ceiba particleboard with cassava starch adhesive was 17.27% while that of UF adhesive was 13.22%. The TS values were reduced from 2 to 24 h immersion for all the biomass residues and adhesives used. This worse phenomenon was attributed to the higher hydrogen polymer chains in the cassava resulting in higher water absorption with higher thickness swelling [80]. Ultimately, the commercialization of particleboard requires the appropriate WA standard. It was documented that WA of 35% at 24 h water immersion was recommended by ANSI A208.1 standard, while 8% and 15% of WA at 2 and 24 h immersion respectively is recommended by EN 312 (2005) standard [81]. Some of the previous results obtained for WA and TS of some particleboards produced are displayed in Table 4.

It can be deduced that WA and TS at 2 h immersion when castor husk and pine wood were used in particleboard development ranged from 77.7 to 43.6% and 20 to 10%, respectively while 117.4 to 76.8% and 33.4 to 19.2% were obtained for WA and TS at 24 h immersion, respectively [59]. When bamboo and *Pinus oocarpa* were utilized in particleboard production at 2 and 24 h immersion, WA was respectively 82 – 65% and 92 – 74% while TS was respectively 18.2 – 14.2% and 22 – 16% [64]. From Table 4, it can be deduced that WA and TS are greatly influenced by the type and proportion of the raw materials, the adhesive type, and the production processes used. The time-dependent behaviour of the particleboards helps to provide insights into the behaviour of the particleboard under different moisture conditions. Higher WA indicates lower durability and resistance to moisture. Also, higher TS indicates lower dimensional stability and potential delamination [38, 82]. However, the stability of particleboards could be improved against water through the utilization of water-repellent substances [83, 84].

Table 4. Water absorption and thickness swelling of various particleboards used

Materials for particleboards	WA (%)		TS (%)		Ref.
	2h	24h	2h	24h	
Castor husk and Pinewood	77.6 – 43.6	117.4 – 76.8	20 – 10	33.4 – 19.2	[59]
Mauritia flexuosa and *Eucalyptus spp.* Wood	47.3– 89.6	65.47 – 109.97	10.53 – 19.53	19.74 – 24.13	[60]
Cotton wastes and Eucalyptus wood	120.7 – 138.9	138.84 – 151.97	11.34 – 23.93	14.17 – 27.45	[61]
Sugarcane bagasse and Eucalyptus wood	16.1 – 45.7	30.5 – 73.6	7.9 – 15.8	13.5 – 16.2	[62]
Coffee parchment and Eucalyptus wood	120.54 – 84.72	138.08 – 109.44	11.78 – 6.38	12.95 – 9.83	[63]
Bamboo and *Pinus oocarpa*	82.0 – 65.0	92.0 – 74.0	18.2 – 14.2	22.0 – 16.0	[64]
Jupati and Eucalyptus wood	NA	53.79 – 95.77	NA	16.89 – 24.92	[65]
Sugarcane bagasse and Eucalyptus wood	5.8	20.0	5.6	20.1	[66]
Oat Hulls and Eucalyptus grandis	5.2 – 6.8	NA	4.2 – 5.5	NA	[67]
Hevea brasiliensis and *Pinus oocarpa*	125.52 – 73.24	139.58 – 99.74	22.82- 10.14	28.48 – 12.75	[68]
European Black Pinewood and Licorice root	48.25 – 39.07	59.26 – 54.90	17.12 – 13.25	20.19 – 17.65	[69]
Soybean pods and Eucalyptus wood	116.08 – 151.48	121.5 – 164.03	10.38 – 42.78	15.04 – 53.18	[70]
Sugarcane bagasse in fiber lengths (5 mm and 8 mm)	NA	53.2 – 10.4	NA	42.0 – 14.7	[71]
Angelim, Cambara, Canelao, Cedar and Itauba	19.89 – 40.49	27.86 – 42.64	3.57 – 10.11	7.48 – 11.59	[72]
Peanut Hull and *Pinus oocarpa*	65.05 – 76.71	71.97 – 88.24	15.63 – 26.98	22.46 – 31.12	[73]

Pterocarpus violaceus wood and *Pinus oocarpa* wood	73.4 – 70.1	85.0 – 81.2	17.5 – 19.9	24.4 – 21.4	[74]
Miriti petioles and *Pinus oocarpa* wood	92.01 – 162.63	104.03 – 201.2	15.45 – 38.26	21.3 – 43.89	[75]
Maize cob and *Pinus oocarpa*	54 – 40	70 – 90	25.8 – 18.6	37.5 – 30.0	[76]
Pinus oocarpa wood, Castor hull, and Sugarcane Bagasse	35.1 – 61.0	46.1 – 89.6	7.1 – 12.6	7.3 – 18.4	[77]

*NA- Not Available

3.3 Modulus of elasticity (MOE) and Modulus of rupture (MOR)

The MOE and MOR are some of the mechanical properties required to be determined to ascertain the quality and usefulness of particleboards produced. The maximum load-carrying capacity of a material during bending which is proportional to the maximum moment carried by the material is MOR [52]. MOE and MOR of some particleboards developed are shown in Table 5. The MOE and MOR of particleboards made from *Broussonetia papyrifera* wood were studied. The outcome of the particleboard produced revealed a high-performance board. The optimum MOE and MOR values were 4.9 GPa and 27 MPa at a board density of 1.1 g/cm^3. The varying manufacturing parameters used to obtain the optimum responses were temperature (180, 200, and 220^{o}C), time (15, 30, and 45 min), pressure (4.0-6.0 and 4.5-6.5 MPa), particle size (coarse and fine), and density (0.8, 1.0, 1.1, and 1.2 g/cm^3). A trend of MOE and MOR increment with density increment was reported [49]. Due to the high compaction ratio which caused the intimacy of the particles bonding together, the higher mechanical strength of the board at higher board density was reported [49]. The increase in the particleboard's strength could be attributed to the increased heat conductivity of the board resulting in the degradation of the cellulose and hemicellulose of the biomass particles.

Srichan and Raongjant [55] investigated the physico-mechanical and thermal behaviours of single-layer particleboard produced using bamboo shoot sheaths. Diphenylmethane Diisocyanate adhesive with 7% resin content was used as a binder. The study reported that the denser the board, the more the MOE and MOR. More so, a smaller particle size (0.5 mm) tends to assist in obtaining better MOE and MOR than the 0.6 mm particle size of the bamboo shoot sheaths. As stipulated by JIS standard, the minimum MOE value of 3000 MPa and MOR value of 18 MPa are recommended. The board produced using bamboo shoot sheath particles at 0.5 mm and 0.6 mm size and using diphenylmethane diisocyanate (MDI) resin as adhesive showed lower MOE and MOR values compared to the JIS standard except for one [55]. The reason for the low MOE and MOR can be attributed to the low density of the bamboo shoot sheath. The values of the MOE for all the samples produced were between 250 and 1700 MPa while MOR values were between 3 and 19 MPa. A sample produced using 0.5 mm particle size gave the highest MOR (19 MPa) at 800 kg/m^3 density. This sample has the only MOR that surpasses the JIS standard (MOR $\geq$ 18MPa). Due to the values of the MOE (250 – 1700 MPa) and MOR (3 – 19 MPa) obtained, the produced particleboards were not recommended for structural works but for non-structural works.

To meaningfully recycle waste products from the leather industry, Kibet et al. [51] produced particleboards from leather shavings and waste papers. The resin and catalyst used in the production of the particleboard were unsaturated polyester (UP) and methyl

ethyl ketone peroxide (MEKP), respectively. Two percent (2%) catalyst (methyl ethyl ketone peroxide) was mixed with the resin by mass. The range of values of the MOR was between 11.44 and 20.11 MPa at 50 wt.% and 100 wt.% waste papers, respectively. Effective adhesion observed in the particleboard was linked to lower moisture of the waste papers which resulted in decreased trap voids in the product. Also, the MOE ranged from 4.15 to 5.65 GPa at 100 wt.% leather ratio and 100 wt.% waste paper ratios, respectively. Proper adhesion and compaction of the waste paper particles and the resin were linked to the high value of MOE at 100 wt.% waste papers whereas low density with high moisture content was reported to be responsible for the low MOE recorded for the 100 wt.% leather particles. With the reported results, it can be deduced that the produced wood-leather panel met with the JIS standard for utilization for various applications including the structural and interior of a building.

In 2020, Mitchual et al. [52] investigated the properties of particleboards produced using biomass of cocoa pod, plantain pseudostem, ceiba, and cocoa stem at particulate levels. However, it was reported that particleboards obtained from plantain pseudostem with UF resin gave the highest MOE (2413 MPa) while the cocoa pod-cassava starch adhesive particleboard gave the least MOE (1031 MPa). A comprehensive display of the results is presented in Fig. 6. Aside from the cocoa pod-made particleboards, all the boards produced were acceptable for general utilization and production of furniture since ANSI A208.1 requirements were met. The particleboard with the high MOE was characterized and linked to a comparatively high aspect ratio of the plantain pseudostem which was higher compared to other materials.

As observed in MOE, the range of MOR values was from 4.95 MPa for cocoa pod and 16.54 MPa for plantain pseudostem (Fig. 7). ANSI A208.1 standard was met for the produced particleboards except for cocoa pod-based particleboards when either cassava starch or UF adhesives were used. The standard stipulated that a minimum of 10 MPa MOR must be attained for interior fitments in a building structure. The utilization of UF as an adhesive gave better MOR compared to when cassava starch was used.

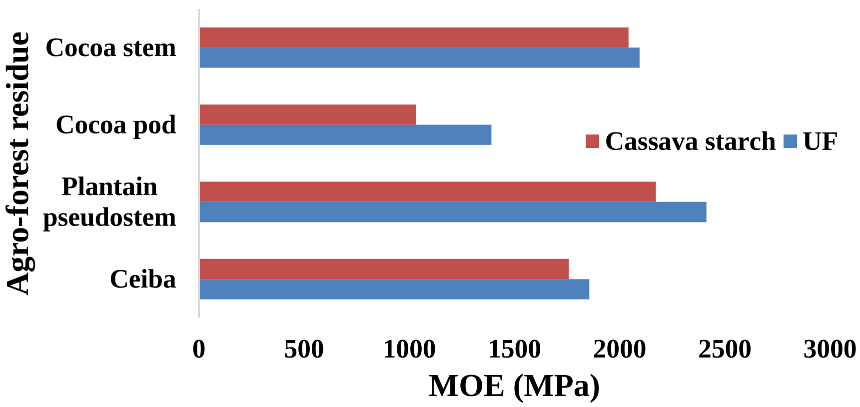

Fig. 6. MOE of different agro-forest residues for particleboard production [52]

Similarly, Hartono et al. [78] characterized the MOE and MOR of various particleboards produced from Elephant dung and wood shavings. From the study, the MOE and MOR values ranged from 1952 to 2573 MPa and 18.6 to 27.4 MPa, respectively. It was revealed that when more wood shaving was added to the mix ratio, higher MOE was obtained. This observation was the same for MOR. The high values of MOE and MOR were attributed to the large dimensions of the wood shavings compared to the elephant dung fibers.

Except for 100 wt.% Elephant dung fiber particleboards, the MOE values of all other fabricated particleboards met with JIS A 5908-2003 standard while all fabricated particleboards met with JIS standard for MOR with 8 MPa required minimum.

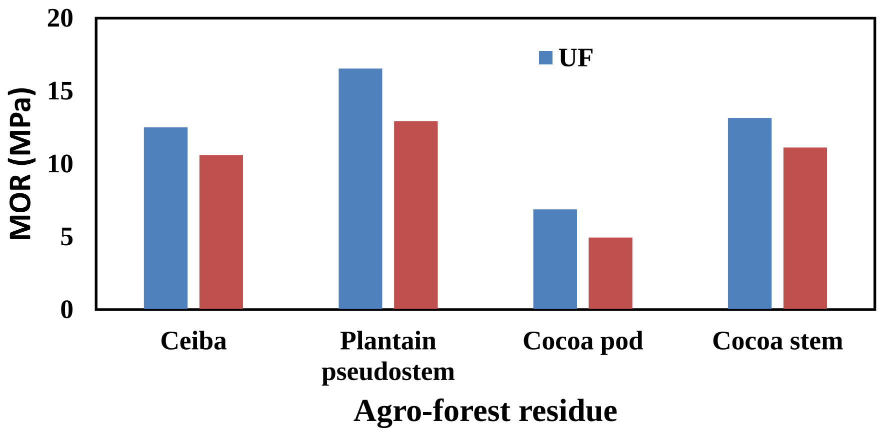

Fig. 7. MOR of different agro-forest residues for particleboard production [52]

Particleboards were produced from walnut wood shavings using UF as adhesive [34]. In the study, the MOE and MOR values were compared with the EN 312 standard under three categories (Type P5, Type P6, and Type P7) [81]. Based on the walnut wood particle substitution range, the produced particleboard with soft particles under standard pressure and at lower resin content satisfied the high requirements of technical standards for construction boards. The type P6 which could be used for heavy-duty load-bearing boards in dry conditions was met. However, the standard P5-type board requirements were satisfied by the remaining boards, which could be useful as load-bearing boards in humid conditions. Other works in this regard are the utilization of Pentung bamboo using sucrose-based for the production of particleboards was investigated [85]. In the investigation, increasing the pressing temperature increased the MOR to some values greater than 13 MPa, which is the JIS A5908 (2003) standard [54]. It was indicated that the raw materials' chemical components influenced the bonding properties of the sucrose-based particleboards. However, improved MOR was observed with samples with ammonium dihydrogen phosphate (ADP) serving as a phosphate catalyst. A similar trend was observed for the MOE values; although, the sucrose-only adhesive-based particleboards fell short of the required 3 GPa MOE values according to the JIS A 5908 (2003) standard.

Table 5. MOE and MOR of various particleboards

Materials for particleboards	MOE (MPa)	MOR (MPa)	Ref.
Castor husk and Pinewood	3111.8 – 2382.8	18.4 – 12.0	[59]
Mauritia flexuosa and *Eucalyptus spp*. Wood	1286.41 - 855.73	10.91 - 6.95	[60]
Cotton wastes and Eucalyptus wood	726.47 - 205.12	8.63 - 3.87	[61]
Sugarcane bagasse and Eucalyptus wood	1707.11 – 2501.97	11.61 – 17.08	[62]
Coffee parchment and Eucalyptus wood	648.62 – 400.73	8.17 – 4.43	[63]
Bamboo and *Pinus oocarpa*	2077.0 – 1636.0	16.7 – 13.9	[64]
Polyol/Pre-polymer and *Pinus spp.*	1479.80 – 2439.60	13.40 - 19.40	[86]
Jupati and Eucalyptus wood	1469.11 – 1084.57	6.66 – 4.75	[65]

Sugarcane bagasse and Eucalyptus wood	2848	22.60	[66]
Oat Hulls and *Eucalyptus grandis*	2349 – 1942	18 – 24	[67]
Hevea brasiliensis and *Pinus oocarpa*	934.75 – 1054.35	5.63 – 9.87	[68]
European Black Pinewood and Licorice root	2142.21– 2582.62 N/mm^2	12.02 – 16.42 N/mm^2	[69]
Soybean pods and Eucalyptus wood	1297.68 – 435.21	7.57 – 2.41	[70]
Sugarcane bagasse in fiber lengths (5 and 8 mm)	2.85 – 1.53	21.20 – 14.9	[71]
Angelim, Cambara, Canelao, Cedar and Itauba	935.62 – 611.90	5.09 – 2.12	[72]
Peanut Hull and *Pinus oocarpa*	1430.91 – 668.35	9.44 – 4.26	[73]
Pterocarpus violaceus wood and *Pinus oocarpa* wood	2653 – 2577	11.6 – 13.3	[74]
Miriti petioles and *Pinus oocarpa* wood	1087.2 – 1273.27	6.45 – 7.36	[75]
Maize cob and *Pinus oocarpa*	1190 – 200	8.0 – 1.0	[76]
Pinus oocarpa wood, Castor hull, and Sugarcane bagasse	2068 – 3111	12.0 – 18.4	[77]

3.4 Internal Bonding Strength, Flexural Strength, Compression Ratio

The internal bonding strength, flexural strength, and compression ratio of particleboards are part of the parameters to be investigated to determine the proper utilization of the products produced. Some various factors affect the IBS values of particleboards. The coating of each particle on the board with the adhesive resin is important for the IBS improvement. For instance, Pedzik et al. [87] increased the walnut wood content with a relatively lower number of particles in the boards, and with UF resin as a binder, better particle coating, as well as higher IBS values, were attained at 50% walnut particles. It was higher with an increased degree of sizing. or. More so, using more resin as an adhesive for the particles was reported to produce improved IBS. The IBS improved with an increased percentage of walnut particles from 0 to 50% and with an increased resin content of between 10 and 12%. The IBS value when 50% of walnut particles were used was around 28% higher than the reference board produced at 1.5 N/mm^2 applied pressure [87]. Modified starch was used as a binder in the production of particleboard from rubberwood with target densities of 0.60, 0.70, and 0.80 g/cm^3. The adhesive used was 15% corn starch-modified with glutardialdehyde. It reported that the IBS increased as the target density increased respectively as 0.62, 0.88, and 1.02 N/mm^2. The analysis revealed that the optimum IBS could be attained at target densities between 0.70 and 0.80 g/cm^3 in which higher panel density could slightly improve the IBS [88].

Another factor that influences the IBS is the board's density. When MDI adhesive was utilized in the production of particleboards using bamboo shoot sheaths, the IBS values were directly proportional to the boards' densities. That is, as the density of the board increased, the IBS value also increased. Unlike the study of Pedzik et al. [34], the effects of the particle size were insignificant on the IBS value. However, the IBS values of the particleboard surpassed the JIS standard of 0.3 MPa which ensured good particleboard development. The high IBS value was linked to the efficient bonding of the particles of the bamboo with the MDI adhesive. The strength of panels increases with increased density; hence, it fulfills the strength requirements for structural materials and building panels [34, 88, 89].

Particleboard was produced using Sumatran elephant dung and wood shavings at different mixed ratios of 100/0, 90/10, 80/20, 70/30, 60/40, and 50/50 (% w/w). The mixed particle at each ratio was sprayed with 7% isocyanate adhesive. The physical and mechanical properties of the particleboards produced were examined. The IBS values of the particleboards produced in the study of Hartono et al. [78] ranged from 0.16 to 0.34 MPa (100/0 to 50/50 ratio, respectively). The maximum IBS (0.34 MPa) was obtained with the 50/50 ratio of elephant dung fibers and wood shavings while the least IBS (0.16 MPa) was at a 100/0 ratio. These values were reported to have met with the JIS A 5908 (2003) standard [54], which stated that particleboard should have a minimum IBS value of 0.15 MPa. The increase of the wood shavings and decrease of the elephant dung in the ratios was reported to have led to higher internal bond value. The increased density of the particleboards as the wood shavings increased resulted in increased IBS value. Composite boards were developed by Ekpenyong et al. [90] where treated groundnut shell particles (TGP) and untreated groundnut shell particles (UGP) were utilized at 0 to 100% mixture of both raw materials. The binder used was cassava starch at a ratio of 1:3 with the composite mix. The composite mixing ratios of UGP to TGP were 100:0, 75:25, 50:50, 25:75, and 0:100. The least flexural strength value was 1.040 N/mm^2 at 100%UGP:0%TGP and the maximum flexural strength value was 2.255 N/mm^2 at 0%UGP:100%TGP. The study revealed that due to the treatment given to the groundnut shell particles, better and stronger interfacial adhesion was obtained relative to the UGP. Hence, the more the TGP in the composites, the higher the flexural strength. More so, it was reported that the IBS of the TGP was directly proportional to the amount of TGP in the composites. The particleboard produced in the study was suggested to be useful for wall partitioning or ceiling boards.

Particleboard was developed using leather shavings and waste papers at different mix ratios of 100:0, 25:75, 50:50, and 75:25). The resin used was unsaturated polyester while methyl ethyl ketone peroxide was used as a catalyst. The percentage content of resin used was 60, 70, 80, and 90%, which served as the matrix. The mechanical properties of the developed panels were examined. The sample with 100% waste papers gave the highest IBS (13.61 MPa) while the least IBS (5.83 MPa) was obtained at 100% leather waste. As the waste paper content was reduced with increased leather waste content, the IBS value decreased. The waste paper bonded well with the resin compared to the leather waste; leading to improved IBS. Also, at constant particle blend ratios, the IBS decreased from 6.46 MPa (60% resin) to 2.82 MPa (90% resin). It was observed that resin content increase reduced the IBS of particleboards made from leather shavings and waste papers [51]. With further analysis, the IBS reduced as the percentage content of leather shaving increased with reduced waste paper content. Good bonding of the particles of waste papers with the resin used compared to the leather shavings was the reason for the increase in IBS value. The hydrophobic nature of some fibers results in the difficulty of the resin adhesive to chemically react. Hence, it necessitates the hydroxyl group reaction of the resin adhesive [36]. Iswanto et al. [36] investigated the IBS of sandwiched particleboards produced using non-woody biomass of sugar palm fibers, cornstalk, and sugarcane bagasse while bamboo strand was used as reinforcement. The binder used was 8% isocyanate resin. The IBS values ranged between 0.03 and 0.40 N/mm^2. The least IBS value was 0.03 N/mm^2 when sugar palm fibers were used in the core while the maximum IBS value (0.40 N/mm^2) was obtained when sugarcane bagasse was used in the core. The non-absorbent nature of the sugar palm fibers led to the low IBS value. Petung bamboo was used to produce particleboard using sucrose-based adhesive as the binder in the study of Widyorini [85]. The IBS of the particleboards was significantly affected considering the pressing temperature and sucrose-based adhesive. The IBS of the sample produced using only sucrose as the adhesive and pressed at 160^{o}C was the least (0.08 MPa), which indicated that higher pressing temperatures are needed when sucrose only is used as the adhesive. However, the IBS increased from 0.65 to 0.79 MPa when the pressing temperature increased from 180 to 200^{o}C, respectively. Widyorini [85] revealed that many factors could be responsible for bonding mechanisms which are not limited to adhesive content, utilized raw materials, or pressing time. Table 6 further displays some IBS and compression ratios as obtained from the literature.

Table 6. IBS and FS of various particleboards

Materials for particleboards	IBS (MPa)	CR	Ref.
Castor husk and Pinewood	1.10 – 0.91	1.3 – 2.6	[59]
Mauritia flexuosa and *Eucalyptus spp.* Wood	0.51 – 0.11	1.23 – 1.96	[60]
Cotton wastes and Eucalyptus wood	0.26 – 0.16	1.2 – 1.4	[61]
Sugarcane bagasse and Eucalyptus wood	0.4 – 0.69	1.11 – 6.67	[62]
Coffee parchment and Eucalyptus wood	0.34 – 0.18	1.30 – 1.91	[63]
Bamboo and *Pinus oocarpa*	0.81 – 0.66	1.34 – 2.00	[64]
Jupati and Eucalyptus wood	NA	1.16 – 1.49	[65]
Sugarcane bagasse and Eucalyptus wood	1.18	-	[66]
Oat Hulls and *Eucalyptus grandis*	1.84 – 1.60	1.49 – 3.50	[67]
Hevea brasiliensis and *Pinus oocarpa*	0.14 – 0.56	1.06 – 0.93	[68]
European Black Pinewood and Licorice root	0.33 – 0.55 N/mm^2	1.5	[69]
Soybean pods and Eucalyptus wood	0.48 – 0.07	1.21 – 2.95	[70]
Sugarcane bagasse in fiber lengths (5 and 8 mm)	0.34 – 1.18	NA	[71]
Angelim, Cambara, Canelao, Cedar and Itauba	0.53 – 0.24	0.98 – 1.40	[72]
Peanut Hull and *Pinus oocarpa*	0.54 – 0.22	1.28 -2.57	[73]
Pterocarpus violaceus wood and *Pinus oocarpa* wood	0.93 – 0.66	8.6 – 12.0	[74]
Miriti petioles and *Pinus oocarpa* wood	NA	1.3 – 3.95	[75]
Maize cob and *Pinus oocarpa*	11.0 – 0.3	1.4 – 3.9	[76]
Pinus oocarpa wood, Castor hull, and Sugarcane bagasse	0.35 – 1.09	1.31 – 6.74	[77]

*NA- Not Available

4. Chemical, Thermal, and Microstructural Properties of Particleboards Made from Biomass

The determination of the chemical properties of particleboards produced from different biomass is very important. The use of agricultural wastes for the production of particleboard is limited by the cellulose content of the biomass. The cellulose-ordered structure results in tighter and denser structure particleboards leading to better strength, improved rigidity, and stable dimensions compared with lignocellulosic particleboards [34]. The strength of the particleboards can be improved through various chemical composition interactions. With the improved strength, the particleboards can be utilized in various interior building applications. Unfortunately, limited studies have examined the chemical properties of produced particleboards. Most studies considered the chemical properties of the raw biomass before being used with other biomass and adhesives in the production of the particleboards. They failed to consider the chemical properties of the particleboards after production in which various interactions of the different constituents would have erupted chemical reactions.

Fitri et al. [1] determined the chemical composition of particleboards made from rice straw (50 wt.%) and polypropylene (50 wt.%) using X-ray fluorescence. The study observed that the major constituents are SiO_2 (35%), K_2O (25%), and CaO (15%). The chemical compositions involved when particleboards were manufactured from sunflower stalks treated with sodium hydroxide were lignin, hemicellulose, and α-cellulose contents, extractive contents, and monosaccharide composition [3]. The study revealed that the treatment of Sunflower stalk particles with alkali has effects on the chemical composition and thermal stability. Thus, the contents of the chemical components like extractive contents, hemicellulose, and lignin were lowered with the rise in NaOH concentrations from 1 to 5%. As a result of the chemical degradation of the particles, there was a reduction of thermal stability as the NaOH concentration increased.

The chemical analysis of the untreated groundnut shell particles (UGP) and treated groundnut shell particles (TGP) for various lignocellulosic constituents were investigated when groundnut shells were used to produce particleboards by Ekpenyong et al. [90]. The cellulose, hemicellulose, and lignin content of the two categories of fibers (UGP and TGP) were analyzed. The analysis for UGP revealed 38.89% cellulose, 27.03% hemicellulose, and 19.61% lignin while TGP showed 45.74% cellulose, 23.52% hemicellulose, and 12.69% lignin. The chemical compositions of UGP and TGP differ because of the alkaline treatment given to the groundnut shell particles (TGP). As reported by [90], the alkaline treatment of fibers increased the cellulose content to 45.74% compared to the untreated fibers (36.89%). A high cellulose content of agro-residues in the production of particleboard has been attributed to giving the particleboard excellent mechanical properties. This makes high cellulose content agro-residues potentially suitable for particleboard production. However, agro-residues with lower cellulose contents have negative effects on the mechanical properties of particleboards [9, 34, 91, 92].

Thermal conductivity analysis is crucial in the determination of the insulation properties of particleboards. This would assist particleboard manufacturers in optimizing production by selecting suitable materials and ensuring compliance with standards and regulations. Particleboards produced from mulberry wood pruning waste with the usage of urea-formaldehyde resin as a binder were characterized by Ferrandez-Villena et al. [93]. The average thermal conductivity values obtained for the particleboards varied between 0.065 and 0.068 W/mK. These values were lower compared to those obtained for other woods such as Date palm (0.083 W/mK), Hemp (0.111 W/mK), and Sisal (0.070 W/mK); but have similar values of 0.065 W/mK with cork panels. The thermal conductivity of the particleboards was not influenced by the particle size of the raw materials. The production of particleboard from papyrus fiber using natural rubber latex as a binder was achieved by Tangjuank and Kumfu [94]. The study investigated the thermal properties of the particleboard produced. The thermal property (conductivity) of the particleboard was 0.029 W/mK, a value lower than that of commercial particleboards at 0.092 W/mK. The value of the thermal insulation obtained showed that the papyrus fiber exhibited good thermal insulation since it has a lower thermal conductivity value compared to the commercial particleboard. Low thermal conductivity is desired to minimize heat transfer and maximize energy efficiency. Hence, lower thermal conductivity is an indication of better insulation properties; thereby, making the material suitable for various applications. Low thermal conductivity of particleboards reduces heat transfer and energy consumption in buildings leading to cost savings and environmental benefits [93, 95].

One of the most important parameters for selecting thermal insulation of particleboards is fire resistance [96]. It is the capability of a material to resist fire and can be considered for interior applications such as ceilings and walls. More so, there is a relationship between thermal conductivity values and the density of the particleboards. Tangjuank [96] observed and reported that the higher-density particleboards of 210 kg/m^3 have the least insulating effect (0.035 W/mK) when pineapple leaves are used in the production of particleboard. This observation was linked to the fact that low-density particleboards are not well compacted hence they possess a large number of voids filled with air, which serves as one of the poorest conductors. This implies that less heat is being conducted in lower-density boards compared to the higher-density boards. The pineapple leaves particleboards were adjudged excellent thermal insulating materials.

The thermal properties of Sunflower particleboards were investigated by Lenormand et al. [95]. The particleboards were produced without binder. However, the board fabrication was done using a hot hydraulic press. Three particleboard densities (50, 75, and 100 kg/m^3) were desired. It was reported that the thermal conductivity of the materials increased with the density. The least (50 kg/m^3) and densest particleboards (100 kg/m^3) have thermal conductivity values of 38.08 and 42.41 mW/mK, respectively. When density is low, there is increased porosity in the particleboard which could lead to low thermal conductivity. Table 7 displays the density and thermal conductivity values for different biomass materials used in the production of particleboards.

Table 7. Density and thermal conductivity of different particleboards

Particleboard from biomass	Density (kg/m^3)	Thermal conductivity (W/mK)	Ref.
Pineapple leave	210	0.035	[96]
Papyrus fibers	258	0.029	[94]
CCB-treated *Pinus sp.* Wood (100% wood)	0.55 g/cm^3	0.11	[97]
60% wood/40%tire Rubber	0.78 g/cm^3	0.14	[97]
Sunflower	50 – 100	0.038 – 0.042	[98]
Bamboo shoot sheaths	400 – 800	0.066 – 0129	[55]
Spruce	NA	0.062 – 0.091	[99]
Black pine	NA	0.074 – 0.105	[99]
Beech	NA	0.103 – 0.139	[99]
Oak	NA	0.118 – 0.154	[99]
Chestnut	NA	0.087 – 0.120	[99]
Coir fiber	300 – 500	0.120 – 0.169	[100]
Red pine wood and Gypsum	0.845 – 1.333	0.7404 – 0.5021	[101]
Narrow-leaved Cattail fibers	200 – 400	0.0438 – 0.0606	[102]
Norway Spruce residues and coniferous bark	0.232 – 0.291	0.049 – 0.074	[103]
Leave fiber of Camel's foot	528.6 – 538.4	0.0321 – 0.0409	[104]
Bark fiber of Camel's foot	558.3 – 711.8	0.0394 – 0.0434	[104]
Newspaper waste	NA	0.066 – 0.125	[105]

*NA- Not Available

Analyzing the particleboard's morphology is very germane for the examination of the compactness of the raw biomass particles and their interaction with the binders used. It also helps to examine the pores formed in the particleboards produced. During the micrograph analysis of particleboards produced from cocoa pods using starch and urea formaldehyde as adhesives in the study of Mitchual et al. [52], major micropores and loosed particles were observed on some of the samples. The study observed that there was detachment of the particles from the adhesives. The bonding between the adhesives and the particles was reported to be poor owing to the high bulk density and low aspect ratio of the biomass material. However, a contrary observation was reported for some other samples such as Ceiba, cocoa, and plantain pseudostem where the inter-particle spaces of the particles were filled with adhesives such as UF and cassava starch. Hence, there is better compaction and agglomeration of the particles and adhesives leading to improved mechanical properties.

The overall strength properties of particleboards are dependent on the glue line between the particles [106]. Ulker and Hiziroglu [106] observed in the micrograph that there was a relatively uniform distribution of the starch adhesive leading to improved bonding among the particles. The cross-sectional view of the particleboard produced when glutardialdehyde-modified starch was employed as a binder which showed granulated modified corn starch. The larger the particle size, the more voids in the structure of the particleboards. This was the experience when peach nut shells with glass powder and tea fiber were used in the production of particleboards at particle sizes of 900 μm and 150 μm, respectively, using phenol-formaldehyde as a binder [107]. It was reported that the 900 μm particle size particleboard showed many voids in the structure while the 150 μm particle size particleboard showed no void in the particleboard's structure. This observation supported the water absorption characteristics of the particleboards in which structures with more voids tend to absorb more water which is deleterious to the particleboard when stored. A typical micrograph of particleboard is displayed in Fig. 8.

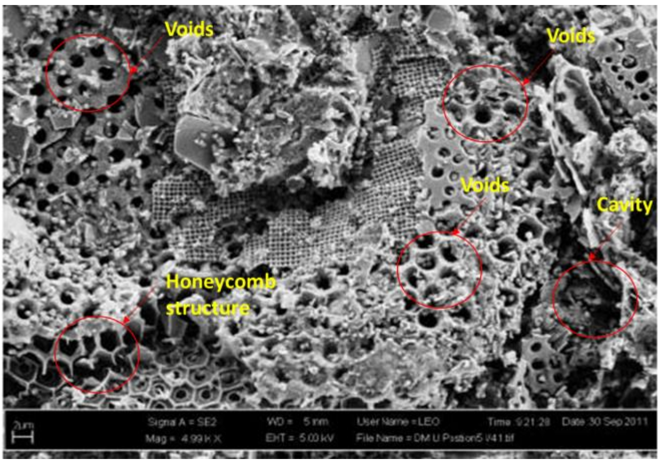

Fig. 8: Micrograph of a particleboard [108]

5. Challenges and Prospects for Future Works on Particleboards

There is a major challenge of inconsistent raw materials supply for the manufacturing of particleboards all over the world. Many producers of particleboards are unyielding in adopting alternative feedstock for their production; rather, they are still seeking the usual raw materials [34, 36, 51]. This kind of issue needs to be tackled appropriately. Manufacturers of particleboards should believe in the utilization of alternative raw materials such as agro-waste materials or biomass. Many developing countries are faced with serious environmental health challenges as a result of the accumulation of various agricultural residues without properly discarding them. Proper waste management and utilization policies especially in the context of agro-residue-based particleboards should be encouraged [19]. Although particleboards from agro-wastes have been greatly researched and have advanced scientifically and technologically, the wider and commercial acceptability of particleboards is limited due to some challenges. The utilization of fresh agro-residue leads to more transportation and storage costs due to its higher moisture content and heaviness [109]. Hence, high moisture content agro-residues are less compressible during particleboard production. With different processing parameters that have been used by various researchers, it is important to optimize the processing parameters. For instance, the pressing time, temperature, and pressure should be optimized for sufficient compaction/compression ratio and strength [110, 111]. For appropriate bonding, more resins as adhesives are required to cater to the higher volume of agro-residues in the production of particleboards. When fewer resins are used, improper bonding is achieved and the board's final performance is adversely affected [112].

Furthermore, particleboard manufactured using agro-residues is liable to deteriorate in dimension and absorb more water. Hence, the particleboard's water absorption and dimensional stability should be critically examined. This implied that hydrophilic raw materials such as husk, stalk, shell, and straw of various biomass used in the manufacturing of particleboards could be solved by introducing hydrophobic agents (wax) during the fabrication process. Although promising results have been documented on the physical and mechanical properties of agro-based particleboards, wood-based particleboards are of better strength. Therefore, the strength of agro-based particleboards could be increased by introducing woody particles at proper resin dosage and pressing parameters. Further studies are recommended on the critical examination of the fire-resistance characteristics of the particleboard. There is no sufficient information on this aspect. More so, more studies should be done to optimize the manufacturing process of the particleboard. More studies should also be done on the thermal stability of the particleboard by considering the thermal conductivity and insulation of the particleboard.

6. Conclusion

The appropriate utilization of biomass and environmental wastes for a sustainable environment is germane to the reduction of environmental pollutants. Particleboards produced from the recycling of agricultural biomass have been examined in this study. The properties of the particleboards produced with these agro-residues showed similar or superior physico-mechanical properties that met the requirements of different standards for proper utilization for sustainable construction. The density of particleboard depends on the density of the biomass used, the adhesive used, and the compaction pressure applied during production. The density helps to classify particleboards into low-density, medium-density, and high-density boards. The durability and storability of particleboards can be assessed through a water absorption test, which could be influenced by the particle sizes of the biomass used. Also, the quality and usefulness of particleboards were ascertained via the modulus of elasticity and modulus of rupture. The denser the particleboard, the higher the modulus of elasticity and the modulus of rupture. The modulus of elasticity and modulus of rupture are positively influenced to be better with a smaller particle size of the biomass used. Hence, the particle size of the biomass used plays an important role in the determination of the properties of particleboards. The insulation property of particleboards is obtainable through thermal conductivity analysis. Embracing this development could lead to fulfilling the sustainable development goals featuring growth in the economy, protection of the environment from pollution, and social inclusion. With the utilization of these various biomass for the particleboards, the challenge of deforestation is drastically reduced, and more entrepreneurial opportunities are created. Panel production continuation is ensured since agro-waste materials are used as alternative or complementary raw materials. Hence, the production and the products are economical and eco-friendly. Further studies should be considered on the optimization of the processing parameters and critically examining the fire-resistance characteristics.

References

[1] Fitri N, Mursal, Ismail I. Physical and chemical properties of particleboards made from rice straw and plastic waste. IOP Conference Series: Journal of Physics, 2020; 1460: 012146. https://doi.org/10.1088/1742-6596/1460/1/012146

[2] Adeleke AA, Ikubanni PP, Orhadahwe TA, Christopher CT, Akano JM, Agboola OO, Adegoke SO, Balogun AO, Ibikunle RA. Sustainability of multifaceted usage of biomass: A review. Heliyon, 2021a; 7: e08025. https://doi.org/10.1016/j.heliyon.2021.e08025

[3] Guler G. Chemical, physical and mechanical properties of particleboards manufactured from sodium hydroxide-treated sunflower (*Helianthus annus L.*) stalks. Journal of Barlin Faculty of Forestry, 2019; 21(3): 758–770. https://doi.org/10.24011/barofd.588056

[4] Yasina M, Waheed Bhutto A, Bazmi A, Karim S. Efficient utilization of rice-wheat straw to produce value-added composite products. Journal of Environmental Chemical Engineering, 2010; 1: 1–8.

[5] Dukarska D, Czarnecki R, Dziurka D, Mirski R. Construction particleboards made from rapeseed straw glued with hybrid pMDI/PF resin. European Journal of Wood and Wood Product, 2017; 75: 175–184. https://doi.org/10.1007/s00107-016-1143-x

[6] Ikubanni PP, Adeleke AA, Adediran AA, Agboola OO. Physico-mechanical properties of particleboards produced from locally sourced materials. International Journal of Engineering Research in Africa, 2018; 39: 112-118. https://doi.org/10.4028/www.scientific.net/JERA.39.112

[7] Luo P, Yang C, Li M, Wang Y. Manufacture of thin rice straw particleboards bonded with various polymeric methane diphenyl diisocyanate/urea formaldehyde resin mixtures. BioResources, 2020; 15, 935–944. https://doi.org/10.15376/biores.15.1.935-944

[8] Xu Y, Sun XS, Wang D. Chapter 1: Wheat Section 1: Cereals and Soybeans. In: Integrated Processing Technologies for Food and Agricultural By-Products. Edited by Pan, Z., Zhang, R. and Zicari, S.; 2019; p. 3–20.

[9] Taha I, Elkafafy MS, ELMously H. Potential of utilizing tomato stalk as raw material for particleboard. Ain Shams Engineering Journal, 2018; 9(4): 1457–1464. https://doi.org/10.1016/j.asej.2016.10.003

[10] Araújo CKC, Campos CI, Camargo SKCA, Camargo BS. Caracterização mecânica de painéis particulados de média densidade produzidos a partir de resíduos de madeira. Revista Gestão Industrial, 2019; 15(1): 197-211. https://doi.org/10.3895/gi.v15n1.9159

[11] Brito FMS, Junior GB, Surdi PG. Properties of particleboards made from sugarcane bagasse particles. Revista Brasileira de Ciencias Agrarias, 2021; 16(1): 1–7. https://doi.org/10.5039/AGRARIA.V16I1A8783

[12] Zakaria R, Bawon P, Lee SH, Salim S, Lum WC, Al-Edrus SSO, Ibrahim Z. Properties of particleboard from oil palm biomasses bonded with citric acid and tapioca starch. Polymers, 2021; 13(20): 3494. https://doi.org/10.3390/poly13203494

[13] Nurdin H, Hasanuddin H, Kurniawan A. Particleboard made from areca fiber with tapioca adhesive. Journal of Physics: Conference Series, 2020; 1594 (012031). https://doi.org/10.1088/1742-6596/1594/1/012031

[14] Lim JX, Ong TK, Ng CK, Chua IW, Lee YB, Yap ZY, Abu Bakar R. Development of particleboard from green coconut waste. Journal of Physics: Conference Series, 2021; 2120 (012034). https://doi.org/10.1088/1742-6596/1594/1/012031

[15] Barbu MC, Sepperer T, Tudor EM, Petutschnigg A. Walnut and hazelnut shells: untapped industrial resources and their suitability in lignocellulosic composites. Applied Science, 2020; 10: 6340. https://doi.org/10.3390/app10186340

[16] Mirski R, Dziorka D, Banaszak A. Properties of particleboards produced from various lignocellulosic particles. Bioresources, 2018; 13(4): 7758–7765. https://doi.org/10.15376/biores.13.4.7758-7765

[17] Mari E., Villena E. Properties of particleboard from wood wastes and cashew nut shell residue. Philippine Journal of Science, 2016; 145(1): 1-8.
[18] Ghofrani M, Ashori A, Mehrabi R. Mechanical and acoustic properties of particleboards made with date palm branches and vermiculite. Polymer Testing, 2017; 60: 153 –159. https://doi.org/10.1016/j.polymertesting.2017.03.028
[19] Lee SH, Lum WC, Boon JG, Kristak L, Antor P, Pedzik M, Rogozinski T, Taghiyari HR, Lubis MAR, Fatriasari W, Yadav SM, Chotikhun A, Pizzi A. Particleboard from agricultural biomass and recycled wood waste: a review. Journal of Materials Research and Technology, 2022; 20: 4630-4658. https://doi.org/10.1016/j.jmrt.2022.08.166
[20] Food and Agriculture Organization: Forestry production and trade (2023). Available at https://www.fao.org/faostat/en/#data/FO. Accessed 22nd February 2024
[21] Adeleke AA, Odusote JK, Lasode OA, Ikubanni PP, Malathi M, Paswan D. Mild pyrolytic treatment of Gmelina arborea for optimum energetic yields. Cogent Engineering, 2019a; 6: 1-13. https://doi.org/10.1080/23311916.2019.1593073
[22] Adeleke AA, Odusote JK, Lasode OA, Ikubanni PP, Malathi M, Paswan D. Densification of coal fines and mildly torrefied woody biomass into composite fuel using different organic binders. Heliyon, 2019b; 5(7): 1-7. https://doi.org/10.1016/j.heliyon.2019.e02160
[23] Adeleke AA, Odusote JK, Ikubanni PP, Lasode OA, Malathi M, Paswan D. Essential basics on biomass torrefaction, densification and utilization. International Journal of Energy Research, 2021b; 45(2): 1375-1395. https://doi.org/10.1002/er.5884
[24] Ajimotokan HA, Ehindero AO, Ajao KS, Adeleke AA, Ikubanni PP, Shuaib-Babata YL. Combustion Characteristics of fuel briquettes made from charcoal particles and sawdust agglomerates. Scientific African, 2019; 6: 1-9. https://doi.org/10.1016/j.sciaf.2019.e00202
[25] Ikubanni PP, Omololu T, Ofoegbu W, Omoworare O, Adeleke AA, Agboola OO, Olabamiji TS. Performance evaluation of briquette produced from a designed and fabricated piston-type briquetting machine. International Journal of Engineering Research and Technology, 2019; 12(8): 1227 – 1238.
[26] Fajobi MO, Lasode OA, Adeleke AA, Ikubanni PP, Balogun AO. Effect of biomass co-digestion and application of artificial intelligence in biogas production: A review. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2022a; 44(2): 5314-5339. https://doi.org/10.1080/15567036.2022.2085823
[27] Fajobi MO, Lasode OA, Adeleke AA, Ikubanni PP, Balogun AO. Investigation of physicochemical characteristics of some selected lignocellulose biomass. Scientific Reports, 2022b;12: 2918. https://doi.org/10.1038/s41598-022-07061-2
[28] Adegoke SO, Adeleke AA, Ikubanni PP, Nnodim CT, Balogun AO, Falode OA, Adetona S. Energy from biomass and plastic recycling: A review. Cogent Engineering, 2021; 8 (1994106): 1 – 46. https://doi.org/10.1080/23311916.2021.1994106
[29] Ohijeagbon IO, Adeleke AA, Mustapha VT, Olorunmaiye JA, Okokpujie IP, Ikubanni PP. Development and characterization of composite particleboard produced from sawdust and pulverized polypropylene plastic. Case Studies in Construction Materials, 2020; 13(e00365): 1-8. https://doi.org/10.1016/j.cscm.2020.e00365
[30] Mirindi D, Panthi K, Thach TNS, Hunter J. A review of the evolution and performance of particleboard from different types of organic waste and adhesives. EPiC Series in Built Environment, 2024; 5: 740-749.
[31] Baharuddin MNM, Zain NM, Harun WSW, Roslin EN, Ghazali FA, Md Som SN. Development and performance of particleboard from various types of organic waste and adhesives: A review. International Journal of Adhesion and Adhesives, 2023; 124 (103378). https://doi.org/10.1016/j.ijadhadh.2023.103378
[32] Mahieu A, Vivet A, Poilane C, Leblanc N. Performance of particleboards based on annual plant byproducts bound with bio-adhesives. International Journal of Adhesion

and Adhesives, 2021; 107 (102847). https://doi.org/10.1016/j.ijadhadh.2021.102847
[33] Nunes L, Cintura E, Parrcha JL, Fernandes B, Silva V, Faria P. Cement-bonded particleboards with banana pseudostem waste: Physical performance and bio-susceptibility. Infrastructures, 2021; 6(6): 86. https://doi.org/10.3390/infrastructures6060086
[34] Pedzik M, Janiszewska D, Rogozinski T. Alternative lignocellulosic raw materials in particleboard production: A review. Industrial Crops and Products, 2021; 174: 114162. https://doi.org/10.1016/j.indcrop.2021.114162
[35] Betené ADO, Ndiwe B, Krishnan GS, Wedaïna AG, Tchoupmene CM, Djakou CBN, Taoga MM, Betené FE, Atangana A. Processing of tropical agro-industrial waste for particleboard manufacture: Dimensional stability and mechanical performance. Journal of Building Engineering, 2023; 76: 107369. https://doi.org/10.1016/j.jobe.2023.107369
[36] Iswanto AH, Hakim AR, Azhar I, Wirjosentono B, Prabuningrum DS. The physical, mechanical and sound absorption properties of sandwich particleboard (SPb). Journal of Korean Wood Science and Technology, 2020; 48(1): 32-40. https://doi.org/10.5658/WOOD.2020.48.1.32
[37] Ejiogu IK, Odiji MO, Ayejagbara MO, Shekarri TNB, Ibeneme U. Mechanical properties of urea formaldehyde particle board composite. American Journal of Chemical and Biochemical Engineering, 2018; 2: 10-15. https://doi.org/10.11648/j.ajcbe.20180201.12
[38] Akinyemi BA, Afolayan JO, Ogunji OE. Some properties of composite corncob and sawdust particleboards. Construction and Building Materials, 2016; 127: 436-441. https://doi.org/10.1016/j.conbuildmat.2016.10.040
[39] López YM, Paes JB, Rodríguez EM, Gustave D, Gonçalves FG. Wood particleboards reinforced with thermoplastics to improve thickness swelling and mechanical properties. Cerne, 2018; 24(4): 369-378. https://doi.org/10.1590/01047760201824042582
[40] Sun S, Liu L. Manufacturing tubular particleboards via multidimensional-interface extrusion and their physiomechanical properties. BioResources, 2021; 16(1): 1091-1100. https://doi.org/10.15376/biores.16.1.1091-1100
[41] Hata T, Kawai S, Sasaki H. Production of particleboard with steam-injection. Wood Science and Technology, 1990; 24: 65–78. https://doi.org/10.1007/BF00225307
[42] Xu J, Han G, Wong DE, Kawai S. Development of binderless particleboard from kenaf core using steam-injection pressing. Journal of Wood Science, 2003; 49(4): 327-332. https://doi.org/10.1007/s10086-002-0458-7
[43] Li X, Zheng X, Li H. Steam-injection pressing technology of man-made board. Key Engineering Materials, 2011; 474-476: 1351-1355. https://doi.org/10.4028/www.scientific.net/KEM.474-476.1351
[44] Zhang Y, Gu J, Tan H, Di M, Zhu L, Weng X. Straw-based particleboard bonded with composite adhesives. BioResources, 2011; 6(1): 464-476. https://doi.org/10.15376/biores.6.1.464-476
[45] Dhawale P, Vineeth S, Gadhave R, Mahanwar P. Cellulose stabilized polyvinyl acetate emulsion: Review. Open Journal of Organic Polymer Materials, 2021; 11: 51-66. https://doi.org/10.4236/ojopm.2021.112002
[46] Abd Rahman WW, Md Yatim A, Mat Zlan A, Kasim J, Mohd Yunus N. Effects of the resin content and particle size on the properties of particleboard made of *Neolamarckia* and *Leucaena* particles. BioResources, 2019; 14(3): 6079-6087. https://doi.org/10.15376/biores.14.3.6079-6087
[47] Ashori A, Nourbakhsh A. Effect of press cycle time and resin content on physical and mechanical properties of particleboard panels made from the underutilized low-

quality raw materials. Industrial Crops and Products, 2008; 28(2): 225 – 230. https://doi.org/10.1016/j.indcrop.2008.02.015
[48] Yusoff NF, Mohammed Tamat NS, Kasim J. Effects of board density and resin content on the mechanical and physical properties of oil palm frond particleboard. In: Yacob N, Mohamed M, Megat Hanafiah M. (eds) Regional Conference on Science, Technology and Social Sciences (RCSTSS 2014). Springer, Singapore, 2016. https://doi.org/10.1007/978-981-10-0534-3_39
[49] Chen M, Zheng S, Wu I, Xu J. Study on preparation of high-performance binderless board from *Broussonetia papyrifera.* Journal of Wood Science, 2023; 69: 1-14. https://doi.org/10.1186/s10086-023-02092-3
[50] Eyide O, Amenaghawon NA, Modebe LU, Mene JA. Optimization of mechanical properties of bonded particle boards produced from agricultural waste wood chips. Journal of Applied Science and Environmental Management, 2023; 27(4): 733-740.
[51] Kibet T, Tuigong DR, Maube O, Mwasiagi JI. Mechanical properties of particleboard made from leather shavings and waste papers. Cogent Engineering, 2022; 9: 2076350. https://doi.org/10.1080/23311916.2022.2076350
[52] Mitchual SJ, Mensah P, Frimpong-Mensah K, Appiah-Kubi E. Characterization of particleboard produced from residues of plantain pseudostem, cocoa pod and stem and ceiba. Materials Science and Applications, 2020; 11: 817-836. https://doi.org/10.4236/msa.2020.1112054
[53] American National Standards Institute (ANSI), Particle Board Standard ANSI. A208.1-1999, Composite Panel Assoc., Gaithersburg, MD, 1999.
[54] JIS, Japanese Industrial Standard, Particleboards, Japanese Standard Association, Japan, 2003, 5908.
[55] Srichan S, Raongjant W. Characteristics of particleboard manufactured from bamboo shoot sheaths. E3S Web of Conferences, 2020; 187(0301): 1-9. https://doi.org/10.1051/e3sconf/202018703011
[56] Odeyemi SO, Abdulwahab R, Adeniyi AG, Atoyebi OD. Physical and mechanical properties of cement-bonded particleboard produced from African balsam tree (*Populous balsamifera*) and periwinkle shell residues. Results in Engineering, 2020; 6: 100126. https://doi,org/10.1016/j.rineng.2020.100126
[57] ISO 8335, Cement Bonded Particle Board: Board of Portland or Equivalent Cement Reinforced with Fibrous Wood Particles, International Organization for Standardization, Stockhom, 1987.
[58] IS 14276, Indian standard, Cement Bonded Particle Boards Specification, Bureau of Indian Standards (BIS) Division, New Delhi, 1995.
[59] Silva DW, Scatolino MV, do Prado NRT, Mendes RF, Mendes LM. Addition of different proportions of castor husk and pine wood in particleboards. Waste and Biomass Valorization, 2018; 9(1): 139–145. https://doi.org/10.1007/s12649-016-9742-7
[60] Faria LD, Guimarães COJ, Mendes ML, Junior B G J, Article R. Conventional Low-density Particleboards Produced with Particles from *Mauritia Flexuosa* and *Eucalyptus spp.* Wood. Clean Technologies and Environmental Policy, 2021. https://doi.org/10.21203/rs.3.rs-980174/v1
[61] Scatolino MV, Protásio TP, Souza VM, Farrapo CL., Guimarães Junior JB., Soratto D, Mendes RF, Mendes LM. Does the addition of cotton wastes affect the properties of particleboards? Floresta e Ambiente, 2019; 26(2). https://doi.org/10.1590/2179-8087.030017
[62] Farrapo C, Wisky Silva D. Effect of association of sugarcane bagasse with Eucalyptus wood on the quality of particleboard. Key Engineering Materials, 2016; 668, 341-347. https://doi.org/10.4028/ww.scientific.net/KEM.668.341
[63] Scatolino MV, Costa AO, Guimarães Júnior JB, Protásio TP, Mendes RF, Mendes LM. Madeira de eucalipto e pergaminho de café na produção de aglomerados:

Propriedades físicas e mecânicas. Ciencia e Agrotecnologia, 2017; 41(2): 139–146. https://doi.org/10.1590/1413-70542017412038616
[64] Teodoro R, Raabe J, Silva DW, Mendes RF, Mendes LM, Tonoli GHD. Functionally graded MDP panels using bamboo particles. Key Engineering Materials, 2016; 668: 39–47. https://doi.org/10.4028/www.scientific.net/KEM.668.39
[65] de Araújo Veloso MCR, Lopes FM, Corrêa Furtini AC, da Silva MG, Mendes LM, Guimarães JB. Low-density particleboard properties produced with jupati particles and eucalyptus wood. Revista Brasileirade Ciencias Agrarias, 2020; 15(4). https://doi.org/10.5039/AGRARIA.V15I4A8414
[66] Sartori DL, Cravo JCM, Barrero NG, Fiorelli J, Junior HS, Nakanishi EY. Painel modular em madeira e chapas de partículas de bagaço de cana-de-açúcar para curral de bovinos. Acta Scientiarum-Technology, 2015; 37(1): 3–9. https://doi.org/10.4025/actascitechnol.v37i1.21239
[67] Varanda LD, Do Nascimento MF, Christoforo AL, Silva DAL, Lahr FAR. Oat hulls as addition to high density panels production. Materials Research, 2013; 16(6): 1355–1361. https://doi.org/10.1590/S1516-14392013005000131
[68] Faria DL, Eugênio TMC, Lopes DE, Protásio TP, Mendes LM, Junior, JBG. Particleboards produced with different proportions of *Hevea brasiliensis*: Residual wood valorization in higher value-added products. Ciencia e Agrotecnologia, 2021; 45. https://doi.org/10.1590/1413-7054202145021420
[69] Cengiz G. Production of particleboards from licorice (Glycyrrhiza glabra) and European black pine (Pinus Nigra Arnold) wood particles. Scientific Research and Essays, 2015; 10(7): 273–278. https://doi.org/10.5897/sre2015.6193
[70] Martins EH, Vilela AP, Mendes RF, Mendes LM, Vaz LEVSB, Guimarães Junior JB. (2018). Soybean waste in particleboard production. Ciencia e Agrotecnologia, 2018; 42(2): 186–194. https://doi.org/10.1590/1413-70542018422015817
[71] Fiorelli J, De Lucca Sartori D, Cravo JCM, Savastano H, Rossignolo JA, Do Nascimento MF, Lahr FAR. Sugarcane bagasse and castor oil polyurethane adhesive-based particulate composite. Materials Research, 2013; 16(2): 439–446. https://doi.org/10.1590/S1516-14392013005000004[73]
[72] Longo BL, Da Cunha AB, Rios PD, Terezo RF, De Almeida CCF. Caracterizacą̃o tecnológica de paineís particulados produzidos com resíduos de cinco espécies tropicais. Scientia Forestalis/Forest Sciences, 2015; 43: 907–917. https://doi.org/10.18671/scifor.v43n108.15
[73] Brito FMS, Silva BA, de Carvalho IM, Baúti SB, Mendes LM, Guimarães JB. Technological properties of medium-density particleboards produced with peanut (*Arachis hypogaea*) and *Pinus oocarpa* hulls. Floresta e Ambiente, 2022; 29(2): e20210101. https://doi.org/10.1590/2179-8087-FLORAM-2021-0101
[74] Farrapo CL, Mendes RF, Guimeraes Junior JB, Mendes LM. Utilization of *Pterocarpus violaceus* wood in the particleboard production. Scientia Forestalis, 2014; 42: 329-335.
[75] Furtini ACC, dos Santos CA, de Novais Miranda EH, Villarruel DCV, Gomes DAC, Ferreira GC, da Silva MG, Mendes LM, Guimarães Júnior JB. Using miriti petiole to produce particleboards. Ambiente Construído, 2023; 23(2): 149-162. https://doi.org/10.1590/s1678-86212023000200668
[76] Scatolino MV, Silva DW, Mendes RF, Mendes LM. Uso do sabugo de milho na produção de painéis aglomerados. Ciencia e Agrotecnologia, 2013; 37(4): 330–337. https://doi.org/10.1590/S1413-70542013000400006
[77] Silva DW, Farrapo CL, Mendes RF, Mendes LM, Tonoli GHD, Guimarães JB. Use of castor hull and sugarcane bagasse in particulate composites. Key Engineering Materials, 2016; 668: 381–389. https://doi.org/10.4028/www.scientific.net/KEM.668.381
[78] Hartono R, Dalimunthe AM, Iswanto AH, Herawati E, Sutiawan J, de Azevedo ARG. Mechanical and physical properties of particleboard made from the sumatran

elephant (*Elephas maximus sumatranus*) dung and wood shaving. Polymers 2022; 14: 2237. https://doi.org/10.3390/polym14112237

[79] Salleh KM, Hashim R, Sulaiman O, Hiziroglu S, Wan Nadhari WNA, Abd Karim N, Jumhuri N, Ang LZP. Evaluation of properties of starch-based adhesives and particleboard manufactured from them. Journal of Adhesion Science and Technology, 2014; 29(4): 319-336. https://doi.org/10.1080/01694243.2014.987362

[80] Witono JR, Noordergraaf IW, Heeres HJ, Janssen LPMB. Water absorption, retention and the swelling characteristics of cassava starch grafted with polyacrylic acid. Carbohydrate Polymers, 2014; 103: 325-332. https://doi.org/10.1016/j.carbpol.2013.12.056

[81] EN 312. Particleboards-Specifications. European Committee for Standardization 312, Brussels-Belgium, 2005.

[82] de Melo RR, Muhl M, Stangerlin DM, Alfenas RF, Junior FR. Properties of particleboards submitted to heat treatments. Ciencia Florestal, 2018; 28(2): 776-783. https://doi.org/10.5902/1980509832109

[83] Ferrandez-Garcia A, Ferrandez-Garcia MT, Garcia-Ortuño T, Ferrandez-Villena M. Influence of the density in binderless particleboards made from sorghum. Agronomy, 2022; 12(6): 1387. https://doi.org/10.3390/agronomy12061387

[84] Yilmazer S, Aras U, Kalaycioglu H, Temiz A. Water absorption, thickness swelling and mechanical properties of cement bonded wood composite treated with water repellent. Maderas Ciencia y Tecnologia, 2023; 25: 1-10. https://doi.org/10.4067/s0718-221x2023000100434

[85] Widyorini R. Evaluation of physical and mechanical properties of particleboard made from Petung bamboo using sucrose-based adhesive. BioResources, 2020; 15(3), 5072-5086. https://doi.org/10.15376/biores.15.3.5072-5086

[86] Ferro FS, de Almeida DH, Magalhães de Souza A, Icimoto FH, Christoforo AL, Lahr FAR. Influence of proportion polyol/pre-polymer castor-oil resin components in static bending properties of particleboards produced with Pinus sp. Advanced Materials Research, 2014; 884–885, 667–670. https://doi.org/10.4028/www.scientific.net/AMR.884-885.667

[87] Pedzik M, Auriga R, Kristak L, Antov P, Rogozinksi, T. Physical and mechanical properties of particleboard with addition of walnut (*Juglans regia L.)* wood residues. Materials, 2022; 15: 1280. https://doi.org/10.3390/ma15041280

[88] Amini MHM, Hashim R, Hiziroglu S, Sulaiman NS, Sulaiman O. Properties of particleboard made from rubberwood using modified starch as binder. Composites Part B: Engineering, 2013; 50: 259 – 264. https://doi.org/10.1016/j.compositesb.2013.02.020

[89] Auriga R, Auriga A, Borysiuk P, Wilkowski J, Formalczyk O, Ochmian I. Lignocellolosic biomass from grapevines as raw material for particleboard production. Polymers, 2022; 14: 2483. https://doi.org/10.3390/polym14122483

[90] Ekpenyong NE, Ekong SA, Nathaniel EU, Thomas JE, Okorie US, Robert UW, Akpabio IA, Ekanem NU. Thermal response and mechanical properties of groundnut shells' composite boards. Researchers Journal of Science and Technology, 2023; 2(1): 42-57.

[91] Amilia W, Rusdianto AS, Sofiana W. Characteristics of tobacco stem particleboard in printing load variations and storage time. Journal La Lifesci, 2020; 1: 8–14. https://doi.org/10.37899/journallalifesci.v1i3.115

[92] Fahmy Y, Fahmy TYA, Mobarak F, El-Sakhawy M, Fadl MH. Agricultural residues (Wastes) for manufacture of paper, board, and miscellaneous products: background overview and future prospects. International Journal of ChemTech Research, 2017; 10: 424–448. https://hal.science/hal-01613635

[93] Ferrandez-Villena M, Ferrandez-Garcia A, Garcia-Ortuno T, Ferrandez-Garcia MT. Acoustic and thermal properties of particleboards made from mulberry wood (*Morus*

alba L.) pruning residues. Agronomy, 2022; 12: 1803. https://doi.org/10.2290/agronomy12081803

[94] Tangjuank S, Kumfu S. Particleboards from papyrus fibers as thermal insulation. Journal of Applied Sciences, 2011; 11: 2640–2645. https://doi.org/10.3923/jas.2011.2640.2645

[95] Aladegboye OJ, Oyedepo OJ, Awolola TJ, Oguntayo OD, Babatunde OY, Ilesanmi OT, Ikubanni PP. Physicomechanical and thermal properties of particleboard produced using waste ceramic materials and corncob. Advances in Materials Science and Engineering, 2024; 2024: 8839814. https://doi.org/10.1155/2024/8839814

[96] Tangjuank S. Thermal insulation and physical properties of particleboards from pineapple leaves. International Journal of Physical Sciences, 2011; 6(19): 4528 – 4532.

[97] Da Silva Bertolini M, Christofiro AL, Rocco Lahr FA. Thermal insulation particleboards made with wastes from wood and tire rubber. Key Engineering Materials, 2015; 668: 263–269. https://doi.org/10.4028/www.scientific.net/KEM.668.263

[98] Lenormand H, Gle P, Leblanc N. Investigation of the acoustical and thermal properties of sunflower particleboards. Acta Acustica United with Acustica, 2017; 103: 149 – 157. https://doi.org/10.3813/AAA.919040

[99] Bozikova M, Kotoulek P, Bilcik M, Kubik L, Hlavacova Z, Hlovac P. Thermal properties of wood and wood composites made from wood waste. International Agrophysics, 2021; 35: 251–256. https://doi.org/10.31545/intagr/142472

[100] Kiran MC, Mamatha BS, Anand N, Prakash V, Murthy N. Efficiency of coir particleboard for acoustic and thermal applications. Open Journal of Acoustics, 2019; 9: 39–47. https://doi.org/10.4236/oja.2019.93004

[101] Kaya AI, Yalcm OU, Turker Y. Physical, mechanical, and thermal properties of red pine wood-gypsum particleboard. Bilge International Journal of Science and Technology Research, 2021; 5(2): 139–145. https://doi.org/10.30516/bilgesci.956.352

[102] Luamkanchanaphan T, Chotikaprakham S, Jarusombati S. A study of physical, mechanical and thermal properties of thermal insulation from narrow-leaved cattail fibers. APCBEE Procedia, 2012; 1: 46–52. https://doi.org/10.1016/j.apcbee.2012.03.009

[103] Medved S, Tudor EM, Barbu MC, Young TM. Thermal conductivity of different bio-based insulation materials. Les/Wood, 2021; 70(1): 73–82. https://doi.org/10.26614/les-wood.2021.v70n01a05

[104] Abubakar M, Raji A, Hassan MA. Comparative study of thermal insulation boards from leaf and back fibers of Camel's foot (*Piliostigma thonningri L*). Nigerian Journal of Technology, 2018; 37(1): 108–114. https://doi.org/10.4314/njt.v37i1.14

[105] Theasy Y, Yulianto A, Astuti B. Effect of thickness on thermal conductivity based on waste newspaper particleboard. Journal of Natural Sciences and Mathematics Research, 2017; 210: 210–214. https://doi.org/10.21580/jnsmr.2017.3.1.1696

[106] Ulker O, Hiziroglu S. Some properties of Eastern red cedar (*Juniperus virginiana L.*) particleboard panels made using modified starch as binder. Dryna Industrija, 2020; 71(4): 371 – 377. https://doi.org/10.5552/drvind.2020.1947

[107] Sahin A, Tasdemir HM, Karabulut AF, Guru M. Mechanical and thermal properties of particleboard manufactured from waste peachnut shell with glass powder. Arabian Journal for Science and Engineering, 2017; 42(4): 1559–1568. https://doi.org/10.1007/s13369-017-2427-0

[108] Funk M, Wimmer R, Adamopoulos, S. Diatomaceous earth as an inorganic additive to reduce formaldehyde emission from particleboards. Wood Material Science and Engineering, 2017; 12(2): 92-97. https://doi.org/10.1080/17480272.2015.1040066

[109] Dukarska D, Rogozinski T, Antov P, Kristak L, Kmieciak J. Characterisation of wood particles used in the particleboard production as a function of their moisture content. Materials, 2021; 15(1): 48. https://doi.org/10.3390/ma15010048
[110] Nguyen TT, Redman A, Leggate W, Vandi L, Bailleres H, Heitzmann M. Processing parameters optimization of cotton stalk (*Gossypium hirsutum* L.) particleboards with emulsifiable polymeric isocyanate adhesive. BioResources, 2021; 16(2): 4149-4170.
[111] Zhang B, Hua J, Cai L, Gao Y, Li Y. Optimization of production parameters of particle gluing on internal bonding strength of particleboards using machine learning technology. Journal of Wood Science, 2022, 68: 21. https://doi.org/10.1186/s10086-022-02029-2
[112] Mirindi D. A review of particleboard development and performance using non-toxic and biodegradable adhesives. International Journal of Engineering Trends and Technology, 2024, 72(5): 252 – 260. https://doi.org/10.14445/22315381/IJETT-V7215P126