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Review Article

Particleboard from agricultural biomass and recycled wood waste: a review

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ABSTRACT

The use of alternative raw materials such as agricultural biomass and recycled wood waste and by-products in particleboard production is a viable approach to respond to the increased global demand for wood-based materials, and it is a key circular economy principle as well. Wood chips are the second most costly element after resin in particleboard production, where both elements accounting for more than 50% of the overall production cost. Therefore, a significant cost reduction could be achieved by replacing wood chips with lignocellulosic agricultural wastes. Agricultural biomass exists in abundant post-harvest and post-production processes and can be served as an ideal alternative for particleboard manufacturing. This study aimed to review and evaluate the current state-of-the-art particleboard production using a wide variety of environmentally-friendly

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Non-wood
Alternative raw material
Environmentally friendly

agricultural biomass, recycled wood waste, and by-products. In this review, the agricultural biomass used for particleboard production was classified into seven different groups based on the part of the plant which they are extracted from, i.e. straw, stalk, bagasse, seed/fruit, leaf, grass, and palms. Particleboards' properties of these raw materials were also compared in terms of their mechanical parameters. The last part of this review concluded the challenges and future potential of using agricultural biomass and recycled wood waste.

1. Introduction

Particleboard is an engineered wood product manufactured from wood chips bonded with a synthetic resin or another suitable binder under exposure to a hot press at certain pressure and temperature. Particleboard is one of the major wood-based products in global trade. Its global demand and production have seen an upward trend in recent years. According to IMARC Group [1], the global market for particleboard reached a total value of 21 billion US dollars in 2020. The group anticipates a compound annual growth rate (CAGR) of 4.4% during the next six years.

In 2020, the production quantity of particleboard reached 96.01 million m^3 worldwide (Fig. 1), which represents a decrease of 4.7% compared to the previous year (100.74 million m^3). Mainland China produced the highest quantity of particleboard in 2020, amounting to 29.43 million m^3 in volume or 30.65% of the total production quantity worldwide. Several European countries such as Germany, Poland, Italy, Austria, and France are among the leading producers of particleboard. Asia is the largest producer of particleboard, followed by Europe, the Americas, Africa, and lastly, Oceania (Fig. 2).

In 2020, the total import volume of particleboard was 22.04 million m^3. Germany was the largest particleboard importer with approximately 1.90 million m^3, followed by the United States of America and Poland (Fig. 3). European countries were the largest particleboard importers (54.43%), followed by Asia (26.51%), Americas (15.89%), Africa (2.83%), and Oceania with only 0.34% (Fig. 4).

In 2020, the total export volume of particleboard was estimated to be 21.97 million m^3, where Thailand was the main exporter worldwide with 2.55 million m^3 (Fig. 5). As shown in Fig. 6, European countries are the largest particleboard exporters (69.95%), followed by Asia (19.28%) and the Americas (9.77%). Africa and Oceania exported a very small amount of particleboard in 2020, which amounted to 0.72% and 0.28%, respectively.

The data shows that the countries with the highest production of boards are also the largest importers. The major raw materials used in particleboard production are wood chips acquired from forest thinning and timber waste [3]. Commonly, medium-sized and small-sized softwoods are the preferred wood species for particleboard production. However, an upward trend in the use of hardwood species has been observed in recent years in certain countries around the world [4]. However, the decreasing supply of timbers from natural forests made it difficult to meet the increasing future demand for particleboard. Furthermore, wood chip prices were reported to have increased up to 30% from 2006 to 2011 [5]. The price of the wood chips was reported to be around RM 300 per ton as of 2014, while the estimated price for the plant residues

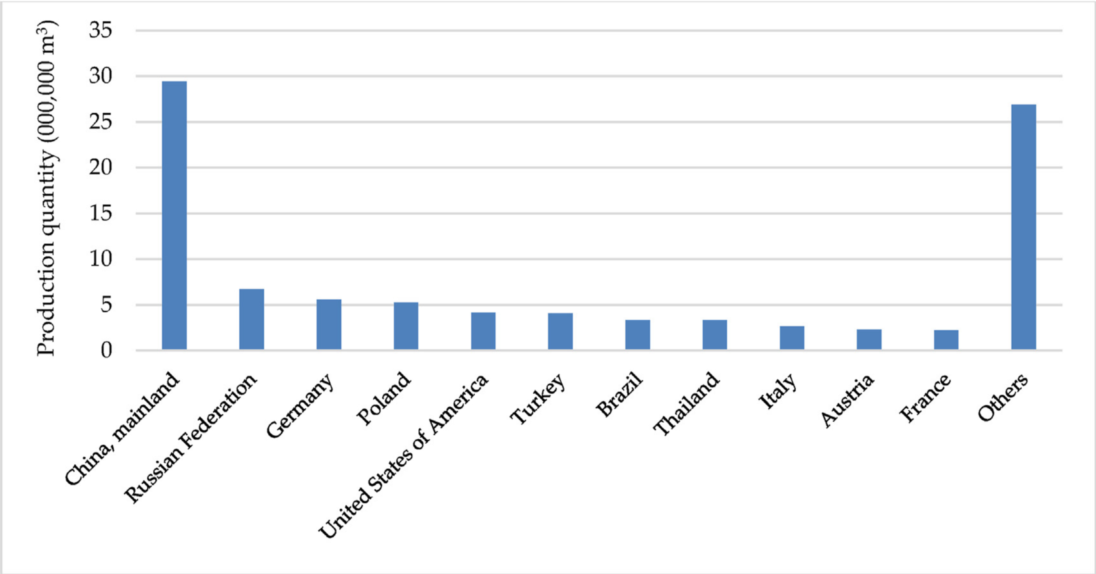

Fig. 1 – Global particleboard production quantity (m^3) in 2020 [2].

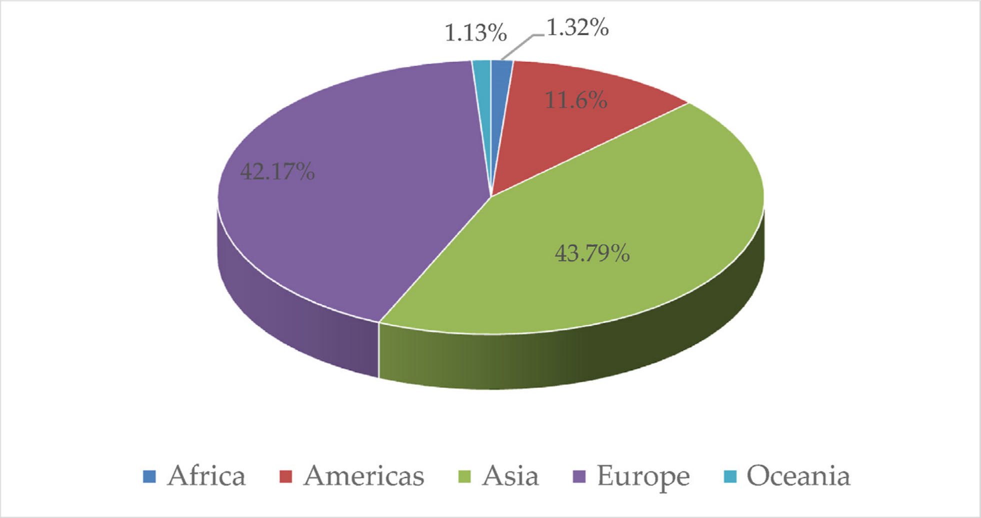

Fig. 2 – Particleboard production quantity by region in 2020 [2].

is at least 50% below the price of the wood chips [6]. Reforestation woods such as *Pinus* spp. and *Eucalyptus* spp. are the most widely used for commercial particleboard manufacturing [7].

In Southeast Asia, rubber (*Hevea brasiliensis*) and sengon wood (*Paraserianthes falcataria*) have been used as the main raw material for particleboard production as they are medium-density hardwoods with a natural whitish color [8–11]. Other less known or underutilized wood species have also been used for particleboard manufacturing (Table 1).

The increased global demand for wood raw materials, growing environmental concerns, and recent legislative regulations related to cascading wood use and prioritizing value-added applications of wood resources have posed critical challenges to the wood-based panel industry in terms of wood supply. Strategies to address these shortages may be vital, particularly in countries with a low forest area. The optimization of available wood and lignocellulosic raw materials, as well as the search for alternative natural feedstocks derived from abundant and renewable agricultural residues and wood by-products, to replace wood in particleboard manufacturing, is a viable strategy for reducing the negative environmental impact and improving the resource efficiency of the wood-based panel industry. Agricultural waste is a huge pool of untapped biomass resources that can be converted in various ways and may even represent economic and environmental burdens [23,24]. Markedly, the utilization of agricultural biomass in particleboard manufacturing should be economically profitable, and the boards produced should meet the requirements described in the technical standards.

The cost of the raw materials used, namely adhesive and wood chips, constitute the majority of the cost of the final particleboard panels (Table 2). The total material cost represents 40–60% of the total production cost. It was reported that the cost of adhesive amounted to 30–50% of the total material cost of the particleboard production, while the remaining

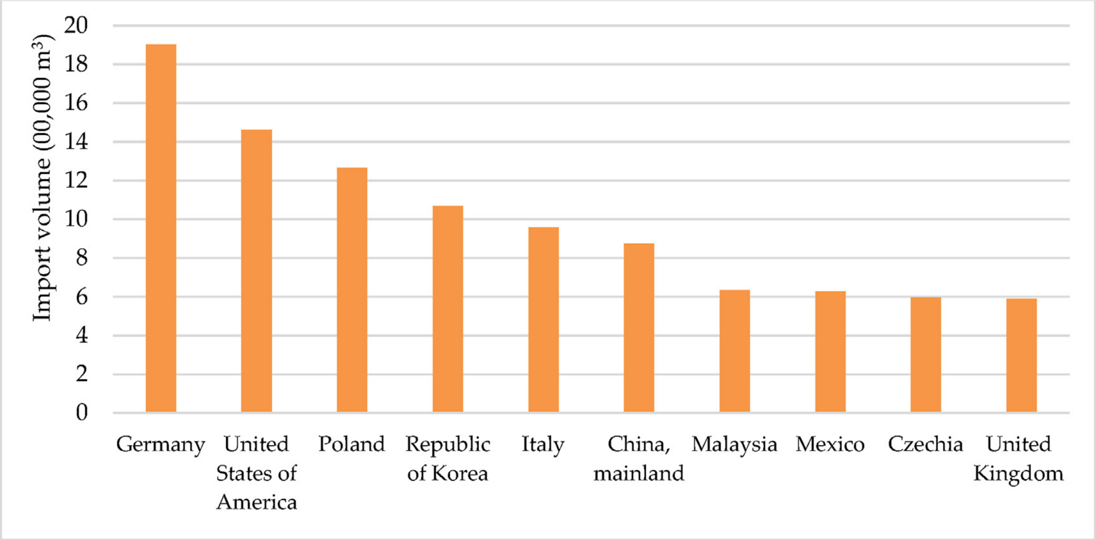

Fig. 3 – Particleboard import volumes (m^3) in 2020 – leading countries worldwide [2].

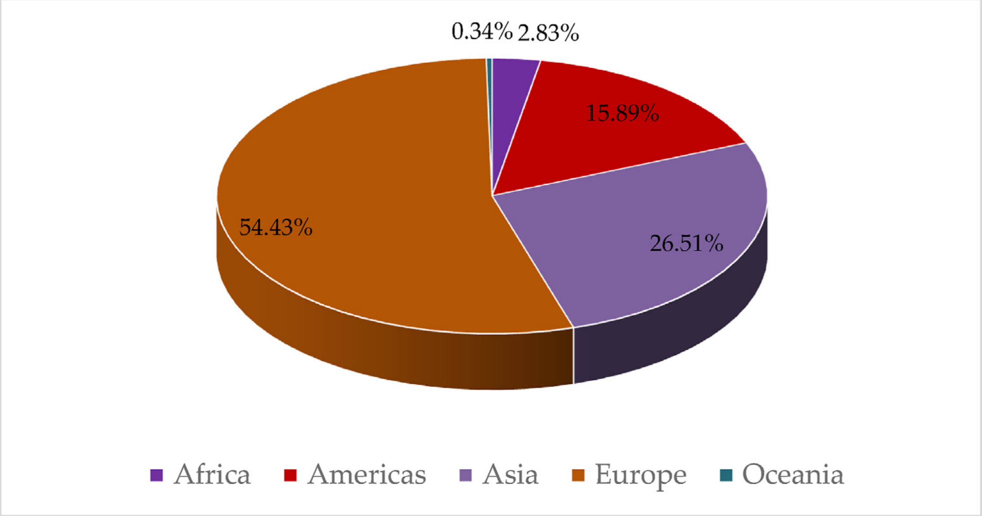

Fig. 4 – Particleboard import volumes in 2020 by region [2].

50–70% of the material cost is wood chips [25]. Therefore, it is assumed that adhesive and wood chips respectively represent 15–30% and 30–40% of the total production cost. Other primary cost components such as energy, manpower, and processing cost of the particleboard represent around 15–20%, 5–20%, and 25–30%, respectively. In contrast to Solt et al. [25], who reported that wood chips are more expensive than adhesive, van Dam et al. [26] reported that adhesive is slightly more expensive than wood chips. According to the authors, material costs account for 66% of total production costs, with adhesive accounting for 34% and wood resources accounting for 32%. Meanwhile, according to Klimek and Wimmer [6], wood chips are the second most expensive component after adhesive in particleboard production, accounting for roughly 20% of total production costs. The disparities could be attributed to the high variability of transportation costs and cultivated volumes. Whatever the scenario, it is undeniable that the material cost, which includes the cost of adhesive and wood chips, frequently accounts for more than half of the total production cost. The cost of agricultural biomass is estimated to be 50% less than that of wood chips [6]. As a result, replacing wood chips with alternative, non-wood raw materials could result in significant cost savings.

This study aimed to review and summarise the current state-of-the-art particleboard production using various agricultural biomass and wood by-products as environmentally friendly feedstocks. In this review, the agricultural biomass used for particleboard production was classified into seven different groups based on the respective plant parts derived from, i.e. straw, stalk, bagasse, seed/fruit, leaf, grass, and palms. This study compared the exploitation properties of particleboards made from agricultural biomass (keeping the division into groups), processed wood waste, and by-products divided into two density ranges.

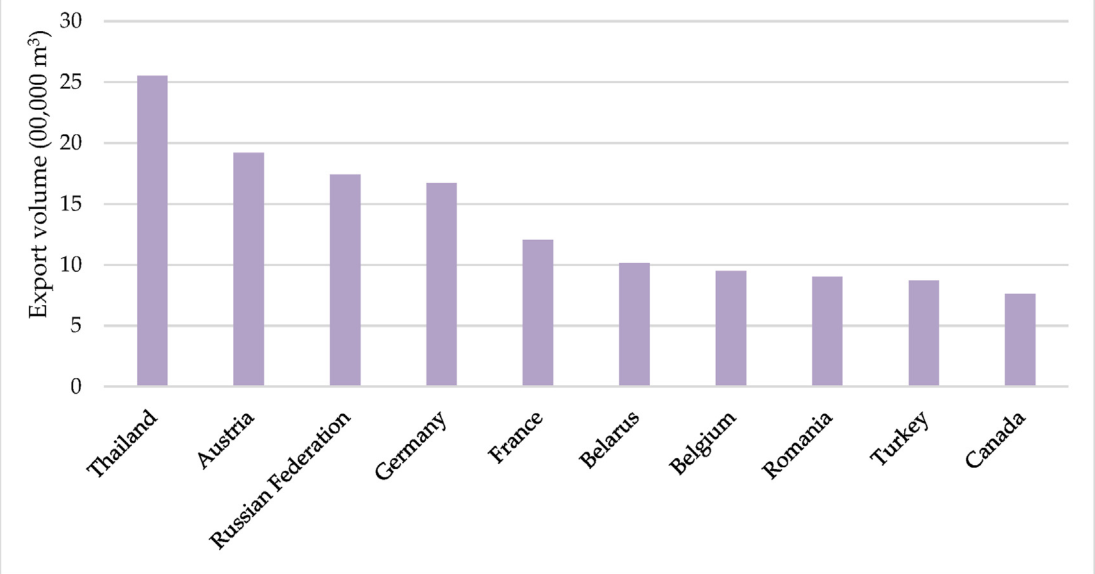

Fig. 5 – Particleboard export volumes in 2020 – leading countries worldwide [2].

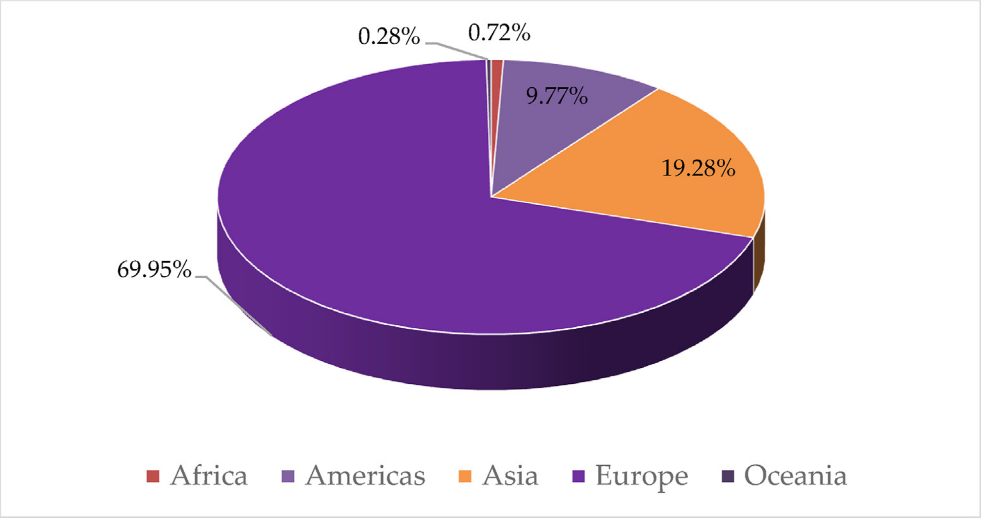

Fig. 6 – Particleboard export volumes in 2020 by region [2].

2. Adhesives used in particleboard manufacturing

Adhesive and wood particles/chips are the two major components of particleboard. Approximately 95% of the total adhesives used for manufacturing wood-based panels are based on formaldehyde. These resins are made by reacting formaldehyde with other chemicals such as urea, melamine, phenol, resorcinol, or combinations [27]. Urea-formaldehyde (UF), melamine fortified UF (MUF), melamine–urea–phenol-formaldehyde resin (MUPF), melamine-formaldehyde (MF), phenol-formaldehyde (PF), phenol–urea-formaldehyde (PUF), polymeric methylene diisocyanate (pMDI), as well as natural, bio-based adhesives such as tannins, lignins, carbohydrates, and natural rubber latex are among the commonly used adhesives in particleboard manufacturing [27]. Among these, aminoplastic resins derived from non-renewable petrochemical materials such as MF and UF are the most prevalently used adhesives in particleboard manufacturing. These resins are normally characterized by a molar ratio of formaldehyde to urea (F/U) between 1.00 and 1.10 [28]. UF resins, with an estimated annual consumption of about 11 million tons of solids worldwide, are the most widely used adhesive system in particleboard production, accounting for about 85% of the total volume due to their chemical versatility, high reactivity, water-solubility, low curing temperatures, short press times, colourless glue line, and relatively low cost [29].

In recent years, some experiments were made to improve physical, mechanical, and biological properties, reduce hot-press time, and reduce formaldehyde emission of UF resin by addition of different nano-fillers (such as nano silver, nano copper, and nano-minerals like wollastonite) to produce wood-based composite panels [30–35]. Though the initial results were promising both at laboratory scale and pilot batch at factories, the experiments have not yet been used at full industrial scales. PF resins are the second most important type of wood adhesives, with an estimated annual consumption of approx. three million tons worldwide are used to produce water- and weather-resistant particleboard. Meanwhile, polymeric 4,4-diphenyl methane diisocyanate (pMDI) is mainly used for manufacturing exterior-grade particleboard [27], or in applications where concerns about the harmful free-formaldehyde emission associated with UF adhesives, are present. pMDI has excellent adhesion properties and can be used in significantly lower proportions than UF, PF, and MUF

Table 1 – Particleboard made of less known or underutilized wood species.

Raw material	Adhesive	Source
Athel (*Tamarix aphylla*)	Polymeric 4,4′-diphenylmethane diisocyanate (pMDI) and urea-formaldehyde (UF) resin	[12]
Eastern redcedar (*Juniperus virginiana*)	UF	[13]
Peterebi (*Cordia trichotoma*)	UF	[14]
Willow (*Salix* spp.)	UF	[15]
Kiri (*Paulownia tomentosa*)	UF	[16]
Kadam (*Anthocephalus chinensis*)	UF	[17]
Peach, apple, pear, cherry and apricot tree branches	UF	[18]
Mangrove tree (*Rhizophora* spp.)	Binderless	[19]
Date palm (*Phoenix dactylifera*)	UF	[20]
Mangrove tree (*Rhizophora* spp.)	gum Arabic	[21]
Mangrove tree (*Rhizophora* spp.)	Tannin	[22]
Sengon (*Paraserianthes falcataria*)	Natural rubber latex	[11]

resins. Due to their relatively high price, isocyanates are mostly used in adhesive systems in combination with traditional formaldehyde-based resins to enhance their performance. However, pMDI could also be used to bind raw materials that are difficult to glue, such as bagasse, straw, leaves, or straw [27].

3. Agricultural biomass as raw material for particleboard manufacturing

3.1. *Classification and availability of agricultural biomass*

According to Alwani et al. [36], agricultural biomass can be classified depending on the part of the plant from which they are extracted. Agricultural biomass can be divided into wood and non-wood biomass. Wood biomass includes hardwood and softwood species. Non-wood biomass can be categorized into leaf, grass, seed, fruit, stem, straw, and stalk [36]. Most non-wood biomass is small in diameter, except for oil palm trunks and bamboo. This characteristic has restricted their practicability to be processed into veneer, lumber, or strips [37]. Therefore, non-wood biomass is suitable to serve as a feedstock for particleboard production where the size and dimensions of the materials are not emphasized. In this study, several non-wood biomasses have been identified as raw materials for particleboard production. For comparison purposes, these biomasses, either dicotyledonous or monocotyledonous, were classified according to Fig. 7.

Common agricultural waste used in particleboard production is in the forms of straw, stalk, shell, husk, leaves, stem, etc. These post-harvesting and post-production wastes can serve as an alternative source for particleboard manufacturing. The resources of some selected agricultural crops worldwide are displayed in Table 3. Staple food such as rice, maize, wheat, and barley have the highest harvested area (ha), and their corresponding production quantity (tons) is also among the highest. The figures in Table 3 imply the abundance of the biomass generated after harvesting and processing. The respective parts of the crops used in particleboard production are also listed in Table 3.

3.2. *Characteristics of agricultural biomass for particleboard manufacturing*

Summarised information on the chemical composition, i.e. cellulose and lignin content of wood and non-wood biomass as natural feedstocks for particleboard manufacturing, is presented in Table 4. According to Pedzik et al. [4], agricultural waste generally has a slightly lower cellulose content than softwood and hardwood. This might restrict the potential of agricultural biomass in particleboard production as cellulose is responsible for the strength and dimensional stability of the resultant boards. Stalk-based biomass, pineapple leaves, and bamboo have relatively higher cellulose content than the other biomass, which might make them favorable for producing particleboard with high mechanical strength. On the other hand, lignin is an amorphous, complex three-dimensional aromatic biopolymer with hydrophobic properties and can contribute to the particleboard's mechanical strength, biological durability, formation of char, and ultraviolet degradation [70,71]. Lertwattanaruk and Suntijitto [71] stated that lignin could aid in softening the particles during hot pressing, easing their resination [72].

4. Particleboard made from agricultural biomass

4.1. *Straw-based particleboard*

In 2020, the production quantity of wheat was 760.93 million tons worldwide, preceded only by sugarcane and maize. With this huge production capacity, finding novel methods to utilize the remaining wheat straw in value-added applications effectively is essential. Han et al. [87] created UF-bonded wheat straw particleboard, but its properties were inferior to those of commercial particleboard. A similar finding was made for the reed straw particleboard. However, silane coupling agents were used to improve the particleboard's bondability. The treatment was found to enhance the wheat straw and reed straw particleboard performance to varying degrees. Epoxide silane was found to be more effective for reed straw particleboard, while amino silane was found to be more effective for wheat straw particleboard. The surface appearance of straw-based particleboard is shown in Fig. 8.

Despite the resultant inferior performance of straw particleboard, some researchers found that straw could serve as a suitable raw material for the surface particleboard layer, provided pMDI resin or a combination of UF and pMDI were employed [88]. Rice straw was successfully used as a partial substitution of wood particles up to 20% without adversely affecting the mechanical properties of the particleboard [89,90]. Li et al. [60] produced rice straw particleboard bonded with pMDI and found that its properties exceeded the M-2 specification of the American National Standard for Wood Particleboard [ANSI A208.1] [91]. However, rice straw is high in ash and silica content, which interferes with its bonding ability and leads to low internal bonding strength. Hence, pretreatment is necessary to remove the excessive ash and silica content.

Rapeseed straw, like wheat and rice straw, has a similar chemical composition to wood, with less cellulose and lignin but more hemicellulose and extractives. Furthermore, rapeseed straw has better gluability than wheat straw because its chemical substances are distributed throughout the entire mass, unlike wheat straw. Rapeseed straw can be easily glued even when conventional wood adhesives was used. Dukarska

Table 2 – Cost estimation for particleboard manufacturing based on main cost components [25].

Cost component	The portion in production cost
Adhesive	15–30%
Wood raw materials	30–40%
Energy	15–20%
Manpower	5–20%
Processing cost	25–30%

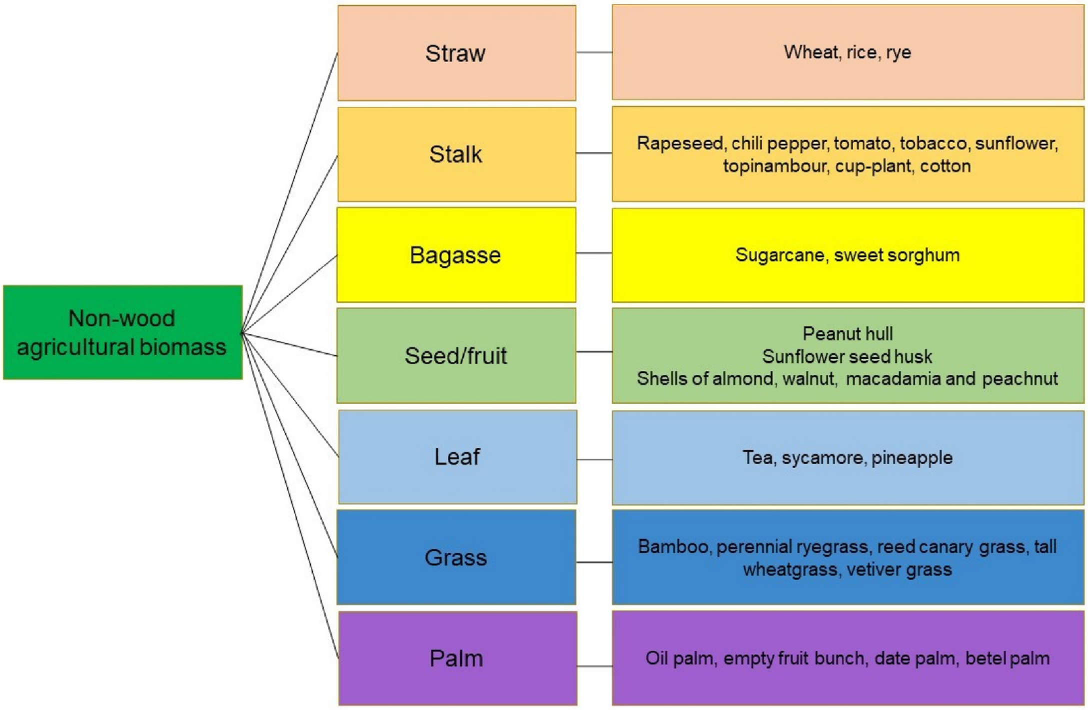

Fig. 7 – Classification of non-wood biomass used in particleboard manufacturing.

et al. [92] manufactured rapeseed straw in five densities (450–650 kg/m^3). With increasing density, the particleboard's bending strength (MOR), modulus of elasticity (MOE), and internal bond (IB) value increased. The particleboard met the requirements of the P7 type, i.e., boards with increased load-carrying capacity intended for use in humid conditions, according to EN 312 [93]. One of the most significant issues with cereal straws as a raw material for particleboard manufacturing is their seasonal availability, resulting in inconsistent supply throughout the year. White mustard (*Sinapis alba* L.), harvested at different times than cereals, is an excellent substitute. White mustard is a high-yielding, fast-growing crop, and its straw can be used as a feedstock in particleboard production [92].

4.2. *Stalk-based particleboard*

Chili pepper [46], tobacco [67], cotton [94,95], sunflower [96], sorghum [78], Miscanthus [97], rapeseed [77], tomato [68], kenaf [98,99], topinambour [100], and cup-plant [72] have all used plant stalks as raw materials for particleboard production. Their chemical composition varies among agricultural biomass and significantly impacts the physical and mechanical performance of the resulting particleboard. Fig. 9 shows the surface appearance of stalk-based particleboard.

The physical and mechanical properties of particleboard made from some selected plant stalks are given in Table 5. Under the same processing parameters, i.e. UF resin content 8%, pressing temperature 170 °C, and pressing time 4 min, particleboard made from chili pepper stalk [46] had lower thickness swelling (TS) and water absorption (WA) values compared to that of its rapeseed stalk counterpart [77]. This might be attributed to the chili pepper stalk's higher lignin content than the rapeseed stalk (25.4% vs 15.3%, respectively). Lignin, with relatively higher hydrophobicity, is the main contributor to the less water accessibility of plants [101]. Nourbakhsh et al. [102] also found that agricultural biomass with lower lignin content tends to have higher water uptake. Both particleboards made from chili pepper stalk and rapeseed stalk achieved the minimum requirements for MOR, MOE, and IB, according to the Korean Standard KS F 3104 for PB type 8.0 [KS F 3104 [103]]. However, a certain amount of wood particles or a higher amount of resin could be employed to attain a more satisfactory outcome [77].

High holocellulose content in tobacco stalks (~68%) is the main reason for its inferior dimensional stability. Apart from that, its anatomical properties, such as long fiber (1.23 mm) with large cell lumen width (15.4 μm), also contributed to its dimensional instability compared to wood particles [67]. Markedly, particleboard made from tobacco stalks has better termite resistance than particleboard made from *P. falcataria* L. Nielsen, as shown by Acda and Cabangon [67]. After exposure to *Coptotermes gestroi* Wasmann, particleboard made from 100% *P. falcataria* experienced 43% weight loss compared to only 1.5% in particleboard made from 100% tobacco stalk. Weight loss caused by termites decreased as the proportion of tobacco stalks increased. Incorporating 25% tobacco stalks has already led to significant resistance against termites. Nevertheless, 50% of tobacco stalks are needed for the underground field exposure test to protect from subterranean termites, *Macrotermes gilvus* Hagen. 100% weight loss was recorded in the particleboard made from 100% *P. falcataria,* while only 1.32% weight loss was observed for particleboard made with 100% tobacco stalks, indicating its high resistance against

Table 3 – Global resources of selected agricultural crops [2] and their application in particleboard production.

Raw material	Area harvested (000,000 ha)	Production quantity (000,000 tonnes)	Crop yield (hg/ha)	Part used in particleboard production	Source
Agave fibers	0.06	0.04	7047	Bagasse	[38]
Almonds, with shell	2.16	4.14	19,147	Shell	[39]
Areca nuts	1.23	1.80	14,650	Fiber	[40]
Bananas	5.20	119.83	230,294	Stem	[41]
Barley	51.60	157.03	30,432	Straw	[42]
Buckwheat	1.86	1.81	9752	Stalk	[43]
Cashew nuts, with shell	7.10	4.18	5887	Shell	[44]
Castor oil seed	1.22	2.05	16,776	Cake	[45]
Chilies and peppers, green	2.07	36.14	174,576	Stalk	[46]
Coconuts	11.58	61.52	53,148	Pit and fiber	[47]
Dates	1.24	9.45	301,692	Palm branches	[48]
Eggplants	1.88	56.62	13,637	Stalk	[49]
Hazelnuts, with shell	1.02	1.07	10,562	Shell	[50]
Hemp tow waste	0.08	0.25	32,068	Hurd	[51]
Hempseed	0.01	0.01	5164	Shiv	[52]
Jute	1.40	2.69	4900	Stick	[53]
Linseed (flax)	3.54	3.37	5392	Shive	[51]
Maize	201.98	1162.35	57,547	Cob	[54]
Manila fiber (abaca)	0.17	0.11	6177	Fiber	[55]
Pineapples	1.08	27.82	258,056	Leaves	[56]
Poppy seed	0.04	0.02	6397	Husk	[57]
Ramie	0.03	0.06	19,055	Stem	[58]
Rapeseed	35.50	72.38	20,390	Straw	[59]
Rice, paddy	164.19	756.74	46,089	Straw	[60]
Rye	4.45	15.02	33,781	Straw	[61]
Seed cotton	31.84	83.11	26,103	Stalk	[62]
Sorghum	40.25	58.71	14,585	Bagasse	[63]
Sugar cane	26.47	1869.72	706,434	Bagasse	[64]
Sunflower seed	27.87	50.23	18,020	Husk	[65]
Tea	5.31	7.02	13,227	Leaves	[66]
Tobacco, unmanufactured	3.24	5.89	18,188	Stalk	[67]
Tomatoes	5.05	186.82	369,798	Stalk	[68]
Walnuts, with shell	1.02	3.32	24,989	Shell	[39]
Wheat	219.01	760.93	34,744	Straw	[69]

subterranean termites. The authors attributed the termite resistance to the presence of nicotine in tobacco stalks, which might act as a potent insecticide for termites. Apart from its chemical and anatomical properties, Klimek et al. [72] demonstrated that the adhesive used and loading level during particleboard production also play a vital role in the performance of the resultant particleboard. pMDI at 4% and 6% content levels resulted in better mechanical and physical properties than UF resin at 8% and 12% content. Kenaf stalks particleboard [104] had higher MOR than the particleboard made from tobacco or sunflower stalks, kiwi pruning, grapevine stalks, and tea leaves residues [105]. However, its IB was inferior to tobacco, sunflower stalks, vine stalk, and kiwi pruning boards, mainly due to its less fibrous anatomical structure and bark content [90].

4.3. *Bagasse-based particleboard*

Bagasse, also called megass, is the dry pulpy fibrous material that remains after the extraction of the sugar-bearing juice from sugarcane or sorghum stalks. It is estimated that 250 kg of bagasse could be generated from every ton of sugarcane. The sugarcane bagasse is normally used as fuel for steam generation to supply energy [65]. It could benefit society and the economy if this sugarcane bagasse were converted into panel products such as particleboard and other fiber composites [106,107]. Sugarcane bagasse has been proven to produce particleboard with acceptable physical and mechanical properties, with or without the incorporation of wood particles [108,109]. Particleboard made of sugarcane bagasse is shown in Fig. 10. However, particleboard made from sugarcane has lower mechanical strength compared to that of its eucalyptus and pine counterparts [110]. Therefore, in some cases, the incorporation of wood particles is necessary to improve the performance of particleboard. A study by Buzo et al. [111] stated that sugarcane bagasse particleboard bonded with castor oil-based polyurethane (PU) resin could attain the best mechanical and physical properties after the incorporation of 60% pine particles. A similar observation was obtained by Yano et al. [112], who reported that the incorporation of 50% industrial timber residue improved the mechanical performance of sugarcane bagasse particleboard.

Particleboard made from sweet sorghum particles, on the other hand, has low dimensional stability, MOE, and IB properties. However, these drawbacks can be overcome by layering surface treatment, as reported by Iswanto et al. [63]. Using citric acid (CA) and sucrose as a binder, sweet sorghum bagasse particleboard was found to have superior

Table 4 – Chemical composition of wood and non-wood biomass.

Group	Raw material	Cellulose	Lignin	References
Wood	Spruce wood	45.4	28.2	[72]
	Pine wood	49.5	27.5	[73]
	Eucalyptus camaldulensis Dehn.	49.67	19.14	[74]
	Softwood	40–44	25–32	[75]
	Hardwood	40–44	18–25	
Straw	Rapeseed straw	28.83	21.35	[76]
	Wheat straw	39.3	20.7	[73]
	White mustard straw	36.7	21.6	[73]
Stalk	Rapeseed stalk		15.3	[77]
	Tomato stalk	43.11	12.29	[68]
	Sunflower stalk	40.9	21.6	[72]
	Topinambour stalk	30.9	16.3	
	Cup-plant stalk	38.6	21.4	
	Sorghum stalk	45.9	17.2	[78]
	Chili stalk		25.4	
Bagasse	sweet sorghum bagasse	34.78	23.02	[79]
	sugarcane bagasse	35.2	22.2	[80,81]
Seed/fruit	Coffee husk	19–26	18–30	
	Coffee hull	40–49	33–35	
	Hazelnut husk	34.5	35.1	[82]
	Cotton carpel	31.2	20.5	
	Macadamia shells	29.5	40.1	
Leaf	Pineapple leaves	66.2	4.28	[83]
Grass	Perennial ryegrass (*Lolium perenne* L.)	29.21	28.85	[74]
	Vetiver grass		17.03	[84]
	Petung bamboo (*Dendrocalamus asper*)	43.41	24	[85]
	Wulung bamboo (*Gigantochloa atroviolacea*)	45.19	24.16	
	Apus bamboo (*Gigantochloa apus*)	42.38	22.71	
Palm	Oil palm trunk	39.4	6.64	[86]
	Oil palm frond	54.35	8.96	
	Empty fruit bunch	37.82	12.16	

dimensional stability and MOE than PF and pMDI-bonded sweet sorghum bagasse but lower MOR and IB [79,114]. As shown in Table 6, at the same density level and resin content, citric acid-bonded sugarcane bagasse particleboard had inferior MOR and MOE values than citric acid-bonded sweet sorghum bagasse particleboard. However, the IB strength and dimensional stability of the sugarcane bagasse particleboard were better [79,115].

Fig. 8 – The surface appearance of straw-based particleboard (own photo).

4.4. *Hull-, husk- and shell-based particleboard*

Hull refers to the outer covering of a fruit or seed, while husk refers to the dry, leafy or stringy exterior of certain vegetables or fruits, which must be removed before eating the meat inside. Sunflower seed husk and the hull are suitable materials for particleboard manufacturing as they have similar chemical compositions to wood [65]. The husks of sunflower seeds make up to 21–30% of their total weight; therefore, a huge amount of residues are often generated during sunflower oil extraction [116]. Gertjejansen et al. [117] investigated the performance of particleboard made from 100% sunflower hulls. They reported that the resultant particleboard had surpassed the minimum requirements for MOR and MOE as stated in Commercial Standard (CS) 236-66 [118]. Nevertheless, the IB strength was inferior and adding 50% aspen flakes was required to improve the IB strength. Cosereanu et al. [65] investigated the effects of particle size and geometry on the performance of particleboard made from sunflower seed husks. Two particle sizes were used, namely coarse (2–3 mm) and fine particles (0.5–1 mm). Single-layer particleboard made from fine particles has a higher density and performs better in terms of WA, TS, MOR, and IB than its coarse particle

Fig. 9 – Surface appearance of stalk-based particleboard (own photo).

counterparts. Fine particles are easy to press, resulting in higher density and compacter board and correspondingly better performance. Particleboard produced displayed good thermal conductivity with values ranging between 0.075 and 0.079 W/mK. Except for MOE, MOR, and TS, the particleboard made from sunflower seed husk failed to meet the minimum requirements for particleboard for general use (type P1) and moisture resistance particleboard (type P3). It is therefore recommended to be used for furniture components or other structural applications that are not subject to load-bearing.

Shells of almond, walnut, macadamia, and peachnut have been utilized in particleboard production (Table 7). Pirayesh et al. [39] produced walnut (*Juglans regia* L.) shell- and almond (*Prunus amygdalus* L.) shell-based particleboard bonded with UF resin. The results revealed that the 100% walnut shell particleboard had the lowest MOR, MOE, and IB values. Markedly, particleboard made from 100% almond shell exhibited better mechanical properties than walnut shell particleboard. However, both types of particleboard were inferior compared to particleboard made from hornbeam (*Carpinus betulus* L.) and beech (*Fagus orientalis* L.) wood. Interestingly, particleboard made from walnut and almond shells exhibited lower TS and WA than wood-based particleboard.

In a study by Wechsler et al. [121], macadamia (*Macadamia integrifolia*) nut shells and castor (*Rícinos communis*) oil-based resin was used to produce particleboard. Even with a much higher density (987 kg/m^3), the MOR of macadamia particleboard was lower than pine particleboard (691 kg/m^3) by half, while the MOE value was almost three-times lower. However, macadamia particleboard displayed better IB, TS, and WA than pine particleboard. Lower absorption and water-induced swelling of macadamia particleboard could be attributed to the superior moisture resistance of macadamia nut shells. Cellulose is responsible for the strength and stiffness of the agro-fibers. Therefore, lower MOR and MOE are expected for macadamia shell particleboard as macadamia shell has lower cellulose content (30%) than pine wood (44%). Owing to their superior moisture resistance, macadamia nut shell/castor oil particleboard has the potential for use in humid environments.

Barbu et al. [50] investigated the feasibility of using walnut and hazelnut shells in particleboard manufacturing. The authors fabricated various panels using walnut or hazelnut shells bonded with MUF or PU resin and a target density of 1000 kg/m^3 (Fig. 11). MOR and MOE values were 40–50% lower for MUF resin bonded nutshell boards compared to spruce particleboard and 65% higher when PU adhesive was used. When compared to spruce particleboard, the developed composites had significantly higher WA and TS values, as well as close-to-zero free formaldehyde content, meeting the requirements of the E0 emission grade (≤2.5 mg/100 g) for both walnut and hazelnut shell raw materials, and of the super E0 category (≤1.5 mg/100 g) when PU resin was used EN ISO 12460-5 [122].

The possibility of manufacturing particleboard from groundnut shell and rice husk wastes, bound with a modified adhesive system, was evaluated by Akinyemi et al. [123]. The authors investigated the effects of the addition of different levels of groundnut shells and rice husks in the composition of the panels, i.e. 30–70, 70–30, 50–50%, and 100% for each of the waste materials. The developed composites exhibited significantly deteriorated dimensional stability values, failing to

Table 5 – Physical and mechanical properties of particleboard manufactured from selected plant stalks.

Raw Materials	Adhesive type	Adhesive (%)	Density (kg/m^3)	MOR (MPa)	MOE (MPa)	IB (MPa)	TS, 24 h (%)	WA, 24 h (%)	References
Rapeseed stalk	UF	8	684	11.7	1798	0.47	50.3	90.4	[77]
Chili pepper stalk	UF	8	701	12.2	1856	0.61	43.9	82	[46]
Tomato stalk	UF	16	950	20.5	1123.9	0.91	18.1	N/A	[68]
Sunflower stalk	MDI	4	600	~10.2	~1600	~0.5	~35	~122	[72]
	MDI	6	600	~12.2	~1840	~0.6	~30	~92	
	UF	8	600	~8	~1600	~0.32	~41	~122	
	UF	12	600	~10.2	~1800	~0.4	~39	~108	
Topinambour stalk	MDI	4	600	~10.4	~1840	~0.55	~29	~78	
	MDI	6	600	~11.8	~1920	~0.62	~27	~64	
	UF	8	600	~8.4	~1780	~0.42	~41	~134	
	UF	12	600	~9.8	~1840	~0.54	~40	~122	
Cup-plant stalk	MDI	4	600	~12.2	~2040	~0.54	~43	~92	
	MDI	6	600	~12	~2100	~0.62	~33	~80	
	UF	8	600	~9.6	~1720	~0.38	~66	~152	
	UF	12	600	~11	~1900	~0.42	~57	~130	

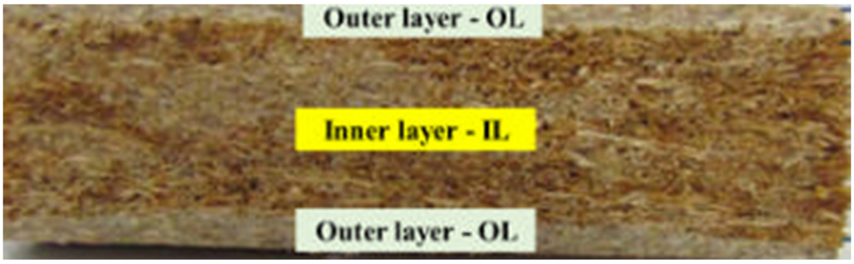

Fig. 10 – Three-layer particleboard with green coconut fiber as outer layers (OL) and sugarcane bagasse fibers as an inner layer (IL) (Fiorelli et al. [113], with permission).

comply with the standard requirements. The highest density and IB values of 0.98; 0.97 g/cm^3 and 0.24; 0.23 N/mm^2 were determined for the samples fabricated with 30% rice husks + 70% groundnut shells and 50% rice husks + 50% groundnut shells, respectively. The best mechanical properties were obtained for the panels manufactured from 30% rice husks and 70% groundnut shells.

4.5. *Leave-based particleboard*

Owing to its high phenolic content, waste leaves of *Camelia sinensis* L. are considered a promising alternative material for particleboard manufacturing [66]. A study by Yalinkilic et al. [124] reported that tea leaves, as a substrate for growing mushrooms, resulted in very poor mycelial development and almost no fruit body formation. Therefore, it is anticipated that particleboard made from waste tea leaves should have superior biological durability. Yalinkilic et al. [66] fabricated three-layer particleboard from waste tea leave bonded with UF resin. The boards were exposed to brown-rot fungus (*Tyromyces palustris* (Berk. et Curt) Murr.), white-rot fungus (*Coriolus versicolor* (L. ex Fr.) Quel.) and subterranean termites (*Coptotermes formosanus* Shiraki). Particleboard made from waste tea leaves proved biologically resistant against decay fungi and termites. However, the boards' dimensional stability and mechanical properties should be further improved. Apart from its superiority in biological durability, tannins, protein, and amino acid that exists in abundance in tea leaves could actively react with formaldehyde [125]. As a result, lower formaldehyde emission from the resultant particleboard is expected. The same authors reported ha the UF-bonded waste tea leaves boards emitted significantly lower formaldehyde compared to conventional poplar particleboard, indicating that tea leaves could act as formaldehyde scavengers.

One of the waste tea leaves particleboard issues is its inferior mechanical properties. Board with higher density or incorporation of a certain amount of wood particles is necessary. Batiancela et al. [126] incorporated 10–80% *P. falcataria* (L.) Nielsen wood particles in the waste tea leave particleboard. Compared to wood, waste tea leaves are less hygroscopic as they have a smaller amount of cellulose and hemicellulose [127]. Particle boards with 100% waste tea leaves have significantly lower TS and WA values. In addition, blades of tea leaves consist mainly of thin-walled parenchyma cells, making them easily compressed during mat consolidation and resulting in good IB [128]. However, adding *P. falcataria* wood particles enhanced the MOR and MOE of the boards. Particleboard produced with incorporation of 20–50% wood particles surpassed the minimum requirements of TS, WA, IB, MOR, and MOE for general use particleboard set by EN 312-2.

Tree leaves are another underutilized biomass that could be converted into particleboard [129]. However, conventional UF resin is not suitable to be used as a binder for bonding tea leaves as the leaves have a waxy epidermal surface layer [130]. Extractives such as wax, inorganic silicon, and fat are found in this waxy layer and could interfere with its compatibility with a water-based adhesive such as UF [131]. Therefore, isocyanates such as MDI are commonly used for bonding agricultural residues that are difficult to glue. A comparison between the physical and mechanical properties of leave-based particleboard, bonded with UF resin and MDI, is

Table 6 – Physical and mechanical properties of particleboard manufactured from selected bagasse.

Raw Materials	Adhesive type	Adhesive (%)	Density (kg/m^3)	MOR (MPa)	MOE (MPa)	IB (MPa)	TS, 24 h (%)	WA, 24 h (%)	References
Sweet sorghum bagasse	Citric acid	20	800	21.8	5200	0.89	10.1	N/A	[79,114]
	Citric acid-sucrose	20	800	12.5	2500	0.41	20.1	35.2	
	PF	12	800	32.9	4500	0.78	20.6	N/A	
	PMDI	8	800	34.1	4600	1.33	23.1	N/A	
Sugarcane	Citric acid	15	800	17.38	3361	0.73	5.42	42.92	[115]
		20	800	18.22	3429	0.98	5.48	30.47	
		25	800	21.88	3944	1.03	4.43	29.48	
Sugarcane	UF	8	672	12.5	2095	0.46	17.8	47.1	[110]
Eucalyptus	UF	8	657	16.7	2823	1	14.9	37.8	[110]
Pinus	UF	8	654	15.2	2621	0.84	15.6	39	[110]

Table 7 – Physical and mechanical properties of particleboard manufactured from selected hulls, husks, and shells.

Raw Materials	Adhesive type	Adhesive (%)	Density (kg/m^3)	MOR (MPa)	MOE (MPa)	IB (MPa)	TS, 24 h (%)	WA, 24 h (%)	References
Hazelnut husk	UF	10/8*	700	11.9	N/A	0.505	19.6	43.5	[82]
	MUF	10/8	700	10.1	N/A	0.39	29.3	47.7	
	PF	10/8	700	12	N/A	0.482	16.2	44.5	
	UF	10/8	600	8.18	N/A	0.349	22.1	64.2	
	MUF	10/8	600	7.7	N/A	0.336	24.6	73.7	
	PF	10/8	600	8.49	N/A	0.343	18.9	55.2	
Rice husk	soybean protein	10	800	8.3	1875	0.23	43.58	88.67	[119]
Sunflower seed husk	UF	16	682	5.82	1703	0.24	10.2	55.4	[65]
		16/14	555	5.33	1645	0.18	9.2	53.4	
Peanut hull	UF	10/8	505	2.9	571	0.16	12.34	94.88	[120]
		10/8	591	5.24	732	0.22	14.01	79.17	
		10/8	706	8.54	1190	0.3	16.65	68.45	
		10/8	796	10.4	1485	0.4	25.71	77.57	
		11/9	503	3.12	654	0.17	11.83	97.85	
		11/9	605	5.94	814	0.24	13.09	83.81	
		11/9	697	9.9	1274	0.32	15.34	67.85	
		11/9	794	12.14	1719	0.41	21.02	70.43	
walnut shell	UF	11/9	700	6.63	1208.9	0.26	~7	~20	[39]
almond shell	UF	11/9	700	~9	~1400	~0.35	~11	~45	
macadamia shell	castor oil resin	20	987	4.3	380	1.33	2.7	10.5	[121]

Note: *adhesive level (%) on surface layer/core layer.

presented in Table 8. At 4% MDI content, even at a lower density level, leave-based particleboard had higher strength properties than its 8% UF-bonded counterparts. MDI-bonded sycamore (*Platanus orientalis*) leaves particleboard was produced by Aghakhani et al. [132]. The particleboard was reported to have achieved desired properties for partition, wall, and ceiling paneling applications. Board density and pressing time is the most influential factors in the physical and mechanical properties of the particleboard, while the effect of pressing temperature is less significant. Higher density and longer pressing time produced particleboard with higher mechanical properties and dimensional stability. Wood particles could be added to improve the performance of sycamore leaves particleboard. Pirayesh et al. [133] reported that the combination of 20% sycamore leaves and industrial wood particles resulted in particleboard with increased MOR, MOE, and IB values.

4.6. *Grass-based particleboard*

From the literature, grass-based particleboard is relatively scarce. There are only five grasses identified to be converted into particleboard by several researchers, namely Perennial ryegrass (*Lolium perenne* L.), Reed canary grass (*Phalaris arundinacea*), Jose tall wheatgrass (*Agropyron elongatum*), Vetiver grass (*Chrysopogon zizanioides*), and bamboo. Perennial ryegrass, also called English ryegrass, winter ryegrass, or ray grass, is an important pasture and forage plant cultivated worldwide. Reed canary grass is a tall, perennial bunchgrass that mainly grows as ornamental plants. It is regarded as an

Fig. 11 – Hazelnut (left) and walnut shell (right) particleboard (Barbu et al. [50], open access).

Table 8 – Physical and mechanical properties of particleboard manufactured from selected leaves.

Raw Materials	Adhesive type	Adhesive (%)	Density (kg/m^3)	MOR (MPa)	MOE (MPa)	IB (MPa)	TS, 24 h (%)	WA, 24 h (%)	References
Sycamore	MDI	4	600	15.92	1958	0.57	18.05	34.2	[132]
(*Platusorientalis*) leaves	MDI	4	700	16.63	2021	0.63	16.12	32.72	
Waste tea (*Camellia sinensis*) leaves	UF	8	650	13	1200	0.346	~18	~40	[126]
Sugarcane leaves	UF	12	510	N/A	N/A	N/A	52.17	187.2	[134]

invasive plant in the wetland. Jose tall wheatgrass is an introduced tall, cool-season, salt-tolerant, perennial bunchgrass planted for grazing, haying, or erosion control. Vetiver grass, also called khus, is a perennial bunchgrass that shares many morphological characteristics with other fragrant grasses, such as lemongrass. The roots of vetiver grass are oil-bearing and can be used in perfumes.

Clippings of perennial ryegrass, together with *Eucalyptus camaldulensis* Dehn. wood particles have been used by Nemli et al. [74] in the production of UF-bonded particleboard. The particleboard made from 100% grass clippings had the lowest mechanical strength. Grass clippings could only be used as a substitution for wood in a relatively small amount. Eucalyptus particleboard substituting 6% and 13% grass clippings were reported to achieve desired mechanical properties for general uses and interior fitments and improved dimensional stability. Grass has a waxy layer on the surface; therefore, water-based UF resin is deemed unsuitable to be used as a binder during the production of grass-based particleboard. Panichnava and Nimityongskul [135] reported that polyvinyl acetate-based adhesive is a more suitable binder for vetiver grass than urea-formaldehyde and corn starch. Although the cost of polyvinyl acetate-based adhesive is slightly higher than that of corn starch-based adhesive, it is, however, still 40% cheaper than bagasse boards. Meanwhile, pMDI also performed better in bonding vetiver grass particleboard than formaldehyde-based resins (UF and PF) [136]. pMDI-bonded Saline Jose tall wheatgrass particleboard also exhibited better properties than its UF-bonded counterparts [137]. Isocyanate-based adhesives such as MDI (diphenylmethane diisocyanate), pMDI or polyurethane (PUR), PVA (polyvinyl alcohol), and PVAc (polyvinyl acetate), and acryl-based adhesives are suitable options [138,139]. Fig. 12 shows the image of the reed canary grass particleboard.

Fig. 12 – Reed canary grass particleboard by Trischler et al. [139], licensed under Creative Commons Attribution-NonCommercial 4.0 International License.

Bamboo is a perennial woody grass often confused with trees due to its tree-like appearance and woody features. Bamboo shares similar characteristics with all types of grass as its internodal stem are hollow. Unlike trees, bamboo does not have a vascular cambium layer or meristem cells at the top of its culm. In addition, bamboo has no bark [140]. All these characteristics make bamboo grass. Information on the physical and mechanical properties of particleboard manufactured of different bamboo species, bound with 10% UF resin, is presented in Table 9. Generally, the properties of the particleboard made of bamboo did not differ greatly as its chemical composition did not vary much among species. The density of the boards is the main factor that affects the performance of bamboo particleboard. MOR and MOE values increased along with increasing density. In contrast, the dimensional stability was inversely affected by increasing board density.

4.7. *Palm-based particleboard*

The carbohydrate content of oil palm trunk (OPT) is high, while the lignin content is low [145]. The cellulose content of OPT and empty fruit bunch (EFB) is comparable to that of softwood and hardwood. In contrast, oil-palm frond has a higher cellulose content than softwood and hardwood. However, oil palm biomasses have lower lignin content compared to softwood and hardwood species [146]. For many years, oil palm trunk has been recognized as a lignocellulosic material suitable for producing value-added composite panels. Due to the high proportion of soft parenchyma tissues in the central region of the trunk, only the outer part of the oil palm trunk is traditionally used during the lumber production process [147]. According to Bakar et al. [148], the unused inner part can account for up to 70% of total weight and is frequently considered waste. These wastes have the potential to be an excellent material for particleboard production. Particleboard made of OPF, OPT, and EFB is shown in Fig. 13.

Because oil palm trunk has a lower density than rubberwood, using it as the core layer of particleboard could result in a higher compaction ratio, according to Lee et al. [9]. In theory, the higher the compaction ratio, the lower the density of wood materials. High compaction improves particleboard performance [149]. However, in the study conducted by Lee et al. [150], this was not the case. The core layer of the three-layer particleboard was the oil palm trunk, and the surface layers were rubberwood. Based on their findings, the authors concluded that particleboard made entirely of rubberwood

Table 9 – Physical and mechanical properties of particleboard manufactured from selected bamboo species.

Raw Materials	Adhesive type	Adhesive (%)	Density (kg/m^3)	MOR (MPa)	MOE (MPa)	IB (MPa)	TS, 24 h (%)	WA, 24 h (%)	References
Bambusabalcooa	UF	10	849	15.7	1936.9	N/A	16.5	47.9	[141]
Bambusa vulgaris	UF	10	873	17.7	2144.2	N/A	15.1	45.9	
Gigantochloascortechinii	UF	10	561	12.52	1959	0.45	11.07	45.75	[142]
	UF	10	641	17.95	2684	0.72	11.6	39.52	
	UF	10	721	20.21	2934	0.88	12.69	37.16	
Bambusa vulgaris	UF	10	754	13.85	N/A	0.62	23.1	N/A	[143]
Dendrocalamus giganteus	UF	10	630.74	7.48	1515.55	N/A	8.58	48.23	[144]
	Castor oil	10	705.29	4.76	711.14	N/A	13.53	58.84	

outperformed mixed-species particleboard. Despite having a higher compaction ratio, oil palm trunk particleboard had lower strength properties than pure rubberwood particleboard [9]. Because the oil palm trunk has a lower density, it takes up a large volume per unit weight in the core layer. At the same time, it resulted in a larger surface area per unit weight, making adequate resin coverage difficult. As a result, adequate particle–particle bonding was not possible, negatively impacting the boards' strength properties. However, the authors concluded that if processing parameters such as pressing temperature and time were carefully manipulated, oil palm trunk had a promising potential as a partial replacement for rubberwood in producing particleboard [9,150,151]. It was also reported that binderless particleboard made from oil palm trunks met the requirements of Japanese Industrial Standard (JIS) A 5908 type 8 (MOR 8 MPa) [152].

As a lignocellulosic material, oil palm frond has the potential to be used effectively in the production of composite panels. Unfortunately, compared to other biomasses, the use of oil palm fronds in particleboard production is relatively limited. The oil palm frond is thought to be a suitable material for the production of binderless particleboard. According to Laemsak and Okuma [153], the hemicellulose content of oil palm fronds is 1.5–3 times that of wood. Aside from that, lignin could be removed from the cell wall of oil palm fronds using steam-explosion treatment [152]. After steam-explosion treatment, a good bonding strength could be created between oil palm frond fiber and these chemical substances during the hot-pressing process. Lignin and polysaccharides are the main chemical components contributing to the oil palm frond's ability to self-bind [154].

EFB produces approximately four million tonnes of fiber per year [155]. The use of EFB as an alternative raw material in manufacturing particleboard is considered viable [156]. EFB has fiber strength comparable to rubberwood fiber. Because of its high toughness and cellulose content, EFB is well suited for composite applications [157,158]. Previous research, however, has shown that combining EFB with other hardwood species in particleboard production is a more viable option [159]. When compared to its OPT and OPF counterparts, EFB particleboard frequently has inferior properties. Zakaria et al. [160] prepared a citric acid solution containing 12.5 and 25% wt tapioca starch, which was then used as a binder for particleboard made from oil palm biomass (empty fruit bunch, oil palm trunk, and oil palm frond). A 12.5 wt% tapioca starch addition was beneficial, as evidenced by improved mechanical and physical properties. The particleboard made from oil palm frond and trunk bonded with 87.5 wt% citric acid and 12.5 wt% starch met the minimum MOR requirement for type 8 particleboard specified in Japanese Industrial Standard (JIS) A 5908.

Date palm (*Phoenix dactylifera* L.), one of the oldest fruit crops in the Middle East and North Africa, has also been used in particleboard production. The addition of palm frond pruning to the MDF mat significantly improved IB in the produced panels [161]. The performance of particleboard manufactured from date palm branches showed that the panels' MOR, IB, and TS values fulfilled the technical standard requirements [162]. The date palm's trunk and rachis or branches were used to produce particleboard in the study by Amirou et al. [163]. PF- and MUF-bonded particleboard fabrication from date palm trunk and branches is deemed viable. PF-bonded boards have better performance than MUF-bonded boards. Ghofrani et al. [48] recommended that branches of the date palm are a good replacement for fibrous material for particleboard production. Particleboard produced is suitable for indoor applications, including absorbing noise, maintaining indoor living spaces' temperature, and partially or completely substituting insulation boards in wooden constructions. Betel palm (*Areca catechu* Linn.) is grown for its seed crops, a fruit locally called Pinang. The trunks of betel palm were chipped, and particleboard was produced from it. Betel palm can be used to make value-added panels without significantly affecting board properties [164].

Binderless particleboard from oil palm has also been produced by Hashim et al. [165]. The study suggested that core parts, mid-parts, and fronds of the oil palm trees could be used to produce binderless particleboard with acceptable MOR and IB of 10.9 N/mm^2 and 0.5 N/mm^2, respectively. The good properties of the binderless oil palm particleboard might be associated with the pseudo-plasticity and viscoelasticity of starch-rich parenchyma cells found in trunks. Furthermore, the hemicellulose content of oil palm fronds was 1.5–3 times higher than common hardwood species [153]. This may result in improved particle bonding and lead to satisfactory bending properties. Unfortunately, the WA and TS of the panels performed poorly.

4.8. *Summary*

Based on the findings of the above section, it is noted that agricultural biomass could serve as potential raw materials for

Table 10 – The physical and mechanical properties of particleboard produced using recycled wood waste as raw material.

Sources/Type of Wood Waste	Adhesive	Variable	Density (kg/m^3)	MOR (MPa)	MOE (MPa)	IB (MPa)	TS (%)	WA (%)	Reference
Recycled particleboard made from poplar, fir, pine and other waste wood	- Urea-formaldehyde	Hydrothermal treatments -2 bar/119 °C/ 480 min (A) -4 bar/140 °C/ 120 min (B) -6 bar/156 °C/45 min (C) -8 bar/167 °C/ 20 min (D)	650–680	**A** 14.24 **B** 13.28 **C** 12.11 **D** 13.15	**A** 2248 **B** 2357 **C** 2343 **D** 2402	**A** 0.652 **B** 0.518 **C** 0.378 **D** 0.501	**A** 37.03 **B** 38.89 **C** 42.10 **D** 37.20	**A** 92.47 **B** 40.79 **C** 44.17 **D** 38.78	[167]
Recycled construction waste - Oak (*Quercus* spp.) - Lauan (*Shorea* spp.)	- Phenol formaldehyde - PMDI	PMDI/PF ratio - 50:50 - 70:30 - 100:0	800–830	**50:50** 14.5 **70:30** 16.9 **100:0** 18.4	**50:50** 2210 **70:30** 2290 **100:0** 2650	**50:50** 0.24 **70:30** 0.31 **100:0** 0.34	**50:50** 11.9 **70:30** 11.3 **100:0** 6.4		
Waste packaging wood boxes from - plywood - solid pine (*Pinus* sp.) wood	- Urea-formaldehyde	Heat treatment temperature (°C) - 180 (A), 200 (B), 220 (C) Proportions of heat-treated particles (%) - 0, 25, 50, 75, 100	600	**0** 8.95 **25** 6.31 **50** 5.50 **75** 4.71 **100** 4.37	**0** 837 **25** 678 **50** 645 **75** 624 **100** 611	**0** 0.89 **25** 0.52 **50** 0.44 **75** 0.37 **100** 0.37	**0** **25** ≈27 (A), ≈29 (B), ≈26 (C) **50** ≈31 (A), ≈24 (B), ≈20 (C) **75** ≈25 (A), ≈19 (B), ≈16 (C) **100** ≈26 (A), ≈15 (B), ≈10 (C)	**0** **25** 81.7 (A), 81.7 (B), 82.8 (C) **50** 83.9 (A), 78.9 (B), 79.7 (C) **75** 81.2 (A), 78.2 (B), 74.2 (C) **100** 83.6 (A), 70.2 (B), 55.1 (C) *WA for 2 h	[170]
Recycled wood waste - furniture, pallets, crates, baskets, packages	- Urea-formaldehyde - liquefied wood waste	Type of liquefied wood waste - Bark(B) - Beech saw dust (BSD) - Pine saw dust (PSD) - Wood powder (WP)	643–652	**Control** 10.4 **B** 10.6 **BSD** 10.7 **PSD** 10.6 **WP** 8.0	**Control** 2097 **B** 2189 **BSD** 2104 **PSD** 2247 **WP** 1645	–	**Control** 40 **B** 29.1 **BSD** 27.9 **PSD** 28.6 **WP** 29.7	**Control** 101.5 **B** 86.1 **BSD** 84.5 **PSD** 83.9 **WP** 86.0	[177]

Construction and demolition of wood waste	- Urea-formaldehyde	Type of wood waste - Medium density fiberboard (MDF) - Medium-density particleboard (MDP) - Plywood - Timber	670–710	**MDF** 4.59 **MDP** 6.49 **Plywood** 7.12 **Timber** 9.69 **Mix** 7.19	**MDF** 597 **MDP** 1013 **Plywood** 1299 **Timber** 1392 **Mix** 1891	**MDF** 0.18 **MDP** 0.75 **Plywood** 0.36 **Timber** 0.96 **Mix** 0.76	**MDF** 21.27 **MDP** 15.16 **Plywood** 9.42 **Timber** 5.04 **Mix** 5.46		**MDF** 73.62 **MDP** 44.41 **Plywood** 79.40 **Timber** 48.92 **Mix** 52.94	[178,179]
- Fresh spruce log - Recycled hardboard, MDF board, pallet, old furniture (R1) - Recycled faulty PB (R2)	- Urea-formaldehyde	Type of recyclate - R1, R2 Ratio of recyclate - 0, 20, 50, 100	649–658	**R1** 10.6–14.7 **R2** 9.3–14.4	**R1** 2155–2666 **R2** 2194–2800	**R1** 0.55–0.75 **R2** 0.55–0.74	**R1** 16.57–22.76 **R2** 9.72–13.29		**R1** 49.23–60.02 **R2** 33.46–43.43	[180]
Recycled wooden pallet from spruce	- Urea-formaldehyde	The ratio of recycled spruce pallet - 0, 20, 50, 100	653–657	**0** 14.60 **20** 12.1 **50** 12.4 **100** 10.0	**0** 2616 **20** 2471 **50** 2276 **100** 2012	**0** 0.79 **20** 0.70 **50** 0.68 **100** 0.61	**0** 23.81 **20** 18.67 **50** 27.87 **100** 23.67		**0** 68.31 **20** 50.95 **50** 76.80 **100** 56.77	[181]

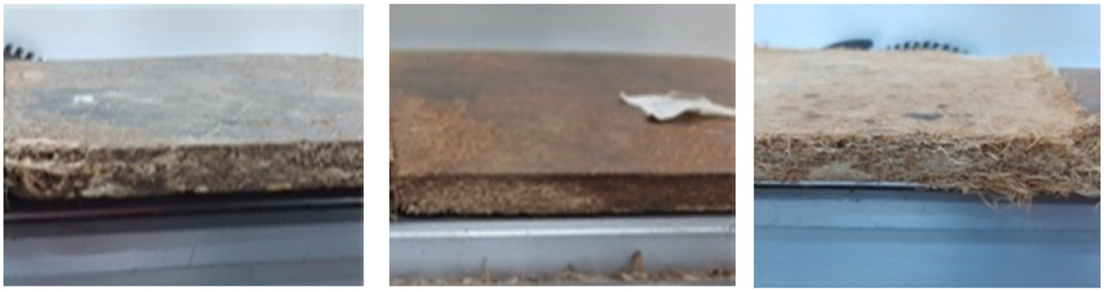

Fig. 13 – Particleboard made of oil palm frond (left), oil palm trunk (middle), and empty fruit bunch (EFB) (own photo).

particleboard manufacturing. However, every type of agricultural biomass has its own issue that prevents it to be used effectively. Bagasse is among the best materials for particleboard manufacturing as particleboard manufactured from it often displayed satisfactory physical and mechanical properties. Still, in some case, the incorporation of some portion of wood particles are necessary to further enhance its performance. Straw-, leaves- and grass-based particles suffered from the waxy surface layer that prevents the effective spreading of water-based UF resin and inevitably leads to poor adhesion and bonding. Meanwhile, hull-, husk- and shell-based particleboard has low mechanical strength due to the low cellulose content of the raw materials. On the other hand, stalk-based particleboard has high holocellulose content that resulted in high thickness swelling. Palm-based such as OPT and OPF has high carbohydrate content but low lignin content while EFB has comparable cellulose content but lower lignin content with hardwood and softwood. Interventions have been carried out by many researchers to enhance the performance of the agricultural biomass-based particleboard. Most of them involve the incorporation of wood particles or using higher resin content. For agricultural biomass having waxy surface layers, isocyanate-based adhesives such as MDI and pMDI are recommended. Polyurethane (PUR), PVA (polyvinyl alcohol), PVAc (polyvinyl acetate), and acryl-based adhesives are suitable options too. Silane coupling agents have also been used to improve the bondability of straws.

5. Particleboard made from recycled wood

A summary of the physical and mechanical properties of particleboard produced using recycled wood waste as raw materials is presented in Table 10. The surface appearance of the post-production particleboard is shown in Fig. 14. Most studies looked at the effect of different types of wood waste, different ratios of wood waste, and different types of recycled wood treatments on the physical and mechanical properties of recycled-wood particleboard. The most common adhesives used were UF and PF resins. However, other adhesive systems such as mixtures of liquefied wood binders and UF and a mix of pMDI and UF were also utilized by researchers.

The treatments to which the wood particles and wood waste were subjected prior to particleboard manufacturing influence the mechanical and physical properties of the final products. Lykidis and Grigoriou [166] conducted a study to investigate the effects of hydrothermal treatments of wood particles on the physical and mechanical properties of recycled-wood particleboard. The hydrothermal treatment was utilized to degrade the bonding of UF adhesive in old and faulty particleboard to retrieve the detached wood particles for new particleboard production. It was revealed that the MOR value of the boards showed a significant reduction. Similar results were also reported in other literature and were mainly due to the thermal decomposition of wood [167–169]. However, it is worth noting that the MOE value of the recycled-wood particleboard was significantly higher when compared to the control particleboard. To fully understand the effect of thermal treatment on the properties of the boards, the authors suggested that a chemical composition analysis of the treated particles be conducted in future studies. The authors also suggested that to produce particleboard that meets requirements at the time, a mixture of new particles and recycled wood particles treated with the milder hydrothermal condition could be used in the production.

Fig. 14 – The surface appearance of post-production particleboard.

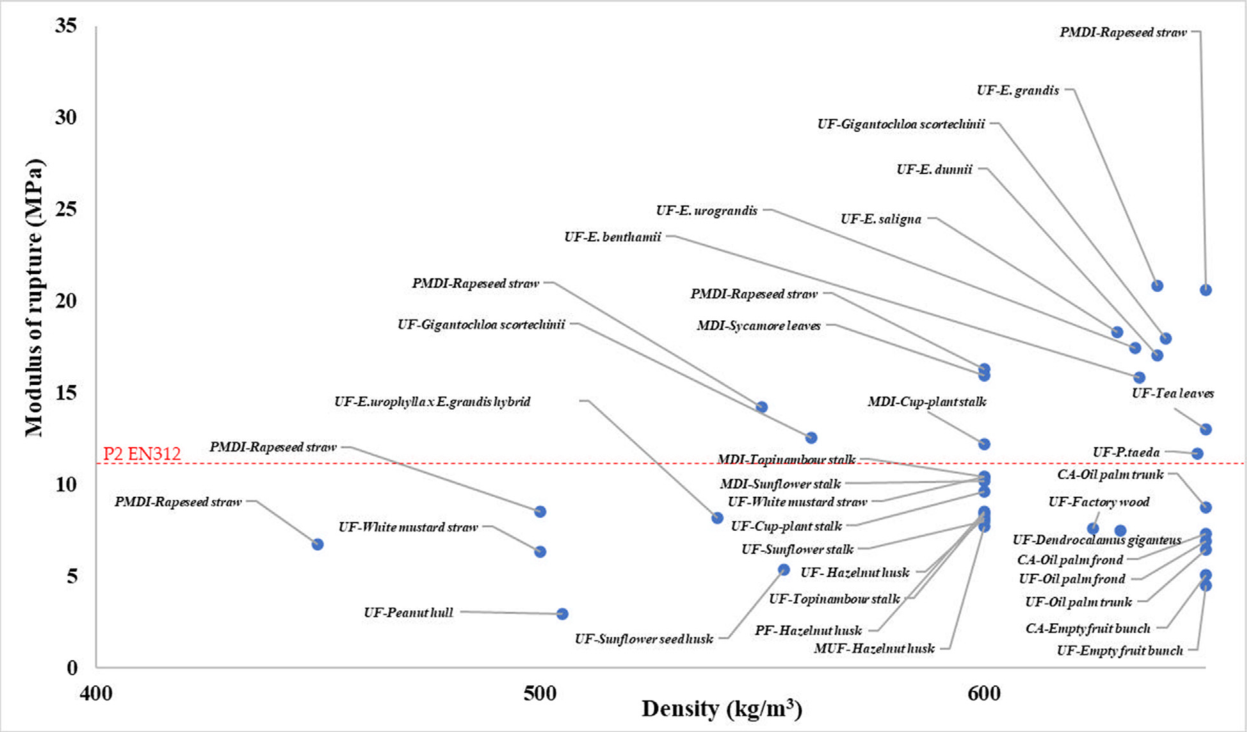

Fig. 15 – Modulus of rupture (MOR) – density chart for particleboard (400–650 kg/m^3) made with agricultural biomass and conventional wood.

Andrade et al. [170] studied particleboard's physical and mechanical properties from different proportions of thermally treated recycled pine particles. The authors also performed a chemical composition analysis for the thermal-treated recycled particles. TS and WA values of particleboard made from thermally treated particles were not significantly lower than those of the control panels. However, conferences produced with particles treated at 220 °C showed a significant reduction in WA compared to other samples. This result was in agreement with those obtained by Paul et al. [171]. This phenomenon was explained by the partial degradation of hemicelluloses, which was reflected in the thermogravimetric analysis results. The relative content of lignin and cellulose showed an increment. The IB decreased slightly but complied with the specification (0.10 N/mm^2) given in the ANSI standard A208.1/99 for low-density boards. The movement of extractives caused IB reduction in the surface of the particles, which would hinder wood-adhesive bonding [172]. Generally, increasing the proportion of heat-treated particles resulted in a decrease in the MOR and MOE values of the boards. However, the reduction is insignificant. The MOR and MOE decreased with increasing treatment temperature, which was expected as high temperatures degrade the structure of the wood, thus resulting in lower mechanical properties [173–176].

The adhesive system used in the production of particleboard also exerts significant influences on the properties of the boards produced. Formaldehyde-based adhesives are some of the most widely used binders in particleboard production. However, other suitable binders are also being explored but are often used together with formaldehyde-based adhesive. Li et al. [52] conducted a study investigating the properties of particleboard made from recycled wood bonded with pMDI and PF adhesive with different pMDI to PF ratios. Janiszewska et al. [177] incorporated different liquefied wood waste binders into a conventional UF adhesive system to produce recycled-wood particleboard.

For the particleboard produced with different pMDI to PF ratios, the authors found that MOR and MOE values increased with an increasing pMDI to PF ratio. Furthermore, the particleboard produced with higher pMDI contents also showed higher IB. This result was in contrast with that reported by Papadopoulos [182]. However, a combination of other parameters such as mat moisture content, pressing temperature, pressing time, and adding other additives could cause a slight IB difference. The increase in IB was explained by Bao et al. [183] that pMDI could penetrate wood cells and the intermediate lamellae between them, where it can interact with the accessible moisture held in the wood. Moreover, pMDI may react with the chemical components of the wood (the hydroxyl groups in polysaccharides or the phenolic groups in lignin) to form urethane structures, which are likely to further aid adhesion. Markedly, the TS values reduced when the pMDI to PF ratio increased.

Janiszewska et al. [177] investigated the physical and mechanical performance impact of several types of liquefied wood waste binders and recycled wood particleboard. From the results obtained from the experiment, the authors observed that the MOR and MOE values of recycled-wood particleboard bonded with liquefied wood waste and UF adhesive were similar to those of the control particleboard, regardless of the type of liquefied wood waste binders used. The slight reduction in MOR and MOE in the particleboard bonded with liquefied wood powder binder was attributed to the relatively low density of tested samples (629 kg/m^3) compared to the density of other samples of approximately 650 kg/m^3. Liquefied wood waste binders decreased the TS and WA of all samples. Nuryawan et al. [184] studied the effect of liquefied adhesive made from oil palm stem particleboard properties and reported similar findings. Thus, it can be concluded that all raw materials used to make liquefied wood waste binders have a favorable impact on the TS and WA of the boards.

The properties of recycled-wood particleboard also depend on the type of recycled wood waste used. Azambuja et al. [178] carried out research to determine the properties of particleboard made from different types of wood waste, i.e., medium density fiberboard (MDF), medium-density particleboard (MDP), plywood, and timber residues. The authors observed that the particleboard made from recycled timber residue displayed the highest MOR, MOE, and IB values. This result could be associated with the higher slenderness ratio of the recycled timber particles, resulting in better bending strength [29]. On the other hand, particleboard produced from MDF recorded the lowest MOR, MOE, and IB values. As a reference, the MOR, MOE, and IB of the control panels made from fresh particles from pine logs were 8 N/mm^2, 1378 N/mm^2, and 0.91 N/mm^2, respectively. Regarding the IB of all samples, only particleboard made from recycled MDF particles did not meet the requirement stated in EN 312. To utilize other types of recycled wood waste despite the reduction of mechanical performance they induced, the authors suggested that those wastes be used as the inner or core layer in the production of layered particleboard. The study of other processing parameters is required to improve the mechanical performance of recycled wood particleboard further.

Besides the type of wood waste, the ratio of wood waste to fresh wood particles also affects the properties of the board manufactured. This prompted Iždinský et al. [180] to evaluate the physical and mechanical properties of particleboard made from different wood wastes with different ratios. The particleboard was produced with particles from the fresh spruce log and particles from recycled hardboard, MDF board, pallet, old furniture (R1), and recycled faulty particleboard (R2). The authors observed that particleboard produced from 100% fresh spruce particles exhibited the highest MOR, MOE, and IB values. The MOR, MOE, and IB of particleboard specimens made from a mixture of fresh wood particles and recycled wood products showed a slight decrease. However, the physical properties such as TS and WA of the specimen made from recycled wood, both R1, and R2, demonstrated major improvement. The authors concluded that although the addition of R1 improved the TS and WA of the specimens, the improvement was considered non-significant (r^2, 0.0001–0.09). On the other hand, the addition of R2 showed a significant positive effect (r^2, 0.63–0.72) on the TS and WA. Similar results were also reported by Azambuja et al. [178]. The results might be attributed to the slower water movement into the particleboard produced with fresh spruce and R2 particles. The existence of cured UF adhesive molecules on the surfaces of R2 particles obstructs the water movement.

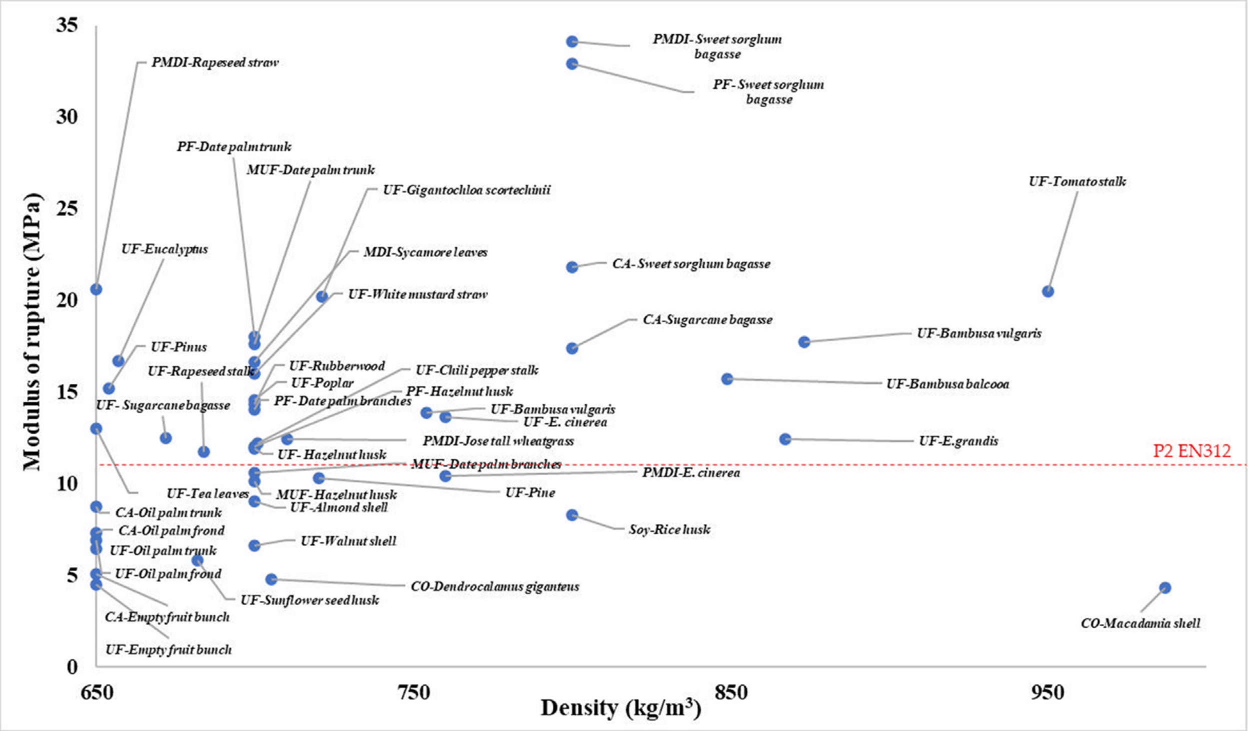

Fig. 16 – Modulus of rupture (MOR) – density chart for particleboard (651–1000 kg/m^3) made with agricultural biomass and conventional wood.

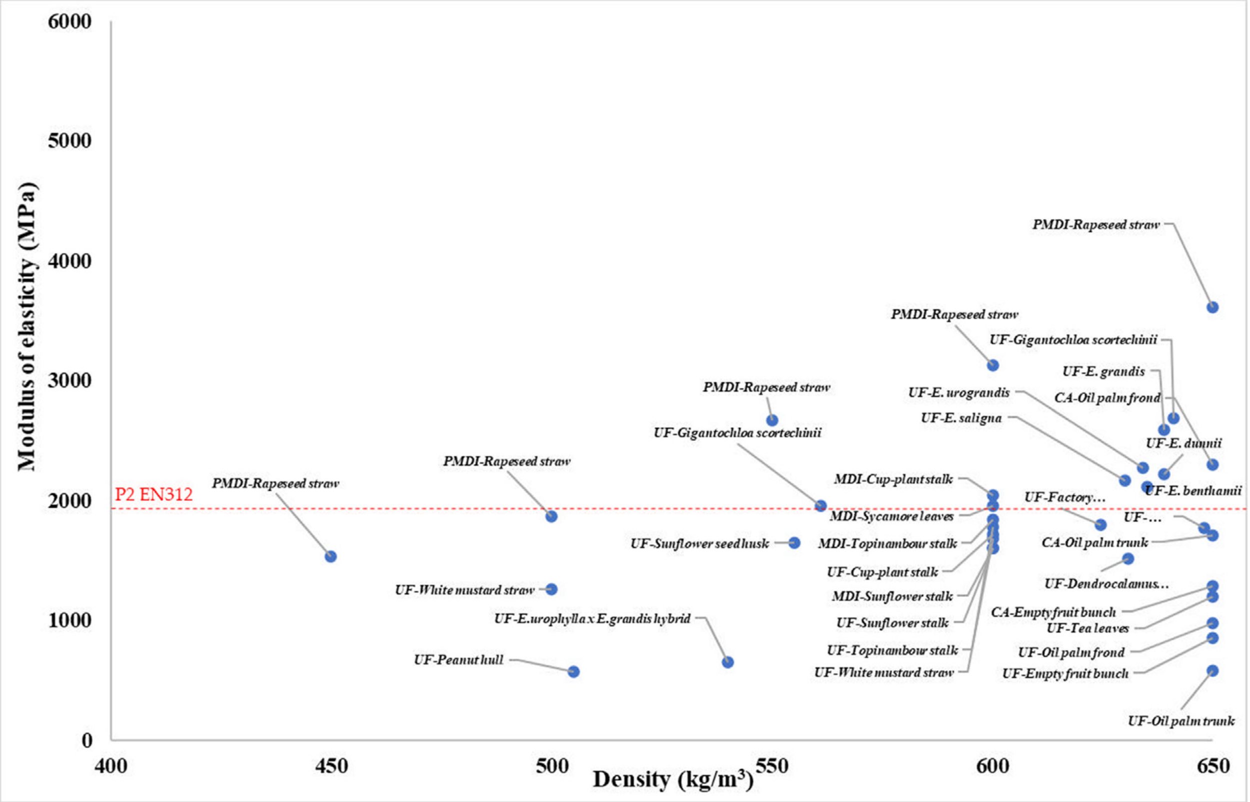

Fig. 17 – **Modulus of elasticity (MOE) – density chart for particleboard (400–650 kg/m³) made with agricultural biomass and conventional wood.**

In a separate study by Iždinský et al. [181], a mixture of particles from the recycled spruce pallet and the fresh spruce log produced recycled-wood particleboard. The results showed an interesting trend which indicated that the TS and WA values of the particleboard decreased slightly below the control values with the introduction of 20% particles from the recycled spruce pallet, with a 22% and 25% reduction in TS and WA values, respectively. However, further increment of particles from a recycled spruce pallet at 50% increased the TS and WA values above the control value. Similar findings were found in other studies [180,185]. The addition of recycled spruce pallet particles, on the other hand, negatively impacted the boards' mechanical properties. The reductions observed were 32% (MOR), 23% (MOE), and 23% (IB). This result could be attributed to deteriorated or polluted wood in particleboard based on recycled spruce pallet particles, as it is well known that wood attacked by decaying fungi or aggressive chemicals has reduced mechanical properties [186]. Laskowska and Mamiski [185] also concluded that the type, amount, and quality of recycled wood particles significantly impacted particleboard properties. Despite a significant reduction in mechanical properties, all the boards produced meet the EN 312 minimum requirement of IB (0.35 N/mm^2) for type P2 particleboard.

6. Comparison between conventional wood-based particleboard vs agricultural and recycled wood-based particleboard

Inspired by Klimek and Wimmer [6], MOR-density and MOE-density charts for particleboard made from different agricultural biomass and conventional wood species were drawn and are illustrated in Fig. 15, Fig. 16, Fig. 17 and Fig. 18, respectively. The charts could provide an easier visual comparison of the properties of particleboard made from various types of agricultural biomass and conventional wood species. As Klimek and Wimmer [6] suggested, the MOR of particleboard from agricultural biomass does not necessarily follow the trend where the MOR increased along with increasing board density. For example, soybean protein-bonded rice husk particleboard having a density of 800 kg/m^3 and castor oil-bonded macadamia shell particleboard having a density of 987 kg/m^3 did not meet the requirements of the P2 class in EN 312. Bagasse-based and bamboo particleboard have higher MOR compared to the other type of agricultural biomass. A similar observation was obtained for MOE, as shown in Fig. 17 and Fig. 18. Irrespective of adhesive types, bagasse-based particleboard exhibited superior MOE than the other agricultural biomass.

The study by Osman et al. [187] also demonstrated that both bagasse and cotton stalks resulted in particleboards with relatively higher mechanical properties than particleboards made from straws and shells.

7. Environmental performance of agricultural biomass and recycled wood particleboards

Life cycle assessment (LCA) is an important and powerful tool to assess the potential environmental impacts of a product system. However, LCA studies on agricultural biomass and recycled wood particleboards are relatively scarce. Some of the available studies are summarized in this section.

In a study by dos Santos [188], laboratory-fabricated particleboards were manufactured using sugarcane bagasse and pine wood shavings. Generally, bagasse particleboards had lower impacts in all categories than pine shavings particleboards, except for the consumption of energy resources (CES), where bagasse particleboards consumed 9.9% more energy than pine shavings particleboards. Bagasse particleboards had 33.1% and 32.4% lower consumption of renewable resources (CRR) and consumption of non-renewable resources (CNR), respectively, compared to pine shavings particleboards. Slightly lower potential photochemical ozone creation (POC) and human toxicity potential (HTP) was produced by bagasse particleboards. In terms of global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP), bagasse particleboards completely stand out in comparison to pine shavings particleboards, with more than 50% lower impacts in these categories.

However, the study conducted by dos Santos et al. [188] is of laboratory scale and therefore unable to reflect the true scenario at an industrial scale. Following that, Silva et al. [189] analyzed the life cycle impacts of bagasse particleboards at an industrial scale. In the study, 50% sugarcane bagasse was used to substitute 50% wood particles in the production of UF-bonded particleboards. The authors compared the environmental performance of Brazilian conventional particleboards [190] and bagasse particleboards. Bagasse particleboards caused fewer impacts on abiotic depletion (ADPe) and ecotoxicity (ECP), mainly due to the reduction in the use of glyphosate in forest management activities. Other impact categories such as AP, ecotoxicity (ECP), EP, GWP, ozone layer depletion (ODP), photochemical oxidation (POCP), human toxicity—cancer effects (HTPC), and human toxicity—noncancer effects (HTPNC) did not differ much between conventional and bagasse particleboards. Application of UF resin, electricity, and heavy fuel oil were the main reasons for this finding. Nevertheless, bagasse particleboards caused lower land-use impacts, indicating less land demand than wood particleboards. Therefore, bagasse particleboard is a good candidate to substitute conventional wood particleboard due to its better environmental performance. Finally, the authors suggested that 75% sugarcane bagasse can be added during particleboard manufacturing to produce panels with better environmental performance.

Ramos et al. [191] compared the environmental performance and thermal behavior of corn cob particleboard,

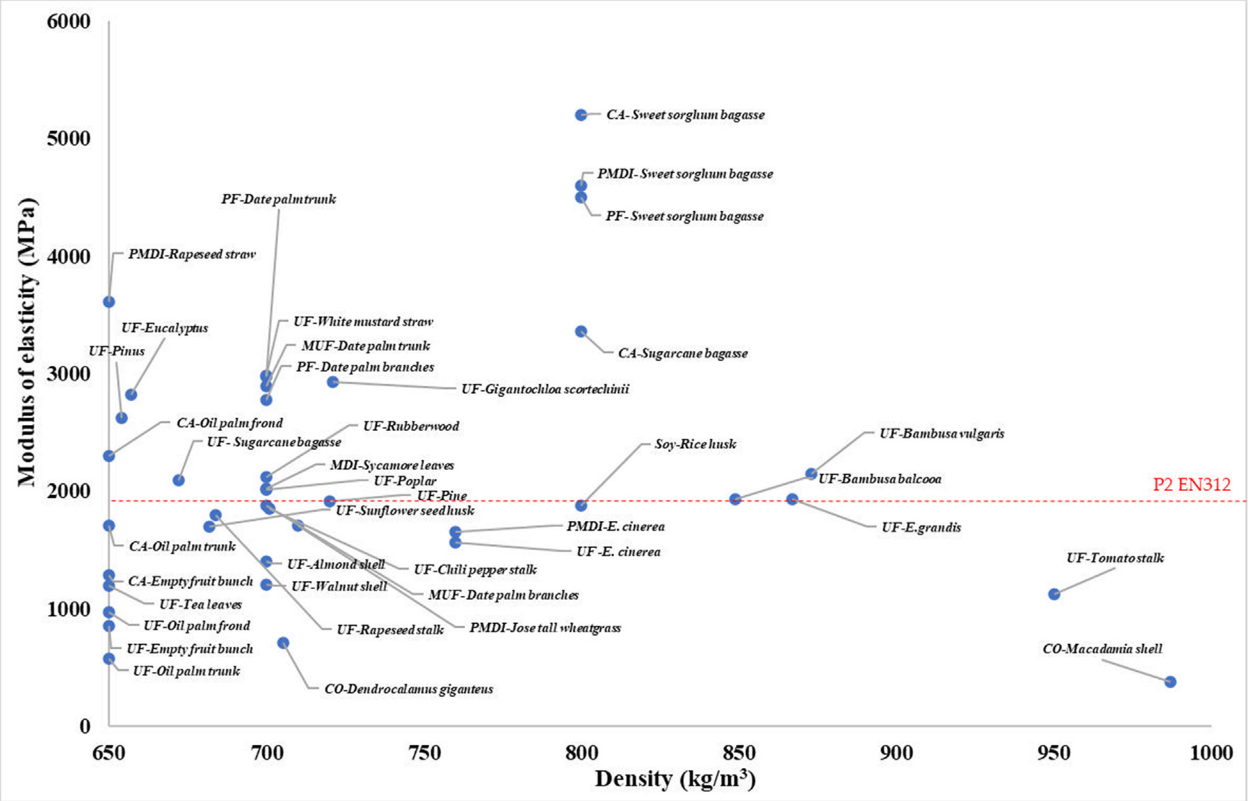

Fig. 18 – Modulus of elasticity (MOE)– density chart for particleboard (651–1000 kg/m^3) made with agricultural biomass and conventional wood.

bonded with two types of adhesives, i.e. polyvinyl acetate (PVA) and Fabricol AG222 (FAG222) as insulation materials. Through the assessment of impact categories, it was found that EPS had a higher impact on GWP, ODP, and HTP. Markedly, both PVA-bonded and FAG222-bonded particleboard showed satisfactory environmental impacts. However, the PVA-bonded panel exhibited better results when landfilling was the preferred disposal technique.

In the production process of 1 m^3 particleboard, Shang et al. [192] discovered a reduction of 40 kg CO_2 equivalent (CO_2 eq) of greenhouse gas (GHG) emission between straw particleboard (600 kg CO_2 eq GHG emission) and wood particleboard (640 kg CO_2 eq GHG emission). On the other hand, straw particleboard consumed less non-renewable energy (2700 MJ) than wood particleboards (2800 MJ). The LCA results demonstrated that the environmental impacts of using straw for manufacturing straw particleboard and cement-bonded particleboard were significantly reduced by 6% and 10%, respectively, compared with using wood as a feedstock. The share of wood resources in processing and drying of the raw material with regards to non-renewable energy consumption and GWP impact was higher than straw particleboards as the moisture content of natural wood is higher. Moreover, due to the omittance of the peeling machine, straw particleboard consumed lower non-renewable energy. The authors concluded that the straw particleboard is the optimal scheme for recycling and reusing crop straw resources. However, power consumption during forming process and straw transportation distance are the main constraints that affect its environmental performance and should be improved.

In the case of using recycled wood waste in cement-bonded particleboard production, Hossain et al. [193] reported that recycling wood waste at a rate of 10% could save around 11,016 tonnes of CO_2 eq per year. The total savings of GHGs emissions for cement-bonded particleboard production could reach 55,079 tonnes of CO_2 eq per year if 50% of the total wood waste could be recovered and reutilized yearly for the production of cement-bonded particleboard. Reutilization of wood waste reduced the induced emission, increased carbon sequestration, and avoided emission, which led to the increased saving of GHGs emissions. Hoglmeier et al. [194] compared the environmental performance of utilizing recovered wood in cascades versus primary wood in manufacturing particleboard. Overall, the environmental footprint caused by the cascading system was around 10%–25% lower than the primary wood system. The authors concluded that the cascading effects are minor compared to the use of primary wood. However, when considering land occupation and transformation, cascading proved to be an even more preferable treatment option for waste wood as a reduction of 99.1% and 51.2% was recorded, respectively. Markedly, applying agricultural biomass and recycled wood in particleboard manufacturing provides environmentally benign alternatives to conventional wood.

8. Problems, prospects, and challenges

Particleboard manufacturers face an inconsistent supply of raw materials, and the absence of an established supply chain, particularly in the Asia Pacific region, is a major challenge [37]. Manufacturers still stick to conventional raw materials for particleboard production and hesitate to adopt alternative feedstocks. It is a malicious cycle where the manufacturers blame the inconsistent supply of raw materials. At the same time, the planters are reluctant to convert their cultivations because there is no demand for them. This weak link must be solved for the agricultural–waste-based particleboard to flourish. Accumulating agricultural wastes without proper discarding measures could pose a serious environmental threat to developing countries [195]. Introducing relevant policies should enhance awareness and market acceptability among stakeholders and the public.

Despite the scientific and technological advances, there are substantial challenges regarding the wider industrial utilization of agricultural biomass in particleboard manufacturing. Fresh agricultural biomass has a higher moisture content which makes it heavier, incurring higher transportation and storage costs [196]. More importantly, raw material with high moisture content is less compressible during board pressing. Adjustments in the processing parameters might be necessary. In addition, agricultural biomass generally has a lower apparent density than conventional wood particles. Low density causes a high volume per unit weight of agricultural biomass than wood particles [9]. Therefore, a sufficient compaction ratio might not be achieved within a limited pressing time. Moreover, a higher volume of agricultural biomass requires more resin for sufficient coverage to attain adequate bonding. Using the same resin content for agricultural biomass used for wood particles means that every particle is covered with less adhesive, which could adversely affect the final performance of the resultant boards.

Another issue of the particleboard fabricated of agricultural biomass is its deteriorated dimensional stability and water absorption. This issue is more significant on the straw-, stalk-, husk- and shell-based particleboard and could be overcome by adding hydrophobic agents such as wax during the production process. Meanwhile, grass- and leave-based particleboard have relatively lower TS and WA values due to their waxy layer on the surfaces and lower cellulosic content. However, due to the waxy layer, water-based UF resin is unsuitable for use as a binder during grass- and leave-based particleboard production. Bagasse-based particleboard gives satisfactory physical and mechanical properties compared to the other agricultural biomass counterparts. Nevertheless, most agricultural biomass-based particleboard panels have relatively poorer mechanical strength than those of wood-based panels. The incorporation of woody particles is deemed necessary to improve the strength of particleboard.

Meanwhile, the introduction of recycled wood particles in producing new particleboard shows promising results. Nevertheless, it is interesting to note that the content ratio of recycled wood particles was not proportional to the physical and mechanical properties values. Further studies on various treatment conditions and different ratios of recycled wood particles are required to determine the optimum parameters to produce particleboard with the best physical and mechanical properties.

An important issue with particleboard and other engineered wood products, fabricated from agricultural waste biomass and/or recycled wood waste is the lack of sufficient information about their fire characteristics and reaction to fire. The combustion of wood-based panels such as particleboard, widely used in the building sector, is a major problem due to the recent stringent fire safety regulations [28,197]. Some studies have been carried out to investigate the reaction to fire of wood-based composites made from agricultural biomass [198–201], but publications focused on this problem are still rather limited. It will be an interesting field to explore in the future.

9. Conclusions

In many cases, particleboards manufactured from alternative raw materials exhibit similar or even better mechanical properties than conventional wood-based particleboards. Hence, boards made from agricultural biomass and recycled wood waste could ensure sustainable development, which features three key elements: economic growth, social inclusion and environmental protection. Furthermore, the pressure on other forest-based resources can be significantly reduced, and additional employment opportunities can be created. The changes in the current raw material structure in particleboard technology, via the applications of alternative raw materials, will positively impact the continued growth dynamics of wood-based particleboard production. Complementing the shortage of wood raw materials by introducing agricultural biomass and recycled wood as alternative raw materials can ensure the continuity of panel production in a more economically viable and environmentally friendly manner.

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Data availability

The authors confirm that the data supporting the findings of this study are available on request.

Human and animal rights and informed consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lee Seng Hua reports administrative support was provided by Putra Malaysia University. Lee Seng Hua reports a relationship with Putra Malaysia University that includes: non-financial support. Lee Seng Hua has patent None pending to None.

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