International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V72I5P126

Volume 72 Issue 5, 252-260, May 2024

Review Article

A Review of Particleboard Development and Performance Using Non-Toxic and Biodegradable Adhesives

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Received: 25 January 2024 Revised: 04 April 2024 Accepted: 11 April 2024 Published: 26 May 2024

Abstract *- The demand for wood-based materials in particleboard production is increasing, but so are the costs and concerns about the environment and health. As a result, researchers have been exploring alternative raw materials. This review critically examines the development of particleboards using novel adhesives derived from food waste and agricultural by-products, comparing them to the commonly used Urea-Formaldehyde (UF) resins. The study focuses on the environmental and health risks associated with UF resins, including their potential to cause cancer and respiratory problems. In search of sustainable and safer alternatives, the research investigates bio-based adhesives as potential solutions for the sustainability challenges in particleboard manufacturing. The study includes a thorough analysis of the chemical composition and properties of urea-formaldehyde resin, recognizing its strong tensile strength and bonding capabilities but also highlighting the environmental and health risks it poses. In contrast, the study explores a range of alternative binders, such as soy protein, lignin, tannin, and starch-based adhesives. These bio-based adhesives, derived from renewable sources, are examined for their eco-friendliness and potential to mitigate the negative impacts of conventional adhesives in particleboard production. The findings of the study reveal that particleboards made with alternative adhesives not only match but sometimes even surpass the physical and mechanical properties of those made with UF resin. Importantly, these alternative adhesives are non-toxic, making them suitable for construction applications and reducing the health risks associated with the high levels of formaldehyde emissions from UF resin-based particleboards. This research confirms the feasibility of using sustainable materials in particleboard production and aligns with global efforts for environmental conservation and public health protection. By addressing research gaps, this study contributes significantly to the advancement of sustainable and health-conscious practices in the particleboard industry.*

Keywords *- Particleboard, Urea-formaldehyde, Alternative adhesives, Physical properties, Mechanical properties.*

1. Introduction

The burgeoning demand for particleboards in the construction industry, alongside escalating health concerns, has spurred researchers to investigate the root causes of these issues [1]–[4]. Particleboard is a staple in a myriad of construction and furniture applications, including flooring, walls, ceilings, office dividers, bulletin boards, cabinets, furniture, and countertops. This heightened demand has consequently exerted significant pressure on natural forest resources, particularly in developing countries where rapid population growth, urbanization, and the proliferation of modern architecture exacerbate forest over-exploitation [5]. Historically, the manufacturing of particleboards has involved bonding wood particles with synthetic resin adhesives, with Urea-Formaldehyde (UF) being the predominant choice [6]–[7]. Despite its effectiveness, UF resin has become a source of serious environmental and health concerns, prompting a reassessment of particleboard production methods. The use of UF resins in particleboards is particularly alarming due to the health risks they pose. In environments such as bathrooms and kitchens, where humidity and water contact are common, these particleboards can release formaldehyde, leading to various health issues. These include respiratory problems like asthma and chronic bronchitis, skin, upper respiration, eye irritation, and an increased risk of cancer, with formaldehyde classified as a carcinogen linked to nasopharyngeal cancer and leukaemia [8]–[9]. In response to these pressing concerns, there has been a growing interest in exploring alternative adhesives for particleboard production. Research and industrial endeavours have shown that binders derived from food waste and agricultural by-products, such as gum Arabic [10], sugar cane molasses [11], and cassava starch [12], offer a sustainable and potentially less harmful alternative to traditional adhesives. The adoption of such bio-based adhesives could significantly diminish the environmental footprint of particleboard production and mitigate health risks associated with formaldehyde emissions. This study aims to provide a comprehensive review of the current landscape of particleboard production, focusing on the environmental and health impacts of Urea-Formaldehyde adhesives and the exploration of alternative, non-toxic, and biodegradable binders from the food and agriculture industries.

2. Composition and Properties of Urea-Formaldehyde

Particleboard production frequently employs resins such as Phenol-formaldehyde (PF), Melamine-formaldehyde (MF), and predominantly Urea-formaldehyde (UF), each selected for their specific properties [13]. Urea-formaldehyde, a thermosetting resin or polymer characterized by its opacity, primarily comprises urea and formaldehyde. It is renowned for its high reactivity, excellent bonding strength, and cost-efficiency. UF resin is known for its high tensile strength, flexural modulus, and resistance to heat, chemicals, and abrasion, attributed to its dense cross-linked polymer structure. The physical properties of UF resins can be tailored by adjusting the formaldehyde-to-urea ratio, the pH of the reaction mixture, and the reaction time and temperature. UF resin typically exhibits a viscosity range of 180-290, a density of 1.25 kg/m³, a pH of around 8.1, a gel time of 63 seconds, and a solid content of 59%. Notably, it contains approximately 0.75 mg/100g of free formaldehyde [14]. In terms of mechanical properties, UF resin has a high elastic modulus (Young's modulus) of 9.0 GPa, a tensile strength of 30 MPa, and an elongation at break of 1.0%. Additionally, the resin possesses a specific heat capacity of 1200 J/kg-K and thermal conductivity and expansion rates of 0.4 W/m-K and 55 µm/m-K, respectively [15]. At the molecular level, the reaction between urea and formaldehyde results in a complex network of polymers. However, in the presence of water, this reaction undergoes hydrolysis, leading to the release of formaldehyde (CH2O) and the production of ammonia (NH3): CO(NH2)2 + H2O → CH2O + NH3 [16]. This hydrolysis process is significant as it can lead to formaldehyde emissions, particularly when UF-based particleboards are exposed to water or humid conditions. In the production of particleboards, UF resin serves as a crucial adhesive component, binding wood particles into a cohesive unit. The adhesive properties of UF resin are largely due to its ability to polymerize and form a robust network that holds the wood particles together. The primary reaction in the formation of UF resin as an adhesive involves the condensation of formaldehyde with urea, resulting in the creation of methylene and methylene ether linkages [17]. This reaction can be as:

$$NH_2CONH_2+CH2O \rightarrow NH_2CONHCH_2OH$$

$$NH_2CONHCH_2OH+NH_2CONH_2 \rightarrow NH_2CONHCH_2NHCONH_2+H_2O$$

These reactions result in the formation of a non-crystalline thermosetting polymer, which, upon curing, creates a strong, cross-linked network. This network is critical for the adhesive's ability to bond wood particles effectively, giving the particleboard its structural integrity and strength. The hardening of UF resin, induced by heat during the particleboard manufacturing process, transforms it into a rigid, insoluble, and infusible polymer, ideal for creating stable and durable particleboards. However, the presence of free formaldehyde in the resin, a by-product of the incomplete reaction between urea and formaldehyde, poses significant health risks. In conditions where the particleboard is exposed to moisture or high humidity, this free formaldehyde can be released into the environment, leading to potential health hazards. Therefore, while UF resin's ability to act as an effective adhesive is well-established, its use in particleboard production is scrutinized due to these associated health risks.

3. Food Waste and Agricultural By-Products as Adhesives

3.1. Protein-Based Adhesives

Protein-based adhesives, sourced from agricultural products such as soy, palm, canola, cottonseed, and sunflower oils, are increasingly being recognized for their potential in particleboard production [18]–[19]. Among these, soybeans are particularly notable, with their residual soybean meal being processed into Soy Flour (SF), Soy Protein Concentrate (SPC), and Soy Protein Isolates (SPI).

Soy flour, despite its lower protein content, offers an economical alternative for adhesive formulation. The adhesive efficacy of soy proteins lies in their ability to form strong bonds with wood particles, attributable to their protein content and the formation of a highly ordered spherical structure through hydrogen bonding and other multi-level interactions.

However, the hydrophilic and hydrophobic nature of soy proteins can affect adhesive performance. To enhance their water resistance and bonding strength, modifications such as the addition of tannin-based resin, waterborne epoxy resin, polyacrylamide, and 2-octen-1-ylsuccinic anhydride (OSA) have been proposed [19] (See Figure 1). These modifications enhance the water-resistant bonding performance, making soy protein adhesives suitable for applications like plywood, blockboard, and engineering flooring substrates. Challenges, including the use of excessive chemical modifiers leading to increased costs and potential brittleness, as well as issues with water erosion of the curing structure, necessitate further research for optimization in industrial applications.

3.2. Lignin-Based Adhesives

Lignin, a natural polymer found in plant cell walls, is emerging as a viable alternative binder. With a complex structure primarily composed of phenylpropane units, lignin can be modified to enhance its reactivity and adhesive properties. This adaptability makes it suitable for various wood and construction industry applications.

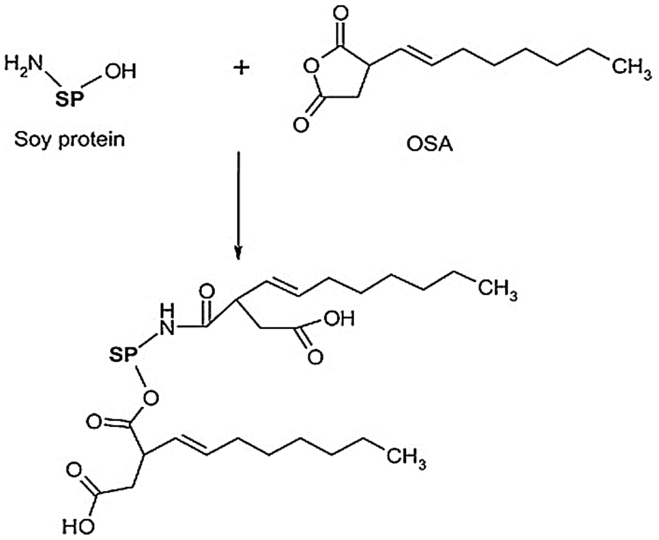

Fig. 1 The schematic illustration of the reaction mechanism between soy protein adhesive and OSA [19]

Lignin's molecular structure is characterized by a highly branched polymer, mainly consisting of phenylpropane units such as coniferyl, sinapyl, and p-coumaryl alcohol, and it varies depending on the source and extraction method. Commercially obtained through processes like kraft and sulfite pulping, lignin's adhesive properties are influenced by the extraction method and agent, impacting its polymerization degree and hydroxyl group presence [21] (See Figure 2). To improve lignin's inherent reactivity limitations, modifications such as partial substitution for phenol in phenol-formaldehyde resins and the development of formaldehyde-free resins by combining lignin with other substances like proteins have been explored. These efforts aim to enhance the environmental and health attributes of lignin-based adhesives, highlighting their growing importance in the bio-based wood adhesives sector [20]–[21].

3.3. Tannin-Based Adhesives

Tannins, natural compounds found in various plant parts, have diverse applications in industries like ink manufacturing and textile dyes [22]. Not all plant species, however, have sufficient tannin concentrations for extraction. Significant sources include pine, quebracho, oak, chestnut, wattle, eucalyptus, myrtle, maple, birch, and willow. The extraction process, which can be done through methods like maceration and Soxhlet extraction, significantly influences the adhesive properties of tannin extracts. Tannins are being researched as components in the development of formaldehyde-free resins, combined with substances like proteins to enhance environmental and health-related properties. Their polyphenolic structure, varying based on botanical origin and extraction process, contributes to their potential as natural and environmentally friendly binders [23] (See Figure 3). Efforts are underway to develop formaldehyde-free tannin-based adhesives for improved safety and sustainability in the wood industry.

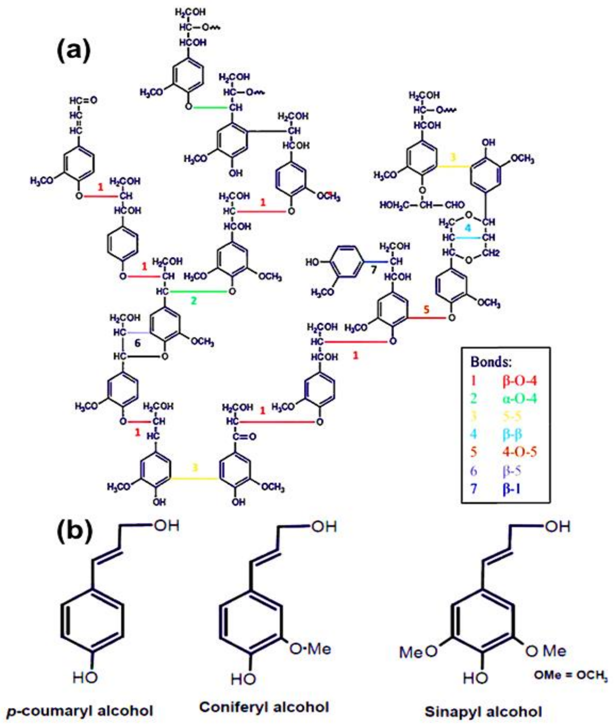

Fig. 2 The schematic illustration of p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol [21]

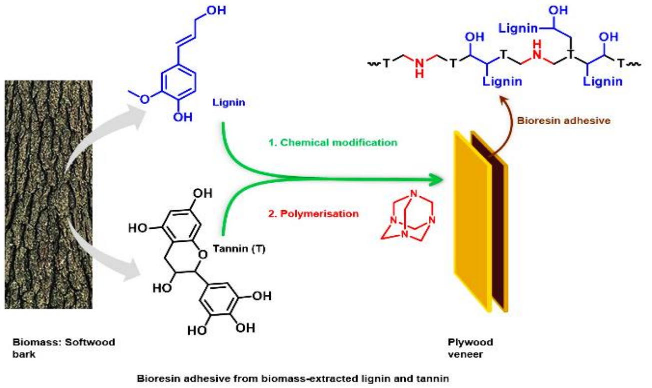

Fig. 3 Bioresin adhesive from biomass-extracted lignin and tannin [23]

3.4. Starch-Based Adhesives

Starch-based adhesives, composed of a network of glucose units, are derived from sources like rice, corn, wheat, tapioca, and potatoes [24]. These adhesives, created by breaking down starch into smaller molecules that react with wood cellulose, are biodegradable and non-toxic, making them an environmentally friendly option for industrial applications. Starch, due to its high free hydroxyl content, low cost, and ease of processing, is ideal for wood-composite adhesives. However, their limited water resistance can be improved through modifications like cross-linking with Maleic Anhydride (MA) [25] (See Figure 4). Research is focused on developing starch-based adhesives with enhanced water resistance and adhesive properties for broader industrial applications.

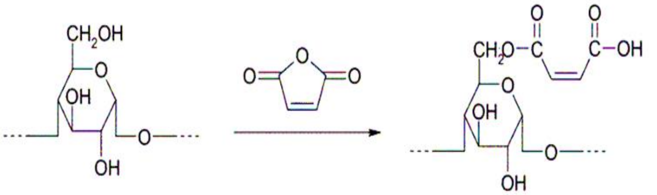

Fig. 4 Use of maleic anhydride (MA) to react with maize starch to create esterified corn starch [25]

4. Materials and Methods

In the fabrication of particleboards, a combination of adhesives - including gum Arabic, castor oil, and sugar cane molasses resins - is employed alongside raw materials such as pine wood fibres and coconut shells. In the pursuit of optimizing the manufacturing process of particleboards, a comprehensive assessment of material bonding, void content visualization, and chemical composition determination is paramount. This is achieved through the utilization of Scanning Electron Microscopy (SEM) for high-resolution imaging of the particleboard's surface, which elucidates the material's morphology, including the distribution and quality of the bonding agent among the fibres.

Concurrently, X-ray Fluorescence (XRF) spectroscopy quantifies the elemental composition of the particleboards, a critical step for identifying chemical elements present in the raw materials or introduced during the manufacturing process that could potentially influence the performance characteristics of the final product. After these initial analyses, particleboards are subjected to a series of tests to evaluate their physical and mechanical properties, following established standards such as those from the American Society for Testing and Materials (ASTM) [26]. Determining the particleboard's dimensional stability according to ASTM D 1037-06a. Equations 1 and 2 are used to determine the dimensional stability:

$$WA\ (\%) = \frac{wf-wi}{wi} \times 100 \qquad (1)$$

$$TS\ (\%) = \frac{tf-ti}{ti} \times 100 \qquad (2)$$

Where *wf* and *wi* represent the final and initial weights, respectively, and *tf* and *ti* denote the final and initial thicknesses, respectively. The mechanical properties, including the bending strength or Modulus of Rupture (MOR) and bending stiffness or young modulus or Modulus of Elasticity (MOE), are determined through a three-point bending test using a universal testing machine. Equations 3 and 4 are used to determine the MOR and MOE:

$$MOR\ (MPa) = \frac{3PL}{(2bd^2)} \qquad (3)$$

$$MOE\ (MPa) = \frac{L^3}{4bd^3} \times \frac{P_1}{y_1} \qquad (4)$$

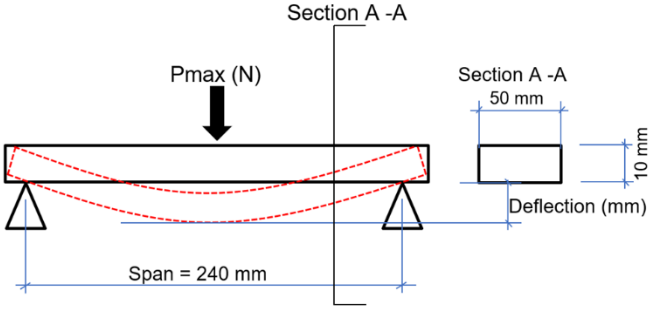

Fig. 5 Schematic diagram for bending test

Where *b* and *d* are the width and thickness of the sample, respectively, *L* is the length of the span, *P* is the maximum load, *P1* is the load at the proportional limit, and *y1* is the centre deflection at the proportional limit load. A schematic diagram test for the bending stiffness and bending strength is depicted in Figure 4. The outcomes of the tests enable the determination of the use and grade of particleboards for construction purposes in accordance with different standards, such as the American National Standards Institute (ANSI) for particleboard [27], as depicted in Appendix 1.

5. Performance of Waste-Based Adhesive Particleboards

In this review, 11 studies (Table 1) were scrutinized to assess the performance of particleboards utilizing waste-based adhesives, highlighting a shift towards more sustainable manufacturing practices. These adhesives, derived from agricultural and food waste, offer an innovative alternative to conventional Urea-Formaldehyde (UF) resins. The data from the reviewed studies demonstrate that the mechanical and physical properties of particleboards made with waste-based adhesives align well with various international standards such as EN (European Norm), ABNT (Brazilian National Standards Organization), and ANSI (American National Standards Institute). Specifically, the modulus of rupture (MOR) values for these particleboards vary significantly, ranging from 11.00 to 31 MPa, indicating their potential in diverse structural applications. These values meet and sometimes surpass the minimum strength requirements set by standards such as ANSI A2081 1999, which stipulates MOR ranging from 11 MPa to 14.5 MPa for M1 and M2 particleboards, respectively, with a minimum acceptable MOR of 3 MPa (Aisien et al., 2015). Furthermore, the Modulus of Elasticity (MOE) across different classes of particleboards varies, starting from 1725 MPa for M1 to 2250 MPa for M2, as per ANSI standards (Hüsnü et al., 2014). The minimum acceptable MOE is noted as 550 MPa, emphasizing the structural robustness required for various applications. In terms of physical properties, these particleboards exhibit water absorption and thickness swelling within the acceptable limits set by international standards. Notably, ANSI/A208.1-1999 specifies a maximum thickness swelling of 8% for general-purpose particleboards (Table 2).

Table 1. Physical and mechanical properties of particleboards produced from food and agriculture waste-based adhesive.

NO	Raw Material	Resin Used	Physical			Mechanical			Ref.
			Standard	WA (%)	TS (%)	Standard	MOR (MPa)	MOE (Mpa)	
1	Rice husk	Soybean protein concentrate (SPC) with carvacrol	ASTM D 1037 12	-	4.37 - 4.52	ASTM D 1037 12	11.00 - 13.31	2410 - 2740	[28]
2	Sugarcane bagasse and Eucalyptus residues	Castor oil-based polyurethane resin (PU-Castor) (10%) Urea-formaldehyde (UF) (10%)	ABNT NBR 14810-2 (2013)	-	10.9-65.6	ABNT NBR 14810-2 (2013)	18-31	2420 - 3020	[29]
3	Coconut fibre Pine Eucalyptus	Polyurethane castor oil (PU-Castor) (10%)	ABNT NBR 14810-2 (2018)		9.33 - 14.54	ABNT NBR 14810-2 (2018)	16.70 - 21.79	1841 - 2924	[30]
4	Macadamia Nutshell	Gum Arabic (20-80%)	ASTM D 1037-06a	9.42 - 38.76	6.22 – 28.46	ASTM D1037-06 section 9	4.20 – 12.21	1050 - 1810	[2]
5	Tea oil camellia shells gum (Eucalyptus Grandis x urophylla)	Polymethylene diphenyl diisocyanate (Polymeric MDI) (8% - 12%)	EN317	[30, 75]	[7, 25]	EN317	4.18 – 7.24	692 - 1095	[31]
6	Sorghum bagasse	Citric acid Molasses	JIS A 5908:2022	6.47 – 11.92	40.28 – 49.26	JIS A 5908:2022	5.65 – 9.69	754 - 1128	[32]
7	Sugar palm dregs	sucrose-citric acid (10, 15, 20 %)	JIS: 2003	47.0 – 98.7	12.4 - 49.3	JIS: 2003	13.6 – 25.2	2500 - 4700	[33]
8	Plum pits	Phenol formaldehyde (PF) Sugar beet Molasses Polyvinyl acetate (PVAc)	EN 317	18.7	4.6	EN 320	11.4-16.3	-	[34]
9	Pinecone	Molasses Phenol formaldehyde (PF) Polyvinyl acetate (PVAc)	EN 312	16.4	4.8	EN 310	17.4	-	[35]
10	Palm trunk	Cement (20 %) + Potato starch (5 – 10%)	European standards	[50, 70]	[25, 35]	European standards	[9, 25]	[1000, 2500]	[36]
11	Rice husk	Soybean protein concentrate (10 %)	ASTM D1037	[40, 55]	[20, 30]	ASTM D1037	11.6 – 18.1	2260 - 2680	[37]

Table 2. Typical thickness swelling, MOR, and MOE

Standard	TS (%)	MOR (MPa)	MOE (MPa)
EN	14	11.5 (P1)	1600
		13 (P2)	
ABNT BNR	22	11	1800
ANSI	8	11 (M1)	1725
		14.5 (M2)	2250
		3 (Min.)	550 (Min.)

6. Performance of Particleboards Using Various Types of Organic Waste Adhesive

In evaluating the use of organic waste materials as adhesives in particleboard production, this review focuses on several types of waste-based adhesives and their impact on the properties of particleboards. The cited studies demonstrate how these innovative adhesives contribute to the mechanical and physical characteristics of particleboards. Rice husk combined with soybean protein concentrate (SPC) and carvacrol showcases effective moisture resistance, indicated by water absorption rates of 4.37-4.52%.

Additionally, these particleboards exhibit substantial strength and flexibility, with a modulus of rupture (MOR) ranging from 11.00-13.31 MPa and a modulus of elasticity (MOE) between 2410-2740 MPa, as documented by Larregle, Chalapud, Fangio, Ciannamea, Stefani, Martucci, and Ruseckaite [27]. In addition, particleboards made from a blend of sugarcane bagasse and eucalyptus residues, combined with castor oil-based polyurethane resin (PU-Castor), demonstrate notable mechanical robustness. The MOR of these boards spans 18-31 MPa, while the MOE ranges from 2420-3020 MPa. The thickness swelling, ranging from 10.9-65.6%, reflects their adaptability to various environmental conditions [29].

Furthermore, coconut fibre paired with polyurethane castor oil (PU-Castor) has been found to produce particleboards with commendable water absorption (9.33-14.54%) and thickness swelling. The MOR and MOE of these boards, falling within 16.70-21.79 MPa and 1841-2924 MPa, respectively, underline their structural integrity [30].

On the other hand, particleboards utilizing macadamia nutshell and gum Arabic as an adhesive exhibit varied physical and mechanical properties. These boards have a higher water absorption range (9.42-38.76%) and an MOR between 4.20-12.21 MPa. The water-soluble nature of gum Arabic influences these characteristics, necessitating considerations for specific applications [2].

Additionally, sorghum bagasse with citric acid molasses adhesive creates particleboards that exhibit a balance of water absorption (6.47-11.92%) and thickness swelling (40.28-49.26%). These boards also maintain a suitable MOR of 5.65-9.69 MPa and MOE of 754-1128 MPa, indicating their potential for various uses (Adelka et al., 2023).

Sugar palm dregs combined with a sucrose-citric acid mixture result in particleboards with higher water absorption rates (47.0-98.7%) and thickness swelling (12.4-49.3%). Despite this, the MOR and MOE values (13.6-25.2 MPa and 2500-4700 MPa, respectively) demonstrate considerable mechanical strength [33]. These findings reveal the potential of using organic waste materials as alternative adhesives in particleboard production, contributing to more sustainable practices.

The physical and mechanical properties of these particleboards meet and, in some cases, exceed the standards set by entities like EN, ABNT, and ANSI, demonstrating their suitability for various applications.

This shift towards eco-friendly resins in particleboard production not only addresses environmental concerns but also opens new opportunities for innovative materials usage in the building and construction industry. In addition, recent studies demonstrated that cabinets, which constitute nearly half of the market share at 49%, could significantly benefit from the integration of sustainable particleboards, while furniture for office use, representing 13% of the market, also presents a substantial opportunity for applying these eco-friendly materials [38] (See Figure 6).

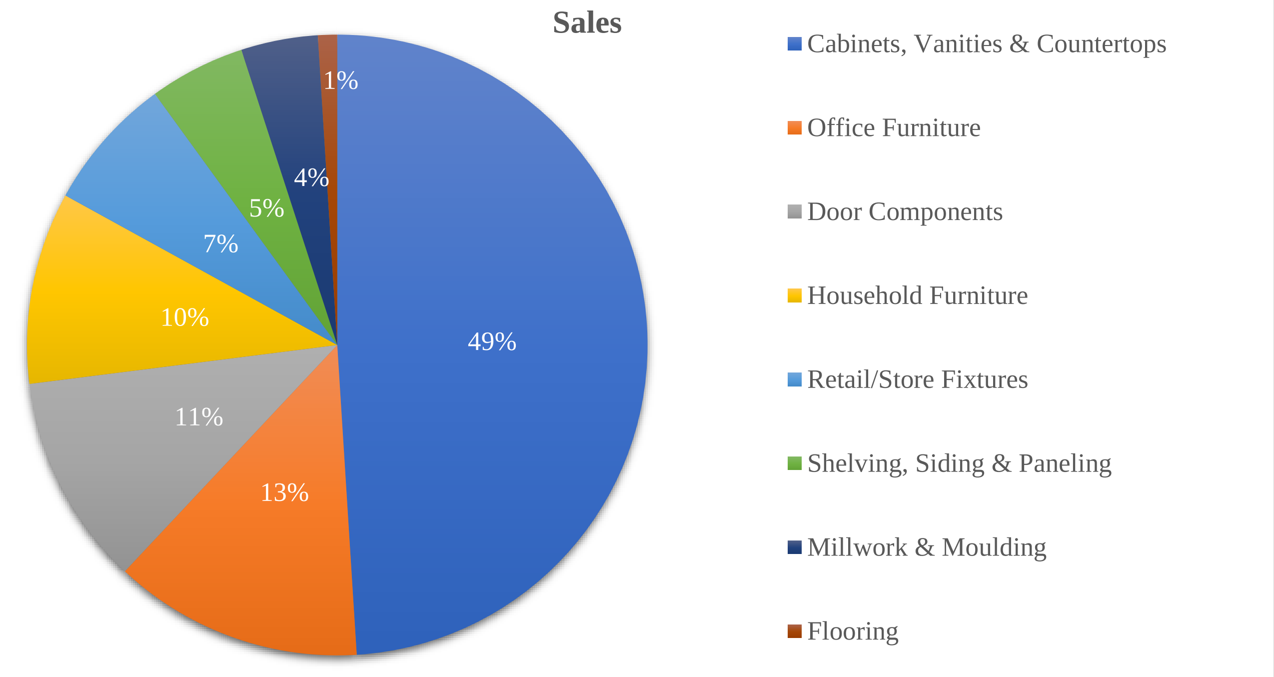

Fig. 6 Uses of Particleboard Shipments [38]

7. Conclusion

This research critically examined the evolution of particleboard manufacturing, shifting towards the use of adhesives derived from agricultural and food waste, a strategic move driven by the increasing demand for wood and the rising costs associated with traditional materials. The study aligns with the urgent need to find sustainable and health-friendly alternatives to urea-formaldehyde (UF) resins, which have raised significant health concerns.

Investigated a wide range of bio-based adhesives, including soy protein, lignin, tannin, and starch-based options, this review highlights their potential to offer sustainable solutions to the environmental and health risks traditionally associated with UF resins. The findings demonstrate that particleboards fabricated with these alternative adhesives not only meet but, in some cases, surpass the physical and mechanical properties of boards made using UF resin. This outcome indicates a crucial transition in particleboard manufacturing towards practices that are more aligned with ecological sustainability and health safety.

The study's results suggest that agricultural and food waste can be effectively repurposed into eco-friendly adhesives for particleboard production. These particleboards meet the minimum requirements established by ANSI/A208.1-1999, EN, JIS, and ABNT standards, making them suitable for various applications, including construction, flooring, housing, work surfaces, educational tools, laboratory equipment, and office furniture. This approach enhances sustainable development by promoting the efficient utilization of resources, reducing waste, and mitigating adverse environmental impacts.

Furthermore, the study proposes several avenues for future research and development within the particleboard market. Optimizing the adhesive qualities of waste materials further to improve the physical and mechanical properties of particleboards is essential. Investigating more alternative, non-toxic, and biodegradable binders can provide viable replacements for traditional resins like UF, addressing both health and environmental concerns. Comprehensive lifecycle assessments are recommended to understand the broader environmental impact of utilizing particleboards based on waste materials. Additionally, market analysis and consumer awareness campaigns are crucial to increase demand for these eco-friendly particleboards.

In summary, this review highlights a significant shift towards more sustainable and health-conscious manufacturing practices in the particleboard industry. By embracing agricultural and food waste as resources for adhesive production, the industry is not only adhering to global environmental goals but also contributing to the circular economy, paving the way for a more sustainable and responsible future in building material production.

Acknowledgments

I would like to thank the reviewers who helped to improve the manuscript's quality. I am so grateful to the Dean of the School of Architecture and Planning at Morgan State University, Dr. Ambibola Asojo, and the Architecture, Urbanism, and Built Environments Program Director, Dr. Kamalesh Panthi, for their efforts in ensuring the study runs smoothly. I would like to express my special thanks to Dr. Tonya Nashay Sanders Thach for her valuable support.

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Appendix 1

Table 3. Uses and grades of Particleboard according to ANSI [38].

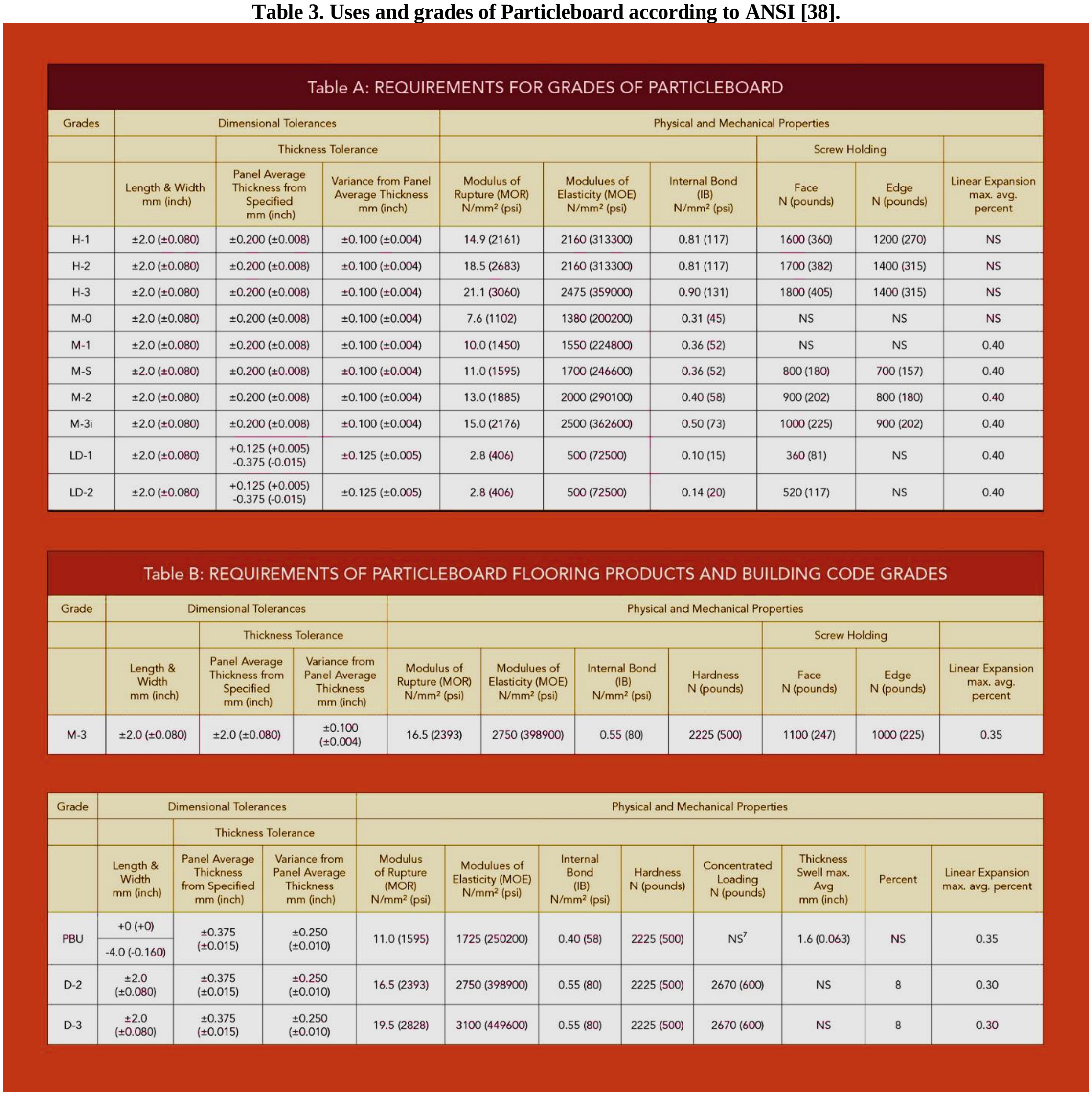

Table A: REQUIREMENTS FOR GRADES OF PARTICLEBOARD

Grades	Dimensional Tolerances			Physical and Mechanical Properties					
		Thickness Tolerance					Screw Holding		
	Length & Width mm (inch)	Panel Average Thickness from Specified mm (inch)	Variance from Panel Average Thickness mm (inch)	Modulus of Rupture (MOR) N/mm² (psi)	Modulues of Elasticity (MOE) N/mm² (psi)	Internal Bond (IB) N/mm² (psi)	Face N (pounds)	Edge N (pounds)	Linear Expansion max. avg. percent
H-1	±2.0 (±0.080)	±0.200 (±0.008)	±0.100 (±0.004)	14.9 (2161)	2160 (313300)	0.81 (117)	1600 (360)	1200 (270)	NS
H-2	±2.0 (±0.080)	±0.200 (±0.008)	±0.100 (±0.004)	18.5 (2683)	2160 (313300)	0.81 (117)	1700 (382)	1400 (315)	NS
H-3	±2.0 (±0.080)	±0.200 (±0.008)	±0.100 (±0.004)	21.1 (3060)	2475 (359000)	0.90 (131)	1800 (405)	1400 (315)	NS
M-0	±2.0 (±0.080)	±0.200 (±0.008)	±0.100 (±0.004)	7.6 (1102)	1380 (200200)	0.31 (45)	NS	NS	NS
M-1	±2.0 (±0.080)	±0.200 (±0.008)	±0.100 (±0.004)	10.0 (1450)	1550 (224800)	0.36 (52)	NS	NS	0.40
M-S	±2.0 (±0.080)	±0.200 (±0.008)	±0.100 (±0.004)	11.0 (1595)	1700 (246600)	0.36 (52)	800 (180)	700 (157)	0.40
M-2	±2.0 (±0.080)	±0.200 (±0.008)	±0.100 (±0.004)	13.0 (1885)	2000 (290100)	0.40 (58)	900 (202)	800 (180)	0.40
M-3i	±2.0 (±0.080)	±0.200 (±0.008)	±0.100 (±0.004)	15.0 (2176)	2500 (362600)	0.50 (73)	1000 (225)	900 (202)	0.40
LD-1	±2.0 (±0.080)	+0.125 (+0.005) -0.375 (-0.015)	±0.125 (±0.005)	2.8 (406)	500 (72500)	0.10 (15)	360 (81)	NS	0.40
LD-2	±2.0 (±0.080)	+0.125 (+0.005) -0.375 (-0.015)	±0.125 (±0.005)	2.8 (406)	500 (72500)	0.14 (20)	520 (117)	NS	0.40

Table B: REQUIREMENTS OF PARTICLEBOARD FLOORING PRODUCTS AND BUILDING CODE GRADES

Grade	Dimensional Tolerances			Physical and Mechanical Properties						
		Thickness Tolerance						Screw Holding		
	Length & Width mm (inch)	Panel Average Thickness from Specified mm (inch)	Variance from Panel Average Thickness mm (inch)	Modulus of Rupture (MOR) N/mm² (psi)	Modulues of Elasticity (MOE) N/mm² (psi)	Internal Bond (IB) N/mm² (psi)	Hardness N (pounds)	Face N (pounds)	Edge N (pounds)	Linear Expansion max. avg. percent
M-3	±2.0 (±0.080)	±2.0 (±0.080)	±0.100 (±0.004)	16.5 (2393)	2750 (398900)	0.55 (80)	2225 (500)	1100 (247)	1000 (225)	0.35

Grade	Dimensional Tolerances			Physical and Mechanical Properties							
		Thickness Tolerance									
	Length & Width mm (inch)	Panel Average Thickness from Specified mm (inch)	Variance from Panel Average Thickness mm (inch)	Modulus of Rupture (MOR) N/mm² (psi)	Modulues of Elasticity (MOE) N/mm² (psi)	Internal Bond (IB) N/mm² (psi)	Hardness N (pounds)	Concentrated Loading N (pounds)	Thickness Swell max. Avg mm (inch)	Percent	Linear Expansion max. avg. percent
PBU	+0 (+0) -4.0 (-0.160)	±0.375 (±0.015)	±0.250 (±0.010)	11.0 (1595)	1725 (250200)	0.40 (58)	2225 (500)	NS[7]	1.6 (0.063)	NS	0.35
D-2	±2.0 (±0.080)	±0.375 (±0.015)	±0.250 (±0.010)	16.5 (2393)	2750 (398900)	0.55 (80)	2225 (500)	2670 (600)	NS	8	0.30
D-3	±2.0 (±0.080)	±0.375 (±0.015)	±0.250 (±0.010)	19.5 (2828)	3100 (449600)	0.55 (80)	2225 (500)	2670 (600)	NS	8	0.30