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A Review of the Evolution and Performance of Particleboard from Different Types of Organic Waste and Adhesives

Derrick Mirindi, Kamalesh Panthi, Ph.D., Tonya Nashay Sanders Thach, PhD, and James Hunter, Ph.D.
Morgan State University
Baltimore, Maryland

The increasing demand and rising price of wood-based materials have led to a need for alternative raw materials in particleboard production. Agricultural waste, such as waste wood and recycled wood waste, as well as food waste, can serve as ideal alternatives to traditional wood chips, which account for more than half of the production cost. Utilizing agricultural waste, food waste, and industry materials is not only cost-effective but also a key principle of the circular economy, leading to reduced carbon dioxide emissions. Nevertheless, there is a lack of an updated, comprehensive assessment of the exploitation of these materials in particleboard production. This article reviews the current state-of-the-art particleboard production using environmentally friendly agricultural and food waste materials and recycled wood waste. The review categorizes particleboards into three groups: particleboards made with agricultural waste, food industry waste, and wood-based waste. The purpose is to compare the mechanical and physical properties of the resulting particleboards and establish their use in building construction according to various particleboard standards. This study demonstrates that wood-based, agricultural, and food waste can be transformed into high-quality, eco-friendly particleboards that surpass industry standards and are suitable for various applications such as construction, furniture, and laboratory equipment. The integration of these waste materials into mainstream production highlights the role of innovative recycling techniques in promoting sustainable urban development and construction practices. This approach significantly contributes to reducing deforestation, preserving natural habitats, and providing affordable housing, supporting a more sustainable and responsible approach to resource management. This review is undertaken to address the critical need for sustainable alternatives in particleboard production amidst environmental and economic challenges. It aims to consolidate recent advancements in using waste materials, providing a comprehensive assessment essential for future research and industry application. This effort aligns with global environmental objectives and advances the circular economy.

Key Words: Particleboard, mechanical properties, physical properties, food waste, agriculture waste, wood-based waste, urea-formaldehyde

Introduction

The demand for wood products exceeds the available supply, thereby fostering conditions conducive to deforestation and forest degradation. Consequently, an impractical escalation in prices ensues due to the burgeoning global population (Mas' ud et al., 2023). Anticipating future population trends, Drewniok et al. (2023) projected that the residential construction inventory is expected to increase by 11%, reaching nearly 2.9 billion m^2 by the year 2050 in the United Kingdom.

Deforestation and forest degradation account for about 15% of global greenhouse gas emissions (Worldwildlife, 2024). Additionally, deforestation is causing the decline of water bodies and rainfall, affecting agriculture and human lives (Duku & Hein, 2021). Deforestation also increases land erosion because forests help hold essential nutrients in the soil (Khodadadi et al., 2023). In the United States, for example, deforestation rates in certain regions, such as the Appalachian Mountains (Murphy, 2023), have a direct impact on local temperatures and can disrupt the habitat for various species.

Reducing carbon dioxide emissions stands as a prominent objective within the strategic agenda of the United States government under the current administration. This strategic framework encompasses aspirations such as the development of urban centers energized by environmentally friendly power sources, thereby contributing to the realization of President Biden's ambitious vision for attaining a net-zero carbon economy by 2050 (Van Coppenolle et al., 2023). A comprehensive strategy is required to develop and implement measures aimed at reducing and mitigating the increasing demand for wood products for construction (Leskinen et al., 2018).

Particleboards are mainly used in partitioning offices and buildings, and as construction increases, their demand also increases, hence contributing to the demand for wood and the resulting deforestation impact. The conventional particleboards are primarily fabricated with wood fibers and urea formaldehyde resin; however, this resin has been termed carcinogenic (Buddi et al., 2023). When particleboards are installed in kitchens or bathrooms and come into contact with water, they have poor moisture resistance, and they can emit formaldehyde, a known substance with detrimental effects on human health. These effects may include conditions such as upper respiratory tract infections, eye irritation, and potentially carcinogenic outcomes (Mirindi et al., 2021).

The use of agricultural and food industry waste materials in particleboard production has the potential to revolutionize the wood industry. Indeed, researchers have successfully fabricated particleboards using a diverse array of materials, including eucalyptus capsules (Rodrigues et al., 2023), pinecones, macadamia shells (Mirindi, 2022), mahogany leaves (Silva et al., 2021), and wheat straw (Silva et al., 2021), as representative instances of agricultural waste sources. Similarly, particleboards manufactured from waste materials such as eggshells (Adediran et al., 2019), rice husks (Chaydarreh et al., 2021), doum palm shells (Betené et al., 2023), and coconut shells (Atoyebi et al., 2021) demonstrate the innovative application of food industry residues in this context. It can alleviate the environmental impacts of deforestation and high wood demand, reduce the cost of raw materials, and contribute to sustainable development (Futuremarketinsights, 2024). This approach reduces the reliance on wood as the primary raw material and provides an effective solution for managing agricultural waste, thereby contributing to a circular economy. In this context, the innovative use of agricultural and food waste in particleboard production emerges as a key strategy for aligning with carbon-neutral efforts. The repurposing of organic waste materials, inherently containing sequestered carbon, into durable construction materials effectively 'locks in' this carbon, preventing its release into the atmosphere. Nonetheless, it is imperative to comprehend the utilization and quality classification of particleboards within the context of building construction, subsequent to the assessment of their physical and mechanical properties in accordance with various particleboard standards. In addition, comparative data on particleboards' physical and mechanical properties, considering different raw materials and adhesive types, can help produce high-performing particleboards in the future.

2. Performance of Waste-based Particleboard

Agricultural waste as a raw material particleboard manufacturing

The utilization of agricultural waste as raw materials in particleboard manufacturing has emerged as a promising avenue in the quest for sustainable construction practices. In an era characterized by environmental consciousness and resource optimization, turning agricultural residues into valuable building materials represents a compelling solution. Lee et al. (2022) review provides an overarching perspective on the utilization of agricultural waste, setting the stage for a nuanced understanding of its potential and limitations in particleboard manufacturing. Prasetiyo et al. (2020) explored the potential of using corn husk as a raw material for particleboards. Their work aligns with sustainability goals but emphasizes the need for evaluating the physical and mechanical properties of particleboards made from corn husk mixed with synthetic adhesives (urea-formaldehyde and phenol-formaldehyde). Building upon this comprehensive review, Pędzik et al. (2022) focused on the physical and mechanical properties of particleboards produced with the addition of walnut wood residues. This study demonstrates the potential of using specific agricultural waste, namely walnut wood residues, to fabricate three-layers particleboards. Jabile et al. (2022) focused on sawdust and rice husk in particleboard applications, addressing the crucial aspects of sourcing and material availability. In addition, Zhi et al. (2021) examined the physical properties of rice husk-pine wood particleboards, while Zvirgzds et al. (2023) investigated the use of seed hemp waste residue in particleboard manufacturing, offering additional insights into the use of specific agricultural wastes.

Food industry byproducts particleboard manufacturing

The use of food industry byproducts in particleboard manufacturing is a promising sustainable practice, yet it demands rigorous research for standard compliance. Boussetta et al. (2022) investigated shrimp waste protein for bio-composite adhesives, indicating its potential in sustainable construction. In contrast, Bacigalupe and Escobar (2021) reviewed soy protein adhesives, emphasizing the need for further research on their practicality and environmental impact. (Barbu et al., 2021) identified Brewer's spent grain as a viable raw material alternative, supporting the shift from traditional wood. Similarly, Borysiuk et al. (2019) focused on sugar beet pulp's (SBP) role in particleboard durability and performance. Farag et al. (2020) studied olive stone waste in particleboard production, considering environmental, aesthetic, and functional qualities for architectural applications. Further research by Kowaluk et al. (2020) and Mahieu et al. (2019) expanded the scope to annual plant byproducts and bio-adhesives, enriching the discourse on sustainable construction materials. Neitzel (2023) provided detailed analysis on the suitability of barley husks, oat husks, and wheat bran for particleboard production, examining their chemical composition and mechanical properties. These studies collectively advance the understanding of alternative, eco-friendly materials in the construction industry.

Wood-based waste material particleboard manufacturing

Wood-based waste as raw materials is a new addition in particleboard manufacturing that has been studied in several research. One of such studies (Azambuja et al., 2018) which delves into the recycling of wood waste from construction and demolition activities to create particleboards. While they contribute to sustainability objectives, their work prompted a critical assessment of the performance of particleboards derived from such sources. The study raises important questions in the context of wood-based waste utilization which, Auriga et al. (2022) sort to answer. The study highlights the viability of using vine pruning waste in the production of particleboards and the importance of recycling wood waste. Foti et al. (2022) explore the development of eco-friendly composites by combining wood dust with recycled polystyrene. Similarly, to Azambuja et al. (2018), the research showcases the potential of wood waste with other materials and emphasizes the importance of evaluating the physical and mechanical properties of these composites. While their work advances the understanding of wood waste utilization, it also introduces the issue of the suitability of the resulting particleboards for various construction applications, particularly concerning structural performance and long-term durability. Conversely, Iždinský et al. (2021) and Iždinský et al. (2020) explored particleboard production from recycled pallets and recycled wood, respectively. These studies accentuate the potential of repurposing wood-based waste streams. However, just like the previous studies, they also encourage a comparative assessment of how these particleboards measure up against traditional wood-based boards, addressing questions of quality, performance, and compliance with industry standards. All the studies identified the potential of wood-based waste in particleboard manufacturing but also identified a major gap in research on this topic.

Material and Method

The production of particleboards involves combining raw materials like pine wood fibers, rice husk, and coconut shell with adhesives such as urea-formaldehyde, castor oil, and epoxy resins. However, to optimize the manufacturing process, it is important to assess the material bonding, visualize the void content, and determine the chemical composition through scanning electron microscopy (SEM) analysis and X-ray fluorescence (XRF) spectroscopy. SEM analysis allows for the high-resolution imaging of the particleboard's surface, providing detailed information on the material's morphology, including the distribution and quality of the bonding agent among the fibers. On the other hand, XRF spectroscopy offers a method to quantify the elemental composition of the particleboards. This is particularly useful for detecting any chemical elements present in the raw materials or added during the manufacturing process, which could influence the performance characteristics of the final product. After this initial step, particleboards are manufactured through a specific timeline. Particleboards then undergo tests to determine their physical properties (such as water absorption and thickness swelling) and mechanical properties (including modulus of rupture and elasticity) as per established standards (e.g., the American Society for Testing and Materials Standard (ASTM, 2024)). The results of tests allow us to establish the use and grade of particleboards in building construction, as defined by organizations like the American National Standards Institute (ANSI) for particleboard (ANSI, 2024).

Performance of waste-based particleboards

The study summarized the mechanical and physical properties of particleboards from various waste materials, referencing standards for water absorption, thickness swelling, and strength (see table 1). Urea-formaldehyde, a common but environmentally harmful adhesive, was frequently used. Particleboard density was shown to affect strength; higher densities yielded more robust boards suitable for diverse uses, while lower densities produced weaker boards. The European Standards EN 312 (2003) set the minimum MOR at 11.5 MPa for basic grade P1 boards and 13 MPa for furniture grade P2 boards, with an MOE requirement of 1600 MPa (Bekalo & Reinhardt, 2010) (see table 2). EN 317 (1993) caps thickness swelling at 14% for general use (Taramian et al., 2007). In contrast, the Brazilian Standard (ABNT BNR) requires an MOR of 11 MPa and an MOE of 1800 MPa, with a maximum 22% thickness swelling for P2 boards (Teixeira et al., 2021). The American National Standard (ANSI A2081 1999) specifies MOR ranging from 11 MPa to 14.5 MPa for M1 and M2 grades, with a minimum MOE of 550 MPa and up to 2250 MPa for higher grades (Hüsnü et al., 2014), and limits thickness swelling to 8% (ANSI/A208.1-1999) (Taramian et al., 2007).

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

No.	Raw Material	Resin Used	Physical			Mechanical			Reference
			Standard	WA (%)	TS (%)	Standard	MOR (MPa)	MOE (MPa)	
1	belangke bamboo & Kemenyan wood	Isocyanate (7%)	ISO 22157:2004	21.72–68.41	4.38–9.57	JIS A 5908 (2003)	6.39–48.37	320–13630	(Iswanto et al., 2022)
2	coconut fibre (Cocos nucifera L,) & Eucalyptus wood	Urea-formaldehyde (9%)	-	50.06 - 115.08	8.06 - 38.70	ASTM D 1037	6.15 - 19.65	1154 - 2157	(de Souza et al., 2023)
3	dung waste from the Sumatran elephant	Isocyanate (7%)	JIS A 5908-2003	38.27–68.58	10.87–30.00	JIS A 5908-2003	20.44–68.27	1952 – 7282	(Hartono et al., 2022)
4	sugar beet pulp (SBP) & Pine wood particles	Urea-formaldehyde	EN 317	86.61 - 108.58	17.91 - 78.04	EN 310	6.05 – 15.64	1176 - 3122	(Auriga et al., 2022)
5	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	(Larregle et al., 2021)
6	Sugarcane bagasse (SCB)	Epoxy resin	ASTM C1763-20	5.18	-	ASTM D7264	29.4-31.74	1170 - 1310	(Guirguis et al., 2023)
7	Macadamia Nutshell	Gum Arabic (20-80%)	ASTM D 1037-06a	9.42 - 38.76	6.22 - 28,46	ASTM D1037-06	4.20 – 12.21	1050 - 1810	(Mirindi et al., 2021)
8	Plantain pseudostem, Coca stem and pod & Ceiba sawdust	Urea-formaldehyde & Cassava Starch	ASTM D 1037-06a	18.17 – 59.46	9.37 – 21.49	ASTM D 7519-11	4.95 – 16.54	1031 - 2413	(Mitchual et al., 2020)
9	Tobacco stalks & Paper mulberry	Urea-formaldehyde (8%)	ASTM D 1037, 2012	77 - 124	32 -42	ASTM D 1037, 2012	10.6 – 13.7	1438 - 1866	(Jimenez Jr et al., 2022)
10	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	(Adelka et la., 2023)
11	Elephant dung & Wood shavings	Isocyanate (7%)	JIS A 5908-2003	38.27–68.58	10.87–30.00	JIS A 5908-2003	20.44–68.27	1952 – 7282	(Hartono et al., 2022)
12	Wood fibres	Urea-formaldehyde (12%)	EN 317 (1993)	47.6 – 135.4	28.2 – 52.7	EN 310 (1993)	7.65 – 27.5	1111 - 2783	(Özdemir et al., 2019)
13	Recycle wood pallets	Urea-formaldehyde (7 – 11%)	EN 317	50.95 – 76.80	18.67 – 27.87	EN 310	10.0 – 14.6	2012 - 2616	(Iždinský et al., 2021)
14	Recycle medium-density fiberboard	Urea-formaldehyde (12%)	Korean Standard F 3200	]20, 100[	]15, 55[	Korean Standard F 3200	]8, 20[	]1500 , 2000[	(Hong et al., 2018)
15	Bagasse sorghum	Maleic acid (20%), Citric acid & Phenol-formaldehyde	JIS A 5908 2003	]20,65[	7 - 8	JIS A 5908 2003	12.0 - 13.0	2800 - 3300	(Sutiawan et al., 2022)

Table 2. Typical thickness swelling, modulus of rupture and modulus of elasticity

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.)

Performance of particleboards of various types of organic waste

Agriculture-derived waste products manifest potential in particleboard production. Coconut fibre combined with 9% *wt* urea-formaldehyde resin yields particleboards exhibiting water absorption of 50.06%–115.08%. Thickness swelling is between 8.06% and 38.70%, while the bending strength and stiffness are within 6.15–19.65 MPa and 1154–2157 MPa, respectively. EN Standard specifies a maximum water absorption at 8% with a thickness swelling of 12%. Macadamia nutshell with gum Arabic resin (20–80%) reveals varied physical and mechanical properties. Results include water absorption of 9.42%–38.76% and modulus of rupture of 4.20–12.21 MPa. Findings highlight that the water-soluble nature of gum Arabic necessitates a reduction of water absorption and thickness swelling. Rice husk combined with soybean protein concentrate (SPC) resin showcases favorable water absorption rates (4.37–4.52%). The mechanical robustness of such particleboards suggests suitability for moisture-resistant applications. Exploring varied raw materials and resins, particleboards from Belangke bamboo and Kemenyan wood with 7% *wt* isocyanate resin demonstrate diverse properties. The raw material-resin combination critically impacts particleboard attributes. Dung waste particleboards with 7% *wt* isocyanate resin emphasize the imperative to explore alternative adhesive systems for optimal performance. On the other hand, particleboards made from sugarcane bagasse and eucalyptus residues using castor oil-based polyurethane resin (PU-Castor) and urea-formaldehyde span a wide property range. Some exhibit low water absorption and commendable mechanical attributes, emphasizing the potential of sugar-based waste particleboards. Research focusing on eco-friendly resins can optimize environmental and performance balance, tailoring properties for specific application requirements.

Conclusion

This research examined the feasibility of producing particleboards using wood-based, agricultural, and food waste as raw materials, along with resin. The study found that most of these particleboards met, and in some cases exceeded, the minimum requirements set by the American National Standards Institute (ANSI/A208.1-1999), the European National (EN), the Japanese Industrial Standards (JIS), and the Brazilian National Standards (ABNT) for general purposes in terms of mechanical and physical properties. The improved performance can be attributed to the toughness and durability of the waste materials when effectively mixed with a suitable binder. These findings indicate that wood-based, agricultural, and food waste can be repurposed to manufacture eco-friendly particleboards that not only meet industry standards but also surpass them. This makes them suitable for various applications, such as construction, flooring, housing, work surfaces, educational tools, laboratory equipment, and office furniture. Additionally, this approach promotes sustainable development by efficiently utilizing resources, reducing waste, and mitigating negative environmental impacts. Transforming waste into valuable products aligns with the principles of a circular economy, prolonging the lifespan of materials and prioritizing environmental sustainability. Therefore, this study represents a significant step towards innovative and sustainable building materials that can play a crucial role in environmental conservation and sustainable urban development. Looking ahead, several recommendations are proposed to further advance the particleboard market. Future research should focus on optimizing the adhesive properties of waste materials to further enhance the physical and mechanical properties of particleboards, expanding their range of applications in construction. It is also important to explore alternative, non-toxic, and biodegradable binders that can replace traditional resins like urea-formaldehyde, which raise concerns related to health and the environment. Comprehensive lifecycle assessments should be conducted to gain a better understanding of the environmental impact associated with the use of particleboards made from waste materials. Furthermore, market analysis should be undertaken to understand consumer preferences and raise awareness about the benefits of using eco-friendly particleboards, thus driving demand. Addressing these areas can help the particleboard industry move towards a more versatile and sustainable future, aligning with global environmental goals and contributing to the circular economy.

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