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Sorghum biomass: A sustainable alternative for particleboard production - A mini review

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ABSTRACT
Sorghum biomass is gaining attention as a sustainable raw material for particleboard production, offering an eco-friendly alternative to conventional wood-based composites. This mini-review synthesizes recent research on the chemical, physical, mechanical, and durability properties of particleboards made from sorghum residues, including bagasse, stalks, and leaves. Quantitative findings show that sorghum particleboards can achieve densities ranging from 0.56 to 1.25 g/cm³, modulus of rupture (MOR) up to 34.1 MPa, modulus of elasticity (MOE) up to 5270 MPa, and internal bond (IB) strength up to 1.92 MPa, meeting the JIS A5908:2003 Type 8 standard in several cases. Moisture content (MC) and thickness swelling (TS) can be optimized to meet dimensional stability requirements through pre-treatment, adhesive formulation, and pressing conditions. Chemically, sorghum biomass has moderate to high cellulose (30–46%) and hemicellulose (21–34%) contents, with lower lignin and ash levels than typical wood, favoring bonding and composite integrity. Synthetic adhesives (UF, PF, pMDI) and natural alternatives (citric acid, maleic acid, sucrose) have been explored, with several formulations showing improved water resistance and biodegradation resistance. Enhanced durability, including termite and fungal resistance, has been observed, particularly in bio-based adhesive boards. However, challenges remain in scaling production and standardizing raw material quality. Future research should prioritize optimizing production methods and improving sorghum-based particleboards' mechanical and durability properties, enabling their use in a wider range of applications.
Keywords: Chemical, Durability, Mechanical, Physical, and Sorghum Biomass

1. Introduction

The global demand for sustainable materials in construction and manufacturing has necessitated the exploration of renewable biomass as an alternative to traditional wood-based resources [1]. Particleboard, a composite material commonly used in furniture, flooring, and interior construction, is typically produced from wood particles bonded with synthetic adhesives [2]. However, the environmental consequences of deforestation, along with increasing costs and limited availability of wood, have prompted significant interest in non-wood biomass sources for particleboard production [3]. Agricultural residues, in particular, hold immense potential as they are abundant, renewable, and often underutilized [4].

Sorghum (*Sorghum bicolor*), a widely cultivated cereal crop, is recognized for its adaptability to diverse agro-climatic conditions and high yield of agricultural residues, such as stalks and leaves [5]. The chemical composition of sorghum biomass, characterized by moderate to high cellulose and hemicellulose content and relatively low lignin levels, aligns with the requirements for particleboard manufacturing. Compared to other agricultural residues, sorghum biomass offers a favorable balance between bonding ability and mechanical performance [6]. However, its properties are strongly influenced by particle size, adhesive type, and production parameters. Thus, understanding these variables is critical to optimizing the performance of sorghum-based particleboards [7].

In addition to mechanical performance, the durability of sorghum particleboards is a key factor in determining their applicability in real-world environments. Durability considerations include resistance to moisture, biodegradation, and thermal aging, all of which influence the long-term performance and lifecycle of the material [8]. While sorghum biomass exhibits promise as a sustainable raw material for particleboard, a comprehensive evaluation of its chemical, physical, mechanical, and durability properties is essential to establish its viability as a wood substitute.

This mini-review synthesizes current research on the potential of sorghum biomass for particleboard production. This paper provides a scientific foundation for further research and development by analyzing the material's chemical composition, physical, mechanical, and durability. The review also identifies critical knowledge gaps and future directions for enhancing the performance and sustainability of sorghum-based particleboards, ultimately contributing to the advancement of eco-friendly composite materials. This mini-review employs a systematic and comprehensive approach to analyze existing research on using sorghum biomass for particleboard production.

2. Method

This mini-review employed a systematic literature review methodology. The literature search was conducted using databases including Scopus, ScienceDirect, SpringerLink, and Google Scholar, with the support of the Publish or Perish software. Boolean operators were used in keyword combinations such as: “sorghum biomass” AND “particleboard” OR “panel” OR “mechanical properties” OR “durability” OR “adhesive.” The search was limited to publications between 2013 and 2024 and included only English-language sources. The inclusion criteria encompassed peer-reviewed journal articles, conference proceedings, and selected technical reports relevant to sorghum biomass particleboard properties. From an initial pool of 157 documents, 34 relevant studies were retained after title/abstract screening and full-text review.

3. Results and Discussion

3.1 Chemical Component

The quality of sorghum biomass particleboard is significantly influenced by the chemical composition of the sorghum biomass, primarily its lignocellulosic components cellulose, hemicellulose, and lignin (Table 1). In addition to these main components, sorghum also contains extractives. Moreover, the ash content, which represents the inorganic mineral constituents in sorghum, can affect the processability and physical properties of the final product. Table 1 summarizes the chemical composition of various sorghum biomass types, showing variability in cellulose, hemicellulose, lignin, extractives, and ash content. These differences are influenced by genetic variation, growing conditions, harvest timing, and analytical methods. Lignin content ranges from 17.2% to 24.3%, lower than most wood species but comparable to other agricultural residues like bagasse and wheat straw, favoring compatibility with bio-based adhesives. Hemicellulose levels (21.85-33.95%) are relatively high and may exceed those in some hardwoods, improving flexibility and bonding. Although cellulose content (30.5-45.9%) is slightly lower than that of wood, it remains sufficient for structural applications. Higher extractive and ash contents, up to 13.8% and 6.6% respectively, may affect adhesive penetration and processing efficiency. Khazaeian et al. [6] explored the potential of using sorghum stalk fibers as an alternative raw material for particleboard manufacturing. The paper evaluated the chemical characteristics of sorghum stalks, comparing them to traditional hardwoods while examining the physical and mechanical properties of particleboards produced with various parameters. In addition, Kusumah et al. [9] reported that sweet sorghum bagasse possesses cellulose and hemicellulose contents comparable to other agricultural residues commonly utilized as raw materials for particleboard production, including kenaf core, sugarcane bagasse, wheat stalk, rice stalk, and bamboo.

Furthermore, Sutiawan et al. [10] reported that the chemical composition of the three sorghum accessions examined showed no significant differences. Their lignin, α-cellulose, and ash contents were comparable to those reported for sweet sorghum in the paper by Kusumah et al. [9]. However, the hemicellulose content of the three accessions was lower than that of sweet sorghum documented in Kusumah et al. [9]. Conversely, the extractive content of the three accessions was higher than that of sweet sorghum reported in the same paper by Kusumah et al. [9].

Table 1. Chemical component of sorghum biomass

Type of Sorghum	Chemical Component					References
	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Extractive (%)	Ash (%)	
Sorghum bicolor	45.90	-	17.20	5.70	6.60	[6]
Sorghum bicolor	34.87	33.95	23.02	2.87	4.20	[9]
Sorghum bicolor accession 4183A	36.44	22.09	24.34	11.61	6.04	[10]
Sorghum bicolor accession Super 1	36.80	21.85	23.52	12.46	6.19	[10]
Sorghum bicolor accession Pahat	30.53	21.90	23.92	13.77	4.21	[10]

3.2 Physical and Mechanical Properties

The physical and mechanical properties of sorghum biomass particleboard are essential indicators of its quality and performance, and they are heavily influenced by factors such as density, moisture content, dimensional stability, and mechanical strength (Tables 2 and 3). Iswanto et al. [11] conducted experiments to evaluate the impact of different resin types—Urea Formaldehyde (UF), Phenol-Formaldehyde (PF), and Isocyanate—along with variations in pressing temperature and time on the physical and mechanical properties of the boards. The results revealed that Isocyanate resin performed best in terms of both physical and mechanical properties, meeting the JIS A5908-2003 standard for most parameters.

Table 2. Physical properties of sorghum biomass particleboard

Focus Research	Density (g/cm^3)	Moisture Content (MC) (%)	Water Absorption (WA) (%)	Thickness Swelling (TS) (%)	References
Resin Types and Pressing Conditions	0.68 - 0.81	2.92-11.06	40.77 - 124.33	6.82-62.14	[11]
Pre-Drying and Citric Acid Content	-	-	35.26-61.75	9.02-23.10	[9]
Pressing conditions	-	-	55.00-85.00	10.10-23.10	[12]
Geometry particle	0.61-0.66	5.42-5.56	102.68 -111.27	28.60-33.03	[13]
Evaluated geometry particle	0.77-0.80	6.61-7.52	37.29-52.07	5.38-10.13	[14]
Types of Adhesives	0.79-0.80	6.61-10.18	37.29-47.51	5.38-17.67	[15]
Types of Adhesives	0.76-0.77	5.65-6.25	25.86-75.88	4.30-33.18	[16]
Adhesive content	-	-	-	-	[17]
Particle size composition	0.72-0.73	6.24-6.62	33.74-40.34	8.01-13.61	[18]
Density on Binderles	0.91-1.25	-	34.02-73.91	26.00-40.00	[19]
Sorghum accession	0.77-0.79	5.50-10.92	20.07-66.23	6.66-27.61	[10]
Adhesive Content and Particle Size	0.57-0.60	8.44-8.93	79.63-94.30	6.60-17.30	[20]
Adhesive Content and Particle Size	0.75-0.79	11.19-12.26	34.49-55.62	5.31-14.12	[21]
Pressing conditions	0.56-0.57	9.15-19.08	70.63-89.67	3.40-6.13	[22]

Meeting the Japanese Industrial Standard (JIS) A5908:2003 is crucial for evaluating the commercial viability of particleboards. This standard sets minimum thresholds for parameters such as density, modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB) strength, moisture content (MC), and thickness swelling (TS). Sorghum-based particleboards that meet these benchmarks demonstrate suitability for structural and non-structural interior applications, including furniture and panelling. Compliance ensures material performance under humidity, mechanical stress, and long-term use conditions, facilitating market acceptance and consumer confidence. Conversely, failing to meet JIS requirements, especially for critical indicators like IB or TS, may limit the boards' application to non-load-bearing or short-term uses, require modification through additives or surface treatments, or exclude them from formal building codes. Therefore, ongoing research into optimizing adhesive systems, board density, and particle geometry is essential to consistently achieve or surpass JIS standards, ensuring broader application and industrial adoption.

Kusumah et al. [9] investigated an environmentally sustainable approach to particleboard production. The paper explored the use of sweet sorghum bagasse as the primary material and citric acid as a natural adhesive, focusing on the effects of pre-drying treatment and varying citric acid content on the physical and mechanical properties of the resulting particleboards. The researchers demonstrated that pre-drying the sorghum bagasse particles significantly improved the physical properties before the hot-pressing process. The mechanical properties were enhanced by increasing citric acid content by up to 20 wt%.

Kusumah et al. [12] investigated the effects of pressing conditions on particleboards made from sweet sorghum bagasse (SSB) and citric acid (CA) as a natural adhesive. The research systematically evaluated the impact of pressing temperature (140–220°C) and pressing time (2–15 minutes) on the physical and mechanical properties of the boards. Results show that 200°C and 10 minutes were the optimal pressing conditions, producing particleboards that met the JIS A 5908-2003 standards for bending strength, IB strength, and dimensional stability. Boards pressed at 220°C displayed a decline in properties due to material degradation, particularly the decomposition of hemicellulose and citric acid.

Table 3. Mechanical properties of sorghum biomass particleboard

Focus Research	Modulus of Elasticity (MOE) (MPa)	Modulus of Rupture (MOR) (MPa)	Internal Bonding (IB) (MPa)	References
Resin Types and Pressing Conditions	970-3700	5.20-26.40	0.03-0.80	[11]
Pre-Drying and Citric Acid Content	3500-5270	15.00-21.80	0.30-1.00	[9]
Pressing Conditions	4500-5200	21.80-34.10	0.78-1.33	[12]
Geometry Particle	1724-2066	9.59-12.50	0.03-0.07	[13]
Evaluated Geometry Particle	1745-3029	10.11-11.88	0.28-0.84	[14]
Types Of Adhesives	2340-2812	11.88-26.83	0.28-0.47	[15]
Types Of Adhesives	3020-3530	10.43-13.54	0.13-0.40	[16]
Adhesive Content	1207-2663	8.34-12.66	0.22-0.35	[17]
Particle Size Composition	1883-2263	6.84-10.92	0.16-0.31	[18]
Density On Binderless	1113-2792	5.40-19.60	0.05-0.37	[19]
Sorghum Accession	2746-3576	11.96-25.73	0.22-0.53	[10]
Adhesive Content and Particle Size	483-546	3.92-5.00	0.08-0.13	[20]
Adhesive Content and Particle Size	250-1623	3.27-7.27	0.10-1.92	[21]
Pressing Conditions	175-847	1.98-4.75	0.03-0.16	[22]

Iswanto et al. [13] examined how particle length influences the physical and mechanical properties of particleboards made from sorghum bagasse. The paper evaluated three particle lengths—3 cm, 5 cm, and 7 cm—using urea-formaldehyde (UF) resin as a binder, with pressing conducted at 130°C, 30 kg/cm² pressure, and a target density of 0.7 g/cm³. The findings show that particleboards made with 3 cm particles exhibited the best overall performance in terms of density, modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB). However, the IB and thickness swelling (TS) did not meet the requirements of JIS A 5908 (2003). The superior performance of 3 cm particles is attributed to their lower slenderness ratio (SR), which enhances resin distribution and inter-particle bonding. Conversely, longer particles (5 cm and 7 cm) displayed higher TS and lower IB values due to uneven resin distribution and increased cavity formation, resulting from higher SR.

Sutiawan et al. [14] investigated the potential of combining Sengon veneer waste and sorghum bagasse with citric acid adhesive for particleboard production. The findings indicate that increasing sorghum bagasse content significantly enhanced the mechanical properties, particularly modulus of elasticity (MOE) and modulus of rupture (MOR), and improved dimensional stability, such as reduced thickness swelling (TS). The composition with 75% sorghum bagasse and 25% Sengon yielded the best results, meeting all JIS requirements for density, moisture content, TS, MOE, and MOR while maintaining a balance between physical and mechanical performance. However, internal bond (IB) and screw-holding power (SHP) were highest in boards with 100% Sengon, reflecting its superior bonding characteristics.

Sutiawan et al. [15] evaluated the physical and mechanical properties of particleboards made from a 25:75 weight ratio of Sengon veneer waste and sorghum bagasse bonded with three types of adhesives: urea-formaldehyde (UF), phenol-formaldehyde (PF), and citric acid (CA). The findings reveal that the adhesive type significantly influenced particleboard performance. Citric acid (CA) adhesive resulted in particleboards with superior physical properties, including reduced water absorption and thickness swelling, attributed to the hydrophobic ester bonds formed between citric acid and lignocellulosic materials. Conversely, urea-formaldehyde (UF) adhesive produced the best mechanical properties, such as higher modulus of rupture (MOR) and internal bonding (IB) strength, due to its effective resin distribution and strong bonding.

Sutiawan et al. [16] explored the potential of using cassava-based maltodextrin (MD) as a natural adhesive for particleboard production. The paper evaluated particleboards bonded with MD's physical and mechanical properties, comparing them to those bonded with citric acid (CA) and malic acid (MA). The findings indicate that particleboards bonded with MD achieved acceptable levels of density, moisture content (MC), modulus of elasticity (MOE), and modulus of rupture (MOR), meeting JIS standards. However, the water absorption (WA), thickness swelling (TS), and internal bond strength (IB) did not meet the standards. Compared to CA and MA adhesives, MD-bonded boards exhibited higher WA and TS due to the absence of ester linkages, which improve water resistance.

Syamani et al. [17] investigated using citric acid (CA) and maltodextrin (MD) as an eco-friendly adhesive for producing particleboards from sweet sorghum bagasse. The paper evaluated the effects of adhesive content (15%, 20%, 25%, and 30%) and hot-pressing times (8 and 10 minutes at 200°C and 5 MPa) on the physical and mechanical properties of the boards. The findings demonstrate that particleboards with 30% CA-MD adhesive content exhibit superior mechanical properties, including modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB) strength. The MOR and MOE exceeded the Type 8 requirements of JIS, while the IB strength surpassed the 0.3 N/mm^2 threshold for Type 18 particleboards. Additionally, the boards displayed excellent dimensional stability, with thickness swelling (TS) consistently below the 12% limit, even after cyclic aging treatments. The performance improvements are attributed to the strong bonding mechanism facilitated by the combination of CA and MD, as forming ester linkages enhances adhesion and water resistance.

Kusumah et al. [18] investigated the impact of varying particle size compositions in a three-layer structure on particleboards' physical and mechanical properties. The findings demonstrate that increasing the ratio of fine particles in the surface layers significantly improves the boards' smoothness, WA, and TS. Type C (25% fine particles on each surface layer) shows the lowest surface roughness and improved dimensional stability. However, the fine particle ratio had minimal impact on MOR, MOE, and IB strength, largely meeting the JIS A 5908-2003 standards for Type 8 particleboards.

Ferrandez-Garcia [19] explored the feasibility of producing adhesive-free particleboards using sorghum residues (stalks and leaves) and evaluated the impact of board density on their physical and mechanical properties. The paper found that increasing the density significantly improved the modulus of rupture (MOR), modulus of elasticity (MOE), and internal bonding (IB) strength, with Type 1250 boards achieving the highest values (MOR: 19.57 N/mm^2, MOE: 2792 N/mm^2, IB: 0.37 N/mm^2). These values meet the European standards for general-purpose dry-use particleboards.

Sutiawan et al. [10] investigated the performance of particleboards produced from different sorghum bagasse accessions (4183A, Super 1, and Pahat) and bonded with maleic acid (MA) adhesive. The results showed that the sorghum accessions had no significant impact on particleboard quality, as the chemical composition of the bagasse was similar across the accessions. Particleboards bonded with MA exhibited excellent dimensional stability (thickness swelling ≤ 12%) and met the JIS standards for modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB) strength.

Sutiawan et al. [20] investigated the influence of maleic acid (MA) adhesive content and particle size classes on sorghum biomass particleboard's physical and mechanical properties (SBMA-particleboard). The research found that increasing MA content up to 15 wt% significantly improved the physical and mechanical properties of the particleboards, with MOE, MOR, and TS values approaching industry standards. Boards manufactured with powder-sized particles (20–40 mesh) exhibited superior dimensional stability and internal bonding strength due to their larger surface area and better adhesive interaction.

Syahfitri et al. [21] investigated the development of eco-friendly roof tile composites using sorghum bagasse (SB) and molasses, focusing on the effects of molasses content and sorghum particle size on physical and mechanical properties. The paper revealed that higher molasses content improved dimensional stability and mechanical properties. Roof tiles with 20% molasses content and mixed particle sizes exhibited optimal results, fulfilling the JIS A 5908:2003 standard for density, moisture content, and internal bonding strength.

Sutiawan et al. [22] investigated the viability of using sorghum bagasse particleboard (TTBSB-particleboard) bonded with maleic acid adhesive as a sustainable alternative for table tennis blades. The results demonstrate that increasing the pressing temperature and time significantly improves the mechanical properties of the TTBSB particleboard. Optimal conditions were identified at 200°C and 20 minutes, yielding particleboards with a better modulus of elasticity (MOE), modulus of rupture (MOR), and internal bonding (IB), which met the requirements of the JIS A 5908:2003 standard. The TTBSB particleboards exhibited excellent dimensional stability, with thickness swelling (TS) values comparable to commercial blades. However, their water absorption (WA) remained higher, attributed to the hydrophilic nature of sorghum bagasse.

3.3 Durability properties

The durability of sorghum biomass particleboard is a critical factor in determining its long-term performance and suitability for various applications, particularly in environments exposed to moisture, biological degradation, and mechanical wear (Table 4). Kusumah et al. [12] demonstrated that the particleboards demonstrated good biological durability, indicating resistance to biological degradation, which is essential for longevity in practical applications. Sutiawan et al. [10] reported that MA-bonded boards demonstrated superior resistance to termite and fungal decay compared to PF-bonded boards, performing comparably to CA-bonded boards. This enhanced durability is attributed to the formation of ester linkages between the carboxyl groups of MA and the hydroxyl groups in sorghum bagasse. Particleboards using citric acid (CA) or maleic acid (MA) adhesives have shown resistance to moisture, decay fungi, and termites, which is crucial for long-term application. For example, CA-MD bonded boards showed low mass loss and high termite mortality, enhancing lifecycle performance. These improvements directly support waste reduction and lifecycle sustainability goals in green construction.

Viviana et al. [23] examined the resistance of sorghum bagasse and acacia wood particleboards against *Coptotermes curvignathus* termite attacks. The paper evaluated the effects of varying adhesive concentrations (8%, 10%, and 12%) and material compositions (100% sorghum, 50% sorghum, 50% acacia, and 100% acacia) on the boards' durability. The results reveal that particleboards with higher adhesive concentrations and greater proportions of acacia wood exhibited significantly lower weight loss and higher termite mortality. Boards with 100% acacia achieved the best durability and were classified as highly resistant (Class I) according to the SNI 01-7207-2006 standard, regardless of adhesive concentration. In contrast, boards made with 100% sorghum and 8% adhesive concentration showed the poorest performance and were classified as poor durability (Class IV) due to the higher susceptibility of sorghum bagasse to termite damage.

Iswanto et al. [24] reported that surface treatments improved resistance to termite attack, with woven bamboo with bark showing the best termite resistance and bamboo strands exhibiting the highest weight loss due to bamboo's starch content, which attracts termites. In Addition, Iswanto et al. [25] reported Silicone and waterproof coatings were particularly effective in improving resistance against termite attack, with silicone offering moderate protection against subterranean termites and waterproof coatings demonstrating high effectiveness against dry-wood termites. Iswanto et al. [26] reported that the particleboards were classified as moderately to durably against subterranean termite attack according to the SNI 01.7207-2006 standard. UF adhesive provided better resistance to termite damage than MDI, but overall durability remained limited due to the high extractive content in sorghum bagasse.

Table 4. Durability of sorghum biomass particleboard

Type of particleboard	Termite resistance		Decay resistance		References
	Termite mortality (%)	Mass loss (%)	White-rot fungus (%)	Brown-rot fungus (%)	
Sorghum Bicolor Bonded with CA	42.80	5.90	21.63	5.34	[9]
Sorghum Bicolor Bonded with PF	46.40	3.92	9.09	5.79	[9]
Sorghum Bicolor Bonded with pMDI	37.90	5.91	31.02	4.54	[9]
Sorghum Bicolor Accession 4183A Bonded with MA	100 (0.20)	16.55	12.39	11.21	[10]
Sorghum Bicolor Accession 4183A Bonded with CA	100 (0.00)	17.60	14.71	14.29	[10]
Sorghum Bicolor Accession 4183A Bonded with PF	100 (0.00)	29.27	24.25	17.51	[10]

3.4 Improving the Quality of Sorghum Biomass Particleboard

Improving the quality of sorghum particleboard involves optimizing several factors, including the chemical composition of the raw material, adhesive selection, processing techniques, and post-treatment methods. Iswanto et al. [27] investigated enhancing particleboard properties by combining sorghum bagasse with wood shavings from Meranti, Cempedak, Mahogany, and Durian wood. The results highlight that including wood shavings significantly improved the mechanical properties of the particleboards. The combination of sorghum bagasse and Cempedak wood shavings produced the best bending strength, with notable increases in modulus of rupture (MOR) and elasticity (MOE). However, the MOE values still fell short of the JIS standard. Adding wood shavings also improved the internal bond (IB) strength, with Durian wood shavings yielding the highest IB value of 3.78 kg/cm^2, exceeding the JIS minimum requirement. Conversely, pure sorghum bagasse particleboards exhibited the weakest IB strength.

Iswanto et al. [24] explored the enhancement of particleboard properties made from sorghum bagasse through various surface layering treatments. The authors aimed to improve the strength and durability of sorghum bagasse particleboard (SBP), which traditionally exhibits weak dimensional stability and mechanical performance. The findings revealed that surface layering significantly enhanced bending strength (MOR and MOE), with woven barkless bamboo and bamboo strands producing the best results due to their dense structure and mechanical integrity. The density of treated boards increased, leading to improved WA and TS compared to untreated samples. However, TS values still did not meet the JIS standard due to the lightweight and porous nature of sorghum bagasse and the water sensitivity of UF resin. The internal bond (IB) strength improved notably with surface treatments, particularly with woven bamboo materials, though the performance varied depending on the extractive content in the materials.

Kusumah et al. [28] investigated enhancing particleboard properties by incorporating sucrose as an additional component to citric acid (CA)-based adhesive. The paper addresses the challenges of brittleness and suboptimal mechanical performance in particleboards made solely with CA. Key findings indicate that particleboards bonded with 15/85 and 10/90 wt.% ratios of CA to sucrose exhibited significantly improved properties. The modulus of rupture (MOR) and modulus of elasticity (MOE) of these boards were comparable to those bonded with phenol-formaldehyde (PF) resin, meeting the JIS A 5908 (2003) standard for type 18 particleboards. The addition of sucrose also reduced the brittleness of the boards, as evidenced by lower load-deflection brittleness values and higher Charpy impact strength.

Iswanto et al. [25] investigated using water-repellent materials as post-treatments to enhance the dimensional stability and durability of particleboards made with sorghum bagasse and bonded using urea-formaldehyde (UF) resin. Results showed that post-treatment increased the density of the boards due to the weight gain from coating materials. The waterproof coating improved dimensional stability most effectively, significantly reducing thickness swelling (up to 65%) and water absorption.

Iswanto et al. [26] investigated the impact of pre-treatment methods and adhesive types on the properties of sorghum bagasse particleboards. The paper evaluated hot water and cold water immersion treatments and compared the performance of urea-formaldehyde (UF) and isocyanate (MDI) adhesives on physical, mechanical, and durability characteristics. The findings indicate that hot water immersion treatment significantly reduced the hygroscopicity of the boards, leading to lower TS and WA values. The treatment removed extractive substances, enhancing the penetration and bonding of adhesives to the sorghum bagasse particles. This effect was particularly evident in MDI-bonded boards, where mechanical properties such as MOE and modulus of rupture (MOR) improved substantially after pre-treatment. In contrast, UF-bonded boards showed reduced MOE and MOR values following hot water immersion, likely due to over-curing and pH sensitivity during the pressing process.

Jamaludin et al. [29] examined the effect of raw material composition and adhesive concentration on particleboards' physical and mechanical properties. The results show that all treatments met the JIS standard for density, moisture content, modulus of rupture (MOR), internal bond (IB), and screw-holding strength. However, only specific combinations satisfied the standard for modulus of elasticity (MOE). Boards with a 50:50 ratio of sorghum to acacia and 10% adhesive concentration provided the best balance of properties, meeting the MOE requirement and producing an optimal balance of density and strength.

Wibowo et al. [30] explored enhancing a bio-based adhesive system by incorporating zinc chloride ($ZnCl2$) as a catalyst. The adhesive, composed of citric acid and sucrose (CASu), produces sorghum bagasse particleboards. The modified adhesive (CASuZn) was tested at optimized pressing conditions of 180 °C for 10 minutes and 200°C for 6 minutes, showing significant improvements in particleboard performance. The mechanical properties, including modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB) strength, exceeded the requirements of JIS A 5908 Type 18 standards, making the particleboards suitable for high-quality applications.

Legesse et al. [31] evaluated the potential of using a hybrid of sorghum stalk (SS) and particleboards. The paper examined the effects of SS-SB ratios (25:75, 50:50, and 75:25), UFR concentrations (50, 60, 70 kg/m^3), and pressing loads (18, 20, and 22 MPa) on physical and mechanical properties. The findings indicate that increasing the UFR concentration and pressing load significantly improved the mechanical properties, with the optimal performance achieved at SS3SB1P3UFR3 (75% sorghum stalk, 22 MPa, and 70 kg/m^3 UFR concentration). Particleboards under these conditions exceeded the JIS A 5908 (2003) standards for MOR (8.79 MPa) and MOE (10.1 GPa).

Tampubolon et al. [32] explored the potential of combining sorghum (*Sorghum bicolor* L.) and Nypa fruit skin fiber (*Nypa fruticans* Wurmb.) as raw materials for particleboard production using a natural adhesive made from citric acid and sucrose. Boards with 100% sorghum and 30% adhesive achieved better dimensional stability, with the lowest WA and TS values among all treatments. However, the modulus of rupture (MOR) and modulus of elasticity (MOE) did not meet the standard except for boards with 100% nypa and 30% adhesive, indicating that the higher lignin and cellulose content of nypa contributed to better mechanical performance. The internal bond (IB) strength values varied widely, with no significant improvements from combining sorghum and nypa. Screw holding power (SHP) increased with higher adhesive content but still fell below the required minimum standard.

Prasetiyo et al. [33] explored using a hybrid adhesive made from citric acid (CA) and sucrose to manufacture eco-friendly particleboards. The findings show that boards bonded with a 50:50 ratio of CA to sucrose and 15% adhesive content exhibited the best overall performance, meeting the JIS standard for modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB) strength, and screw holding power (SHP). The MOR ranged from 12.77 to 20.24 MPa, and the MOE ranged from 1.21 to 3.49 GPa, with the hybrid adhesive composition significantly enhancing mechanical properties.

Adelka et al. [34] explored the use of graphene oxide (GO) and zinc oxide (ZnO) nanocatalysts to enhance the physical and mechanical properties of particleboards made from sorghum bagasse. The findings reveal that adding GO nanocatalysts significantly improved the bending strength (MOR and MOE) and dimensional stability (TS and WA) of the particleboards compared to ZnO nanocatalysts. Particleboards with GO nanocatalysts bonded with citric acid adhesive demonstrated the best overall performance, with MOR, IB, and TS values meeting the JIS standard.

4. Conclusion

This mini-review highlights the promising potential of sorghum biomass as a sustainable alternative for particleboard production. Its favorable chemical composition, including high cellulose and hemicellulose content and relatively low lignin, aligns with structural integrity and bonding requirements. Studies demonstrate that sorghum-based particleboards can achieve competitive physical and mechanical properties with proper optimization of processing parameters, such as adhesive type, particle size, and pressing conditions. Moreover, innovative approaches, such as incorporating natural adhesives and hybrid materials, enhance performance and sustainability. However, challenges remain, including improving water resistance, achieving uniform mechanical strength, and expanding its application scope. Future research should focus on refining manufacturing techniques and exploring advanced additives to optimize performance and durability, further cementing sorghum's role in sustainable construction and manufacturing materials.

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