

Performance Evaluation of Medium Density Fiberboard for Structural Use: Influence of Melamine Content, Resin Content, and Density

Bora Jeong ^a, Min Lee ^{b,*} and Sang-Min Lee ^b

The feasibility of improving medium-density fiberboard (MDF) for structural applications was addressed by improving its mechanical and dimensional properties through modifications in resin formulation and board density. Melamine-urea-formaldehyde (MUF) resin was used as the adhesive, with three melamine substitution levels (25%, 27%, and 30%), resin contents ranging from 18% to 26% (based on oven-dry fiber weight), and target densities of 790, 820, and 850 kg/m³. The MDF bonded with MUF containing 30% melamine showed higher modulus of rupture (MOR) and water resistance indicated by lower thickness swelling (TS) and water absorption (WA) than those with 25% melamine. Increasing the resin content improved MOR and significantly reduced TS, with optimal performance at 26% resin content. Higher density positively affected mechanical properties and dimensional stability. The MDF with a density of 851 kg/m³ showed the best results in both MOR and WA, confirming its suitability for structural applications. The optimal formulation of 30% melamine content, 26% resin content, 1% hardener, 1% wax, and a density of 851 kg/m³ met the performance criteria for structural MDF. Notably, under these optimal conditions, the formaldehyde emission was 0.48 mg/L, satisfying stringent environmental standards.

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Contact information: a: Board Chemical Research Team, Technology Research Institute, Dongwha Enterprise, 164 Wolmi-ro, Incheon, Republic of Korea; b: Wood Engineering Division, Forest Products and Industry Department, National Institute of Forest Science, 57 Hoegi-ro, Dongdaemun-gu, Seoul 02455, Republic of Korea; *Corresponding author: mlee81@korea.kr

INTRODUCTION

In response to the urgent global challenge of achieving carbon neutrality, reducing the consumption of fossil fuels and high-emission construction materials has become a key priority (Talvitie *et al.* 2021). Among renewable resources, wood is a particularly attractive alternative due to its ability to replace carbon-intensive materials such as cement, gypsum board, and steel. Wood products not only store biogenic carbon captured through photosynthesis, but they also maintain this carbon storage throughout their service life when used in buildings or furniture (Buchanan and Levine 1999; Amiri *et al.* 2020). Among wood-based materials, those used in construction offer the longest carbon storage period and thus the greatest potential to contribute to climate mitigation goals.

Fiberboard, manufactured by defibrating wood into fine fibers, is one of the most efficient ways to utilize wood resources. Medium-density fiberboard (MDF), developed in the 1960s, is a widely used panel product known for its smooth surface, dimensional

stability, and cost-effectiveness. It has found extensive applications in the furniture and interior finishing industries, including cabinets, wall panels, and flooring (Irle *et al.* 2010). However, conventional MDF suffers from limited mechanical strength and high susceptibility to moisture, making it unsuitable for structural or load-bearing applications.

Oriented strand board (OSB), introduced in the 1970s as a structural alternative to plywood, provides better strength than MDF, but it often lacks dimensional stability and shows moisture sensitivity, particularly under fluctuating temperature and humidity (Irle *et al.* 2010). Therefore, for fiberboard to be used in structural contexts, enhancements in strength and water resistance are essential. Quality standards for structural MDF are defined by country, and for example, the Japanese Industrial Standard (JIS A 5905) specifies detailed property requirements according to the application, as shown in Table 1. This study aimed to develop high-performance MDF that meets these structural grade standards, specifically Type 30.

Table 1. Quality of Structural MDF for Japan

	Thickness	Density (g/cm ³)	Moisture Contents (%)	MOR (N/mm ²)	Wet MOR (N/mm ²)	TS (%)	IB (N/mm ²)
Type 30	9	0.7 - 0.85	5 - 13	30.0	15.0	under 12	0.5
Type 25				25.0	12.5		0.4

While increasing board density and applying highly durable adhesives can improve mechanical properties, these approaches often lead to trade-offs, such as increased material cost and reduced workability, due to higher panel weight.

In the manufacture of fiberboard, several adhesive systems have been explored (Lee *et al.* 2019, 2023). Phenol-formaldehyde and isocyanate-based adhesives offer excellent durability but pose challenges in terms of cost or processing efficiency. MUF resins, often used in combination with other systems, offer a balance between performance and productivity. In particular, the addition of melamine to MUF resins forms a more robust and three-dimensional network structure through its reaction with formaldehyde. This increased cross-link density not only improves the mechanical strength of the panel but also plays a key role in imparting dimensional stability and water resistance by significantly increasing resistance to moisture penetration (Pizzi 2003; Hse and Wang 2008). In addition, there is growing interest in using bio-based or environmentally friendly adhesives, such as chitosan or lignosulfonate derivatives, to enhance both sustainability and product performance (Irle *et al.* 2010; Antov *et al.* 2020).

Recent studies proposed methods to modify MDF for structural use by improving resin systems and optimizing pressing conditions. Segovia *et al.* (2021) reported significant enhancements in modulus of rupture (MOR) and internal bond strength (IB) through formulation adjustments. Similarly, Antov *et al.* (2020) demonstrated that structurally stable MDF could be produced using magnesium lignosulfonate, a bio-based adhesive, underscoring the potential for sustainable panel development. In a broader context, Sathre and O'Connor (2010) conducted a meta-analysis showing that substituting conventional construction materials with wood-based products, including structural panels, could significantly reduce greenhouse gas emissions.

While previous studies have focused on individual variables such as melamine content, resin content, or density, this study aimed to empirically derive an optimal, commercially applicable formulation for structural MDF by considering these three key variables simultaneously. Specifically, the objective was to establish manufacturing conditions for MDF that meet stringent structural standards, such as JIS A 5905 (2014) Type 30, by systematically exploring high melamine content ($\geq 25\%$), high resin content (18-26% range), and high-density conditions (up to 850 kg/m³).

EXPERIMENTAL

Materials

The wood fiber used in this study was Korean red pine (*Pinus densiflora*) sourced from a commercial MDF production line, provided by Dongwha Enterprise (Incheon, South Korea). The initial moisture content of the fiber was $7.5 \pm 0.3\%$. The adhesive was synthesized using industrial-grade 37% formalin, 99% melamine, and 99% urea. A wax emulsion with 40% solid content was added as a water repellent. Ammonium chloride, used as the curing agent, was diluted to 20% (w/w) before application. All chemical components were supplied by Dongwha Enterprise (Incheon, South Korea).

Methods

Synthesis of MUF resin

The resin was synthesized following the three-stage alkaline-alkaline-acidic method described by Jeong *et al.* (2019, 2020). Initially, an aqueous formaldehyde solution (37%) was charged into a reactor, and the pH was adjusted to 8.2 to 8.5 using a 20 wt% sodium hydroxide (NaOH) solution. Melamine was then added at three different substitution levels (25 wt%, 27 wt%, and 30 wt%) under continuous stirring at 40 °C. The mixture was gradually heated to 90 °C and maintained at this temperature for 1 h.

Subsequently, urea was added to set the initial molar ratio of formaldehyde to melamine plus urea (F/(M+U)) at 2.0, and the reaction was allowed to proceed for an additional 10 min. To initiate the condensation reaction, the pH was adjusted to 6.5 to 7.0 using 20 wt% formic acid. Once the viscosity reached 190 to 220 cP, the pH was readjusted to 7.5 to 8.0. Additional urea was then added to achieve a final F/(M+U) molar ratio of 1.0. The resulting resin was cooled to 60 °C, held for 20 min, and then cooled to room temperature. Prior to storage and further characterization, the pH was finally adjusted to 9.0 to 9.2.

The physical properties of the synthesized MUF resin were evaluated in accordance with the general testing method for adhesives outlined in KS M 3705 (2020).

Table 2. General Specification for Preparation of Medium-density Fiberboard

Contents		Specification
Resin		
	Type	Melamine-Urea-formaldehyde resin
	Melamine contents	30%, 27%, 25%
	Solid content	64.4%, 63.8%, 62.8%
	Content	26% to oven dry weight of wood fiber

MDF Panel Manufacturing and Experimental Design

Panel fabrication

The target dimensions of the MDF were 350 mm × 350 mm × 2.7 mm, with a target density of 800 kg/m³. The wax emulsion was added at 1% based on the oven-dry weight of the wood fiber, and the curing agent (ammonium chloride) was applied at 3% based on the adhesive solid content. The synthesized MUF resin, wax emulsion, and curing agent were premixed and uniformly blended with the wood fiber prior to mat formation. The blended fibers were then manually formed into a 350 mm × 350 mm mat using a forming box, ensuring uniform distribution of the target weight.

The prepared mats were hot-pressed at a temperature of 180 °C under a pressure of 40 kgf/cm². The pressing time was controlled at 30 s per mm of board thickness. A summary of the board manufacturing conditions is provided in Table 3.

Table 3. General Specification for Preparation of MDF

Contents		Specification
Board size (L × W × T)		350 mm × 350 mm × 2.7 mm
Target density		800 kg/m ³
Fiber Moisture contents		7.8%
Wax Emulsion		
	Wax type	Paraffin wax
	Solid content	40%
	Contents	1 to oven dry weight of wood fiber
Hardener		
	Type	Ammonium chloride
	Concentration	20%
	Contents	3.0% to solid contents of resin
Blending		
	Atomizing pressure	7.0 kgf/cm ²
	Spray method	Drum mixer
	Spray time	30 min
Pressing		
	Press type	Oil-pressure, Auto-controlled press
	Temperature	180 °C
	Pressure	40 kgf/cm ²
	Time	30 s/mm

Experimental Variables

Effect of resin content

To evaluate the optimal resin content for structural MDF applications, MUF resin synthesized with the selected melamine content (30%, based on initial tests) was applied at three different levels: 18%, 22%, and 26%, based on the oven-dry weight of the wood fiber. These levels were chosen to examine the effect of adhesive loading on bending strength and water resistance, which are critical for structural performance.

The average mat moisture contents prior to pressing were 10.4%, 12.9%, and 10.8% for the 18%, 22%, and 26% resin content conditions, respectively. Other panel

manufacturing parameters, such as hot-press temperature (180 °C), pressure (40 kgf/cm²), and pressing time (30 s/mm), remained constant and are summarized in Table 3.

Effect of density

Density is a crucial factor influencing the mechanical and dimensional stability of MDF. To determine the appropriate density for structural use, boards were fabricated at three target densities: 790, 820, and 850 kg/m³. These values were selected with reference to structural MDF standards, which range from 700 to 850 kg/m³ in JIS A 5905 (2014) and 650 to 800 kg/m³ in ISO 16989-5 (2016).

The MDF panels for the density evaluation were produced using the previously optimized MUF resin and resin content.

The target densities were achieved by controlling the total mass of the blended fiber mat deposited into the forming box for the fixed panel volume (350 mm × 350 mm). All mats were then pressed to a constant target thickness of 2.7 mm using position control during hot pressing.

The mat moisture content prior to pressing ranged from 9.5% to 10.8% across the density levels. Apart from the variation in density, all other manufacturing conditions were identical to those described in Table 3.

Performance evaluation of MDF panels

For all property evaluations, three specimens (n=3) were prepared for each condition, and the results were presented as mean values ± standard deviation (S.D.). Statistical significance between groups was determined using one-way analysis of variance (ANOVA) followed by Tukey's HSD test at a $p < 0.05$ significance level.

Performance evaluation was conducted on MDF panels sequentially manufactured with varying melamine content, resin content, and density. After each experimental stage, the optimal condition was selected based on the comparative performance of the panels, and subsequent tests were performed accordingly. All evaluations were carried out in accordance with ISO 16895 (2016).

The test items included moisture content, density, modulus of rupture (MOR), wet modulus of rupture (Wet MOR), internal bond strength (IB), thickness swelling (TS), water absorption (WA), and formaldehyde emission (FE). FE was measured according to the KS M 1998 (2018) desiccator method.

RESULTS AND DISCUSSION

Characteristics of Synthesized MUF Resin

For structural-grade MDF, adhesives must provide not only adequate bonding strength but also water resistance. In this study, MUF resins with varying melamine substitution levels were synthesized to identify the formulation with optimal performance for structural applications. The physical characteristics of the synthesized resins are summarized in Table 4.

All MUF formulations showed similar pH values and water solubility, suggesting that the aqueous miscibility of the resin remained stable regardless of melamine content. This implies that variations in melamine level did not negatively affect resin homogeneity or stability during fiber blending. However, viscosity showed a slight decreasing trend as

melamine content increased (e.g., 106.0 mPa·s for 25% melamine vs. 90.0 mPa·s for 30% melamine). This lower viscosity, despite the high solid content, can be advantageous for the manufacturing process, as it facilitates better resin spray ability and fiber penetration during blending.

Improved spray ability facilitates more uniform resin distribution across fiber surfaces, which is beneficial for mat integrity and bond development during hot pressing.

Table 4. General Properties of Synthesized Melamine-urea-formaldehyde Resin

Final Molar Ratio	Melamine Content (%)	Solid Content (%)	Specific Gravity (g/mL)	Viscosity (mPa·s)	pH	Water Miscibility (%)	Gel Time (s)
1.0	30	64.4	1.27	90.0	8.1	500	112
	27	63.8	1.27	86.3	8.1	500	114
	25	62.8	1.26	106.0	8.1	500	114

Gel time was found to remain relatively constant across all melamine contents, indicating that within the tested range, melamine substitution had minimal influence on curing rate. This suggests that the reactivity of the system was primarily governed by the acid catalyst and overall formaldehyde-to-nitrogen ratio rather than melamine content alone.

Among the tested resins, the formulation with 30% melamine content showed the highest solid content and the lowest viscosity. A high solid content ensures greater dry adhesive mass available for bonding, while low viscosity supports efficient processing without premature curing or flow issues. These combined characteristics are advantageous for producing MDF with enhanced mechanical performance and water resistance.

Effect of melamine content on MDF properties

The MDF was manufactured using MUF resin formulations containing varying levels of melamine, with a constant resin content of 26% (based on oven-dry fiber weight). It was hypothesized that increasing the melamine content would enhance bonding performance and water resistance, as melamine is known to contribute to network rigidity and crosslink density in amino resins (Hse and Wang 2008). As shown in Table 5, the melamine content in the MUF resin had a pronounced influence on the mechanical properties of the MDF.

Table 5. Comparison of MDF Properties According to Melamine Content in MUF Resin Adhesive

Melamine Content (%)	Resin Content (%)	Density (g/cm ³)	MOR (N/mm ²)	Wet MOR (N/mm ²)	IB (N/mm ²)	TS (%)	WA (%)	FE (mg/L)
25	26	798 ± 5.6	34.64 ± 1.73	6.31 ± 0.38	1.54 ± 0.10	21.35 ± 1.05	38.31 ± 1.53	1.00 ± 0.05
27	26	807 ± 6.3	50.60 ± 2.00	14.49 ± 0.72	1.68 ± 0.12	12.64 ± 0.76	33.63 ± 1.00	0.66 ± 0.04
30	26	796 ± 6.0	52.10 ± 2.08	16.64 ± 0.83	1.71 ± 0.15	11.83 ± 0.71	34.50 ± 0.91	0.48 ± 0.03

An increase in melamine content from 25% to 30% led to a statistically significant ($p < 0.05$) improvement in both MOR and IB. At 30% melamine content, the MDF achieved an MOR of 52.10 N/mm² and an IB of 1.71 N/mm². These values significantly exceed the general performance requirements for structural MDF defined in JIS A5905 (2014) (Table 1), which specify minimum values of 30 N/mm² for MOR and 0.5 N/mm² for IB. This confirms that the increased melamine content contributed positively to strength development in the MDF. This aligns with previous findings that melamine enhances the cross-link density of the MUF resin, forming a more rigid and water-resistant adhesive bond (Pizzi 2003; Hse and Wang 2008). The significant reduction in TS and WA observed at 30% melamine content suggests that this enhanced 3D network effectively protects the fiber-to-fiber bonds and inhibits the penetration of water molecules (Cai *et al.* 2007).

In addition, wet MOR (an important indicator of water resistance and structural reliability under humid conditions) also increased significantly ($p < 0.05$) with higher melamine content. Wet MOR values ranged from 6.31 to 16.64 N/mm² across the formulations, with the highest values again observed at 30% melamine. These results demonstrate that structural stability can be maintained even under moisture exposure when melamine-rich MUF resin is used.

In contrast, MDF produced with 25% melamine resin showed inferior performance across all measured properties. Most notably, the wet MOR and TS values for this group did not meet the threshold specified for structural MDF in Japan, indicating inadequate water resistance. As a result, the 25% melamine formulation was deemed unsuitable for structural applications where durability under load and moisture exposure are required.

Effect of resin content on MDF properties

Based on previous results indicating that MUF resin with 30% melamine content provided better performance, this formulation was selected to evaluate the effect of resin content on MDF properties. Resin contents of 18%, 22%, and 26% (based on oven-dry fiber weight) were applied, and the corresponding physical and mechanical properties of the MDF panels are summarized in Table 6.

A clear positive correlation ($p < 0.05$) was observed between resin content and modulus of rupture (MOR). At 18% resin content, the MOR was 44.8 N/mm²; this increased to 52.1 N/mm² at 22% and further to 55.6 N/mm² at 26%. A similar trend ($p < 0.05$) was found for wet MOR, which rose from 9.7 N/mm² (18%) to 13.6 N/mm² (22%) and peaked at 15.0 N/mm² (26%). These results demonstrate that higher resin content enhances both dry and wet bending strength, likely due to improved inter-fiber bonding and reduced resin starvation at lower levels.

Table 6. Comparison of MDF Properties According to Resin Contents

Resin Content (%)	Density (g/cm ³)	MOR (N/mm ²)	Wet MOR (N/mm ²)	IB (N/mm ²)	TS (%)	WA (%)	FE (mg/L)
26	800 ± 5.0	55.60 ± 1.65	15.01 ± 0.60	2.01 ± 0.11	10.10 ± 0.50	33.26 ± 0.73	0.52 ± 0.04
22	798 ± 5.6	52.10 ± 2.08	13.57 ± 0.68	1.82 ± 0.13	11.45 ± 0.57	34.48 ± 1.03	0.56 ± 0.04
18	803 ± 6.4	44.76 ± 1.80	9.74 ± 0.49	1.41 ± 0.07	12.44 ± 0.49	33.39 ± 1.34	0.88 ± 0.05

The IB also increased significantly ($p < 0.05$) with higher resin content. The IB values were 1.41 N/mm² at 18%, 1.82 N/mm² at 22%, and 2.01 N/mm² at 26%. This trend indicates that sufficient resin availability enhances the cohesion within the fiber network, reinforcing the board core and minimizing failure under tensile stress.

Formaldehyde emission showed an inverse relationship with resin content. The highest emission was observed at the lowest resin content (0.88 mg/L at 18%), while boards with 22% and 26% resin content showed reduced emissions of 0.56 mg/L and 0.52 mg/L, respectively. This reduction may be attributed to more complete curing and lower free formaldehyde residue in well-bonded matrices at higher resin levels. Overall, increasing resin content improved all key performance parameters relevant to structural applications. However, economic and environmental factors, such as material cost and formaldehyde usage, must also be considered in determining the practical upper limits of resin loading.

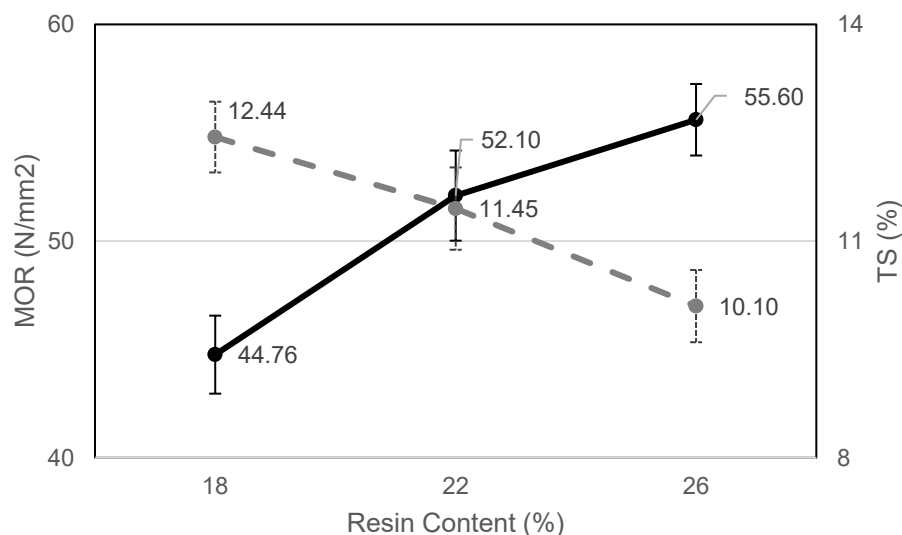


Fig. 1. Effect of resin content on MOR and thickness swelling of MDF

Figure 1 presents the variation in MOR and TS as a function of resin content. As shown, MOR consistently increased with higher resin content, while TS showed a decreasing trend. This inverse relationship suggests that greater resin availability not only improves the mechanical strength of MDF but also enhances its dimensional stability.

Specifically, the TS value at 18% resin content was 12.4%, which decreased significantly ($p < 0.05$) to 10.1% at 26% resin content. The reduction in TS indicates that increased resin loading helps suppress water absorption and subsequent fiber expansion. The adhesive matrix likely forms a more continuous and hydrophobic network that limits water ingress into the fiber structure.

These results confirm that resin content was a critical factor influencing both the physical and moisture-resistant properties of MDF. For structural applications, where both high strength and dimensional stability are essential, a minimum resin content threshold must be maintained to ensure performance reliability.

Effect of board density on MDF properties

To evaluate the influence of board density on the performance of MDF, boards were fabricated using MUF resin with 30% melamine content and a fixed resin content of 26%.

All other manufacturing parameters were held constant. The mechanical and physical properties of the resulting MDF are summarized in Table 7.

A general improvement in performance was observed with increasing board density. At a density of 790 kg/m³, the MOR was 46.4 N/mm², wet MOR was 15.7 N/mm², and IB reached 1.88 N/mm². In contrast, board with a density of 851 kg/m³ showed higher values: MOR of 54.7 N/mm², wet MOR of 16.8 N/mm², and IB of 1.91 N/mm². The improvement in MOR between 790 and 851 kg/m³ was statistically significant ($p < 0.05$). These improvements can be attributed to enhanced inter-fiber contact and more uniform resin distribution, which increase the structural integrity of the panels (Wang and Winistorfer 2003; Candan *et al.* 2012).

Dimensional stability also improved slightly with increasing density. The TS decreased marginally from 10.6% at 790 kg/m³ to 10.5% at 851 kg/m³, while WA showed a more notable reduction, decreasing from 34.3% to 30.2%. These results suggest that higher density boards were structurally more compact, thereby reducing the penetration of water into the fiber matrix.

Table 7. Comparison of MDF Properties According to MDF Density

Density (g/cm ³)	MOR (N/mm ²)	Wet MOR (N/mm ²)	Moisture Contents (%)	IB (N/mm ²)	TS (%)	WA (%)	FE (mg/L)
790 ± 3.9	46.35 ± 1.85	15.68 ± 0.77	5.80 ± 0.15	1.88 ± 0.10	10.62 ± 0.59	34.34 ± 1.37	0.87 ± 0.05
824 ± 4.0	50.60 ± 2.01	16.91 ± 0.85	6.43 ± 0.19	2.04 ± 0.12	10.64 ± 0.51	32.25 ± 0.81	0.98 ± 0.03
851 ± 4.3	54.72 ± 2.19	16.84 ± 0.83	6.39 ± 0.19	1.91 ± 0.11	10.51 ± 0.49	30.17 ± 0.95	0.79 ± 0.05

However, FE did not show a consistent trend with density. The lowest emission was observed in the highest-density board (0.79 mg/L at 851 kg/m³), whereas the medium-density board (824 kg/m³) recorded the highest emission at 0.98 mg/L. This inconsistency likely results from a complex interaction of factors, including resin curing efficiency, distribution uniformity, and residual moisture content within the panel during hot pressing.

In summary, increasing board density led to significant improvements in mechanical strength and moderate gains in dimensional stability. High-density board demonstrated superior properties, making them more suitable for structural applications where load-bearing capacity and environmental durability are critical.

CONCLUSIONS

This study evaluated the feasibility of utilizing medium density fiberboard (MDF) for structural applications by investigating the effects of melamine content in melamine urea formaldehyde (MUF) resin, resin content, and board density on the physical and mechanical properties of MDF. Based on the results, the following conclusions can be drawn:

1. MUF resin containing 30% melamine demonstrated superior modulus of rupture (MOR) and water resistance (as indicated by thickness swelling (TS) and water

absorption (WA)) compared to the 25% melamine formulation. This composition met and exceeded the property requirements for structural MDF, providing a suitable adhesive base for high-performance board production.

2. An increase in resin content resulted in a linear improvement in MOR and a reduction in TS, indicating enhanced bonding performance and moisture resistance. The formulation with 26% resin content achieved the highest MOR (55.6 N/mm²) and the lowest TS (10.10%), confirming its suitability for structural-grade MDF.
3. Higher board density led to improved mechanical properties (MOR, wet MOR, and internal bond (IB)) and dimensional stability (TS, WA). The MDF with a density of 851 kg/m³ showed approximately 8.37 N/mm² higher MOR and 4.17% lower WA compared to board with 790 kg/m³ density. These enhancements are attributed to increased fiber compaction and more uniform resin distribution, underscoring the importance of optimal density design for structural applications.
4. The combination of 30% melamine content, 26% resin content, 1% hardener, 1% wax, and a target board density of 850 kg/m³ was identified as the optimal condition for producing structural-grade MDF. Boards manufactured under these conditions satisfied the strength and durability requirements necessary for use as structural elements.
5. While the identified formulation provided superior performance, its commercial viability may be limited due to the high cost associated with increased melamine content, high resin usage, and dense fiber requirements. Future research should focus on reducing manufacturing costs by incorporating low-cost substitute filler materials or developing alternative adhesive systems that provide a balance between performance and cost-efficiency.

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REFERENCES CITED

- Amiri, A., Ottelin, J., Sorvari, J., and Junnila, S. (2020). "Cities as carbon sinks classification of wooden buildings," *Environmental Research Letters* 15(9), article 094076. DOI: 10.1088/1748-9326/aba134
- Antov, P., Savov, V., and Neykov, N. (2020). "Structural application of eco-friendly composites from recycled wood fibres bonded with magnesium lignosulfonate," *Applied Sciences* 10(18), article 6465. DOI: 10.3390/app10217526
- Buchanan, A. H., and Levine, S. B. (1999). "Wood-based building materials and atmospheric carbon emissions," *Environmental Science & Policy* 2(6), 427-437. DOI: 10.1016/S1462-9011(99)00038-6

- Cai, X., Riedl, B., Zhang, S. Y., and Wan, H. (2007). "Effects of nanofillers on water resistance and dimensional stability of solid wood modified by melamine-urea-formaldehyde resin," *Wood and Fiber Science* 39(2), 307-318.
- Candan, Z., Akbulut, T., Wang, S., Zhang, X., and Sisci, A. F. (2012). "Layer thickness swell characteristics of medium density fibreboard (MDF) panels affected by some production parameters," *Wood Research* 57(3), 441-452.
- Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., and Caldeira, K. (2018). "Net-zero emissions energy systems," *Science* 360(6396), article eaas9793. DOI: 10.1126/science.aas9793
- Dorieh, A., Pour, M. F., Movahed, S. G., Pizzi, A., Selakjani, P. P., Kiamahelleh, M. V., Hatefnia, H., Shahavi, M. M., and Aghaei, R. (2022). "A review of recent progress in melamine-formaldehyde resin-based nanocomposites as coating materials," *Progress in Organic Coatings* 165, article 106768. DOI: 10.1016/j.porgcoat.2022.106768
- Frihart, C. R. (2015). "Introduction to special issue: Wood adhesives: Past, present, and future," *Forest Products Journal* 65(1-2), 4-8. DOI: 10.13073/65.1-2.4
- Hse, C. Y., and Wang, S. Y. (2008). "Melamine-modified urea formaldehyde resin for bonding particleboard," *Forest Products Journal* 58(4), 56-62. DOI: 10.5555/20083126883
- Irle, M., and Barbu, M. (2010). *Wood-based Panels: An Introduction for Specialists*, M. Thoemen, M. Irle, and M. Sernek (eds.), Brunel University Press, London, UK.
- ISO 16895 (2016). "Wood-based panels – Determination of mechanical and physical properties," International Organization for Standardization, Geneva, Switzerland.
- ISO 16989-5 (2016). "Wood-based panels – Determination of density – Part 5: Medium density fibreboard (MDF) for use in load-bearing applications," International Organization for Standardization, Geneva, Switzerland.
- Jeong, B., Park, B.-D., and Causin, V. (2019). "Influence of synthesis method and melamine content of urea-melamine-formaldehyde resins on cohesion and adhesion performance," *Journal of Industrial and Engineering Chemistry* 79, 87-96. DOI: 10.1016/j.jiec.2019.05.017
- Jeong, B., Park, B.-D., and Causin, V. (2020). "Effects of storage time on molecular weights and properties of melamine-urea-formaldehyde resins," *Journal of Korean Wood Science and Technology* 48(3), 291-302. DOI: 10.5658/WOOD.2020.48.3.291
- Ji, X., Li, B., Yuan, B., and Guo, M. (2017). "Preparation and characterizations of a chitosan-based medium-density fiberboard adhesive with high bonding strength and water resistance," *Carbohydrate Polymers* 176, 273-280. DOI: 10.1016/j.carbpol.2017.08.100
- JIS A 5905 (2014). "Fiberboards," Japanese Industrial Standard, Tokyo, Japan.
- KS M 1998 (2018). "Determination of formaldehyde emission from building interior products – Desiccator method," Korean Standards Association, Seoul, South Korea.
- KS M 3705 (2020). "General testing methods for adhesives," Korean Standards Association, Seoul, South Korea.
- Lee, M., Kang, E. C., and Lee, S. M. (2023). "Effects of different flame-retardant treatments on the sound absorption properties of low-density fiberboard," *BioResources* 18(3), 5859-5872. DOI: 10.15376/biores.18.3.5859-5872
- Lee, M., Lee, S. M., Kang, E. C., and Son, D. W. (2019). "Combustibility and characteristics of wood-fiber insulation boards prepared with four different adhesives," *BioResources* 14(3), 6316-6330. DOI: 10.15376/biores.14.3.6316-6330

- Li, K., Geng, X., Simonsen, J., and Karchesy, J. (2004). "Novel wood adhesives from condensed tannins and polyethylenimine," *International Journal of Adhesion and Adhesives* 24(4), 327-333. DOI: 10.1016/j.ijadhadh.2003.11.004
- Pizzi, A. (2003). *Melamine-formaldehyde Adhesives. Handbook of Adhesive Technology (2nd ed.)*, Marcel Dekker, Inc., New York, NY, USA. DOI: 10.1201/9780203912225.ch27
- Sathre, R., and O'Connor, J. (2010). "Meta-analysis of greenhouse gas displacement factors of wood product substitution," *Environmental Science & Policy* 13(2), 104-114. DOI: 10.1016/j.envsci.2009.12.005
- Segovia, F., Blanchet, P., and Essoua, G. G. E. (2021). "Potential of the crude glycerol and citric acid mixture as a binder in medium-density fiberboard manufacturing," *European Journal of Wood and Wood Products* 79(5), 1141-1151. DOI: 10.1007/s00107-021-01719-w
- Talvitie, I., Vimpari, J., and Junnila, S. (2021). "Economic feasibility of wood-based structures—improving urban carbon neutrality strategies," *Environmental Research: Infrastructure and Sustainability* 1(1), article 011002. DOI: 10.1088/2634-4505/abfe05
- Zhang, Y., Ding, L., Gu, J., Tan, H., and Zhu, L. (2015). "Preparation and properties of a starch-based wood adhesive with high bonding strength and water resistance," *Carbohydrate Polymers* 115, 32-37. DOI: 10.1016/j.carbpol.2014.08.063

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