Next-generation Recycling of High-density Fibreboard: Controlled Fibre Recovery Using Thermo-hydro-microwave Synergy

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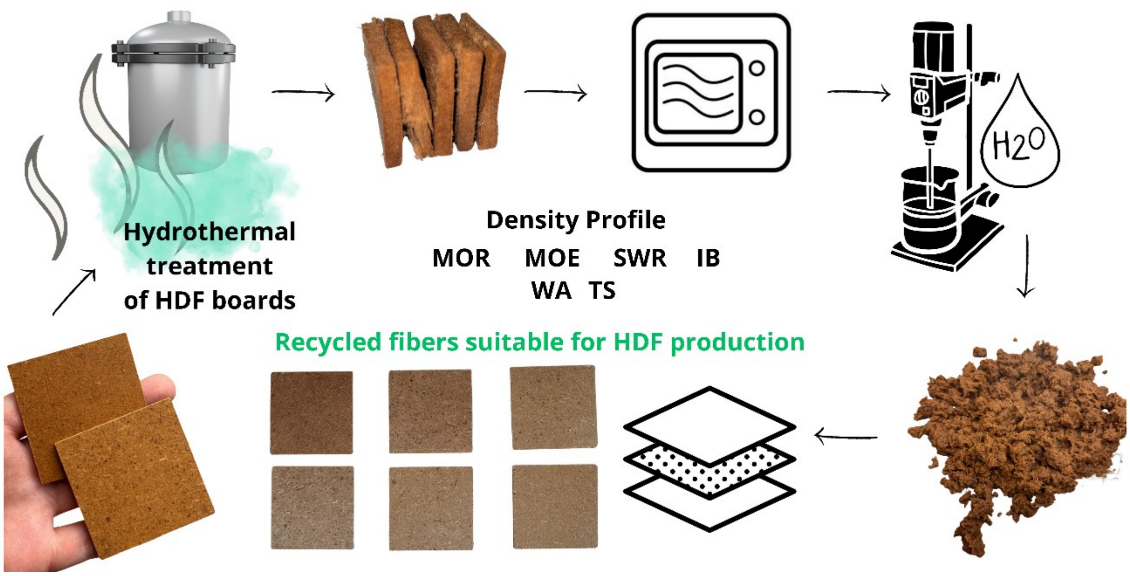
GRAPHICAL ABSTRACT



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Anita Wronka,[a,*] Adam Słupecki,[b] and Grzegorz Kowaluk[a]

This study investigated a next-generation recycling strategy for high-density fibreboard (HDF) based on controlled fibre recovery using thermo–hydro–microwave (THM) synergy. Industrial HDF boards with a target density of 900 kg/m³ were treated in saturated steam at 110 °C and 0.2 MPa for 30 min, followed by two microwave treatment cycles of 30 s each at 800 W. The treated material was subsequently disintegrated in hot water (80 °C), and the recovered wood fibres were separated, dewatered, and dried. The recycled fibres were used to manufacture single-layer and three-layer laboratory-scale HDF panels with different recycled fibre contents. The panels were evaluated for selected mechanical and physical properties, including bending performance, internal bond strength, dimensional stability, surface water absorption, and density profile. The results confirmed that the applied THM-assisted recycling process enabled effective fibre recovery while limiting excessive fibre shortening. Three-layer HDF panels containing 40 to 50% recycled fibres exhibited properties comparable to or exceeding those of reference panels. The findings demonstrate the potential of thermo–hydro–microwave-assisted recycling as a viable approach for closed-loop HDF production and improved material circularity.

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Keywords: High-density fibreboard (HDF); Thermo–hydro–microwave synergy; Fibre separation; HDF recycling; Three-layer boards

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INTRODUCTION

Recycling of wood products such as MDF (Medium Density Fibreboard) and HDF (High Density Fibreboard) is becoming a more relevant sustainability and environmental preservation issue. MDF is widely used in the furniture and construction industries (De Deus *et al.* 2015; Ghazlan *et al.* 2020) due to its favorable physical and mechanical features, but it generates substantial amounts of waste both during the manufacturing process and at the conclusion of the product's life cycle. Traditional waste disposal methods, such as landfilling or incineration, have significant environmental impacts, including emissions and pollution (Amr *et al.* 2021; Farjana *et al.* 2023; Pysarenko *et al.* 2024). Recycling MDF can help to promote sustainable waste management by minimizing the quantity of waste transported to landfills or incineration (Zaharudin *et al.* 2023).

Economically, using recycled fibreboard might reduce demand for virgin wood fibre, which is a major cost factor in MDF and HDF manufacturing. In addition to saving on raw materials, recycling also reduces waste management and landfill costs associated with end-of-life wood panel products. However, the economic viability of using recycled fibres depends on the efficiency of fibre recovery and the cost of energy to operate recycling processes.

With rising environmental consciousness and stricter waste management requirements, MDF recycling is becoming increasingly important. The procedure not only allows for the recovery of important raw materials, but it also helps reduce the amount of garbage sent to landfills, conserve natural resources, and lower production costs (Gürsoy and Ayrilmis 2023). Research confirms that recycling MDF boards offers many benefits, such as improving mechanical properties, including internal bond (IB), and reducing thickness swelling (Moezzipour *et al.* 2018; Gürsoy and Ayrilmis 2023). This article examines the latest MDF recycling technologies and methodologies, the challenges of MDF recycling, and the environmental and economic benefits of implementing these practices. The greatest challenges in recycling MDF boards include the difficulty of recycling the material in its entirety and continuously, due to changes in the properties of wood fibres from MDF waste, which are highly susceptible to mechanical damage, and the challenges associated with resin recycling (Zimmer and Lunelli Bachmann 2023). One of the main issues is the shortening of wood fibres and the formation of dust fractions (Ali *et al.* 2024).

MDF is a composite wood product traditionally manufactured by breaking down softwood into wood fibres using a defibrator. These fibres are then mixed with an adhesive and a synthetic resin binder, such as urea-formaldehyde (UF), and formed into panels under high temperature and pressure. Phenol-formaldehyde resin (PF) and polymeric methylenediphenyl diisocyanates (PMDI) are used much less frequently. Additives may be included to impart additional properties to the MDF, such as fungicides, water repellents, or fire retardants (Mantanis *et al.* 2018). However, not all MDF is identical; its texture, density, colour, and other characteristics can vary based on the materials used (Kubba 2010). Today, MDF boards can be composed of a diverse range of materials, including scrap wood, recycled paper, bamboo, kenaf, carbon fibres, polymers, steel, glass, forest thinnings, and sawmill offcuts (Ismail *et al.* 2020; Pugazhenthi and Anand 2020; Zimmer and Angie Lunelli Bachmann 2023). The incorporation of recycled fibres alters the properties of MDF. While some studies demonstrate that utilizing recycled fibre reduces quality (Moezzipour *et al.* 2017), others suggest that using certain percentages of recycled fibre does not degrade the MDF's qualities (Lubis *et al.* 2018b; Hong *et al.* 2020).

The main advantages of UF adhesives are their low cost, high reactivity, and transparent colour. However, due to their susceptibility to hydrolysis and poor moisture resistance, they are not suitable for outdoor applications (Psonopoulou *et al.* 2025). The susceptibility of UF adhesives to hydrolysis can be an asset in MDF recycling (Franke and Roffael 1998; Nuryawan *et al.* 2020). During the recycling of MDF and HDF, the cured urea-formaldehyde (UF) resin undergoes partial hydrolysis under hydrothermal conditions. Elevated temperature, moisture, and pressure contribute to the weakening of adhesive bonds and facilitate the separation of wood fibres from the cured resin matrix. As a result, fibres can be recovered without aggressive chemical treatments. From an environmental perspective, this process may reduce waste disposal and improve material circularity. However, the degradation of UF resins may also lead to the release of small amounts of formaldehyde or other degradation products, which should be considered when evaluating the environmental impact of recycling technologies (Lubis *et al.* 2018a; Roffael and Hüster 2012). This process can also be improved by providing an acidic environment during hydrolysis (Lubis *et al.* 2018a). However, it is still possible to debond the resin using water at temperatures below 100 °C (Verlag and Jentzsch-Cuvillier 2007), although increasing the parameters of this process may contribute to an even greater reduction in contamination of the recovered wood pulp (Roffael and Hüster 2012).

The annual production of MDF boards worldwide reaches 100 million m^3 (Elias and Bartlett 2018), indicating significant potential for recycling in this sphere of wood-composite production, as about 40.5 million m^3 of MDF waste is generated annually (Irle *et al.* 2019).

Among the various recycling methods for MDF boards, the following methods are distinguished: thermo-hydrolytic disintegration (Bütün-Buschalsky *et al.* 2018; Bütün *et al.* 2019; Bütün Buschalsky and Mai 2021), hydrothermal recycling (Moezzipour *et al.* 2017), electrical method (Moezzipour *et al.* 2018), steam refining (Hagel *et al.* 2021), and steam explosion treatment (Wan *et al.* 2014).

MDF bonded with urea-formaldehyde resin with a target density of 700 kg/m^3 was subjected to thermo-hydrolytic disintegration in an autoclave using only water at 95 °C for 20 to 30 min. Based on observations, modern resins with lower formaldehyde content are easier to recycle, allowing lower recycling temperatures. The use of recycled fibres in this form did not significantly deteriorate the strength parameters or increase formaldehyde emissions (Bütün Buschalsky and Mai 2021).

Another example of hydrolysis aims to examine the impact of temperature, pressure, and time on fibre quality. The study utilized temperatures of 121 °C at a saturated steam pressure of 0.2 MPa and 134 °C at a saturated steam pressure of 0.3 MPa, with three time durations: 30, 45, and 60 min for both conditions. MDF boards were then produced from the recovered fibres, with no observed difference in density between the reference and recycled panels. It was concluded that the most significant factor in MDF recycling is using lower temperatures and pressures with the shortest possible process duration, *i.e.*, 30 min (Savov *et al.* 2023b).

A less common method for recycling MDF is the electrical method. This approach involves treating MDF waste with electricity at specific temperatures for varying durations, altering the chemical composition of the recycled fibres and affecting the production of MDF boards. This method has been tested over two time intervals: 4 min and 2 min at 100 °C. These results were compared with the traditional hydrothermal method, which operates at 105 °C for 150 min under 4 bar pressure. The electrical method involves soaking MDF waste in warm water for about 30 minutes. The wet waste is then mixed with saltwater in a chamber and exposed to an electric field *via* electrodes to break it down into fibres. The electrical heating setup includes an isolation transformer and a heating chamber. Both recycling methods were analyzed for the chemical composition of the recovered fibres, which were then classified. New MDF boards were produced from these recycled fibres, and their mechanical properties and formaldehyde emissions were tested. The study confirmed that the electrical method is milder on the wood raw material than the hydrothermal method, as it does not significantly shorten the fibres or degrade the material. Advantages of the electrical method include lower formaldehyde emissions, which are especially advantageous in today's environmental context (Moezzipour *et al.* 2018).

Steam refining of MDF waste has been investigated as a method to hydrolyse resins and isolate high-performance fibre fractions, enabling their use in applications such as paper packaging (Hagel *et al.* 2021). Steam refining, a method related to steam explosion (Schütt *et al.* 2012), employs high-pressure steam at extreme temperatures to induce autohydrolysis in wood, followed by a refining phase at the end of the steam treatment to mechanically open the structure (Hagel and Saake 2020).

The process of recycling MDF involves several chemical and physical changes to the fibres that degrade their properties and affect the quality of the final product. These include a decrease in fibre length after recycling, leading to deterioration in the mechanical properties of MDF, and changes in the chemical structure of the fibres, resulting in differences between the original and recycled fibres. Fibre deacetylation, a process that removes carbonyl groups from the original fibres, and esterification reactions, which increase carbonyl groups and furfural concentration during hot pressing, further deteriorate the mechanical properties of the recycled fibres. The presence of urea-formaldehyde (UF) resin residues on the surface of recycled fibres negatively affects the quality of MDF. Additionally, a reduction in lignin and hemicellulose content, changes in the chemical composition of the fibres, particularly the reduction of these components, lead to a deterioration in the mechanical properties of MDF. The increased alkalinity of the fibres due to UF resin residues on the fibre surface impacts the chemical and mechanical properties. Furthermore, the addition of recycled fibres increases the gel time of the UF resin, affecting the production process of new MDF (Roffael *et al.* 2016; Moezzipour *et al.* 2018; Zeng *et al.* 2018). Thermogravimetric analysis has shown that the thermal stability of recycled fibres is lower than that of virgin fibres, which may affect the overall performance of recycled MDF (Ahmadi *et al.* 2019).

Table 1. Typical Process Parameters Influencing Fibre Quality During MDF Recycling and Refining Processes

Parameter	Typical Range/Value	Effects of Variation	Recyclability Impact	References
Steaming temperature	175 to 190 °C (optimal ~175 °C)	↑ Temp: ↓ fibre length, ↓ mechanical strength, ↑ dimensional stability	High temp: ↑ fibre degradation, ↓ recyclability	Hamid *et al.* 2008; Camlibel and Akgul 2020
Cooking/ Refining Temp.	130 to 190 °C (optimal ~170 °C)	↑ Temp: ↓ fibre length, ↓ mechanical strength, ↑ dimensional stability	Moderate temp: preserves fibre for recycling	Camlibel and Akgul 2020; Ibrahim *et al.* 2021
Refining Pressure	2 to 8 bar (optimal 6 to 8 bar)	↑ Pressure: ↑ fibre separation, ↑ mechanical strength, > 8 bar: cell wall damage	Excessive pressure: severe fibre damage, ↓ recyclability	Groom *et al.* 2008; Xing *et al.* 2009; Aisyah Humaira and Mohd Tahir 2011
Residence Time	4 to 7 min (steaming/cooking)	↑ Time: ↓ fibre length, ↑ fines, excessive: chemical degradation	Prolonged time: ↑ degradation, ↓ fibre quality	Karl 1998; Adam *et al.* 2012; Savov *et al.* 2023b
Hot Pressing	180 to 220 °C, 32 to 155 bar, 4 to 4.5 min	↑ Temp/Pressure: ↑ density, ↑ dimensional stability, excessive: thermal degradation	↑ Temp/Pressure: ↑ density, ↑ dimensional stability, excessive: thermal degradation	Winandy and Krzysik 2007; Camlibel and Akgul 2020; Minhas *et al.* 2021b

The process of MDF recycling weakens wood fibres through degradation; thus, there have been efforts to improve wood fibres. Modification of recycled wood fibres with kraft lignin improves the mechanical properties and water absorption and reduces formaldehyde emissions in MDF boards made from recycled fibres. It can be concluded that this is a good method for extending the lifespan of too short fibres (Gürsoy and Ayrilmis 2023). The most important parameters used in research on board recycling are summarized in Table 1.

Research on recycled MDF has primarily focused on hydrothermal, steam-based, and electrical methods; however, limited knowledge exists regarding the recovery of fibres through integrated thermo-hydro-microwave (THM) processes. Little investigation has been conducted into the impact of these integrated recycling methods on fibre quality, resin contamination, and the reuse of recovered fibres for the manufacture of new high-density fibreboard panels.

The aim of this study was to assess the quality of HDF panels produced from fibres recovered via THM recycling, as well as to determine how recycled fibres recovered *via* THM recycling affect selected mechanical/physical properties of laboratory-manufactured HDF panels which contain various levels of recycled fibre content. The results of this study will contribute to a better understanding of the feasibility of THM recycling for the reuse of recovered fibres in fibreboard manufacturing, as well as provide data on the potential to increase recycled fibre use in HDF production through the development of new strategies for recycled fibre integration.

EXPERIMENTAL

Preparation of HDF

The HDF panels were made from industrial wood fibre, which was collected (in controlled laboratory conditions) from young pine (*Pinus sylvestris* L.) and spruce (*Picea abies* (L.) H. Karst) trees. The wood was from IKEA Industry Poland (Koszki 90 17-106 Orla). The fibre was obtained from roundwood logs with a butt-end diameter of approximately 7 to 12 cm and a length of about 2.4 m. In this study, the wood fibres were dried to a moisture content of approximately 4% prior to panel production. The target density was 900 kg/m^3, and each panel was designed to be 3 mm thick.

The bonding agent used to manufacture the panels was a melamine-urea-formaldehyde (MUF) adhesive (Silekol S123, Silekol Sp. z o. o., Kędzierzyn-Koźle, Poland). The characteristics of the adhesive resin included a formaldehyde to urea molar ratio of 0.89, a pH of 9.6, 9% of melamine content, and a viscosity of 470 mPa s. The amount of solid content resin used in making the panels (resination) was 12% referred to the dry fibre mass, which is the amount of resin typically used by the HDF industry. The adhesive system, resin content, and pressing conditions were kept constant for all variants. MUF resin was selected because it is commonly used in industrial HDF production, which allows the obtained results to be compared with typical industrial manufacturing conditions.

Upon completion of the project, an array of different recycling techniques employing an autoclave to treat the HDF panels was evaluated. Those fibres recovered from the process under specific criteria will be investigated further using those fibres produced under the following parameters: Samples of the HDF panels were first cut into 5 cm x 5 cm pieces; the samples were treated with steam in an autoclave for 30 min at 110 °C and 0.2 MPa; the above samples were then subjected to 800 W microwave radiation (Midea Galanz 2M217J, Foshan, Guangdong, China) for 60 s, in two separate cycles of 30 s each. Post-treatment samples are shown in Fig. 1.

Fig. 1. Post THM-treatment samples (before disintegration in water)

Following this procedure, the fibres were separated from the samples by mechanical stirring in hot water (80 °C) for approximately 3 min at a moderate speed. After separation of the fibres, the fibre suspension was drained, and the recovered fibres were transferred to a vertical dryer and dried until constant mass was achieved. Additionally, the fibre agglomerates were broken up using a radial fan. The recycled fibres obtained throughout the recycling process were used to produce new HDF panels. In total, nine panel variants were manufactured based on the relative percentage of recycled fibres blended into the fibre furnish. The recovered fibres, shown in Fig. 2, were reused to produce both three-layer and single-layer HDF panels.

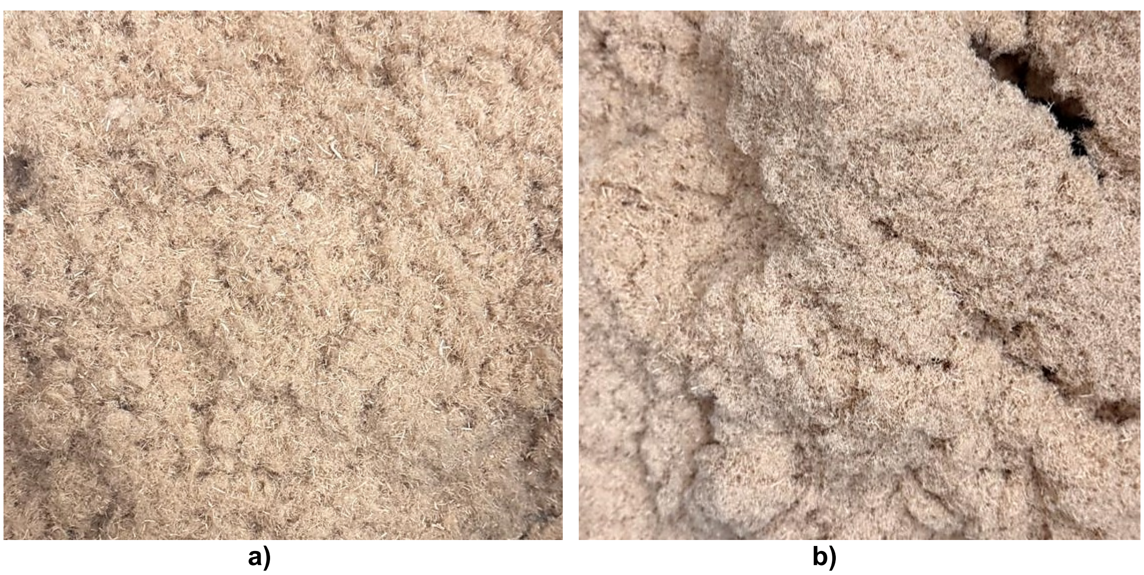

Fig. 2. Virgin (a) and recycled (b) fibres

Three-layer HDF Panels

Three-layer boards (3l) were produced with a fixed layer structure comprising two surface layers and one core layer. The total fibre mass per two panels was 557 g, with 32% in the face layer and 68% in the core layer. Five 3-layer panel variants were manufactured with recycled fibre contents of 0%, 10%, 20%, 30%, and 40% in the core layer. The remaining recycled fibres were incorporated into the surface layers, resulting in a total recycled fibre content of 40% in each fibreboard. The quantities given are for two repetitions of a 320 x 320 mm^2 laboratory format board.

Single-layer HDF Panels

Single-layer (1l) HDF panels were manufactured to assess the influence of recycled fibres without layer differentiation. The total fibre mass per two panels was kept constant at 557 g. Five variants were produced with recycled fibre contents of 10%, 20%, 40%, and 50%, corresponding to recycled fibre masses per panel, respectively. A summary of the produced panels is presented in Table 2.

Table 2. The Summary of the Produced Panels

Panel Type	Number of Layers	Recycled Fibers Share (wt%)	
		Face layers	Core
REF	1	0	0
10-1l	1	0	10
10-3l	3	30	10
20-1l	1	0	20
20-3l	3	20	20
30-3l	3	10	30
40-1l	1	0	40
40-3l	3	0	40
50-1l	1	0	50

In these variants, recycled fibres were homogeneously blended with virgin fibres prior to mat formation. This configuration enabled a direct evaluation of the effect of increasing recycled fibre content on the mechanical performance of single-layer HDF panels. The produced samples are shown in Fig. 3.

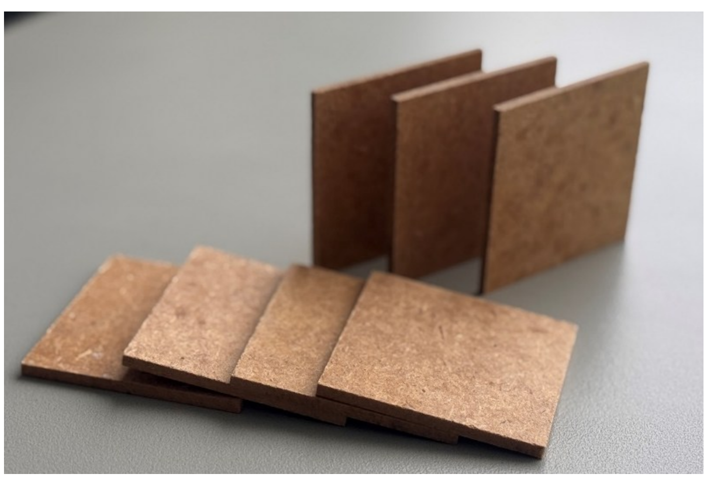

Fig. 3. 5 x 5 cm samples of manufactured HDF boards

Characterization of the HDF Panels

The evaluated properties were selected because they represent the key performance indicators commonly used for the characterization of MDF and HDF panels according to European Standards and are critical for assessing the suitability of recycled fibres for board production. Panel performance was evaluated in accordance with applicable European Standards. The assessment included determination of panel density (EN 323

1993), bending properties, namely modulus of rupture (MOR) and modulus of elasticity (MOE) (EN 310 1993), as well as internal bond strength (IB) (EN 319 1993) and screw withdrawal resistance (SWR) (EN 320 2011). In addition, water-related properties were examined, including water absorption (WA), thickness swelling after 2 and 24 h of water immersion (TS) (EN 317 1993), and surface water absorption (SWA) (EN 382-2 1993).

For each panel variant, a minimum of 12 test specimens were prepared and evaluated, with the exception of the SWA test, for which two specimens per variant were used. Density profile analysis was conducted on three 50 mm × 50 mm specimens from each panel type. Based on initial screening results, a representative density profile was selected for detailed evaluation. The density distribution across the panel thickness was measured using an X-ray densitometer (Grecon DA-X, Grecon, Alfeld, Germany) with a 0.02 mm scanning step. The color parameters of the panels' surface were measured using an X-Rite SP 60 spectrophotometer (X-Rite, Inc., Grand Rapids, MI, USA) according to the CIELab system on 8 samples per panel type.

All mechanical tests were performed on a computer-controlled universal testing machine supplied by the Research and Development Centre for Wood-Based Panels (Czarna Woda, Poland). Where relevant, the experimental results were benchmarked against the performance requirements defined in the corresponding European Standards (EN 622-5 2009).

Statistical Analysis

To statistically analyse the different factors and levels' mean values, this research utilised analysis of variance (ANOVA) and Student's t-test at a significance level of α = 0.05. Duncan's multiple-range test was used for additional comparisons when appropriate. These analyses were conducted using IBM SPSS Statistics (version 20, IBM, Armonk, NY, USA).

RESULTS AND DISCUSSION

Bulk Density of Recycled Fibres

Table 3 shows an increase in the bulk density of recycled fibres compared to industrial (virgin) fibres. This increase in the bulk density of recycled fibres has been attributed to many factors, such as fibre shortening; the greater proportion of fine particles allows for more efficient packing of the fibrous material within a container with fixed volume (Murtala Abdulmumini *et al.* 2013; Lubis *et al.* 2018b). Residual adhesive material from previous bonding processes that was not fully removed during recycling increases the mass of the fibres per unit volume (Lubis *et al.* 2018b). Changes in fibre morphology, reduced elasticity, and the fine fraction filling the voids of adjoining fibres further contribute to denser packing of recycled fibres (Husain *et al.* 2019).

Table 3. The Bulk Density of the Fibres

Fibre Type	Bulk Density (kg/m$^{3)}$	
	Average	Standard Deviation
Virgin	19.1	0.2
Recycled	31.6	0.1

Modulus of Rupture of Tested Panels

The modulus of rupture values for the various combinations of single-layer (1l) and three-layer (3l) engineered wood panels that contain varying amounts of recycled fibres can be found in Fig. 4. All the engineered wood panel types tested were above the MOR minimum requirement specified in the EN 622-5 (2009) for MDF (as indicated by the dashed line).

The reference panel exhibited the highest MOR value. For panels made with recycled fibres, the three-layer (3l) panels tended to have higher MOR values than the corresponding single-layer (1l) panels, assuming equal total amounts of recycled fibre. This trend was most pronounced in the 30% and 40% levels of recycled fibre where the 3l panels were at least equal to or greater than the REF panel MOR values.

In contrast, the 1l panels showed a gradual decrease in MOR values with increasing amounts of recycled fibre, with the lowest MOR values observed with the 40% and 50% recycled fibre variants. The high performance of the 3l panels is likely due to the placement of virgin fibres in the surface layers, which are important for bending strength, and to the placement of recycled fibres primarily in the core layer.

The reference panel did not statistically differ significantly from 10-1l, 10-3l, 30-3l, or 40-3l. Panels 20-1l, 20-3l, 40-1l, and 50-1l showed significantly higher values compared with the reference. No significant differences were observed among those higher-performing variants.

According to the literature, the MOR performance of MDF and HDF panel boards can be maintained at acceptable levels with up to approximately 20 to 24% recycled fibre content, provided that at least 12% UF is used as resin, and pressing conditions are optimized (Lubis *et al.* 2018b; Hong *et al.* 2020; Savov *et al.* 2025). As recycled fibre content rises above this level, MOR decreases significantly due to fibre shortening, increased fines content, and resin contamination from recycling (Lubis *et al.* 2018b; Xu *et al.* 2025).

The MOR performance was found to be strongly influenced by panel arrangement. When comparing three-layer *versus* one-layer panels made from the same amount of recycled material, the three-layer type provided consistently better performance because bending stress passes through the virgin surface material, with the recycled material concentrated in the core. Recycled fibres in single-layer panels are uniformly distributed; therefore, when recycled fibre content increases, a larger percentage of recycled fibres is included in the two outer surfaces (1st layer and 3rd layer), resulting in a more dramatic reduction in MOR potential compared to the three-layer panel (Groom *et al.* 2008) and the opposite is true for a three-layer panel (Ayrilmis *et al.* 2017; Hong *et al.* 2020; Savov *et al.* 2025).

Fine quality virgin fibres present in the top layers increase the MOR by providing greater fibre continuity and increasing the bonding between fibres (Hong *et al.* 2020; Xu *et al.* 2025). The degradation of short fibres will remain an important concern, and high levels of fines will lead to decreased load-transfer efficiency; nonetheless, optimised fibre length distributions can partially recover MOR (Li *et al.* 2024; Bekhta *et al.* 2025).

The MOR is affected by the amount and type of resin used, and a minimum of 12% UF resin is necessary to achieve satisfactory MOR. Higher levels of resin or systems using MUF resins with melamine substitutions produce stronger resistance to bending; however, the effects of density on MOR are greater than those of resin content alone (Ismail *et al.* 2020; Minhas *et al.* 2021a). There are several chemical modifications that can be made (*e.g.*, kraft lignin and lignin-based adhesives) to recover MOR when a high percentage of recycled fibres is used; however, durability to moisture will be an issue (Antov *et al.* 2021; Tang *et al.* 2025).

In conclusion, the combination of virgin material surface layers on three-layer panels, with appropriate resin content, optimal density, and fibre processing, will provide the best way to maintain MOR in both MDF and HDF boards made with recycled fibre.

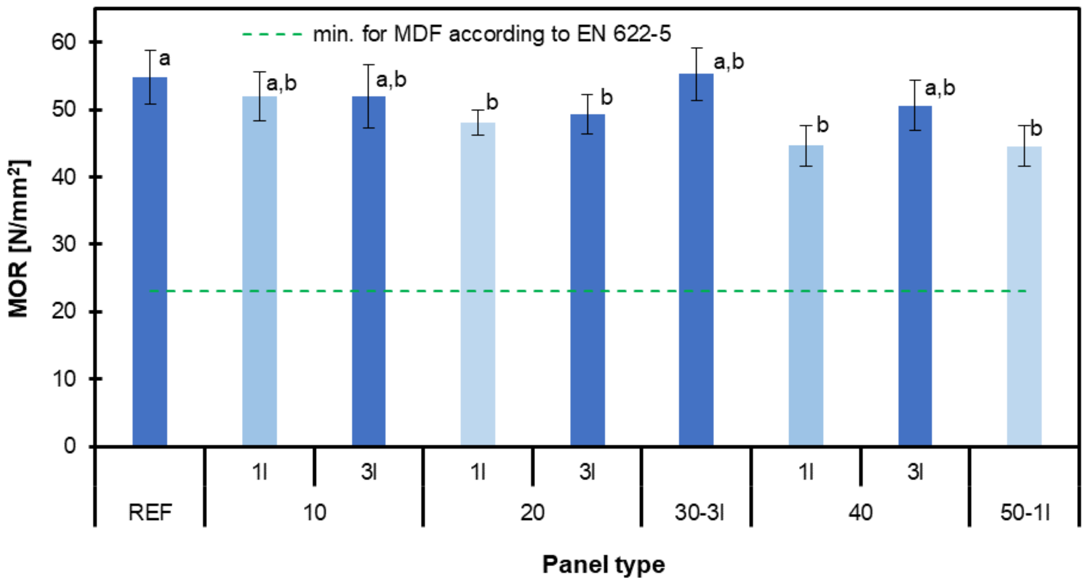

Fig. 4. Modulus of rupture of tested panels

The stiffness of single-layer and three-layer HDF panels with varying amounts of recycled fibre is shown in Fig. 5. Each panel type exceeded the minimum MOE for MDF set by EN 622-5 (2009) (the dashed line indicates the minimum MOE). The reference panel had very high stiffness, whereas the panels with recycled fibre had MOEs that largely depended on the panel structure rather than solely on the amount of recycled fibre.

At an equivalent level of recycled fibre, three-layer panels exhibited a higher MOE than single-layer panels. This difference was most significant when the panels were made using a higher percentage of recycled fibre. Virgin fibre surface layers provided stiffness to the panels, whereas single-layer panels showed a decrease in MOE as the amount of recycled fibre increased, due to fibre shortening and increased fines resulting from the elastic deformation of recycled fibres.

Based on this information, it can be concluded that stiffness is less sensitive to the amount of recycled fibre than bending strength, provided the correct panel structure has been used. The three-layer panels with virgin fibre surface layers compensated for the lower quality of the recycled core fibres, enabling the panels to maintain high MOE even when made with large amounts of recycled fibre. At equivalent recycled fibre contents, three-layer panels exhibited significantly higher MOE values than single-layer panels, as indicated by different statistical groupings ($p < 0.05$). The reference panel, 10-1l, and 10-3l did not differ statistically significantly from each other. Panels 20-1l and 40-1l showed significantly different values compared with those three variants. The remaining variants (20-3l, 30-3l, 40-3l, and 50-1l) exhibited intermediate behavior and did not differ significantly from either the reference group or the higher-value variants.

The modulus of elasticity has been found to decrease with increasing amounts of recycled fibre. This is attributed to two main factors: 1) the shorter length of recycled fibres, and 2) the increased ratio of fines to fibres in the recycled material (Lubis *et al.* 2018b; Xu *et al.* 2025). The literature indicates that recycled fibre contents ranging from 10% to 20% do not produce a significant reduction in the MOE; however, if recycled fibre exceeds 20%, a marked reduction in stiffness will occur (Lubis *et al.* 2018b; Hong *et al.* 2020; Xu *et al.* 2025). Three-layer panels exhibit higher MOE than one-ply panels made from the same amount of recycled fibre. This is because the elastic deformation of two virgin fibre surface layers protects the recycled fibres from deformation, thereby improving stress distributions across the panel. Consequently, three-layer structures allow higher incorporation of recycled fibre while maintaining panel stiffness (Ayrilmis and Akbulut 2018; Hong *et al.* 2020).

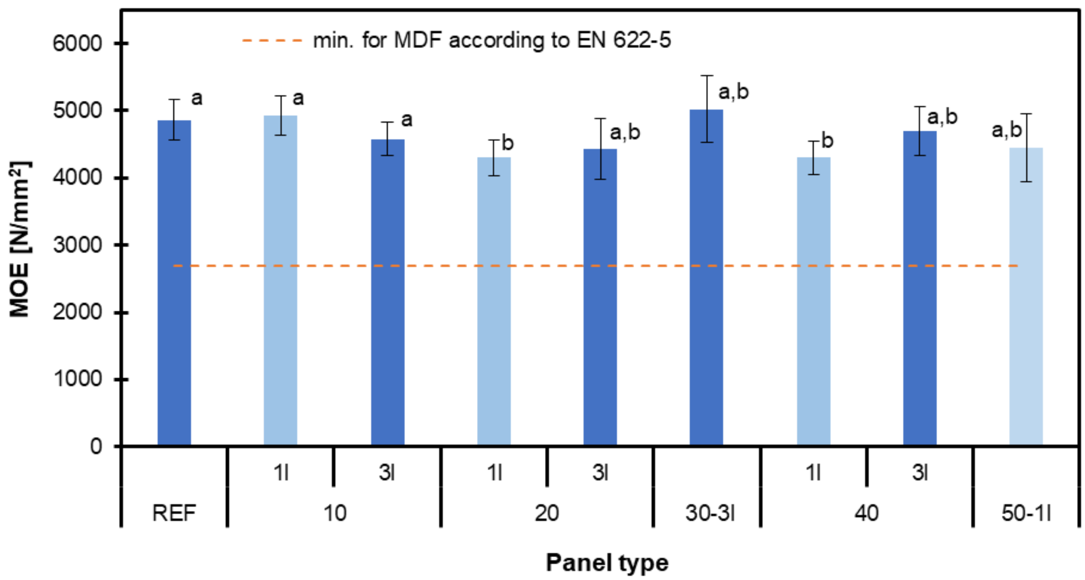

Fig. 5. Modulus of elasticity of tested panels

Internal Bond

Figure 6 shows internal bond strength values for the reference panel and for panels manufactured with various amounts of recycled fibre and different layer configurations. All panels tested had IB values above the minimum IB requirements specified in Danica Norm's EN 622-5 (2009) for MDF. Compared with the reference panel, panels made with recycled fibre had IB values similar to or higher than those of the reference panel, depending on the type of recycled fibre used and the panel configuration. The three-layer panels showed an IB consistently higher than that of single-layer panels at an equivalent amount of recycled fibre, with the highest IB recorded for three-layer panels containing 40% recycled fibre.

Because there was no clear trend of decreasing IB value with increasing recycled fibre content, it can be concluded that the internal bond strength of the test panels was determined predominantly by the panel's density distribution and structure, rather than solely by the recycled fibre used. This behaviour is attributed to the presence of cured UF resin on the surface of the recycled fibre and the optimised distribution of adhesive/resin in the recycled core layer, which compensated for fibre length loss and higher amounts of fines associated with reclaimed material (Lubis *et al.* 2018c; Zeng *et al.* 2018; Akbulut and Ayrilmis 2019; Park *et al.* 2024; Savov *et al.* 2025). The reference panel, 10-1l, 10-3l, 20-3l, 30-3l, and 40-1l formed a homogeneous group with no statistically significant differences among them. Panel 40-3l showed significantly different values compared with these variants. Panels 20-1l and 50-1l exhibited intermediate results and did not differ significantly from either group.

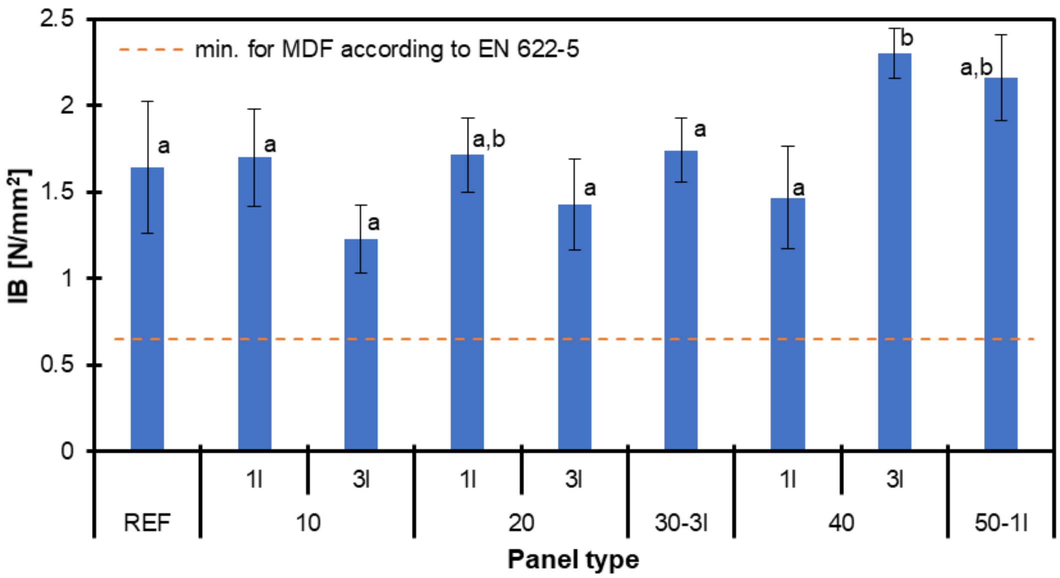

Fig. 6. Internal bond of tested panels

Screw Withdrawal Resistance for the Tested Variants

Figure 7 presents the screw withdrawal resistance (SWR) of the reference panel and panels manufactured with different recycled fibre contents and layer configurations. The response was differentiated by both the level of recycling and the type of panel structure used at that level. In general, three-layer panels had higher SWR values than their single-layer counterparts at the same level of recycled fibres. The reference panel did not statistically differ significantly from 20-1l or 40-1l. Panels 10-3l, 20-3l, and 30-3l showed significantly different values compared with the reference. Variants 10-1l, 40-3l, and 50-1l showed intermediate behavior and did not differ significantly from either the lower or higher group. The SWR values for single-layer panels were no greater than those of the reference panel and generally did not exceed those of single-layer panels containing a high percentage of recycled fibres. Letters above each bar indicate which panels had statistically different groupings from one another. The variance in screw withdrawal strength observed across different specimens can be attributed to an interrelationship between the morphological characteristics of the recycled fibres and the distribution of density within the panel. The recycled fibres have shorter lengths than those of virgin fibres and also contain a higher percentage of fines, resulting in reduced mechanical interlocking between the screw's threads and the fibrous matrix when the material is substituted at higher percentages (Roffael *et al.* 2016; Savov *et al.* 2025). Additionally, three-layered panels have a much higher density in the surface layer than do one-layered panels and density is shown to be the principal factor to improve screw anchorage and SWR performance (Farajollah Pour *et al.* 2022; Hu *et al.* 2023). Prior research has shown that increased surface densification can offset some of the negative effects on screw withdrawal strength due to fibre shortening and the generation of fines during recycling. When the amount of recycled fibre is at moderate levels and also at the time of observation of the SWR results, the panels with 3-layers have shown to be significantly higher, in comparison with the 1-layer panel. This can be attributed to the adhesive properties of the density profile of the 3-layered panel, meaning that the improved density profile, rather than the fibre composition of the recycled fibres alone, will play a significant role in the higher SWR value of the 3-layered panel (Farajollah Pour *et al.* 2022).

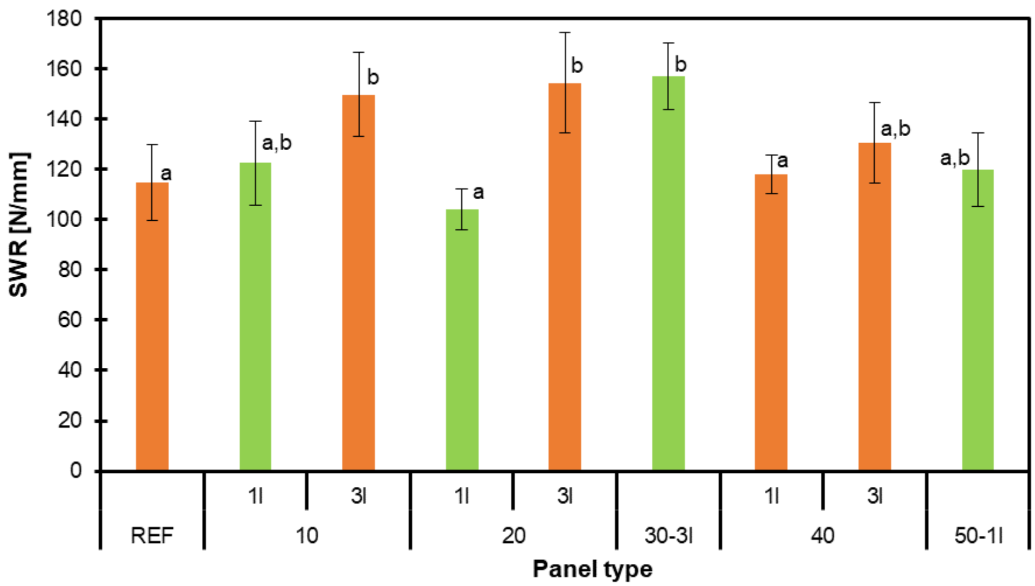

Fig. 7. Screw withdrawal resistance for the tested variants

Water Absorption, Thickness Swelling

Figure 8 shows the amount absorbed by the 3 panels made with different types of recycled fibre, along with their corresponding layer configurations, after 2 h and 24 h of full immersion in water. As expected, there was an increase in water absorption from 2 to 24 h of immersion, but there was also a much greater increase in all panels after 24 h than at the equivalent time. Compared to the reference panel, panels containing recycled fibre had similar or slightly higher water absorption, depending on the level of recycled fibre and the panel structure. The 3-layered panels demonstrated much lower absorption than their single-layered counterparts at equivalent levels of recycled fibre after 24 h of immersion. There was no single trend in water absorption with increasing recycled fibre levels; the panel's structure and density had a much greater impact on water absorption than the recycled fibre content. The reference panel showed statistically significant differences compared with the 10-1l, 10-3l, 20-1l, 20-3l, 40-1l, 40-3l, and 50-1l panels. No significant differences were found among these latter variants. Panel 30-3l did not differ significantly from either the reference or the higher-absorption group. The reference panel did not statistically differ significantly from 20-1l, 20-3l, or 50-1l. Panel 10-1l showed significantly different values compared with the reference. The remaining variants (10-3l, 30-3l, 40-1l, and 40-3l) showed intermediate results and did not differ significantly from either group.

A typical pattern of water absorption for HDF panels is an increase in absorbed water between 24 and 2 h of soaking, due to increased water penetration into the product's porous structure (Minhas *et al.* 2021b; Cavailles *et al.* 2024). The lack of an obvious monotonic increase (as with successive increments) indicates that the mode by which HDF absorbed was more because of the structure (layers) and density distribution, *versus* that of only containing recycled fibre (Hong *et al.* 2020; Minhas *et al.* 2021b; Xu *et al.* 2025). Three-layered panels absorb less water than a single-layered panel; this effect is greater after 24 h of immersion, because the denser outer layer inhibits moisture from diffusing inward. Therefore, it was concluded that if the control of layers and pressing processes was adequately controlled, water resistance could be maintained when using up to 100% (*i.e.*, 25% total) recycled fibre (*i.e.*, 75% virgin fibre) for an HDF panel (Roffael *et al.* 2016; Gürsoy and Ayrilmis 2023; Savov *et al.* 2025).

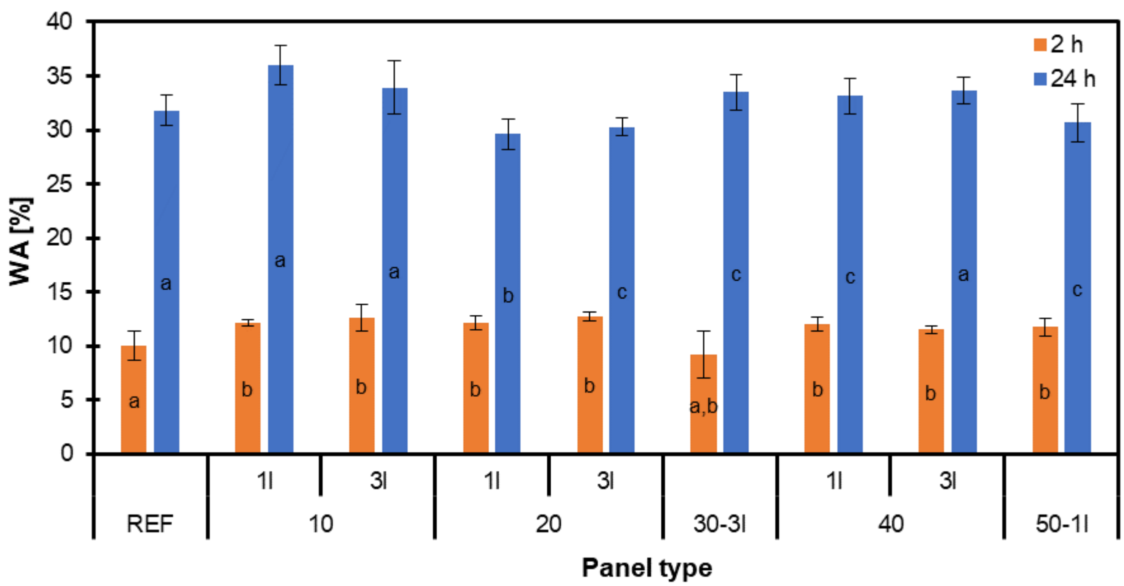

Fig. 8. Water absorption of tested panels

The thickness swelling (TS) of the reference panel, as well as all panels constructed with different amounts of recycled fibre and different designs of layers, at 2 h and 24 h of water immersion is given in Fig. 9. It is seen that the TS for all panels increased with an increase in the immersion time from 2 h to 24 h, and the 24 h TS values were considerably greater than the corresponding 2 h values. All panels tested met the maximum TS values as specified in EN 622-5 (2009) for MDF and HDF after the 24-h immersion period. When comparing TS values between panels containing recycled fibres and the reference panel, the former were either similar to or lower than those of the latter, depending on the recycled fibre content and panel design. Three-layer panels had lower TS values than single-layer panels at the same recycled fibre content, particularly after 24 h of immersion. There were no consistent increases in TS with recycled fibre content, suggesting that the design and density distribution of panel construction were more important than recycled fibre content for thickness swelling. The reference panel statistically differed significantly from 10-1l, 10-3l, 20-1l, 20-3l, 40-1l, 40-3l, and 50-1l panels. These variants did not differ significantly from each other. Panel 30-3l showed intermediate performance and did not differ significantly from either the reference or the higher-thickness-swelling group. Clear stratification was observed for this property. Panels 20-3l, 30-3l, 40-1l, and 50-1l showed statistically significantly higher values than the reference, 10-1l, 10-3l, and 40-3l, which did not differ among themselves. Panel 20-1l differed significantly from both groups, indicating an intermediate level.

Thickness swelling behaviour was primarily controlled by the layer structure and vertical density profile, rather than solely by the recycled fibre content present in the panels. The panels also showed reduced thickness swelling when the surface-to-core ratio was higher than that of the other panels. The moisture ingress and swelling stress in the core were limited by the densified layers at the surface (Ayrilmis *et al.* 2017; Wu *et al.* 2021). Additionally, in some cases there was no clear increase in TS, with an increase in the quantity of recycled fibre used. This suggests that by optimising the density distribution and resin content in relation to the higher proportions of fines and shorter fibres found in recycled fibre, it is possible to achieve sufficient dimensional stability (Yildirim *et al.* 2022; Savov *et al.* 2025). This study demonstrates that by exercising appropriate control over manufacturing processes and the panel structure, it is possible to produce panels with sufficient dimensional stability when substituting for high proportions of recycled fibres (Minhas *et al.* 2021a; Wu *et al.* 2021).

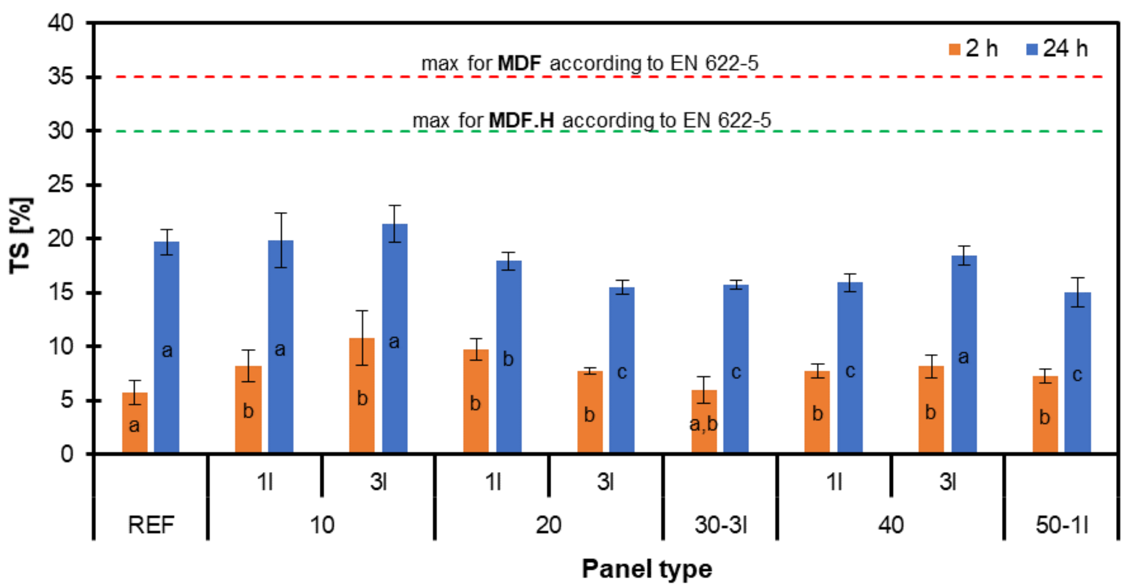

Fig. 9. Thickness swelling of tested panels

Surface Water Absorption

The results of the SWA tests are shown in Fig. 10. Based on the results of surface water absorption (SWA), it can be observed that as the amount of recycled wood fibres increased in MDF/HDF panels, the SWA decreased. This is likely due to changes in the morphology and resin distribution of the recycled wood fibres; the fibres being used were shorter and contained a much higher proportion of fines, thus they also had a larger amount of cured urea-formaldehyde resin on them, which increases the surface hydrophobicity of the fibres and limits the amount of water that can penetrate through them and decreases the SWA (Zeng *et al.* 2018; Kúdela 2020; Xu *et al.* 2025). It is also possible that the increased density of the fibres when using recycled wood fibres further limits the amount of capillary water that can be absorbed at the surface (Zeng *et al.* 2018; Xu *et al.* 2025).

At the same recycled fibre content, three-layer panels exhibited greater SWA than single-layer panels. This can be attributed to the additional presence of virgin fibres on the surface of three-layer boards, which do not contain any hydrophobic resin residue and therefore exhibit greater wettability than single-layer manufactured boards (Hong *et al.* 2017; Kúdela 2020). The recycled core layer does enhance overall water resistance, but the composition of the surface layer is what governs SWA, as the hydrophilic properties of the virgin fibre surface will dominate moisture uptake (Ayrilmis and Akbulut 2018; Kúdela 2020). Therefore, homogeneous single-layer panels with a higher recycled fibre content will have a lower SWA than three-layer panels with virgin fibre surface layers (Hong *et al.* 2017).

In summary, the effect of greater recycled fibre content on reducing SWA is a function of the synergistic interaction between altered fibre morphology and the residual resin coverage, while the increased SWA of three-layer panels is primarily due to the hydrophilic nature of the surface-layer virgin fibres.

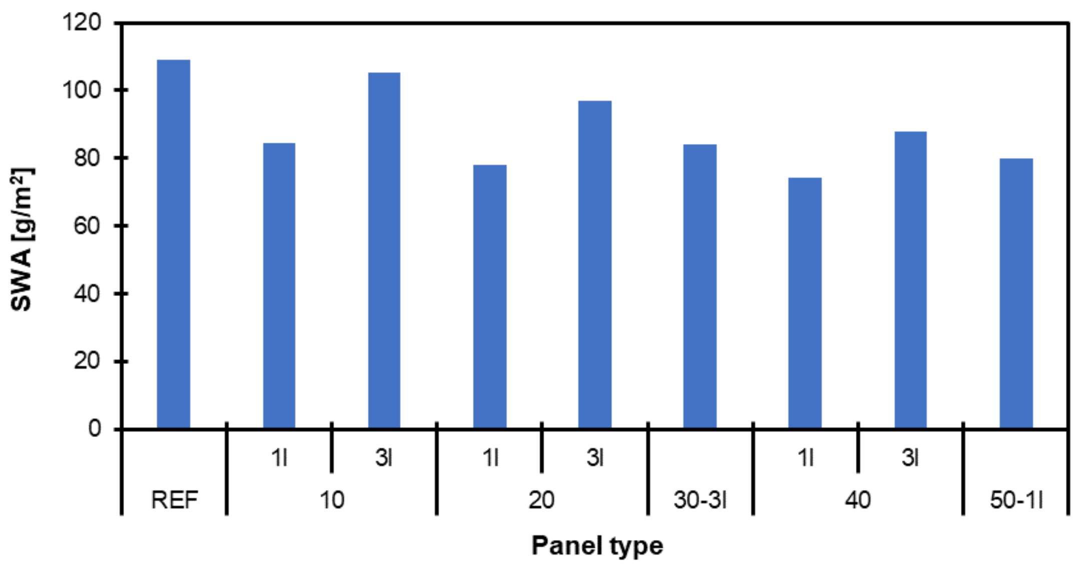

Fig. 10. Surface water absorption of tested panels

Density Profiles of the Tested Panels

Figure 11 shows vertical density profiles of the reference board and four test boards with different proportions of recycled fibres, manufactured with different layer configurations. The observed U-shaped density profile is characteristic of HDF boards and results from more intensive compaction of the surface layers during hot pressing, where the temperature and pressure gradient are highest (Gupta *et al.* 2007). The use of recycled fibres did not alter the basic mechanism of density profile formation, as the pressing process and the target density of the boards were kept constant (Bütün Buschalsky and Mai 2021; Savov *et al.* 2023a; Xu *et al.* 2025). The more pronounced compaction of the surface layers in three-layer boards can be attributed to the controlled distribution of fibre fractions and more favorable packing of the material in the outer layers (Zhou *et al.* 2011). The slight density differences in the middle layer indicate that the proportion of recycled fibres mainly affected local compaction in the surface layers rather than the board's overall structure (Bütün Buschalsky and Mai 2021).

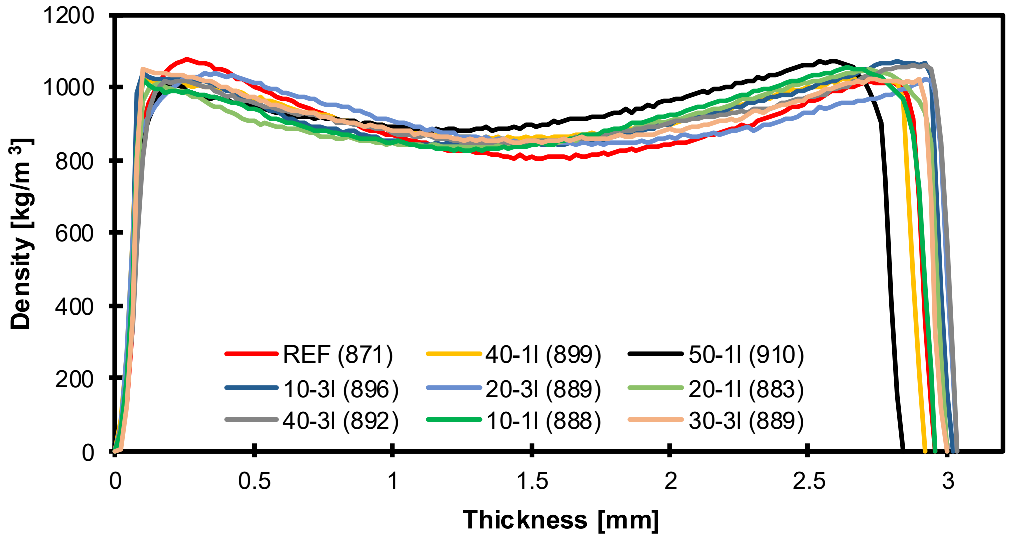

Fig. 11. Density profiles of tested panels

Colour Difference (Δ*E**) of the Tested Panels

The colour differences (Δ*E**) for each of the tested panels relative to the reference panel are illustrated in Fig. 12. The colours of the panels, along with colour coordinates (RGB system), have been shown in Fig. 13. There were larger Δ*E** values for the panels made from recycled fibres than the reference panel; thus, they were visually different from their corresponding reference panels due to the presence of recycled fibres, as well as the way that they were constructed. The single-layer panels had much higher Δ*E** values than the three-layer panels at the same recycled fibre content. In terms of individual single-layer panels, the Δ*E** value increased with increasing recycled fibre content until reaching its highest value (for the 50-1 panel). The Δ*E** values for the three-layer tested panels remained much closer to the reference panel, indicating that the presence of virgin fibres in the surface layers of the three-layer tested panels effectively masked any colour changes that were associated with the fibres used in their core.

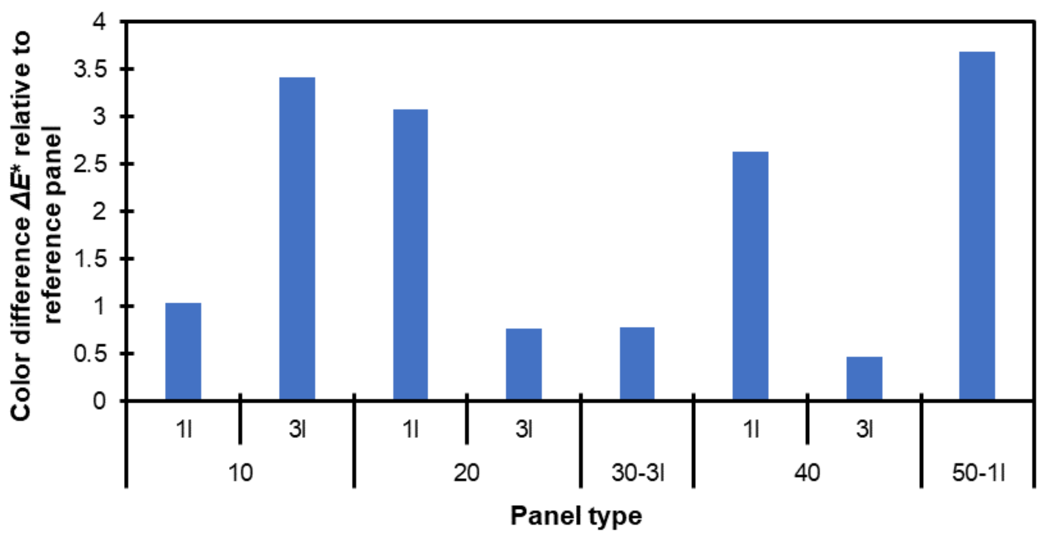

Fig. 12. Colour difference (Δ*E**) of the tested panels in relation to the reference panels

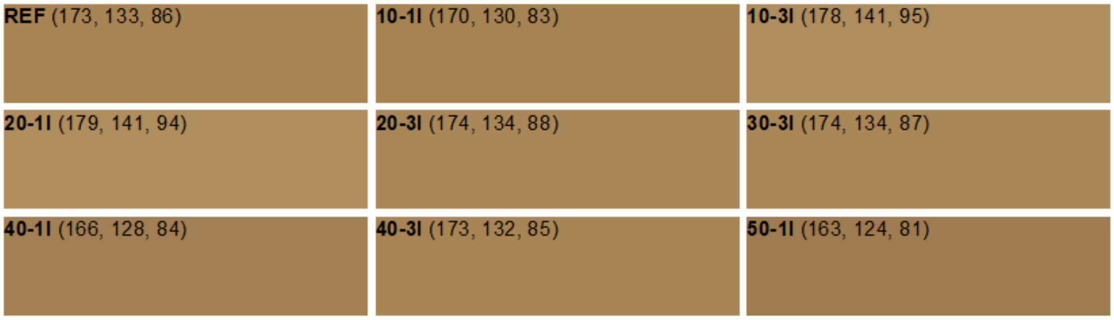

Fig. 13. The face layer colour of the tested panels (RGB coordinates in brackets, respectively)

Overall, the results showed that the structure of a panel had a greater impact on colour stability than the amount of recycled fibre it comprised, and that three-layer panels were a better design for achieving aesthetic integrity in HDF panels manufactured with recycled fibres. The observed colour changes (ΔE^*) in panels containing recycled fibres can be attributed primarily to chemical degradation of residual UF resin during recycling and hot pressing, as well as to physical modifications of fibre morphology (Chen *et al.* 2015; Lubis *et al.* 2018a; Ali *et al.* 2024). Shortened fibres and an increased fines content affect colour uniformity, particularly when recycled fibres are present in the surface layers (Ayrilmis *et al.* 2017; Kúdela 2020). The substantially lower ΔE^* values observed in three-layer panels indicate that the use of virgin fibres in the surface layers effectively masked colour variations originating from recycled fibres in the core, confirming that fibre distribution and panel structure have a stronger influence on colour stability than recycled fibre content alone (Ayrilmis *et al.* 2017; Hong *et al.* 2020; Xu *et al.* 2025).

CONCLUSIONS

The results indicated that the fibre recovery method applied in this study enabled higher levels of recycled fibre substitution than typically reported for medium density fibreboard (MDF) and high density fibreboard (HDF) panels.

1. The fibres that were recycled resulted in about 65% greater bulk density compared to those fibres used in the industrial process. This suggests that the fibres can be efficiently packed while maintaining sufficient functionality for reuse in panel production.
2. Although the literature typically reports acceptable recycled fibre substitution levels of 20 to 30%, the three-layer panels produced in this study achieved MOR values comparable to the reference panel even at 40 to 50% recycled fibre content.
3. Panel stiffness, expressed by the modulus of elasticity, was primarily governed by panel structure rather than recycled fibre content, and the three-layer configuration allowed recycled fibre substitution of up to 50% without critical losses in stiffness.
4. Internal bond strength depended mainly on panel structure and density distribution rather than on recycled fibre content, and three-layer panels retained internal bond values comparable to or higher than the reference panel even at high levels of recycled fibre substitution.
5. Water absorption and thickness swelling were primarily controlled by panel structure and vertical density distribution rather than recycled fibre content, and the three-layer

configuration enabled the maintenance of dimensional stability at high levels of recycled fibre substitution.
6. Surface water absorption decreased with increasing recycled fibre content. This trend may be related to the presence of residual cured resin and the higher bulk density of the recycled fibre furnish, as discussed in the literature. At the same recycled fibre level, three-layer panels exhibited higher surface water absorption than single-layer panels, confirming that SWA was primarily governed by surface layer composition, with hydrophilic virgin fibre surfaces dominating moisture uptake.
7. Screw withdrawal resistance was strongly influenced by surface layer densification and density profile, and three-layer panels exhibited high SWR values at 30 to 40% recycled fibre content, demonstrating that optimized density distribution can compensate for the changes in fibre characteristics associated with recycling.
8. Panel structure controlled colour stability. In three-layer panels, virgin-fibre surface layers masked colour differences associated with recycled fibres in the core.
9. All panels exhibited a stable U-shaped vertical density profile, and the incorporation of recycled fibres at levels of up to 50% did not disrupt the fundamental densification mechanisms under controlled hot-pressing conditions.

Overall, the findings suggest that the combination of the applied fibre recovery strategy, three-layer panel design, and controlled hot-pressing conditions enables recycled fibre substitution levels of 40 to 50%, exceeding conventional limits reported in the literature and indicating promising potential for high-value recycling of HDF fibres.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Use of Generative AI

The authors declare that Grammarly version 1.2.230.1815 (EDU subscription) was used solely to improve the English language quality, including grammar, spelling, and stylistic consistency of the manuscript. No AI tools were used for data analysis, interpretation of results, literature search, reference collation, or the preparation of images, figures, graphs, or diagrams.

REFERENCES CITED

Adam, A. B. A., Basta, A. H., and El-Saied, H. (2012). "Properties of medium-density fiberboards from bagasse digested with different retention times," *Forest Prod. J.* 62(5), 400-405. https://doi.org/10.13073/0015-7473-62.5.400

Ahmadi, M., Moezzipour, B., and Moezzipour, A. (2019). "Thermal stability of wood fibers produced from recycled medium density fiberboards," *Drv. Ind.* 70(2), 149-155. https://doi.org/10.5552/drvind.2019.1833

Aisyah Humaira, A., and Mohd Tahir, P. (2011). "Effects of different thermo-mechanical refining pressure on the performance of medium density fibreboard (MDF) made from kenaf (*Hibiscus cannabinus* L.) core," in: ICCM International Conferences on Composite Materials, Jeju Island, Korea.

Akbulut, T., and Ayrilmis, N. (2019). "Some advantages of three-layer medium-density fibreboard as compared to the traditional single-layer one," *Journal of Wood Science* 65(1), article 46. https://doi.org/10.1186/s10086-019-1822-4

Ali, L., Alam, A., Kuttiyathil, M. S., Alalabi, A., Al-Kwradi, M., and Altarawneh, M. (2024). "Exploring the potential of chemical recycling of waste medium-density fiberboards (MDF) under oxidative and pyrolytic conditions," *Sustain. Chem. Pharm.* 41, article 101685. https://doi.org/10.1016/j.scp.2024.101685

Amr, S. S. A., Bashir, M. J. K., Abujayyab, S. K. M., and Ahmad, W. (2021). "Sustainable solutions for environmental pollutants from solid waste landfills," in: *Sustainable Solutions for Environmental Pollution: Waste Management and Value-Added Products*, Volume 1, Scrivener Publishing LLC, Beverly, MA, USA, pp. 305–341. https://doi.org/10.1002/9781119785439.ch8

Antov, P., Savov, V., Trichkov, N., Krišťák, Ľ., Réh, R., Papadopoulos, A. N., Taghiyari, H. R., Pizzi, A., Kunecová, D., and Pachikova, M. (2021). "Properties of high-density fiberboard bonded with urea–formaldehyde resin and ammonium lignosulfonate as a bio-based additive," *Polymers* 13(16), article 2775. https://doi.org/10.3390/polym13162775

Ayrilmis, N., Akbulut, T., and Yurttaş, E. (2017). "Effects of core layer fiber size and face-to-core layer ratio on the properties of three-layered fiberboard," *BioResources* 12(4), 7964-7974. https://doi.org/10.15376/biores.12.4.7964-7974

Ayrilmis, N., and Akbulut, T. (2018). "Screw withdrawal resistance and surface soundness of three-layer fiberboard having coarse fibers in core layer," *Drv. Ind.* 69(4), 379-385. https://doi.org/10.5552/drind.2018.1804

Bekhta, P., Ráheľ, J., Pipíška, T., Nociar, M., Leiter, L. M., and Rousek, R. (2025). "Properties of particleboards made from mixture of oversized fibers from MDF waste process and wood particles of Norway spruce (*Picea abies*)," *Wood Material Science and Engineering* 20(3), 571-579. https://doi.org/10.1080/17480272.2024.2362753

Bütün Buschalsky, F. Y., and Mai, C. (2021). "Repeated thermo-hydrolytic disintegration of medium density fibreboards (MDF) for the production of new MDF," *European Journal of Wood and Wood Products* 79(6), 1451-1459. https://doi.org/10.1007/s00107-021-01739-6

Bütün, F. Y., Sauerbier, P., Militz, H., and Mai, C. (2019). "The effect of fibreboard (MDF) disintegration technique on wood polymer composites (WPC) produced with recovered wood particles," *Compos. Part A- Appl. S.* 118, 312-316. https://doi.org/10.1016/j.compositesa.2019.01.006

Bütün-Buschalsky, F. Y., Mayer, A., Ostendorf, K., Gröne, O.-E., Klein, K., Schöpper, C., Mertens, O., Krause, A., and Mai, C. (2018). "Recovering fibres from fibreboards for wood polymer composites production," *Int. Wood Prod. J.* 9, 1-8. https://doi.org/10.1080/20426445.2018.1462965

Camlibel, O., and Akgul, M. (2020). “Mechanical and physical properties of medium density fibreboard with calcite additive,” *Wood Research* 65(2), 231-244. https://doi.org/10.37763/wr.1336-4561/65.2.231244
Cavailles, J., Vaca-Medina, G., Wu-Tiu-Yen, J., Peydecastaing, J., and Pontalier, P. Y. (2024). “Influence of thermocompression conditions on the properties and chemical composition of bio-based materials derived from lignocellulosic biomass,” *Materials* 17(8), article 1713. https://doi.org/10.3390/ma17081713
Chen, S., Li, S., Mu, J., and Feng, Y. (2015). “Influence of urea formaldehyde resin on the pyrolysis characteristics and gas evolution of waste MDF,” *Wood Res.* 60(1), 113-124.
De Deus, P. R., Alves, M. C. de S., and Vieira, F. H. A. (2015). “The quality of MDF workpieces machined in CNC milling machine in cutting speeds, feedrate, and depth of cut,” *Meccanica* 50(12), 2899-2906. https://doi.org/10.1007/s11012-015-0187-z
Elias, R., and Bartlett, C. (2018). “Briefing: Closing the loop for medium-density fibreboard,” *Proc. Inst. Civ. Eng. Waste Resour. Manag.* 171(2), 33-35. https://doi.org/10.1680/jwarm.17.00043
EN 310. (1993). “Wood-based panels. Determination of modulus of elasticity in bending and of bending strength,” European Committee for Standardization, Brussels, Belgium.
EN 317. (1993). “Particleboards and fibreboards. Determination of swelling in thickness after immersionin water,” European Committee for Standardization, Brussels, Belgium.
EN 319. (1993). “Particleboards and fibreboards. Determination of tensile strength perpendicular to the plane of the board,” European Committee for Standardization, Brussels, Belgium.
EN 320. (2011). “Particleboards and fibreboards – Determination of resistance to axial withdrawal of screws,” European Committee for Standardization, Brussels, Belgium.
EN 323. (1993). “Wood-based panels – Determination of density,” European Committee for Standardization, Brussels, Belgium.
EN 382-2. (1993). “Fibreboards—Determination of surface absorption—Part 2: Test method for hardboards,” European Committee for Standardization, Brussels, Belgium.
EN 622-5. (2009). “Fiberboards. Specifications. Requirements for dry process boards (MDF),” European Committee for Standardization, Brussels, Belgium.
Farajollah Pour, M., Hatefnia, H., Dorieh, A., Valizadeh Kiamahalleh, M., and Mohammadnia Afrouzi, Y. (2022). “Research on medium density fiberboard (MDF) behavior against screw axial withdrawal: Impact of density and operational variables,” *Structures* 39, 194-206. https://doi.org/10.1016/J.ISTRUC.2022.03.025
Farjana, S. H., Tokede, O., Tao, Z., and Ashraf, M. (2023). “Life cycle assessment of end-of-life engineered wood,” *Sci. Total Environ.* 887, article 164018. https://doi.org/10.1016/j.scitotenv.2023.164018
Franke, R., and Roffael, E. (1998). “For recycling particle board and MDF boards,” *Holz als Roh- und Werkst.* 56(1), 79-82. https://doi.org/10.1007/s001070050268
Ghazlan, A., Ngo, T., Tran, P., Le, V. T., Nguyen, T., Whittaker, A. S., and Remennikov, A. (2020). “Enhancing toughness of medium-density fiberboard by mimicking nacreous structures through advanced manufacturing techniques,” *J. Struct. Eng.* 146(3), article 2552. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002552

Groom, L. H., So, C., Elder, T., Pesacreta, T., and Rials, T. (2008). "Effects of refiner pressure on the properties of individual wood fibers," in: *Characterization of the Cellulosic Cell Wall*, Blackwell Publishing, Hoboken, NJ, USA, pp. 219-230. https://doi.org/10.1002/9780470999714.ch17

Gupta, A., Jordan, P., and Pang, S. (2007). "Modelling of the development of the vertical density profile of MDF during hot pressing," *Chemical Product and Process Modeling* 2(2), article 1075. https://doi.org/10.2202/1934-2659.1075

Gürsoy, S., and Ayrilmis, N. (2023). "Effect of lignin modification of recycled and fresh wood fibers on physical, mechanical, and thermal properties of fiberboard," *Forests*, 14(10), article 2007. https://doi.org/10.3390/f14102007

Hagel, S., and Saake, B. (2020). "Fractionation of waste MDF by steam refining," *Molecules (Basel, Switzerland)* 25(9), article 2165. https://doi.org/10.3390/molecules25092165

Hagel, S., Joy, J., Cicala, G., and Saake, B. (2021). "Recycling of waste MDF by steam refining: Evaluation of fiber and paper strength properties," *Waste and Biomass Valorization* 12(10), 5701-5713. https://doi.org/10.1007/s12649-021-01391-4

Hamid, Z.-H., Mehdi, F., Ahmad, J.-L., and Ali Akbar, E. (2008). "Properties of medium density fiberboard made from wet and dry stored bagasse," Journal of Agricultural Science and Technology, 10(5), 461–470

Hong, M. K., Lubis, M. A. R., and Park, B. D. (2017). "Effect of panel density and resin content on properties of medium density fiberboard," *Journal of the Korean Wood Science and Technology* 45(4), 444-455. https://doi.org/10.5658/WOOD.2017.45.4.444

Hong, M. K., Lubis, M. A. R., Park, B. D., Sohn, C. H., and Roh, J. (2020). "Effects of surface laminate type and recycled fiber content on properties of three-layer medium density fiberboard," *Wood Mater. Sci. Eng.* 15(3), 163-171. https://doi.org/10.1080/17480272.2018.1528479

Hu, W., Liu, Y., and Konukcu, A. C. (2023). "Study on withdrawal load resistance of screw in wood-based materials: Experimental and numerical," *Wood Mat. Sci. Eng.* 18(1), 334-343. https://doi.org/10.1080/17480272.2022.2084699

Husain, S. N. H., Rashid, A. H. A., Shaari, M. F., R, M. N., Hassan, N. N. M., Ahmad, M. R., and Rashid, R. A. (2019). "Mechanical properties evaluation of nonwoven industrial cotton waste produced by needle punching method," *IOP Conference Series: Materials Science and Engineering* 670(1), article 012035. https://doi.org/10.1088/1757-899X/670/1/012035

Ibrahim, Z., Alias, A. H., Ramli, R., Wahab, N. A., Ahmad, M., Osman, S., and Sheng, E. L. (2021). "Effects of refining parameters on the properties of oil palm frond (OPF) fiber for medium density fibreboard (MDF)," *J. Adv. Res. Fluid Mech. Therm. Sci.* 87(3), 64-77. https://doi.org/10.37934/arfmts.87.3.6477

Irle, M., Privat, F., Couret, L., Belloncle, C., Déroubaix, G., Bonnin, E., and Cathala, B. (2019). "Advanced recycling of post-consumer solid wood and MDF," *Wood Mater. Sci. Eng.*14(1), 19-23. https://doi.org/10.1080/17480272.2018.1427144

Ismail, N., Mohmed Jomali, M. A., Abu Bakar, H., Yean Ghing, T., Zaini Nik Soh, N. M., and Aimi Mohd Azam, R. M. (2020). "Influence of varying density on the mechanical and physical properties of medium density fibreboard (MDF) containing kenaf," *IOP Conf. Ser. Mater. Sci. Eng.* 713(1), article 012020. https://doi.org/10.1088/1757-899X/713/1/012020

Karl, M. (1998). “Effect of preheating and refining conditions on radiata pine MDF fibre quality,” in: *APPITA Annual General Conference*, Melbourne, Australia.

Kubba, S. (2010). “Choosing materials and products,” in: *Green Construction Project Management and Cost Oversight*, S. Kubba (ed.), Architectural Press, Boston, MA, USA, pp. 221-266. DOI: https://doi.org/10.1016/B978-1-85617-676-7.00006-3

Kúdela, J. (2020). “Surface properties of a medium density fibreboard evaluated from the viewpoint of its surface treatment,” *Acta Facultatis Xylologiae Zvolen* 62(2), 35-45. https://doi.org/10.17423/afx.2020.62.2.04

Li, Y., Dai, Z., Hu, C., Tu, D., and Yun, H. (2024). “Optimisation of particle distribution and performance in three-layer tubular particleboards using response surface methodology,” *J. Build. Engin.* 82, article 108256. https://doi.org/10.1016/j.jobe.2023.108256

Lubis, M. A. R., Hong, M. K., and Park, B. D. (2018a). “Hydrolytic removal of cured urea–formaldehyde resins in medium-density fiberboard for recycling,” *J. Wood Chem. Technol.* 38(1), article 1316741. https://doi.org/10.1080/02773813.2017.1316741

Lubis, M. A. R., Hong, M. K., Park, B. D., and Lee, S. M. (2018b). “Effects of recycled fiber content on the properties of medium density fiberboard,” *Eur. J. Wood Wood Prod.* 76(5), 1515-1526. https://doi.org/10.1007/s00107-018-1326-8

Lubis, M. A. R., Hong, M. K., Park, B. D., and Lee, S. M. (2018c). “Effects of recycled fiber content on the properties of medium density fiberboard,” *Eur. J. Wood Wood Prod.* 76(5), 1515-1526. https://doi.org/10.1007/s00107-018-1326-8

Mantanis, G. I., Athanassiadou, E. T., Barbu, M. C., and Wijnendaele, K. (2018). “Adhesive systems used in the European particleboard, MDF and OSB industries,” *Wood Mater. Sci. Eng.* 13(2), 104-116. https://doi.org/10.1080/17480272.2017.1396622

Minhas, A. H., Ullah, N., Riaz, A. A., Siddiqi, M. U. R., Abualnaja, K. M., Althubeiti, K., and Muhammad, R. (2021a). “Experimental investigation of vertical density profile of medium density fiberboard in hot press,” *Appl. Sci.* 11(22), article 10769. https://doi.org/10.3390/app112210769

Moezzipour, B., Abdolkhani, A., Doost-hoseini, K., Ahmad Ramazani, S. A., and Tarmian, A. (2018). “Practical properties and formaldehyde emission of medium density fiberboards (MDFs) recycled by electrical method,” *Eur. J. Wood Wood Prod.* 76(4), 1287-1294. https://doi.org/10.1007/s00107-018-1291-2

Moezzipour, B., Ahmadi, M., Abdolkhani, A., and Doosthoseini, K. (2017). “Chemical changes of wood fibers after hydrothermal recycling of MDF wastes,” *J. Ind. Acad. Wood Sci.* 14(2), 133-138. https://doi.org/10.1007/s13196-017-0198-6

Murtala Abdulmumini, M., Bradley, M., Berry, R. J., and Zigan, S. (2013). “The effects of fine content and length on wood pellets bulk density,” in: *ICBMH 2013 - 11th International Conference on Bulk Materials Storage, Handling and Transportation*, Newcastle, Australia.

Nuryawan, A., Risnasari, I., Pohan, A. P., Husna, A. U., Nasution, T. I., Banurea, R., and Hartini, K. S. (2020). “Properties of fibreboard (FBs) and recycle fibreboard (rFBs) and analysis of their wastage after recycling,” *IOP Conf. Ser. Mater. Sci. Eng.* 935(1), article 012060. https://doi.org/10.1088/1757-899X/935/1/012060

Park, S., Park, B.-D., and Kim, Y. (2024). “Big data analysis on manufacturing variables affecting properties of medium density fiberboard,” *Eur. J. Wood Wood Prod.* 82(2), 483-492. https://doi.org/10.1007/s00107-023-02030-6

Psonopoulou, A. A., Kamperidou, V., and Barboutis, I. (2025). "Performance of five melamine–urea–formaldehyde (MUF) resins in spruce three-layer glulam bonds: Adhesion, durability, and mechanical properties," *Applied Sciences* (Switzerland), 15(18), 1-14. https://doi.org/10.3390/app151810263

Pugazhenthi, N., and Anand, P. (2020). "A review on mechanical properties of medium density fiberboard prepared from different fiber materials," *Lecture Notes in Mechanical Engineering*, Springer Science and Business Media Deutschland GmbH, pp. 321-333. https://doi.org/10.1007/978-981-15-3631-1_28

Pysarenko, P., Samojlik, M., Pysarenko, V., Mostoviak, I., Taranenko, A., Taranenko, S., Dychenko, O., Lastovka, V., and Husinsky, D. (2024). "Assessment of landfills and their impact on the soil: A local study in Ukraine," *Rocz. Ochr. Sr.* 26, 178-186. https://doi.org/10.54740/ros.2024.019

Roffael, E., and Hüster, H. G. (2012). "Complex chemical interactions on thermo hydrolytic degradation of urea formaldehyde resins (UF-resins) in recycling UF-bonded boards," *Eur. J. Wood Wood Prod.* 70(4), 401-405. https://doi.org/10.1007/s00107-011-0574-7

Roffael, E., Behn, C., Schneider, T., and Krug, D. (2016). "Bonding of recycled fibres with ureaformaldehyde resins," *Int. Wood Prod. J.* 7(1), 36-45. https://doi.org/10.1080/20426445.2015.1131918

Savov, V., Antov, P., Dudeva, V., and Panchev, C. (2025). "Properties of medium-density fiberboards with different contents of recycled fibers and urea–formaldehyde resin," *Fibers* 13(4), article 40. https://doi.org/10.3390/fib13040040

Savov, V., Antov, P., Panchev, C., Lubis, M. A. R., Lee, S. H., Taghiyari, H. R., Todorova, M., and Petrin, S. (2023a). "Effect of hydrolysis regime on the properties of fibers obtained from recycling medium-density fiberboards," *Fibers* 11(7), article 64. https://doi.org/10.3390/fib11070064

Savov, V., Antov, P., Panchev, C., Lubis, M. A. R., Taghiyari, H. R., Lee, S. H., Krišťák, Ľ., and Todorova, M. (2023b). "The impact of hydrolysis regime on the physical and mechanical characteristics of medium-density fiberboards manufactured from recycled wood fibers," *Fibers* 11(12), article 103. https://doi.org/10.3390/fib11120103

Schütt, F., Westereng, B., Horn, S. J., Puls, J., and Saake, B. (2012). "Steam refining as an alternative to steam explosion," *Bioresource Technol.* 111, 476-481. https://doi.org/10.1016/j.biortech.2012.02.011

Tang, R., Fan, L., Yu, Z., and Zhang, Y. (2025). "Mechanisms and properties for sustainable fiberboard recycling *via* simultaneous utilization of residual urea-formaldehyde resin and lignin," *Polymer Composites* Published Online. https://doi.org/10.1002/pc.70734

Verlag, C., and Jentzsch-cuvillier, I. A. (2007). *On the Chemical-Technological Utilization of Used Wood-Based Materials and Tree Bark*, Cuvillier Verlag, Göttingen, Germany.

Wan, H., Wang, X. M., Barry, A., and Shen, J. (2014). "Recycling wood composite panels: Characterizing recycled materials," *BioResources* 9(4), 7554-7565. https://doi.org/10.15376/biores.9.4.7554-7565

Winandy, J. E., and Krzysik, A. M. (2007). "Thermal degradation of wood fibers during hot-pressing of mdf composites : Part I . Relative effects and benefits of thermal exposure," *Wood and Fiber Science* 39(3), 450-461.

Wu, Y.-M., Lu, S.-G., Zhao, L.-Y., Tang, Z.-Q., and Yang, N. (2021). "Correlation between characteristic parameters of vertical density profile and main physical and mechanical properties of medium density fiberboard," *Chinese J. Wood Sci. Technol.* 35(5), 31-37. https://doi.org/10.12326/j.2096-9694.2020173

Xing, C., Wang, S., and Pharr, G. M. (2009). "Nanoindentation of juvenile and mature loblolly pine (*Pinus taeda* L.) wood fibers as affected by thermomechanical refining pressure," *Wood Sci. Technol.* 43(7–8), 615-625. https://doi.org/10.1007/s00226-009-0266-1

Xu, C., van Blokland, J., Mota, I. F., Alao, P., Daniel, G., and Adamopoulos, S. (2025). "Use of secondary fibres from recycling processes of fibreboard manufacturing and post-consumer waste in medium density fibreboard," *Eur. J. Wood Wood Prod.* 83(5). https://doi.org/10.1007/s00107-025-02323-y

Yildirim, M., Candan, Z., Aksoy, B., and Dundar, T. (2022). "Performance properties of engineered wood composites reinforced by lignosulfonates," *Green Mater.* 11(2), 60-68. https://doi.org/10.1680/jgrma.21.00069

Zaharudin, Z. A., Shuib, A., Hadianti, R., and Rodzi, Z. M. (2023). "Towards sustainable city: A covering model for recycling facility location-allocation in Nilai, Malaysia," *Sci. Technol. Indones.* 8(4), 570-578. https://doi.org/10.26554/sti.2023.8.4.570-578

Zeng, Q., Lu, Q., Zhou, Y., Chen, N., Rao, J., and Fan, M. (2018). "Circular development of recycled natural fibers from medium density fiberboard wastes," *J. Clean. Prod.* 202, 456-464. https://doi.org/10.1016/j.jclepro.2018.08.166

Zhou, C., Dai, C., and Smith, G. D. (2011). "Modeling vertical density profile formation for strand-based wood composites during hot pressing: Part 2. Experimental investigations and model validation," *Compos. Part B- Eng.* 42(6), 1357-1365. https://doi.org/10.1016/j.compositesb.2011.05.037

Zimmer, A., and Lunelli Bachmann, S. A. (2023). "Challenges for recycling medium-density fiberboard (MDF)," *Results Eng.* 19, article 101277. https://doi.org/10.1016/j.rineng.2023.101277

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