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Properties of Medium-Density Fiberboards with Different Contents of Recycled Fibers and Urea–Formaldehyde Resin

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Highlights

What are the main findings?

- The complete replacement of virgin fibers with recycled fibers significantly reduces MDF panel performance, with declines in MOE, MOR, IB strength, and other key properties, making 100% substitution unsuitable for MDF production.
- The optimal recycled fiber content is up to 24%, with at least 12% UF resin to ensure mechanical integrity. Panels with up to 20% recycled fiber maintain acceptable properties, but performance declines sharply between 20% and 40%. Further research is needed for recycled fiber content between 40% and 60%.
- Increasing the UF resin content can help to counteract the negative effects of recycled fibers, with formaldehyde scavenging by amines allowing for higher resin content without significantly increasing formaldehyde emissions.

What are the implications of these findings?

- The findings provide valuable insights for MDF manufacturers, helping to support more sustainable, cost-effective, and high-performance production.
- Future research should focus on improving the recycling process and exploring alternative resins to enhance sustainability and reduce the environmental footprint of MDF production.

Abstract: Recycling wood-based panels is essential for promoting the cascading use of wood, advancing the transition to a circular economy, and maximizing the efficient use of natural resources. While recycling particleboard has become a well-established industrial practice, recycling medium density fiberboard (MDF) panels presents challenges, particularly in preserving material quality. The aim of this research work was to investigate and evaluate the combined effect of recycled MDF fibers and urea–formaldehyde (UF) resin content on the performance characteristics of the panels. MDF recycling was conducted using hydrothermal hydrolysis and hammer mill refinement. Preliminary experiments revealed that the degradation of properties in recycled MDF panels is not uniform with the addition of recycled fibers. The panels retained their properties significantly with up to 20% recycled fiber content, while formaldehyde emissions decreased by 1.2%. Based on these findings, the optimization of recycled fiber and UF resin content was performed, revealing that the maximum allowable recycled fiber content through hydrothermal hydrolysis and hammer mill refinement is 24%, with a minimum UF resin content of 12%. This study highlights the potential for integrating recycled MDF fibers into new panels, contributing to more sustainable production practices. By optimizing the balance between recycled fiber content and UF resin, it is possible to produce MDF panels that meet industry standards while reducing the environmental impact.

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Keywords: MDF recycling; hydrothermal hydrolysis; optimization; urea–formaldehyde resin

1. Introduction

The transition to a circular economy in the field of wood-based materials necessitates the cascading use of wood resources [1–3], including recycling, reuse, and, ultimately, composting of wood waste [4–6]. This approach would yield significant benefits, the most direct of which is the reduction of global deforestation. Additionally, selecting an appropriate recycling technology could lower the energy consumption of wood-processing enterprises [7–11]. These benefits collectively contribute to a more sustainable and resilient wood-processing industry, aligning with global efforts to combat climate change and promote environmental stewardship.

For instance, a key energy-intensive process that consumes a substantial portion of the electrical and thermal energy in the production of medium-density fiberboard (MDF) panels is the refining process [12]. In the context of recycling waste panels, this operation could be replaced with hammer milling or screw devices, both of which require significantly less energy compared to processing solid wood using the most widespread refining method—Asplund's thermomechanical defibration process [13–17].

A comprehensive analysis of fiberboard panel production indicates that, in terms of production volume, these panels are the second most widely manufactured and consumed type after veneer and plywood, surpassing particleboard in overall production volume [18]. However, due to the nature of the bonding within MDF panels, they are significantly more difficult to recycle than particleboard [11,19,20].

At present, particleboard recycling is an established industrial practice. When recycled particles are incorporated into the core layer of new panels, there is no need for additional resin destruction or extraction processes [21,22]. By contrast, due to the critical role of fiber slenderness and the virtual absence of a core layer in modern MDF production [9], resin extraction is highly recommended [10,23]. Recycling MDF panels without resin extraction leads to a considerable deterioration in the properties of the resulting recycled medium density fiberboard (rMDF) panels. Unlike hydrothermal treatment, chemical hydrolysis, or resin extraction via electrolysis, recycling without resin removal also increases the free formaldehyde content in the panels [24–27].

The reduction of formaldehyde emissions in MDF panels through these methods is attributed both to the extraction of the resin itself and to the degradation products that remain in the panels and act as formaldehyde scavengers [28–31]. A comparative analysis of resin extraction methods (hydrothermal treatment, acid hydrolysis, and electrolysis) suggests that hydrothermal hydrolysis is the most cost-effective and environmentally safe process. According to the data presented by Liu et al. [32], the application of hydrothermal hydrolysis using pure water results in an approximately 4% increase in mass loss of UF resin when the hydrolysis temperature rises from 120 °C to 140 °C. This suggests that increasing the temperature beyond 120 °C in hydrolysis with pure water is unwarranted. A particularly noteworthy finding of this study is the conclusion that, when hydrothermal hydrolysis is conducted with a 30 wt.% formaldehyde water solution, the hydrolyzed solution can be directly utilized to synthesize a new UF resin, which exhibits the same functional properties as a standard UF resin. This directly implies that, by selecting an appropriate type and mode of hydrolysis, not only can MDF fibers be recycled, but UF resin itself can be recovered, making this process highly suitable and applicable for the conservation of natural resources [25]. However, a notable drawback of hydrothermal hydrolysis is the prolonged processing time required [33–35]. Another recycling approach

involves steam explosion. Historically, this method of wood fiber defibration has been employed in the production of hardboard panels, and is known as the Masonite process. Despite achieving a significant degree of UF resin extraction, this recycling method is associated with high operational costs, primarily due to substantial steam consumption and challenging working conditions [36].

Previous studies have demonstrated that MDF panels recycled through hydrothermal hydrolysis and hammer milling fail to meet the required standards for physical and mechanical properties [13,33–35]. Therefore, further research is necessary to explore the feasibility of producing panels from a blend of recycled and virgin (industrial pulp) fibers. Preliminary experiments have been conducted to examine the effects of recycled fiber content on panel properties. The main aim of this research work was to establish threshold values for recycled fiber content, and subsequently to evaluate the combined impact of this factor and the presence of UF resins. A slight increase in resin content may represent a viable strategy for mitigating formaldehyde emissions in rMDF panels.

In light of the aforementioned considerations, this study aimed to determine the combined effects of recycled fiber content and urea–formaldehyde (UF) resin on the properties of recycled medium-density fiberboard (rMDF) panels. To achieve this objective, MDF panels were recycled through hydrothermal hydrolysis followed by hammer mill refining. Panels incorporating varying proportions of recycled fibers were fabricated, and their key physical and mechanical properties were assessed. Based on these findings, the range of recycled fiber content was established between 10% and 50%, while UF resin content varied from 8% to 12%. To develop regression-based experimental–statistical models evaluating the influence of these factors on rMDF panel properties, nine panels were produced under controlled laboratory conditions and subsequently analyzed. The results facilitated the determination of the optimal proportions of recycled fibers and UF resin in relation to panel properties.

2. Materials and Methods

In this work, MDF panels were fabricated under laboratory conditions, varying the content of recycled fibers from 0% to 100% in increments of 20%. Accordingly, the panels have recycled fiber content of 0%, 20%, 40%, 60%, 80%, and 100%. On this basis, the optimal range of variation in the content of recycled fibers was determined, and regression analysis and optimization of the panel composition were conducted, varying the UF resin content from 8% to 12%.

The industrial wood fibers used for manufacturing the control MDF panels were produced by the Asplund thermomechanical method using a Defibrator L56 (Valmet, Stockholm, Sweden) in factory conditions at Kronospan Bulgaria PLC (Veliko Tarnovo, Bulgaria). The pulp was composed of mixed wood raw materials—40% hardwoods (European beech (*Fagus sylvatica*) and Turkish oak (*Quercus cerris*)) and 60% softwoods (Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*)). The industrially produced wood fibers had a moisture content (MC) of approximately 10%. The recycled wood fibers used had the same MC value. The UF resin had a molar ratio of 1.0 and a dynamic viscosity of 23.76 $\pm$ 0.52 MPa·s.

The fibers were recycled by applying hydrothermal hydrolysis at a process temperature of 121 °C and a process time of 30 min. This regime is in accordance with previous studies conducted by the authors [34–37] and the results of analyses by other researchers in the field [24,25,32]. Refinement was performed using a hammer mill, as it results in fewer cut fibers compared to disc mills and consumes less energy [13].

UF resin was used as a binder, with a content of 10% based on the dry fibers. This binder content is standard for producing MDF panels [38,39]. The remaining components, paraffin (wax) emulsion and hardener, were respectively 1% relative to dry fibers, and

ammonium sulfate $(NH_4)_2SO_4$ 20% was used at 1%, based on the dry resin [40,41]. The MDF panels, produced under laboratory conditions from both recycled and natural wood fibers, measured 400 mm × 400 mm, with a thickness of 10 mm and a target density of 780 kg/m^3. The slightly increased density of MDF panels was chosen due to the presence of beech and spruce (hardwood) fibers in the pulp [12,42,43]. The panel thickness was selected because thin and ultra-thin wood-based composites are increasingly utilized in interior design and furniture production for a wide range of applications [44,45]. The gluing process was carried out using a laboratory blender equipped with needle-shaped blades rotating at 850 rpm. The adhesive system was applied through a 1.5 mm diameter nozzle at a pressure of 6 atm.

Hot-pressing was carried out at a temperature of 175 °C, using a four-stage regime: pressure in the first stage of 4 MPa and a duration of 15% of the entire cycle; pressure during the second stage of 1.2 MPa and a duration of 15% of the entire cycle; pressure during the third stage of 0.8 MPa and a duration of 60% of the entire cycle; pressure during the fourth stage of 1.5 MPa and a duration of 10% of the entire cycle. This is a widespread regime in hot-pressing without varying the temperature [46–48].

The physical and mechanical properties of the panels were determined by testing eight test samples for each panel and property following the EN standards in the field—EN 310 (modulus of elasticity in bending and bending strength) [49], EN 317 (swelling in thickness) [50], EN 319 (internal bond strength) [51], EN 323 (density) [52], and EN ISO 12460-5 (free formaldehyde emission) [53].

The mechanical properties were evaluated using a WDW-50E universal testing machine (UTM, HST, Jinan, China). The density profile of the panels was assessed in the factory laboratory of Kastamonu Bulgaria AD (Gorno Sahrane, Bulgaria) using a GreCon DENSITYPROFILER (Fagus-GreCon Greten GmbH & Co. KG, Alfeld, Germany). The results of the formaldehyde emission, obtained using the perforator method, were reported using a DR 2800 photo-spectrometer (Hach Lange GmbH, Düsseldorf, Germany).

After determining an appropriate range of variation of the recycled fiber content, regression analysis was used to analyze the combined effect of the recycled fiber content and UF resin on the properties of the MDF panels, and the following regression model was derived:

$$\hat{Y} = B_0 + B_1X_1 + B_2X_2 + B_{12}X_1X_2 \quad (1)$$

where $\hat{Y}$ is the predicted value of the given property;

B_0, B_1, B_2, B_{12}—regression coefficients;

X_1, X_2—the studied factors.

Stepwise regression with 1000 iterations was applied to perform optimization in view of the physical and mechanical properties of rMDF panels. For this purpose, specialized software "*QstatLab*", version 6.0, was used.

3. Results and Discussion

3.1. Effect of the Content of Recycled Fibers (Preliminary Results)

The density of the rMDF panels, with the main statistics, is presented in the Table 1.

The density of the rMDF panels varied from 780 kg.m^{-3} to 794 kg.m^{-3}, or a variation of 1.76%, well below the statistical error of 5%. This minimal variation in the property is due to the method used to fabricate the laboratory panels, which uses metal bars to set the final thickness.

The conducted ANOVA (shown in Table 2) also confirmed the insignificant effect of the composition of the panels on their density.

Table 1. Density of the laboratory fiberboard panels fabricated with different content of recycled fibers.

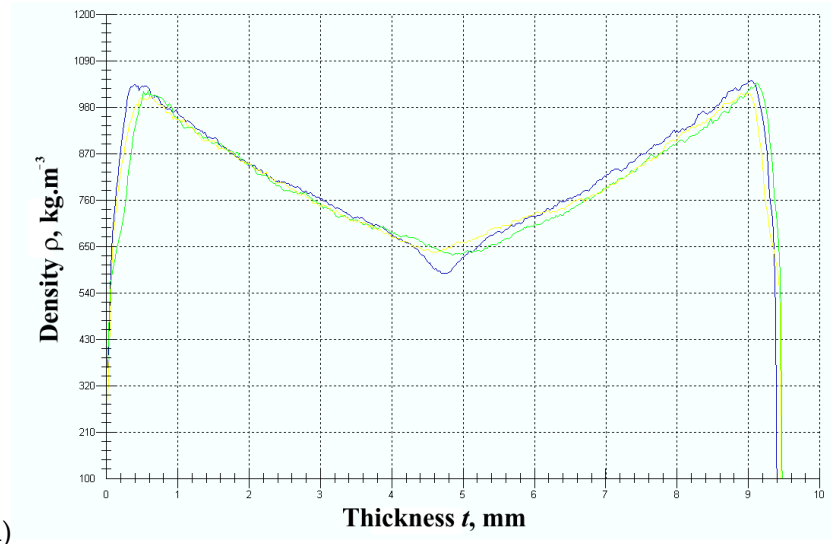
Panel №	Average ρ, kg.m^{-3}	Standard Deviation Sy, kg.m^{-3}	Coefficient of Variation Vy, %	Average Error my, kg.m^{-3}	Probability Py, %
1.	789	37.10	4.70	11.73	1.49
2.	783	43.58	5.57	13.78	1.76
3.	794	41.64	5.25	13.17	1.66
4.	787	43.70	5.55	13.82	1.76
5.	789	49.99	6.34	15.81	2.00
6.	780	27.26	3.50	8.62	1.11

Table 2. ANOVA for the effect of recycled fiber content on the density of the panels.

Source of Variation	Sum of Deviations Squares Q	Degrees of Freedom ν	Variance S^2	Calculated Fisher's Criterion F_{cal}	A Critical Value of Fisher's Criterion, F_{cr}
Content of recycled fibers	1239.10	5	247.8209	0.12	3.48
Error	19,243.62	9	2138.18		

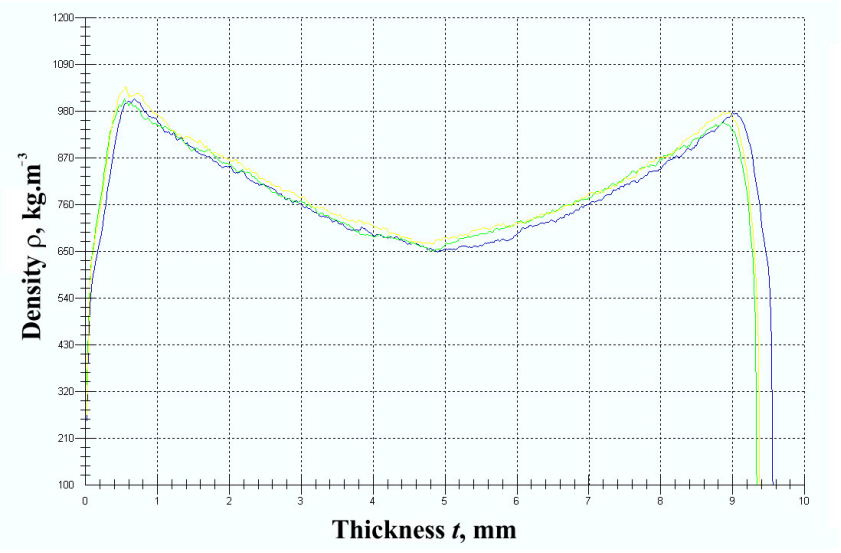
Therefore, this primary characteristic of the panels should not reflect on their other properties. The density profile of the different panels is presented in Figure 1.

The minimum-to-average density ratio of the individual panels varied from 81.16% for the control MDF to 77.19% for the rMDF composed entirely of recycled fibers. Despite the slight average variation of this indicator, a significant deviation can be seen in part of the panels fabricated with recycled fibers, with the minimum-to-average density ratio falling to 72.19% (in panels fabricated entirely with recycled fibers). The tendency for non-uniform density in panels containing recycled fibers is evident in panels with 60% or more recycled fibers (Panel Type C, Panel Type D, and Panel Type E). The uneven density profile in these panels is partly due to the presence of spherical or irregularly shaped fiber bundles (Figure 2), which likely settle in the intermediate part of the mat, leading to noticeable irregularities in the density profile.

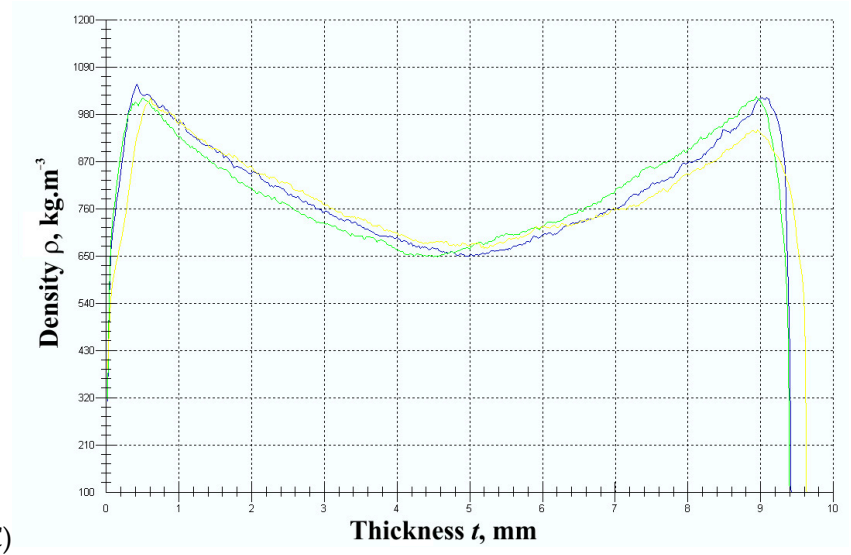


(**A**)

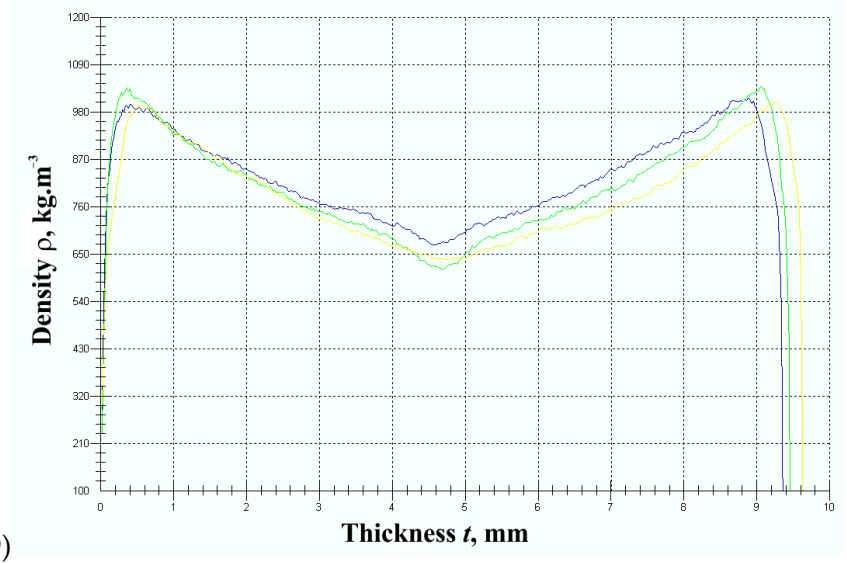
Figure 1. *Cont.*



(**B**)

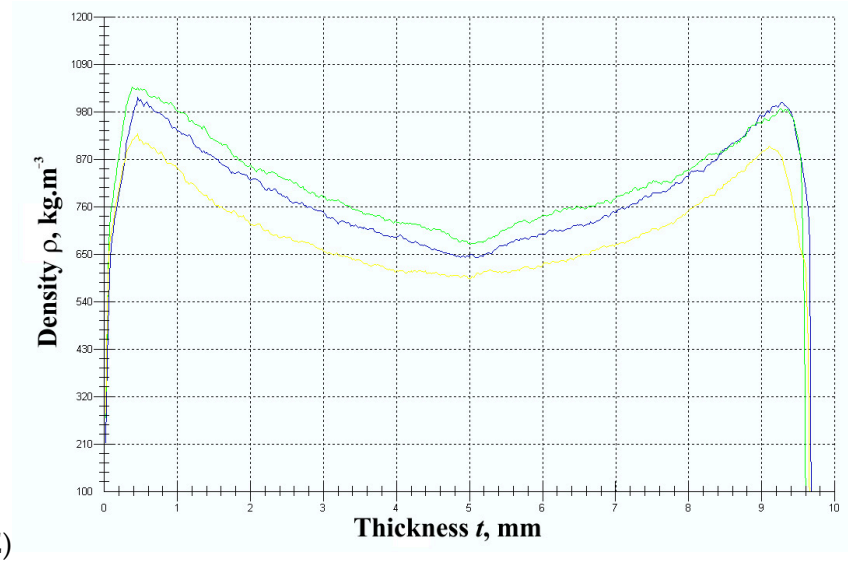


(**C**)

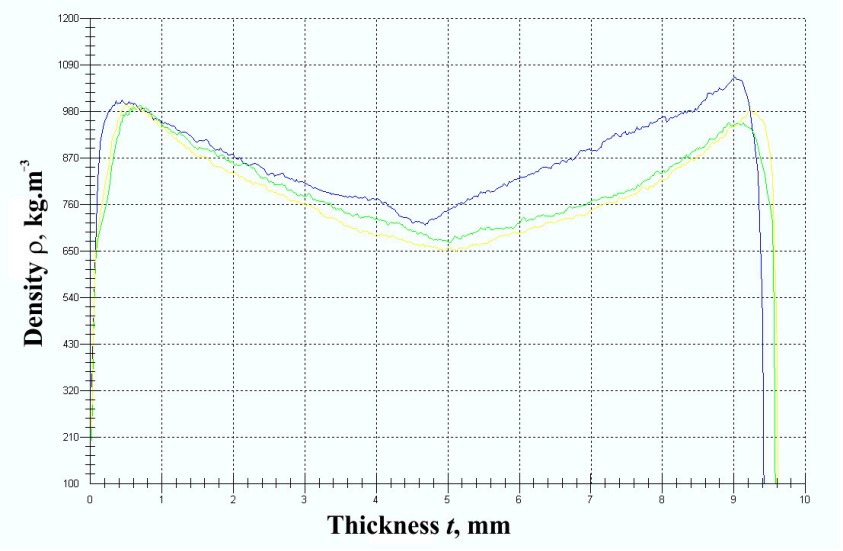


(**D**)

Figure 1. *Cont*.



(**E**)



(**F**)

Figure 1. Density profile of MDF panels manufactured with different content of recycled fibers: (**A**) REF—reference panel (0% recycled fibers; (**B**) Panel Type A (20% recycled fibers); (**C**) Panel Type B (40% recycled fibers); (**D**) Panel Type C (60% recycled fibers); (**E**) Panel Type D (80% recycled fibers); (**F**) Panel Type E (100% recycled fibers).

The variation of the water absorption (WA) of the laboratory-produced MDF panels depending on the content of recycled fibers is presented in Figure 3.

The WA of the panels varied from 38.13% to 58.56%. The results indicate a clear trend in WA as the content of recycled fibers in the MDF panels increases. Initially, replacing up to 20% of virgin fibers with recycled ones did not significantly affect the WA, with only a slight increase of 1.02 times, suggesting that a small proportion of recycled fibers can be incorporated without compromising the panel's dimensional stability. However, a notable change occurred when the recycled fiber content reached 40%. At this point, the WA increased significantly, being 1.09 times higher than panels with 20% recycled fibers, and 1.12 times higher than the control panels made entirely of virgin fibers. This suggests that, beyond a certain threshold, the presence of recycled fibers begins to adversely affect the panel's ability to resist WA. As the recycled fiber content continued to increase, the deterioration in WA became more gradual. Panels fabricated with 60% recycled fibers exhibited a 1.11 times higher WA compared to those with 40% recycled fibers. This relatively smooth increase indicates that the impact of additional recycled fibers on WA is less

pronounced beyond the 40% threshold. The trend continued with panels containing 80% recycled fibers, which exhibited a further increase in WA by 1.56 times compared to those with 60% recycled fibers. Finally, panels made entirely of recycled fibers had a WA 1.17 times higher than those with 80% recycled fibers. This final increment suggests that, while the deterioration in WA continues, it deteriorates at a diminishing rate as the proportion of recycled fibers approaches 100%.

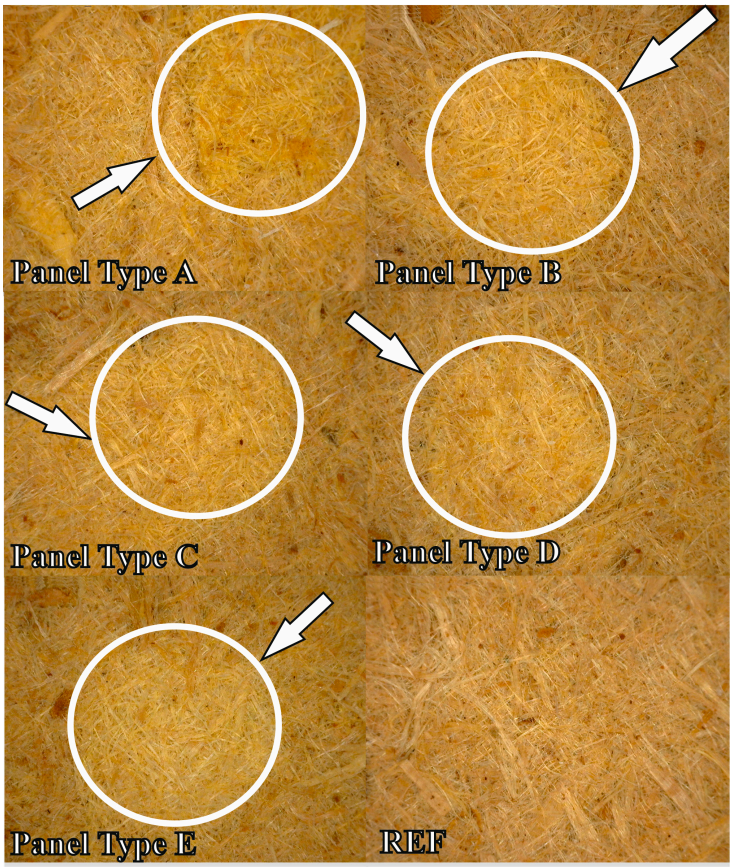


Figure 2. Appearance of MDF panels (magnification × 16) manufactured with varying content (0–100%) of recycled fibers. Outlines indicate compressed bundles of recycled fibers.

The results for the thickness swelling (TS) of the rMDF panels with different participation of recycled fibers are presented in Figure 4.

The thickness swelling (TS) of the panels varied significantly with the replacement of natural fibers by recycled fibers. When virgin fibers were completely replaced with recycled fibers, the TS ranged from 10.91% to 18.69%, indicating an overall deterioration of 1.71 times. When up to 20% of natural fibers were replaced with recycled fibers, the increase in TS was minimal, at only 1.03 times, suggesting that a small proportion of recycled fibers does not significantly affect the TS. However, increasing the recycled fiber content to 40% had a notable negative impact, with TS values 1.08 times higher than those of panels with 20% recycled fibers. Further increases in recycled fiber content to 60% and 80% resulted in TS values 1.11 and 1.09 times higher, respectively, compared to the previous levels. This indicates a relatively smooth increase in TS with higher recycled fiber content. However, when the recycled fiber content reached 100%, the TS showed a significant deterioration of 1.27 times compared to panels with 80% recycled fibers. These results suggest that, while small amounts of recycled fibers can be used without significantly affecting the TS, higher proportions lead to noticeable increases in TS. This trend is consistent with the findings

from other studies, which have shown that replacing natural fibers with recycled ones can adversely affect the physical properties of MDF panels, including TS [26,54].

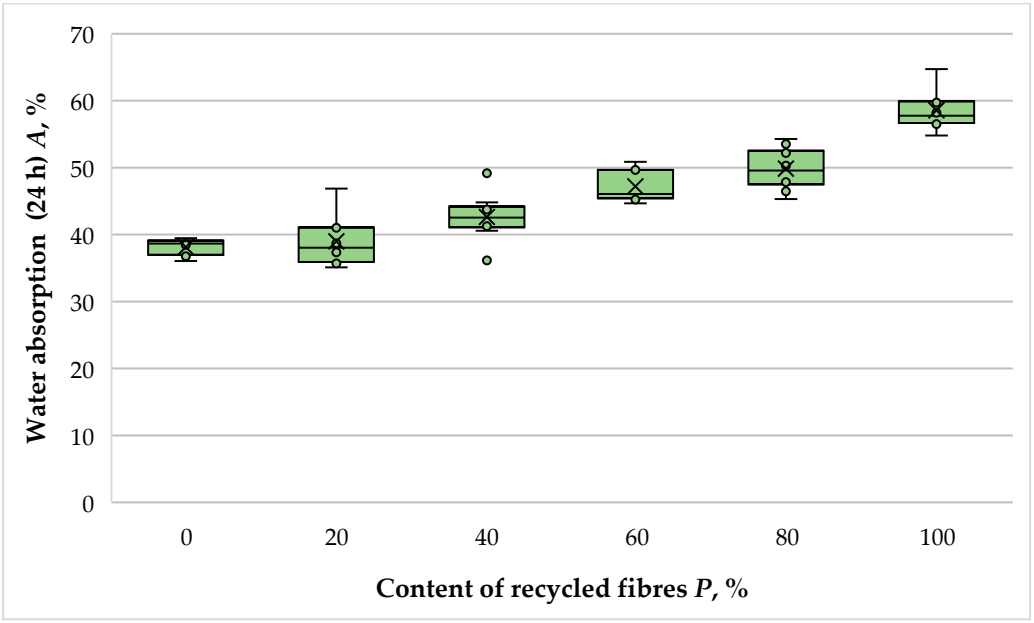


Figure 3. Water absorption (24 h) of MDF panels fabricated with different content of recycled fibers.

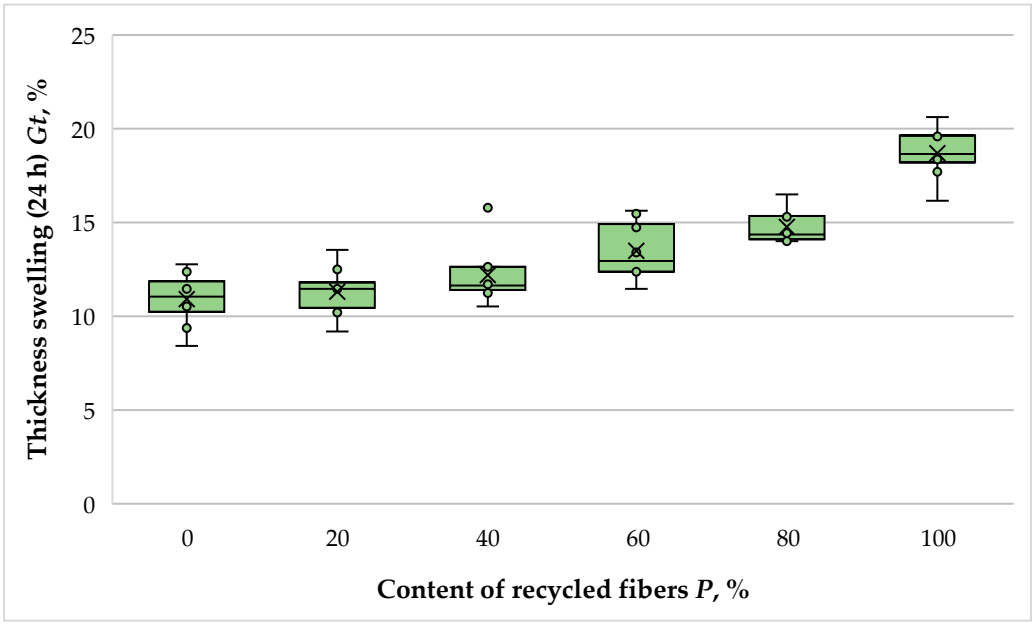


Figure 4. Thickness swelling (24 h) of MDF panels fabricated with different content of recycled fibers.

Despite the established deterioration of the property with the inclusion of recycled fibers, the rMDF panels with up to 80% content of recycled fibers fulfilled the requirements regarding the thickness swelling of MDF panels for general purpose and use in dry conditions—thickness swelling of at most 18% [55].

The variation of the modulus of elasticity (MOE) of the rMDF panels, depending on the content of recycled fibers, is presented in Figure 5.

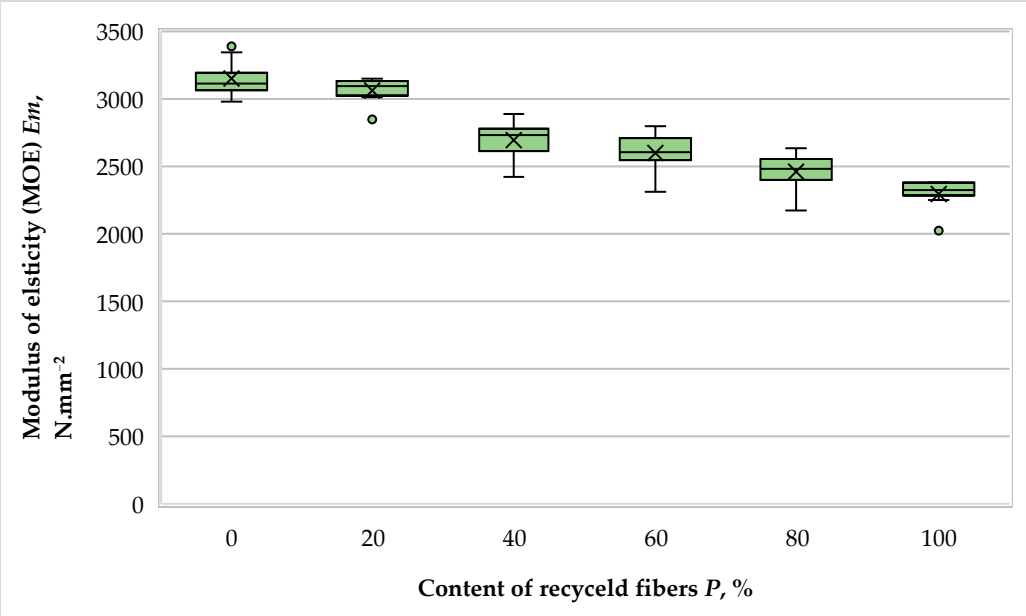


Figure 5. Modulus of elasticity (MOE) of MDF panels fabricated with different content of recycled fibers.

The MOE is a measure of a material's stiffness or rigidity. In the context of MDF panels, the MOE is an important property that reflects the panel's ability to resist bending or flexing when subjected to external forces. Higher MOE values indicate stiffer panels that are less likely to bend, while lower MOE values suggest more flexible panels.

The MOE values of the laboratory-made MDF panels, manufactured with varying content of recycled fibers, ranged from 3151 N/mm^2 to 2295 N/mm^2. This represents a total deterioration of 1.37 times when completely replacing virgin fibers with recycled ones. Initially, the difference in the MOE between the control panel made from industrial pulp and the panel with 20% recycled fiber content was minimal, at only 1.03 times. This indicates that panels with up to 20% recycled fibers exhibited similar stiffness to those made entirely from natural fibers. However, a significant decrease in the MOE was observed when the recycled fiber content was increased to 40%, with a reduction of 1.14 times compared to panels with 20% recycled fibers. This suggests that beyond a certain threshold, the incorporation of recycled fibers begins to adversely affect the stiffness of the panels. Subsequent increases in recycled fiber content led to relatively smooth deterioration in the MOE. Panels with 60% recycled fibers had only 1.05 times lower the MOE than those with 40% recycled fibers. Increasing the recycled fiber content to 80% resulted in a 1.06-times decrease in the MOE, and panels composed entirely of recycled fibers had a 1.07-times lower MOE than those with 80% recycled fibers. Despite the overall deterioration, rMDF panels manufactured with up to 60% recycled fiber content still fulfilled the standard requirement for general-purpose MDF used in dry conditions, which is an MOE of at least 2500 N/mm^2 [55]. This indicates that, while higher proportions of recycled fibers reduce stiffness, panels with moderate levels of recycled fibers can still meet industry standards. These findings are consistent with other studies that have shown the impact of recycled fibers on the mechanical properties of MDF panels [26,35,56].

The results for the bending strength (MOR) of the rMDF panels manufactured with different participation of recycled fibers are presented in Figure 6.

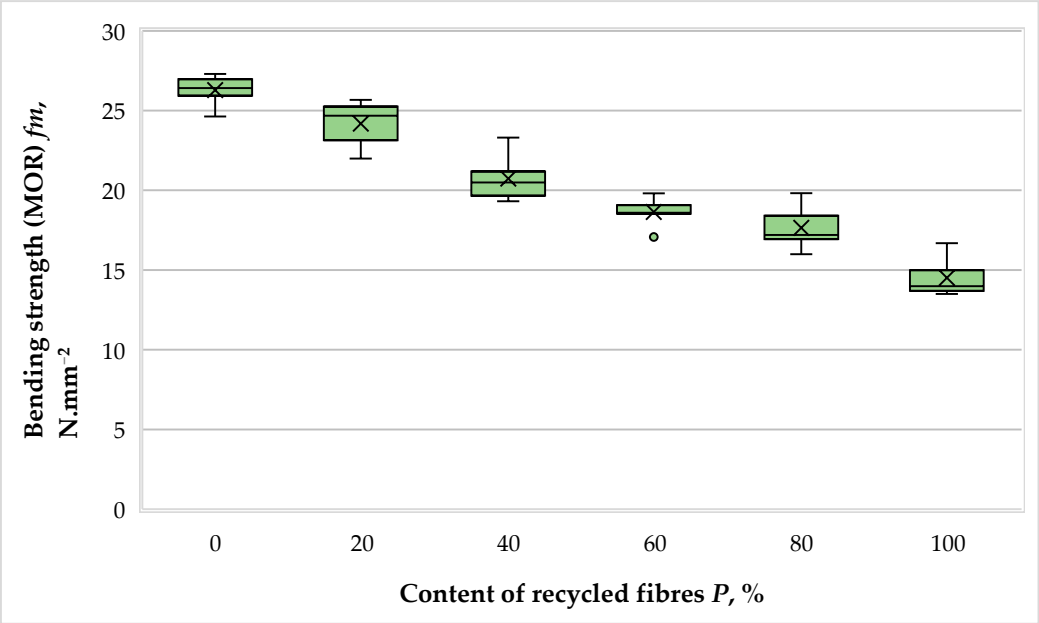


Figure 6. Modulus of rupture (MOR) of MDF panels fabricated with different content of recycled fibers.

The MOR is a measure of the maximum load-carrying capacity of a material before failure in bending, which reflects the material's strength and ability to withstand stress without breaking. In the context of MDF panels, the MOR is an important property that indicates the panel's resistance to bending forces, and understanding the MOR is essential for ensuring that MDF panels meet industry standards and are suitable for certain applications. The MOR values of the laboratory-made MDF panels, manufactured with varying content of recycled fibers, show a clear trend of deterioration as the proportion of recycled fibers increases. When natural fibers were completely replaced with recycled ones, the MOR decreased from 26.28 N/mm^2 to 14.51 N/mm^2, indicating a total deterioration of 1.81 times. Initially, the difference in the MOR between the control panel made from industrial pulp and the panel with 20% recycled fiber content was minimal, at only 1.09 times. This suggests that panels with up to 20% recycled fibers exhibit similar bending strength to those made entirely from industrial (virgin) fibers. However, a significant decrease in the MOR was observed when the recycled fiber content was increased to 40%, with a reduction of 1.17 times compared to panels with 20% recycled fibers. This indicates that, beyond a certain threshold, the incorporation of recycled fibers begins to adversely affect the bending strength of the panels. Further increases in recycled fiber content led to relatively smooth deterioration in the MOR. Panels with 60% recycled fibers had only 1.11 times lower the MOR than those with 40% recycled fibers. Increasing the recycled fiber content to 80% resulted in a 1.06-times decrease in the MOR, and panels composed entirely of recycled fibers had a 1.22-times lower MOR than those with 80% recycled fibers. Despite the overall deterioration, rMDF panels with up to 20% recycled fiber content still fulfilled the standard requirement for general-purpose MDF used in dry conditions, which is an MOR of at least 22 N/mm^2 [55]. These findings are consistent with other studies that have shown the effects of recycled fibers on the mechanical properties of MDF panels [13,35].

The effects of the content of recycled fibers on the internal bond (IB) strength of the MDF panels is presented in Figure 7.

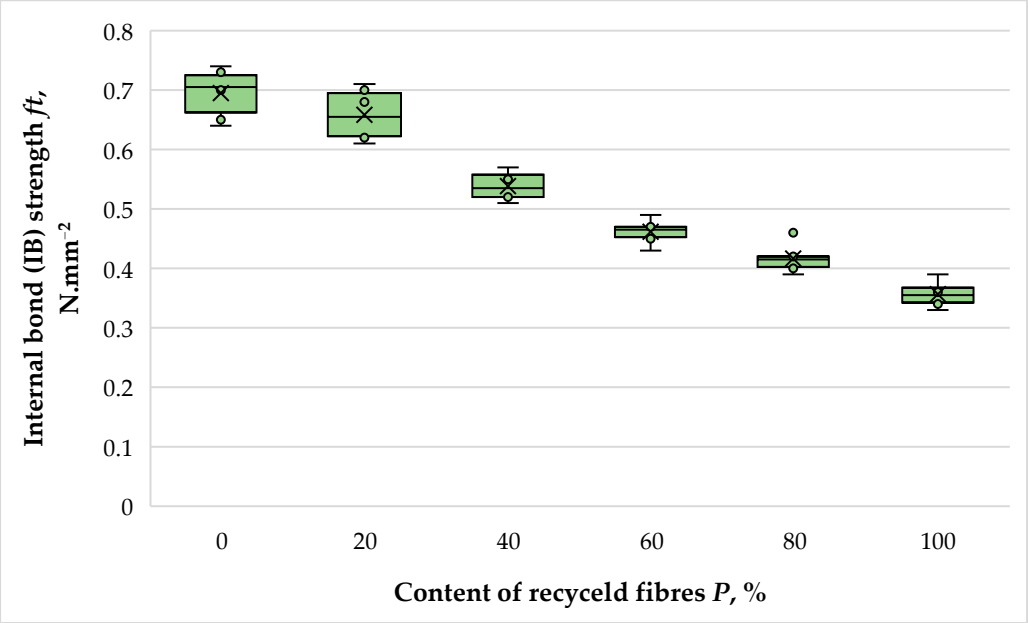


Figure 7. Internal bond (IB) strength of MDF panels fabricated with different content of recycled fibers.

With the complete replacement of virgin fibers by recycled fibers, the internal bond (IB) strength of the panels decreased from 0.70 N.mm^2 to 0.36 N.mm^2, indicating a significant deterioration of 1.95 times. However, when up to 20% of virgin fibers were replaced with recycled fibers, the decrease in the IB strength was only 1.06 times, suggesting a relatively minor impact on the panel's integrity. A significant deterioration of 1.22 times occurred when the content of recycled fibers was increased from 20% to 40%. The subsequent decrease in the IB strength, when increasing the content of recycled fibers from 40% to 60%, was 1.66 times. When the content of recycled fibers reached 80%, the decrease was another 1.11 times. Markedly, a drastic deterioration in the IB strength occurred when recycled fibers completely replaced the natural ones. Panels composed entirely of recycled fibers exhibited a 1.17 times lower transverse tensile strength compared to the panels with 80% recycled and 20% natural fibers. The results obtained are consistent with previous other studies, showing a significant decrease in the IB strength of MDF panels produced with higher recycled fiber content [13,23,34,35]. Treatments like lignin modification or the addition of pMDI resin can improve the IB strength of panels with higher recycled fiber content [13,54].

The variation of the formaldehyde content in rMDF panels fabricated with different participation of recycled fibers is presented in Figure 8.

Under the conditions of the present study, the formaldehyde content decreased from 5.4 mg/100 g o.d. in the MDF panels made of virgin fibers to 3.2 mg/100 g o.d. in the panels composed entirely of recycled fibers. This represents a 1.69-times reduction in formaldehyde content when virgin fibers were fully replaced with recycled ones. This decrease can be attributed to the presence of primary and tertiary amines, which are byproducts of UF resin degradation during hydrolysis. Primary and secondary amines act as formaldehyde scavengers, contributing to the observed reduction. The most significant decline in formaldehyde content (1.2 times) occurred when replacing 20% of virgin fibers with recycled fibers. Beyond this point, the reduction trend became more gradual, with decreases of 1.10 times, 1.11 times, and 1.09 times when increasing the recycled fiber content to 40%, 60%, and 80%, respectively. The difference in formaldehyde content between the MDF panels manufactured with 80% and 100% recycled fibers was relatively small (1.06 times), suggesting that a complete replacement of natural fibers did not provide substantial ad-

ditional benefits in terms of free formaldehyde reduction. For instance, when replacing up to 40% of natural fibers with recycled fibers, the formaldehyde content decreased by 1.32 times, while at 60% recycled fiber content, the reduction reached 1.46 times. Another key observation is that the deterioration in rMDF panel properties was not uniform as the recycled fiber content was increased. When up to 20% of natural fibers were replaced, the panels retained their mechanical properties relatively well, while exhibiting 1.2-times the reduction in formaldehyde content. These findings highlight the need for a detailed investigation into the effects of fiber content within the 40–60% range, as this appears to be a critical transition zone. Additionally, exploring the influence of UF resin content could be valuable, as increasing its concentration might help compensate for the negative effects of recycled fibers. Some studies have suggested that increasing UF resin content is feasible due to the formaldehyde-scavenging action of primary and secondary amines in recycled fibers [57,58].

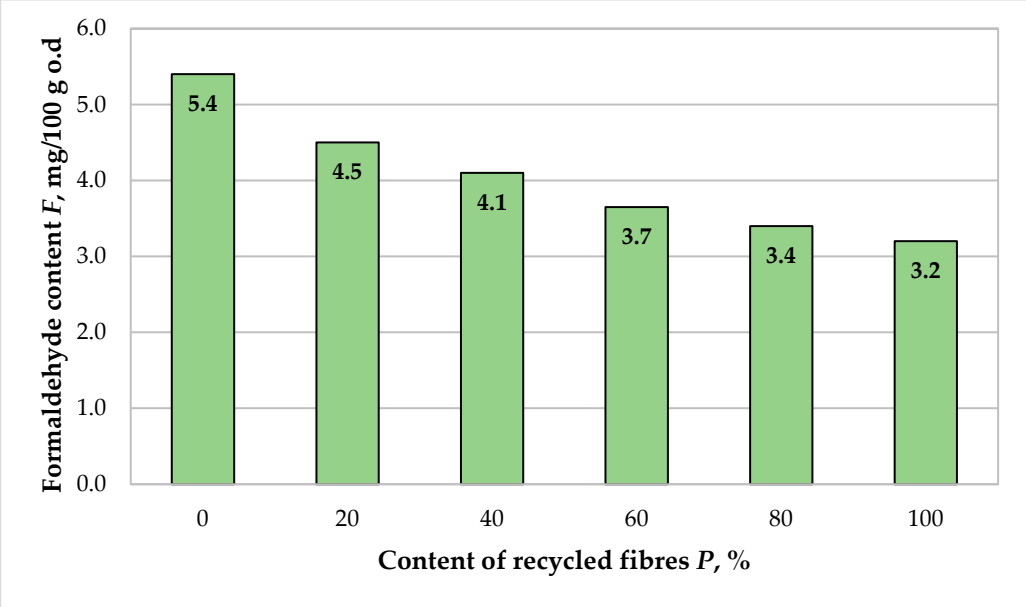


Figure 8. Formaldehyde emission of MDF panels fabricated with different content of recycled fibers.

The findings of this study, which indicate a deterioration in the main physical and mechanical properties of the panels alongside a reduction in free formaldehyde content, align with those reported by other researchers. Nuryawan et al. found that, while recycled fiberboard production is feasible, the resulting panel quality tends to be lower [59]. The study by Roffael et al. [60] demonstrated that thermo-mechanical pulp (TMP) derived from recycled panels can replace up to 30% of wood-based TMP in UF-bonded MDF production without significantly compromising physical and mechanical properties. Furthermore, the formaldehyde released from MDF containing TMP from recycled panels remains largely unchanged, with only minor variations in formate and acetate ion content and volatile acid emissions when compared to MDF produced from virgin fibers. This study suggests that chemical interactions occur between the degraded UF resin in recycled boards and the fresh binder used in MDF production. Lubis et al. [13] also reported a significant decline in panel properties when the recycled fiber content exceeds 30%, even when maintaining the UF resin content. This highlights the potential role of recycled fibers as formaldehyde scavengers, warranting further investigation into whether increasing UF resin content could offset the negative effects of recycled pulp on panel properties.

A fundamental explanation for the deterioration in the physical and mechanical properties of rMDF panels was provided by Moezzipour et al. [26]. The study establishes

that deacetylation occurs in recycled fibers, leading to an increase in carbonyl groups and furfural concentration during hot pressing. The esterification process is identified as the primary driver of property degradation, with these effects intensifying when hydrothermal hydrolysis temperatures exceed 125 °C. At 150 °C, the destruction of hemicelluloses and delignification becomes evident, further accelerating material breakdown. Additionally, the presence of spherical structures in the pulp derived from recycled fibers is recognized as another major factor contributing to the decline in panel quality.

3.2. Combined Effect of the Recycled Fibers and Urea–Formaldehyde Content on MDF Properties

As a result of the preliminary studies, it was determined that there is a significant decline in the properties of the panels with an increase in recycled fiber content from 40% to 60%, with noticeable deterioration occurring even with the addition of 20% recycled fibers. Based on this, for the investigation of the combined effect of recycled fiber content and UF resin on the main physical and mechanical properties and formaldehyde emission of MDF panels fabricated with varying recycled fiber content, the selected recycled fiber content levels were 10%, 30%, and 50%, while the UF resin content was set at 8%, 10%, and 12%, as shown in Table 3.

Table 3. Recycled fiber and UF resin content in the MDF panels.

Panel №	Recycled Fiber Content X1 (Coded)	UF Resin Content X2 (Coded)	Recycled Fiber Content R, % (Decoded)	UF Resin Content P, % (Decoded)
1	-	-	10	8
2	-	+	10	12
3	+	-	50	8
4	+	+	50	12
5	-	0	10	10
6	+	0	50	10
7	0	-	30	8
8	0	+	30	12
9	0	0	30	10

The density of the individual panels, along with the main variation–statistical indicators, is presented in Table 4.

Table 4. Density of MDF panels manufactured with different recycled fiber and UF resin contents.

Panel №	Mean Density ρ, kg.m^{-3}	Standard Deviation *Sy*, kg.m^{-3}	Standard Error *my*, kg.m^{-3}	Coefficient of Variation *Vy*, %	Probability, *Py*, %
1	781	26.82	3.43	9.48	1.21
2	766	58.34	7.62	20.63	2.69
3	779	55.39	7.11	19.58	2.51
4	777	49.94	6.43	17.65	2.27
5	790	74.32	9.41	26.28	3.33
6	781	72.14	9.23	25.50	3.26
7	779	40.14	5.16	14.19	1.82
8	793	47.22	5.95	16.70	2.10
9	772	70.46	9.13	24.91	3.23

The density of the individual panels varied between 766 kg/m^3 and 793 kg/m^3, resulting in a maximum difference of 3.5%. This difference is below the statistical error threshold of 5%, indicating that, in practical terms, the panels can be considered to have

a uniform density. Therefore, this fundamental performance indicator is not expected to influence the other properties of the panels. The insignificance of panel type in relation to density is further confirmed by the one-way analysis of variance (ANOVA), as presented in Table 5.

Table 5. ANOVA for the effect of recycled fiber and UF resin content on the density of the MDF panels.

Source of Variation	Sum of Squares Q	Degrees of Freedom ν	Variance 0 S^2	Calculated Fisher's Criterion F_{cal}	Critical Fisher's Criterion F_{cr}
Panel type	3912.83	7	558.98	0.184	2.178
Error	169,771.38	56	3031.63		
Total	173,684.22	63	-		

The summarized data on the physical and mechanical properties of the panels are presented in Table 6.

Table 6. Physical and mechanical properties of MDF panels manufactured with different recycled fiber and UF resin contents (standard deviations are indicated).

Panel №	Water Absorption A, %	Thickness Swelling Gt, %	Modulus of Elasticity Em, N.mm^{-2}	Bending Strength fm, N.mm^{-2}	Internal Bond (IB) Strength ft, N.mm^{-2}
1	49.19 ± 2.41	18.47 ± 1.17	3346 ± 157	23.91 ± 1.06	0.62 ± 0.011
2	33.67 ± 1.44	11.88 ± 0.50	3719 ± 182	25.51 ± 1.59	0.66 ± 0.011
3	63.43 ± 2.02	22.97 ± 1.37	2524 ± 200	16.74 ± 1.01	0.43 ± 0.016
4	45.44 ± 2.68	17.09 ± 1.13	3486 ± 141	19.8 ± 0.84	0.52 ± 0.012
5	39.3 ± 1.62	13.47 ± 0.80	3383 ± 129	20.18 ± 0.57	0.53 ± 0.017
6	58.65 ± 3.34	21.53 ± 1.16	2999 ± 152	17.45 ± 0.60	0.45 ± 0.013
7	44.51 ± 3.08	17.43 ± 0.87	3083 ± 201	20.9 ± 0.96	0.55 ± 0.012
8	42.4 ± 2.45	15.78 ± 1.04	3490 ± 226	22.68 ± 1.41	0.59 ± 0.016
9	39.98 ± 2.22	16.81 ± 1.05	3365 ± 145	21.4 ± 1.23	0.56 ± 0.017

The results regarding the free formaldehyde content are presented in Figure 9.

The data on formaldehyde content indicate that, despite the increased UF resin content, none of the produced panels exceeded the emission limit for class E1 ($\leq$8 mg/100 g). This can be attributed to the use of UF resin with an ultra-low molar ratio and the role of primary amines in the recycled fibers, which act as formaldehyde scavengers [40].

A direct conclusion from these results is that, in the production of MDF panels incorporating recycled fibers, the UF resin content with an ultra-low molar ratio can be as high as 12% while still complying with E1 standards. However, it should be noted that none of the panels met the requirements for class E0 (below 4 mg/100 g). Additionally, increasing the binder content is associated with higher production costs, which in turn affects the final product price [27,61].

Figure 10 presents the relationship between TS and the content of recycled fibers and UF resin in the panels.

The grey zone represents the combination of factor levels at which the panels failed to meet the EN 622-5 standard requirement for thickness swelling, which must not exceed 15%. As shown in Figure 10, under the experimental conditions, the maximum recycled fiber content that still meets the TS requirement is 34%, which requires a UF resin content of 12%. Even with a recycled fiber content as low as 10%, the UF resin content must be at least 9.6% to satisfy the TS requirement. The optimal (minimum) thickness swelling value of 11.21% (indicated by a white dot in the figure) is achieved at a recycled fiber content of

11.2% and a UF resin content at the upper boundary of 12%. The slight improvement in swelling performance with recycled fiber content up to approximately 11% aligns with the findings of other studies [13,62].

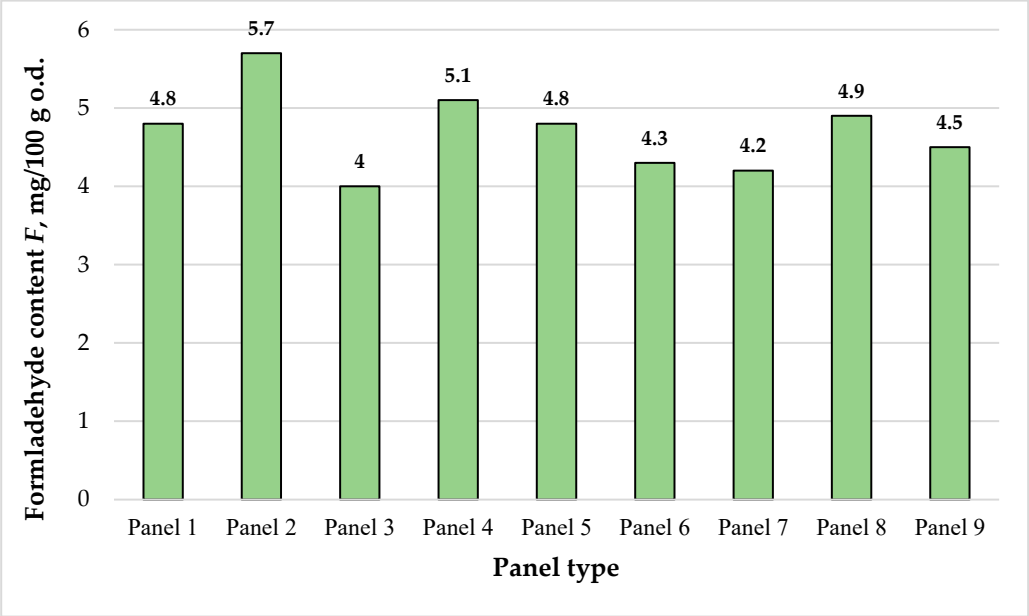


Figure 9. Formaldehyde content in MDF panels manufactured with different recycled fiber and UF resin contents.

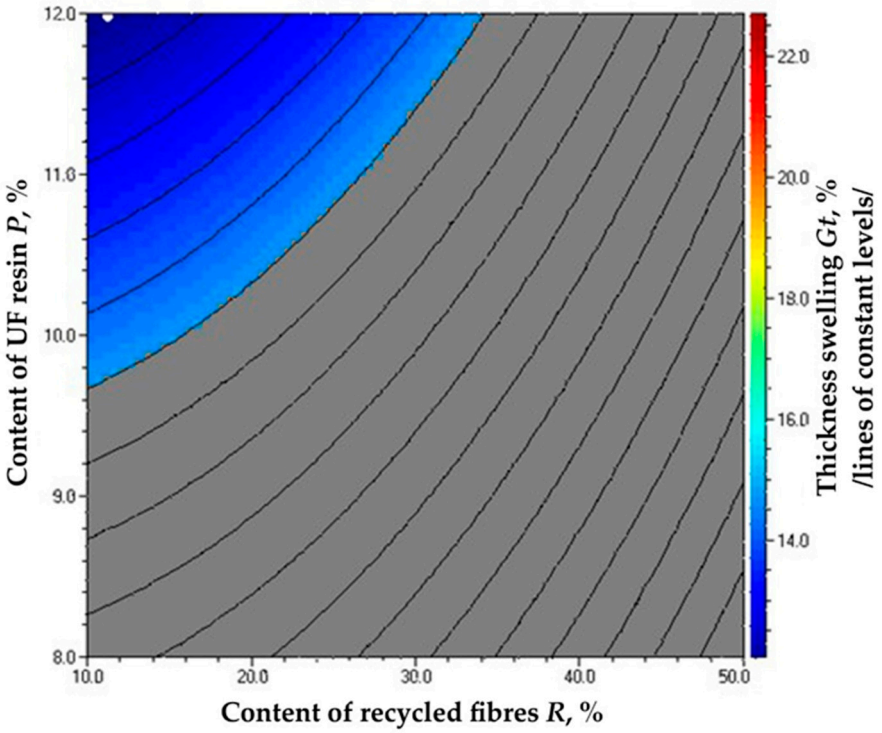


Figure 10. Dependence of thickness swelling (TS) of the laboratory-produced MDF panels on the content of recycled fibers and UF resin.

Figure 11 illustrates the relationship between the MOE and the content of recycled fibers and UF resin in the panels. The data indicate that increasing the recycled fiber content generally leads to a reduction in the MOE due to fiber degradation and reduced

fiber bonding strength. However, a higher UF resin content helps counteract this effect by improving the adhesion between fibers and enhancing the overall panel stiffness.

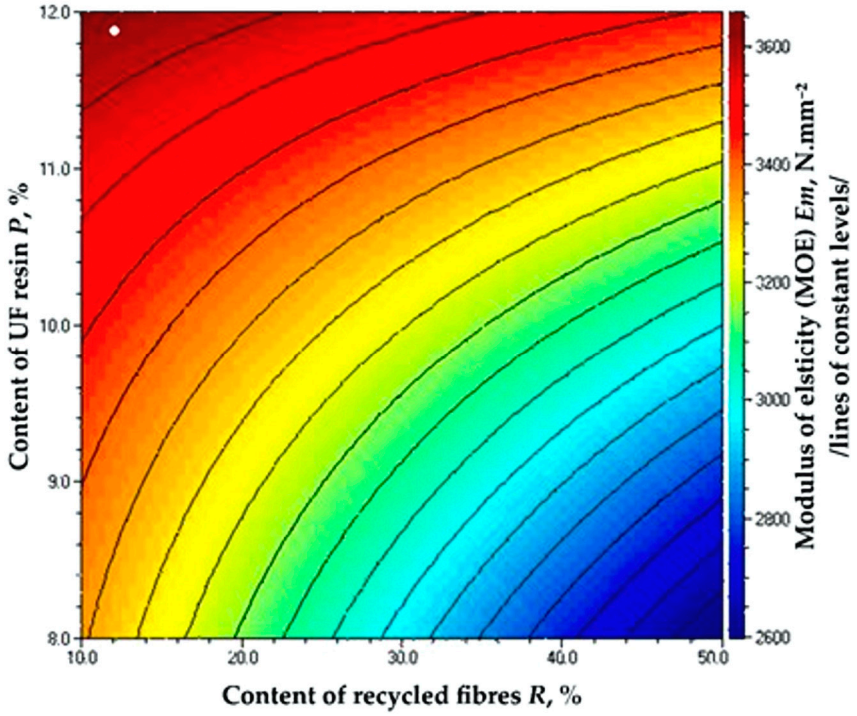


Figure 11. Dependence of the modulus of elasticity (MOE) of the laboratory-produced MDF panels on the content of recycled fibers and UF resin.

As confirmed by previous studies [35], panels incorporating recycled fibers largely retain their stiffness, which directly contributes to maintaining their MOE. Consequently, all panels meet the EN 622-5 requirement for the MOE for general-purpose use in dry conditions, which is at least 2500 N·mm^{-2}. The optimal MOE value of 3638 N·mm^{-2} (indicated by a white dot in the figure) is achieved at a slightly increased recycled fiber content of 10.92% and a UF resin content of 12%. This suggests that a moderate inclusion of recycled fibers, combined with a sufficient resin content, can effectively balance mechanical performance while maintaining compliance with industrial standards.

Figure 12 illustrates the relationship between bending strength, recycled fiber content, and UF resin content in the MDF panels. As the proportion of recycled fibers increases, the bending strength generally decreases, primarily due to the reduced bonding efficiency and lower fiber integrity compared to virgin fibers. However, this decline in strength can be partially offset by increasing the UF resin content, which enhances adhesive properties and fiber cohesion, thereby improving the bending resistance of the panels.

The grey zone in Figure 12 represents the combination of factor levels where the bending strength requirement for general-purpose panels used in dry environments (at least 22 N·mm^{-2}, as per EN 622-5) is not met. As shown in the graph, the maximum recycled fiber content that still satisfies the bending strength requirement is 36%, but this necessitates a UF resin content of at least 12%. Interestingly, with only 8% UF resin content, the recycled fiber content can be as high as 18% while still meeting the required bending strength. This suggests that a lower resin content can be compensated by a suitable level of recycled fibers, thereby achieving an optimal balance between the two factors to maintain the structural integrity of the panels.

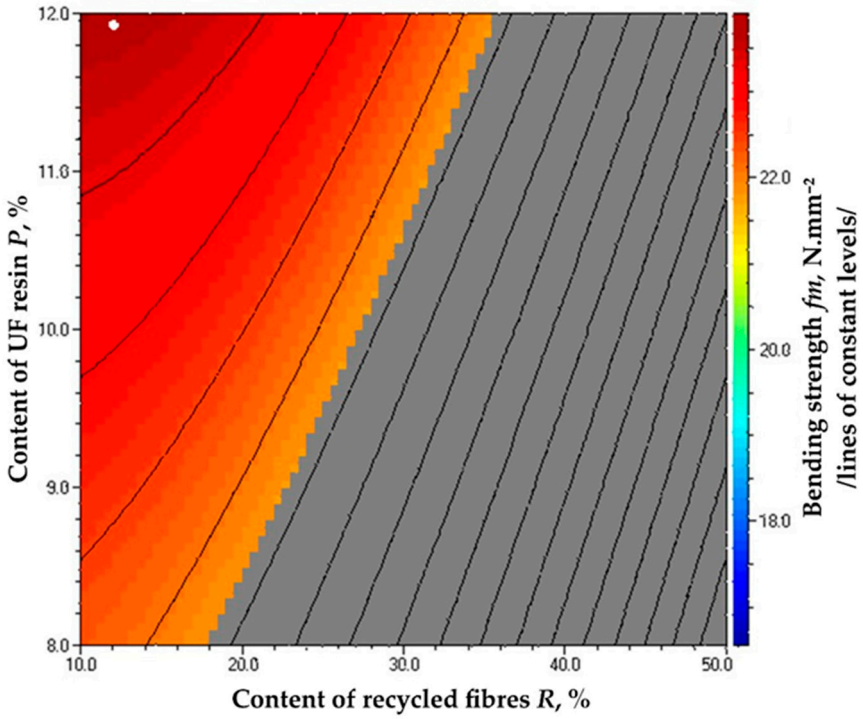


Figure 12. Dependence of bending strength (MOR) of the laboratory-produced MDF panels on the content of recycled fibers and UF resin.

The optimal bending strength value of 23.86 N·mm^{-2} (indicated by a white dot in the figure) was achieved when both the recycled fiber content and UF resin content are set at 12%. This balance between fiber and resin content ensures the desired mechanical performance while maintaining the required strength for general-purpose applications. The correlation between the final resin content in MDF panels and their mechanical properties, including the MOR, was also reported in other studies [63,64].

Figure 13 illustrates the relationship between the IB strength, the content of recycled fibers, and UF resin. As with other mechanical properties, tensile strength is influenced by the fiber–resin interaction. An increase in recycled fiber content generally reduces the tensile strength due to weaker bonding between the fibers. However, adequate UF resin content compensates for this, enhancing adhesion and improving the overall IB strength of the panels.

To meet the IB strength requirement of 0.60 N·mm^{-2} for MDF panels used in general dry environments, the maximum recycled fiber content should be 24%, with a corresponding UF resin content of 12%. When up to 10% recycled fibers are added, the UF resin content must be at least 9.2% to satisfy the tensile strength requirement. The optimal IB strength value of 0.66 N·mm^{-2} (indicated by a white dot in the figure) was achieved with a recycled fiber content of 10.2% and a UF resin content of 12%. This suggests that a moderate level of recycled fibers, combined with an appropriate amount of UF resin, can optimize the mechanical performance of the panels, particularly in terms of the IB strength [16,65].

Figure 14 illustrates the relationship between WA, recycled fiber content, and UF resin content. The water absorption properties of the panels are critical for evaluating their durability and performance in humid or wet environments. As the recycled fiber content increases, the WA tends to rise due to the inherent differences in fiber structure and bonding efficiency compared to virgin fibers. However, the addition of UF resin helps to mitigate this effect by improving the bonding and water resistance of the panels, thereby enhancing their overall performance in environments with high moisture levels [16,20,58].

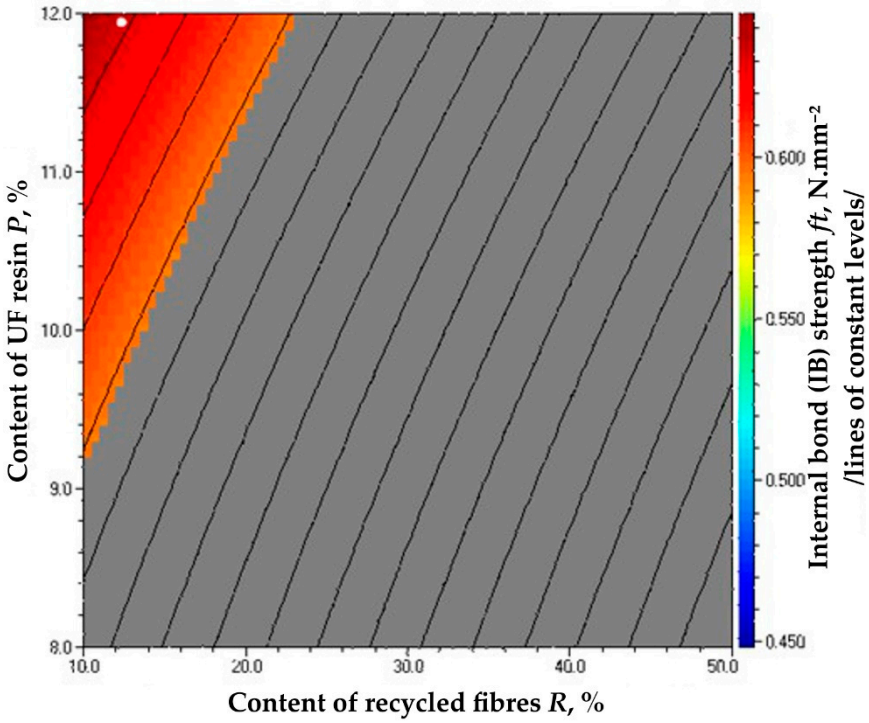


Figure 13. Dependence of internal bond (IB) of the laboratory-produced MDF panels on the content of recycled fibers and UF resin.

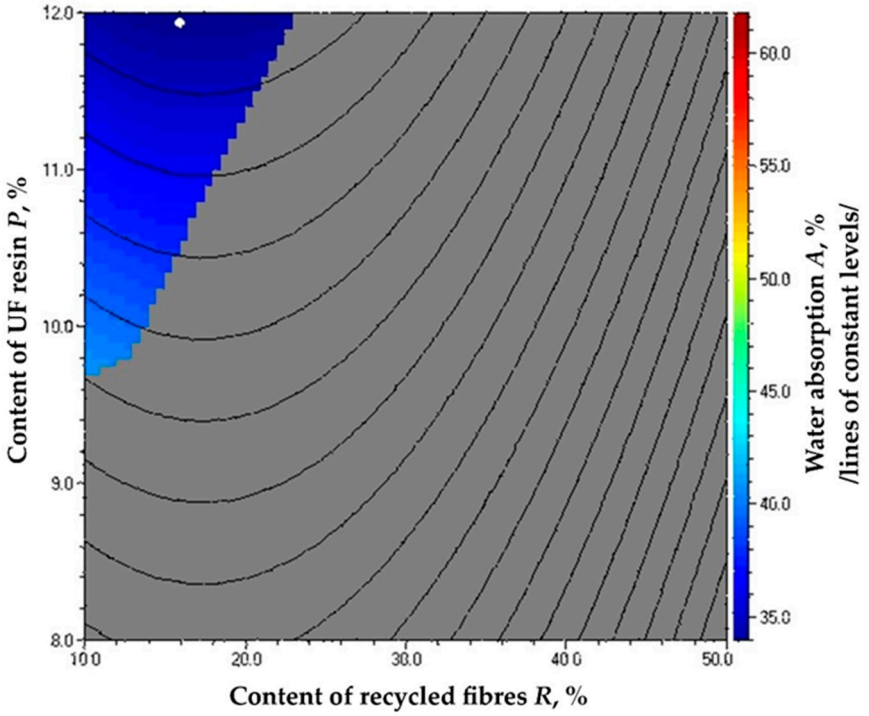


Figure 14. Dependence of water absorption (WA) of the laboratory-produced MDF panels on the content of recycled fibers and UF resin.

As WA is not a standardized property, Figure 14 includes the limitations on other physical and mechanical properties of MDF panels. The optimal minimal WA value of 34.19% (indicated by a white dot in the figure) was achieved with a recycled fiber content of 14.8% and a UF resin content of 12%. Upon analyzing Figure 14, which includes the requirements for the physical properties of MDF panels intended for general use in dry environments, it can be concluded that the maximum recycled fiber content is 24%, with

a UF resin content of at least 12%. When the recycled fiber content is 10%, the panels can meet the standard requirements with a minimum UF resin content of 9.8%. This indicates that, while increased recycled fiber content helps reduce the environmental footprint, it requires careful control of resin content to ensure the panels meet the necessary mechanical performance and durability standards [58,66]. Striking the right balance between recycled fiber content and resin ensures that the panels maintain the required characteristics for use in dry environment applications.

4. Conclusions

The studies conducted on the effect of recycled fiber content on the properties of MDF panels demonstrated a significant deterioration in performance-related properties when recycled fibers completely replaced virgin fibers. Specifically, the MOE values decreased by a factor of 1.37, the MOR by 1.81, the WA by 1.71, the TS by 1.54, and the IB strength by 1.94. These findings clearly indicate that complete substitution of virgin fibers with recycled fibers is not advisable for MDF panel production due to the significant decline in essential properties. Markedly, the formaldehyde content in the recycled MDF (rMDF) panels decreased by a factor of 1.68, which can be attributed to the presence of primary amines. These amines are by-products of UF resin degradation, and they help reduce formaldehyde emission in the final panels. Another significant observation is that the deterioration in the properties of the MDF panels was not uniform as the recycled fiber content was increased. Panels with up to 20% recycled fiber content maintained satisfactory physical and mechanical properties, while formaldehyde content decreased by a factor of 1.2. A notable decline in properties was observed when the recycled fiber content was increased from 20% to 40%, after which the deterioration became more gradual and uniform with further increases in recycled fiber content. This trend suggests the need for further research to explore the impact of recycled fiber content in the 40% to 60% range. To note, the effect of UF resin content should be further investigated. Increasing the resin content could partially mitigate the adverse effects of recycled fibers. The findings suggest that the increased UF resin content may be facilitated by the formaldehyde-scavenging action of primary and secondary amines present in the recycled fibers. The combined effect of recycled fiber content and UF resin indicated that higher recycled fiber content allowed for a higher UF resin content without significantly increasing free formaldehyde levels in the panels, thanks to the enhanced action of primary amines as formaldehyde scavengers. The main contribution of this work is the establishment of the combined effects of recycled fiber content and UF resin on the properties of rMDF panels. Based on the experimental results and subsequent analysis, it was determined that the maximum allowable recycled fiber content through hydrothermal hydrolysis and hammer mill refinement is 24%, with a corresponding UF resin content of at least 12%. Furthermore, for the panels to meet the performance standards for general-purpose MDF in dry conditions, even with a 10% recycled fiber content, the UF resin content must be increased to 9.8%. The findings offer valuable insights for MDF manufacturers, supporting the development of more sustainable, cost-effective, and high-performance products. Future research should focus on refining the recycling process and exploring alternative resins that could improve the performance and sustainability of MDF panels, contributing to the circular economy and reducing the environmental footprint of the industry.

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