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# Enhanced properties of the inner part of date palm wood through double-stage treatment: synergistic effects of low-viscosity melamine–formaldehyde resin impregnation and densification

Peyman Ahmadi<sup>1\*</sup> , Ghanbar Ebrahimi<sup>1</sup> and Alireza Ashori<sup>2</sup>

## Abstract

This study investigates the enhancement of the physical and mechanical properties of date palm wood (*Phoenix dactylifera*) through a two-stage treatment process. This process involves impregnation with low-viscosity melamine–formaldehyde (MF) resin, followed by densification. The goal is to address the inherent weaknesses of palm wood and explore its potential for high-value applications. Wood samples were treated with different resin concentrations 5, 10, and 25% (wt. %) and subjected to a 50% compression ratio. Physical properties such as density, water absorption, and thickness swelling were evaluated, while mechanical tests included bending strength (MOR), stiffness (MOE), impact resistance, and screw-holding capacity (SHC). Additionally, formaldehyde emissions were measured to assess environmental impact. Key findings revealed significant improvements in both physical and mechanical properties. Density increased nearly fourfold in the most intensively treated samples, while water absorption and thickness swelling were significantly reduced, indicating improved dimensional stability. Mechanical properties showed substantial enhancements, with MOR improving by 241%, MOE by 136.36%, and SHC by 114%. Notably, formaldehyde emissions were low, thus meeting the emission limits specified in the Chinese National Standard GB/T 17657. The combination of impregnation and densification demonstrated synergistic effects, often outperforming single treatments. These findings suggest that the proposed treatment method offers a promising approach to valorizing date palm waste, potentially addressing environmental concerns while creating high-performance, environmentally friendly wood products suitable for various applications. This study contributes valuable insights to the field of wood modification, opening new possibilities for utilizing date palm wood in industries requiring materials with enhanced strength and dimensional stability.

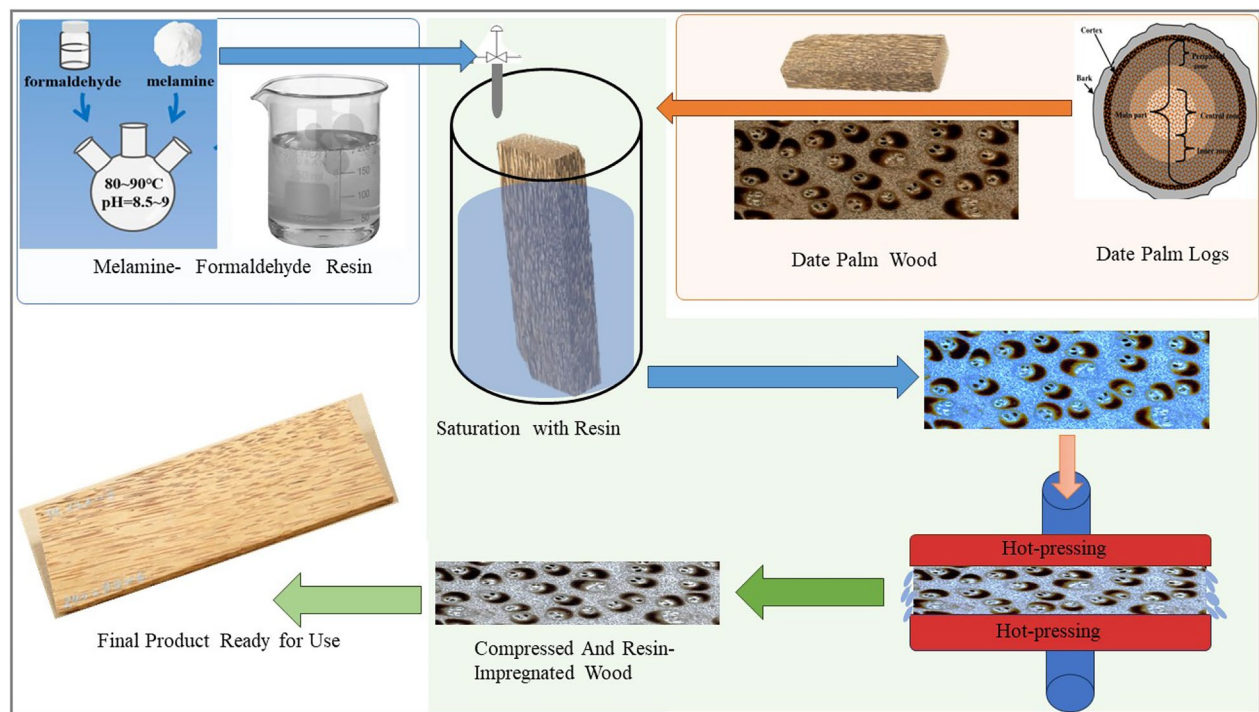
**Keywords** Date palm wood, Melamine–formaldehyde resin, Wood densification, Mechanical properties, Formaldehyde emissions

\*Correspondence:

Peyman Ahmadi  
ahmadi.p@ut.ac.ir

Full list of author information is available at the end of the article

## Graphical Abstract



## Introduction

Date palms (*Phoenix dactylifera*) are a crucial agricultural resource in arid regions of Asia and Africa, where they thrive under challenging climatic conditions. They are not only essential for local economies but also play a significant role in cultural traditions. However, the management of palm waste poses a considerable environmental challenge. When date palms reach the end of their economic life, typically between 20 and 30 years, a substantial amount of waste is generated [1, 2]. The resulting solid waste includes empty fruit bunches, pruned branches, trunks, and pressed fibers [3, 4]. The trunks of date palms represent a significant waste management issue due to their large volume and limited reuse options [5]. Currently, much of this biomass is incinerated, contributing to air pollution and greenhouse gas emissions [6]. However, emerging research suggests that palm waste can be repurposed as an industrial raw material, offering a more sustainable solution. For instance, date palm biomass can be utilized in the production of biofuels, particleboard, and other composite materials. Despite these opportunities, the inherent properties of date palm wood characterized by its low mechanical strength and durability limit its applications in high-value products. The structural weaknesses are attributed to the

wood's anatomical configuration, where adjacent vascular bundles lack a cohesive lignin matrix, resulting in poor resistance to environmental factors [7, 8]. As a response to these challenges, there is a growing interest in repurposing palm wood into higher-value products through innovative treatment methods [9].

Various strategies have been explored to enhance the properties and applicability of palm wood. These include the production of pyrolysis acid [10] and the conversion of palm wood into composite materials such as particleboard, chipboard, oriented strand board (OSB), and medium-density fiberboard (MDF) [11, 12]. Other approaches involve palm wood treatment, heat treatment [13], densification [14], and impregnation [15]. Impregnation with resins has shown promise in improving palm wood's durability and strength. Dungani et al. [8] demonstrated enhanced durability through phenol-formaldehyde (PF) resin impregnation. Other resins, including melamine-formaldehyde (MF), urea-formaldehyde (UF), and melamine-urea-formaldehyde (MUF), have also been investigated for their potential to act as a synthetic lignin, binding vascular bundles and improving overall wood characteristics [16, 17].

However, existing treatment methods often focus on single processes, which may not fully address the

limitations of date palm wood. Existing treatment methods for date palm wood often rely on single processes, which may not fully address its inherent limitations. To overcome these challenges, this study proposes a novel two-stage treatment process that combines (1) impregnation with low-viscosity MF resin and (2) subsequent densification of the resin-impregnated palm wood. This innovative dual approach aims to significantly enhance the mechanical strength and durability of date palm wood while mitigating its natural weaknesses. The hypothesis driving this research is that the combination of resin impregnation and densification will lead to substantial improvements in the mechanical properties of date palm wood. Specifically, it is expected that the low-viscosity MF resin will penetrate the wood structure more effectively, mimicking the role of synthetic lignin and thus enhancing the wood's overall performance. Additionally, densification is anticipated to improve the density and dimensional stability of the wood, making it more suitable for high-performance applications in construction and furniture manufacturing. The novelty of this work lies in its dual approach, integrating two complementary processes—impregnation and densification—into a cohesive treatment strategy. By combining these methods, the study not only seeks to improve the physical and mechanical properties of the wood but also promotes the sustainable use of agricultural waste. This process has the potential to transform low-value palm waste into high-value products, aligning with global efforts toward sustainable resource management. Furthermore, it contributes to the circular economy by enhancing the economic viability of palm-producing regions.

However, existing treatment methods often focus on single processes, which may not fully address the limitations of date palm wood. Existing treatment methods for date palm wood often rely on single processes, which may not fully address its inherent limitations. To overcome these challenges, this study proposes a novel two-stage treatment process that combines (1) impregnation with low-viscosity MF resin and (2) subsequent densification of the resin-impregnated palm wood. Previous research has already explored dual-stage treatments combining resin impregnation with densification in other lignocellulosic materials such as softwoods, hardwoods, bamboo, and oil palm trunk [18, 19]. These studies demonstrated that the combination of resin impregnation and compression can significantly improve density and mechanical properties. However, to the best of our knowledge, such a systematic approach has not yet been applied to date palm wood, particularly its inner part, which is characterized by a loose and porous structure. The originality of the present study therefore lies not in the general concept

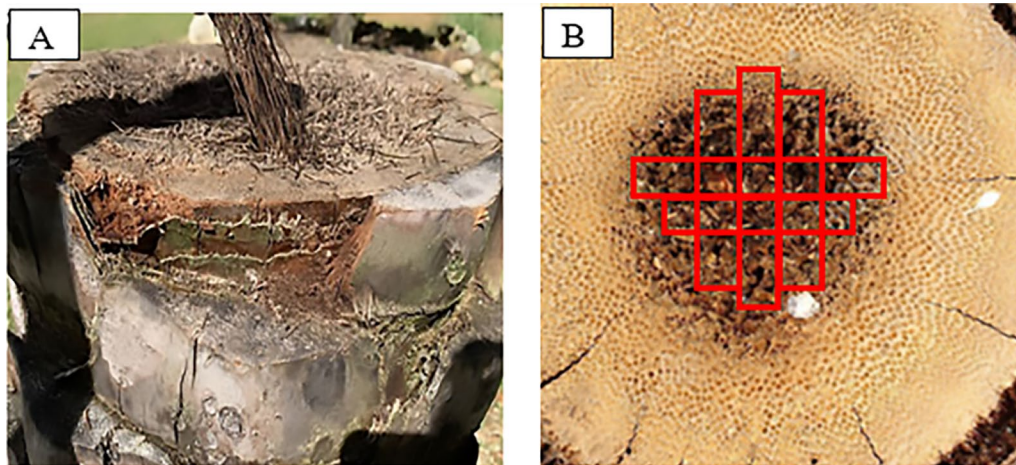
of the dual-stage treatment itself, but in extending it specifically to the underutilized biomass of date palm trunks. This approach highlights a valuable valorization pathway for a large and regionally abundant lignocellulosic resource. In this study, we specifically focused on the inner part of date palm trunks, which in many palms exhibit a loose and porous structure with very low mechanical strength. In some cases, this inner part is highly fragile and therefore discarded as waste. Demonstrating that this least-utilized portion can be effectively reinforced highlights the potential for valorizing palm biomass that is otherwise neglected. This process has the potential to transform low-value palm waste into high-value products, aligning with global efforts toward sustainable resource management. Furthermore, it contributes to the circular economy by enhancing the economic viability of palm-producing regions.

## Materials and methods

### Material

Three date palm (*Phoenix dactylifera*) logs with a 40 cm diameter, sourced from Yazd province in Iran, provided the lignocellulosic material for this study. In this study, a sample was taken from the center (heartwood) of the date palm, which exhibited a completely loose and porous texture with minimal structural resistance, rendering it unsuitable for practical applications (Fig. 1). Before treatment, all samples were conditioned for 2 weeks in a climate chamber maintained at 65% relative humidity and 20 °C temperature. Following ISO standards for evaluating physical and mechanical properties, two sets of samples were prepared. The first set, intended for control and impregnation treatments, and had dimensions of  $20 \times 20 \times 300$  mm<sup>3</sup> (radial  $\times$  tangential  $\times$  longitudinal mm<sup>3</sup>). The second set, designed for densification and double treatment processes, had initial dimensions of  $20 \times 40 \times 300$  mm<sup>3</sup>.

For the impregnation process, samples from both sets were treated with resin. The densification process, applied to the thicker samples  $20 \text{ mm} \times 40 \text{ mm} \times 300 \text{ mm}$ , involved saturating the samples and then compressing them to a final thickness of 20 mm, achieving a 50% compression ratio. Some samples underwent a double treatment, combining both impregnation and densification processes. Following the treatments, the samples were further prepared for property evaluation. All subsequent tests complied with relevant ISO 13061-13 (2016) and ISO 13061-17 (2014) standards for physical and mechanical property assessment, respectively [20, 21]. This methodology ensured a comprehensive evaluation of the effects of various treatments on the date palm wood samples.



**Fig. 1** A Sampling of the inner part of the date palm trunk, B cross section indicates the date palm used as a sample in this study

### Preparation of resin for impregnation

In this research, MF resin was used to impregnate the date palm wood. These resins were specifically prepared with a low formaldehyde ratio and molecular weight to enhance penetration into the wood structure. The resin preparation process began by combining melamine ( $\geq 99\%$ , Sigma-Aldrich, USA) and formaldehyde (37% aqueous solution, analytical grade; Merck, Germany) in a flask, using a molar ratio of 1:1.5. Water was added to the mixture until it comprised about 50% of the total aqueous solution. The pH of the solution was adjusted to 8.5 by adding a 10% aqueous solution of sodium hydroxide (prepared from pellets, analytical grade; Merck, Germany). This mixture was maintained at approximately 85 °C for 2–3 h until the solution became clear. The reaction was continued until the solution became clear, and the endpoint was further confirmed by viscosity stabilization and gel time ( $\sim 210$  s at 100 °C). A dilution test (1:2 resin:water) was performed afterwards as a characterization method to verify resin miscibility and stability, rather than as a synthesis endpoint. In the final step, NaOH solution was added again to adjust the pH of the resin to a range of 8.5–9. The resin was then cooled to ambient temperature. This carefully controlled preparation process ensured a low-viscosity MF resin suitable for effective impregnation of date palm wood while minimizing potential formaldehyde emissions. After resin preparation, its properties include viscosity, acidity, solids content (following ASTM D4426 standard) [22]. The content of free formaldehyde in the resin (according to the sulfite method) was measured. The viscosity of the resin was measured according to ASTM D1084 using a Ford Cup #4 (orifice diameter 4.12 mm) at  $21 \pm 1$  °C (Ford Cup Viscometer, BYK-Gardner, Germany) [23].

### Palm wood treatment

#### Impregnation of palm wood

The impregnation process began with diluting the prepared MF resin to concentrations of 5%, 10%, and 25%, calculated relative to the dry weight of the resin. Prior to impregnation, all specimens were oven-dried at  $103 \pm 2$  °C until constant weight to ensure an initial moisture content of approximately 0%. This step allowed accurate evaluation of weight percent gain and consistent resin uptake during impregnation and densification. Impregnation was performed using a vacuum–pressure process. Uniformity of uptake was checked by comparing specimen weights and by visual inspection of cross-sections after curing. Palm wood samples were then impregnated under 0.5 MPa of pressure for 30 min. Following the impregnation, the treated samples underwent a drying process in an oven maintained at 70 °C, for 24 h. For the densification process, impregnated samples were initially adjusted to a moisture content (MC) of  $40 \pm 5\%$  in order to facilitate plasticization of the cell wall. Prior to all physical and mechanical tests, all specimens were conditioned at 20 °C and 65% relative humidity until reaching an equilibrium MC of  $12 \pm 2\%$ .

#### Densification

The densification process was carried out on the partially cured, impregnated samples. This step involved compressing the palm wood at an elevated temperature of 150 °C under a pressure of 4 MPa. The goal was to achieve a 50% densification ratio, reducing the initial sample thickness from 40 mm to a final thickness of 20 mm. To ensure proper resin curing and to prevent thickness recovery, the compressed samples were maintained under pressure for 20 min. This densification process aimed to further enhance the physical and

mechanical properties of the impregnated palm wood. A comprehensive description of the various treatments applied in this study is summarized in Table 1. For each treatment condition, 12 large specimens ( $20 \times 40 \times 300$  mm<sup>3</sup>) were prepared and treated. Smaller test specimens required for the physical and mechanical tests were then cut from these larger samples, according to the dimensions specified by the respective standards. This allowed multiple test specimens to be obtained from each treated sample.

### Springback

Upon completion of the pressing process, samples were immediately removed from the press to measure the elastic springback of the densified specimens. The samples were then conditioned at 20 °C and 65% relative humidity (RH) for 2 weeks to achieve moisture equilibrium. The total springback (SB) was calculated as a combination of immediate elastic recovery and delayed-elastic springback using Eq. 1. Six samples were used for this test.

$$SB = \frac{T_{12} - T_p}{T - T_p}, \quad (1)$$

where  $T$  represents the initial thickness of the sample before treatment, measured in mm,  $T_p$  is the thickness of the sample immediately after the pressing process, in mm.  $T_{12}$  denotes the final thickness of the sample, in mm after it has been conditioned at 20 °C and 65% RH for 2 weeks.

### Physical tests

The physical properties of the samples were evaluated through several measurements, including bulk density, weight percent gain (WPG), water absorption (WA), and thickness swelling (TS). WPG was calculated based on the weight of the samples before and after impregnation using Eq. 2. Six samples were used for this test:

$$WPG(\%) = \frac{M_0 - M_1}{M_1} \times 100. \quad (2)$$

$M_1$  is the oven dry weight of palm wood before impregnation (g), and  $M_0$  is the oven dry mass of treated wood after impregnation (g).

To determine WA and TS, the initial weight and thickness of samples were measured. The samples were then placed in a vacuum for 30 min, followed by soaking in distilled water for 24 h. After soaking, the thickness and weight were measured again. TS and WA were calculated using Eqs. 3 and 4, respectively:

$$TS(\%) = \frac{T_2 - T_1}{T_1} \times 100, \quad (3)$$

$$WA(\%) = \frac{M_2 - M_1}{M_1} \times 100, \quad (4)$$

where  $T_1$  is the thickness of samples before water immersion (mm),  $T_2$  is the thickness of samples after water soaking (mm),  $W_1$  is the weight of samples before water soaking (g), and  $W_2$  is the weight of samples after water immersion (g).

### Mechanical tests

Bending strength tests, including modulus of elasticity (MOE) and modulus of rupture (MOR), were conducted according to ISO 13061-3 [24]. Five samples ( $20$  mm  $\times$   $20$  mm  $\times$   $300$  mm) were tested using an Instron 4460 machine. Additionally, impact resistance was assessed using a 20-J pendulum. To evaluate the wood's suitability for pallets and frames, screw-holding capacity (SHC) was tested following TS EN 13446 [25]. Wood screws ( $4 \times 50$  mm) were manually inserted into samples, protruding from the surface. The screw removal speed was 4 mm/min. The holding capacity (SHC) was calculated using Eq. 5. Six samples were used for each of these tests:

$$SHC = \frac{F_{\max}}{d \times l_p}, \quad (5)$$

where  $SHC$  is the holding capacity (N/mm<sup>2</sup>),  $F_{\max}$  is the maximum force at the end of the test (N),  $d$  is the diameter of the screw (mm), and  $l_p$  is the screw length entering samples (mm).

### Formaldehyde emissions

For the formaldehyde emission test, small specimens with dimensions of  $50 \times 50 \times 10$  mm<sup>3</sup> (radial  $\times$  tangential  $\times$  longitudinal) were prepared according to GB/T 17657 (desiccator method) [26]. These pieces were sub-cut from the larger treated blocks after impregnation

**Table 1** Summary of treatments applied to date palm wood samples

| No. | Treatments                                | Saturated resin concentration (%) | Code      |
|-----|-------------------------------------------|-----------------------------------|-----------|
| 1   | Control                                   | –                                 | C         |
| 2   | Densification                             | –                                 | D         |
| 3   | Impregnated <sub>MF</sub>                 | 5                                 | I (5%)    |
| 4   | Impregnated <sub>MF</sub>                 | 10                                | I (10%)   |
| 5   | Impregnated <sub>MF</sub>                 | 25                                | I (25%)   |
| 6   | Impregnated <sub>MF</sub> + densification | 5                                 | I (5%) D  |
| 7   | Impregnated <sub>MF</sub> + densification | 10                                | I (10%) D |
| 8   | Impregnated <sub>MF</sub> + densification | 25                                | I (25%) D |

and/or densification to ensure that all specimens had undergone identical treatment. The total exposed surface area of the specimens was adjusted to comply with the requirements of GB/T 17657. Test pieces were then placed in a desiccator for 24 h at 20 °C, with a petri dish containing 30 mL of distilled water inside. The released formaldehyde was absorbed by the water, and its concentration was subsequently determined using the acetylacetone photometric method [27]. The test was performed in triplicate, and the average result was reported.

### Data analysis

Statistical analysis was conducted using SPSS software. A one-way analysis of variance (ANOVA) was performed at a 95% confidence level to analyze the collected data. Additionally, Duncan's multiple range test was used for post hoc comparison of means between groups.

## Results and discussion

### Physical properties of MF resin

The physical properties of the MF resin synthesized in this study are presented in Table 2. The resin had a density of 1.31 g/cm<sup>3</sup>, viscosity of 23 mPa·s, and a solid content of 53.1%. The free formaldehyde content in the resin synthesized at a melamine-to-formaldehyde molar ratio of 1:1.5 was 0.47 ppm, with most melamine

reacting completely with formaldehyde. Some unreacted melamine precipitated at the reactor's bottom, but in insignificant amounts. Higher melamine ratios led to increased precipitation or shorter resin shelf life. A similar conclusion was reached by Airilmies et al. [28], where a decrease in the formaldehyde-to-melamine ratio, while reducing the free formaldehyde content, caused the resin to gel rapidly.

### Physical properties

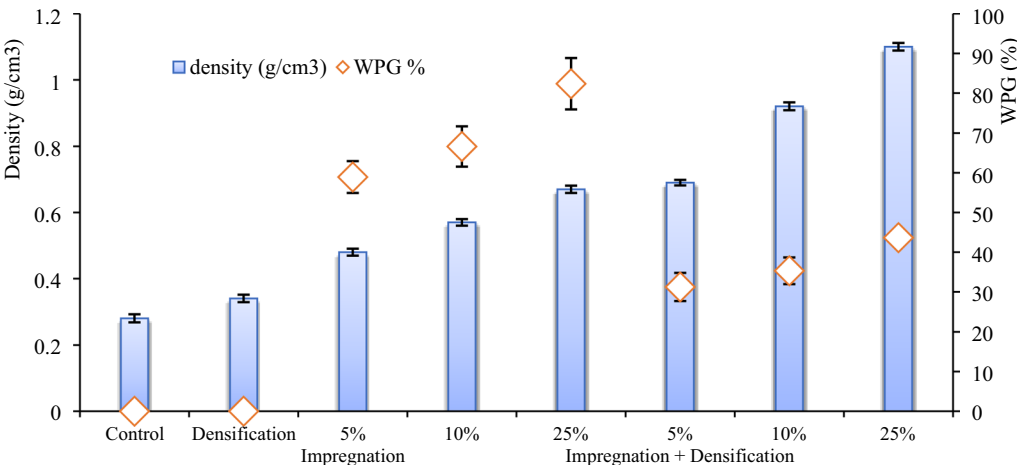
#### Density

The results of the experiment show distinct changes in the density and weight percent gain (WPG) of palm wood samples after undergoing impregnation, densification, and their combination (Fig. 2). The control sample had the lowest density of approximately 0.28 g/cm<sup>3</sup>. Densification alone increased the density to 0.34 g/cm<sup>3</sup>, while impregnation treatments with MF resin led to a progressive increase in density depending on resin concentration, with values ranging from 0.48 g/cm<sup>3</sup> at 5% to 0.69 g/cm<sup>3</sup> at 25%. The highest density, approximately 1.10 g/cm<sup>3</sup>, was observed in samples subjected to both 25% MF impregnation and densification. This indicates a synergistic effect of both treatments. The WPG followed a similar trend. Pure impregnation treatments resulted in significant WPG increases, with the 25% MF treatment yielding the highest value of around 90%. Hasani et al. [29] observed WPG values ranging from 35 to 75% when impregnating date palm wood with a lignin-based resin. This shows a comparable trend to the findings of the current study, where WPG values reached up to 82% for treatments done with 25% resin concentration. However, since Hasani et al. [29] used a different resin system and likely a different concentration, this comparison should be considered as indicative of a similar trend rather. Also,

**Table 2** Physical properties of MF resin synthesized in the laboratory

| Physical properties of MF resin | Solid content (%) | Density (g/cm <sup>3</sup> ) | Apparent viscosity (mPa·s) | Free formaldehyde (ppm*) | pH  |
|---------------------------------|-------------------|------------------------------|----------------------------|--------------------------|-----|
|                                 | 53.1              | 1.31                         | 23                         | 0.47                     | 9.3 |

\*ppm: parts per million



**Fig. 2** Effects of various treatments on density and weight percent gain (WPG) of date palm wood

the progressive increase in density and WPG with higher resin concentrations is consistent with findings from Almi et al. [30] and Elkhail et al. [31], who reported that increased resin concentrations result in higher density and WPG due to the filling of porous structures within the date palm wood.

The maximum WPG of ~90% was observed for the 25% impregnation-only treatment, while the combined impregnation and densification process yielded slightly lower values. This suggests some resin loss during compression markedly reduced WPG, with the combined treatment showing about half the uptake compared with impregnation alone. The data clearly demonstrate that both impregnation and densification significantly impact the physical properties of palm wood, notably increasing its density. The observed increase in density is directly related to resin concentration, with higher concentrations filling the porous structure of the wood more effectively. In particular, the combination of densification and impregnation resulted in the most substantial density increase, as densification compresses the wood structure, allowing the resin to penetrate more deeply into the wood. This aligns with findings from previous studies, such as Ahmad et al. [32] and Shebani et al. [33], which also reported increased density in densified wood impregnated with resin. However, despite the increase in density, the WPG slightly decreased when impregnation was combined with densification, which can be attributed to the mechanical forces exerted during densification. This process causes some of the impregnated material to be expelled from the wood, thus slightly lowering the overall WPG. This phenomenon is in line with the theory that densification can enhance wood properties by increasing compaction, but it may simultaneously reduce the amount of retained resin. This observation is crucial because it suggests a trade-off between maximizing density and maintaining WPG. While densification increases the overall strength and compactness of the wood, the slight reduction in WPG indicates a loss of impregnating material, which could affect other properties such as water resistance or durability. Future studies should further investigate the optimization of these parameters to ensure a balance between density enhancement and resin

retention. In conclusion, the results validate the hypothesis that densification combined with resin impregnation significantly improves wood density. However, the slight reduction in WPG suggests a need for further refinement of the process to minimize resin loss during compression.

The analysis of Table 3 reveals significant changes in springback behavior of palm wood samples subjected to various treatments. Springback is a critical property in densified wood materials, indicating the dimensional stability of treated samples. The control sample exhibited the highest springback, which was 0% for the control (non-pressed) group and  $56.0 \pm 5.9\%$  for densification alone, while the impregnation + densification groups showed reduced springback relative to densification alone (see Table 3 for exact values). Impregnation treatments with MF resin at concentrations of 5%, 10%, and 25% showed no measurable change in springback; the most notable reduction was observed in samples that underwent both impregnation and densification, with springback percentages dropping to around 10–15%. A clear trend of decreasing springback with increasing resin concentration was evident in both impregnation-only and combined treatments. This suggests that higher resin concentrations contribute to better dimensional stability of the treated palm wood. These results align well with findings from related studies in the literature. Salih et al. [34] reported reduced springback in date wood after pre-mechanical compression, comparable to the densification effect observed in this study.

The further reduction in springback achieved through resin impregnation is consistent with results reported by Shams and Yano [35], who found that impregnation with low-viscosity PF resin significantly improved dimensional stability in compressed wood. The synergistic effect of impregnation and densification in minimizing springback aligns with the findings of Srivaro et al. [36], who observed enhanced dimensional stability in thermally compressed coconut wood. Although their study focused on different palm species, the principle of combining treatments for improved stability is similar. The trend of decreasing springback with increasing resin concentration is consistent with observations by Ahmadi et al. [37] on poplar wood impregnated with MF resin. They found

**Table 3** Springback percentages of date palm wood samples under different treatments

| Resin concentration | Control | Densification 25 (%) | Impregnation |     |     | Impregnation + densification |                    |                    |
|---------------------|---------|----------------------|--------------|-----|-----|------------------------------|--------------------|--------------------|
|                     |         |                      | 5%           | 10% | 25% | 5%                           | 10%                | 25%                |
| Springback (%)      | 0*      | $56.00 \pm (5.89)$   | 0            | 0   | 0   | $16.21 \pm (3.10)$           | $14.01 \pm (1.45)$ | $12.36 \pm (2.15)$ |
| DMRT**              | a       | c                    | b            | b   | b   | c                            | c                  | c                  |

\*Control group is non-pressed; springback is therefore defined as 0%

\*\*Duncan's multiple range test

that higher resin concentrations led to better dimensional stability.

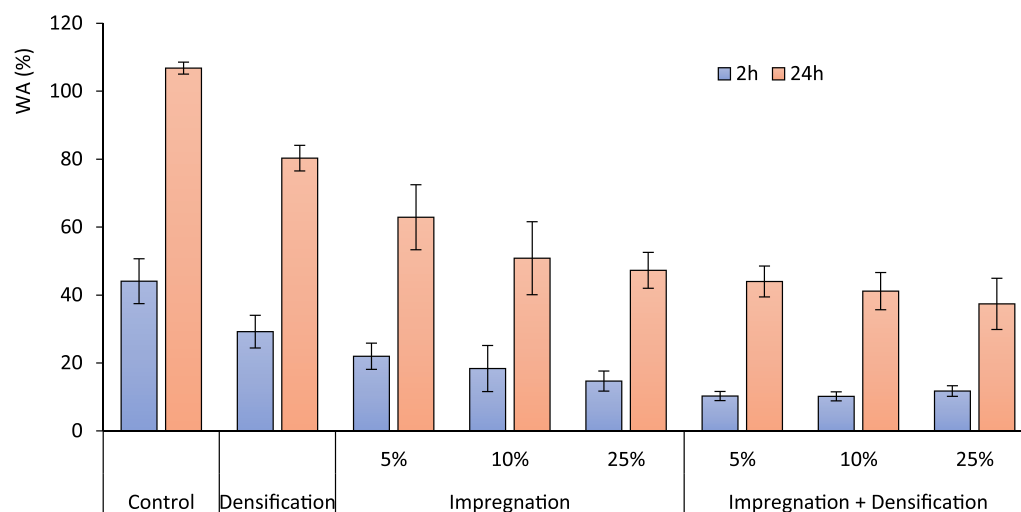
### Water absorption

The analysis of Fig. 3 reveals significant changes in the water absorption behavior of palm wood samples subjected to various treatments. Water absorption is a critical property for wood materials, affecting dimensional stability, durability, and overall performance. The control sample exhibited the highest water absorption, reaching about 100% after 24 h. Densification alone showed a slight reduction in water absorption compared to the control. Impregnation treatments with MF resin at various concentrations (5%, 10%, and 25%) demonstrated progressive reductions in water absorption as resin concentration increased. The most notable reduction was observed in samples that underwent both impregnation and densification, with the 25% MF impregnation plus densification treatment exhibiting the best performance. For all treatments, water absorption increased from 2 to 24 h, but the rate of increase was lower for treated samples compared to the control. This time-dependent behavior is significant for understanding the long-term water resistance of the treated wood. These results align well with findings from related studies in the literature. Hammood [38] reported reduced water absorption in resin-impregnated palm trunk lumber, which is consistent with the results of this study. The progressive decrease in water absorption with increasing resin concentration is in line with results reported by Khairunnisha [39], who found that higher concentrations of PF resin led to better water resistance in treated date palm trunk samples. The enhanced water resistance achieved through combined impregnation and

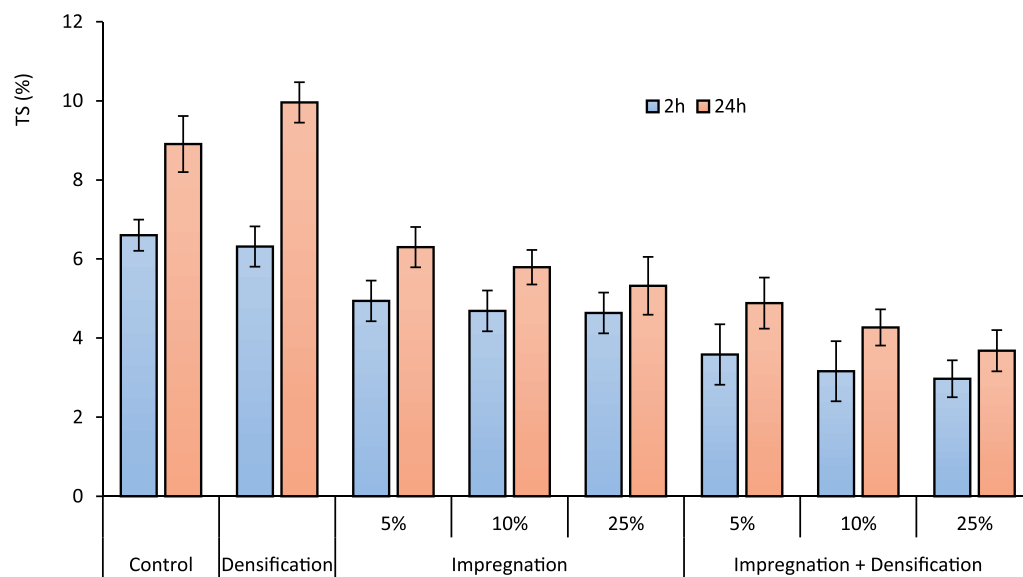
densification treatments is consistent with the findings by Ahmad et al. [29]. They observed improved dimensional stability and reduced water uptake in compreg date palm wood treated with PF resin. The observed increase in water absorption from 2 to 24 h, with treated samples showing a lower rate of increase, is similar to results reported by Sharma and Kelka [40], in their review of palm trunk wood properties. The slight improvement in water resistance due to densification alone is consistent with observations by Iskanderani [41], who reported reduced water absorption in densified palm trunk-based pellets.

### Thickness swelling

The analysis of Fig. 4 reveals significant changes in the thickness swelling behavior of palm wood samples subjected to various treatments. Thickness swelling is a critical property for wood materials, directly relating to dimensional stability and affecting the material's performance in moisture-exposed applications. TS was about 9% for the control and slightly higher (~10%) for densification alone, likely due to collapse and fracture of the weak parenchymatous tissues followed by recovery upon water absorption. In contrast, impregnation and combined treatments reduced TS compared with the control. Densification alone showed a slight reduction in thickness swelling compared to the control. Impregnation treatments with MF resin at various concentrations (5%, 10%, and 25%) demonstrated progressive reductions in thickness swelling as resin concentration increased. The most notable decrease was observed in samples that underwent both impregnation and densification, with the 25% MF impregnation plus densification treatment



**Fig. 3** Water absorption (WA) of treated date palm wood samples at 2 h and 24 h



**Fig. 4** Thickness swelling (TS) of treated date palm wood samples at 2 h and 24 h

exhibiting the best performance, reducing TS to about 2–3% after 24 h. For all treatments, thickness swelling increased from 2 to 24 h, but the rate of increase was lower for treated samples compared to the control. This time-dependent behavior is essential for understanding the long-term dimensional stability of the treated wood. These results align well with findings from related studies in the literature. Fadhli et al. [42] reported reduced thickness swelling in phenolic-resin-treated palm wood, which is consistent with the results of this study using MF resin. The progressive decrease in thickness swelling with increasing resin concentration is in line with results reported by Iskanderani [43], who found that higher concentrations of PF resin led to better dimensional stability in treated date palm trunk samples. The enhanced dimensional stability achieved through combined impregnation and densification treatments is consistent with the findings by Fathi [16] and Ahmad et al. [29]. They observed improved thickness swelling behavior in compreg date palm wood treated with PF resin. The observed increase in thickness swelling from 2 to 24 h, with treated samples showing a lower rate of increase, is similar to results reported by Ali et al. [44] in their study on phenolic compreg rubberwood. TS was about 9% for the control and slightly higher (~10%) for densification alone, plausibly due to partial collapse and microcracking of weak parenchymatous tissues followed by recovery upon wetting. In contrast, impregnation and the combined treatment reduced TS compared with the control. by Mehanny et al. [45] and Szymona et al. [46], who reported reduced thickness swelling in densified palm biomass. Although some heterogeneity in resin distribution cannot be excluded

due to the structure of date palm wood, the low standard deviations of WPG, WA, and TS indicate reasonably uniform impregnation.

#### **Mechanical properties**

Impact resistance (IR) exhibited a non-linear trend among treatments (Table 4 and Fig. 5). Densification alone moderately increased IR compared with the control, mainly due to compaction of cell lumina and reduced voids; however, the improvement was limited by microcracking and brittleness induced during compression. In contrast, MF resin impregnation reinforced weak parenchymatous tissues, improved stress transfer, and enhanced energy dissipation, leading to higher IR values. The combined treatment yielded the greatest improvement, as resin impregnation prior to densification reduced structural damage and provided a crosslinked polymer network within the compacted structure. This synergistic effect significantly increased the ability of the treated wood to absorb impact energy, transforming the inherently brittle inner part of date palm wood into a tougher material suitable for applications requiring higher impact resistance. Similar compensating effects of densification on impact resistance have been reported in compregnated wood and bamboo composites. This nearly fourfold increase surpasses density improvements reported in previous studies on compreg date palm wood [16].

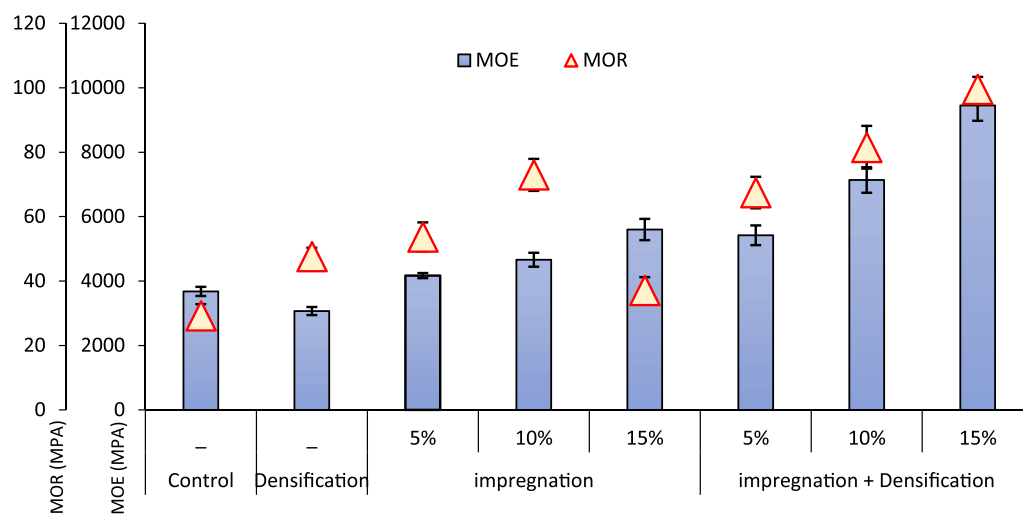
In addition to density, mechanical properties such as the modulus of rupture (MOR) and modulus of elasticity (MOE) showed significant improvements. The MOE increased from 3977.6 MPa in the control samples to

**Table 4** Mechanical properties of date palm wood samples under various treatments

| Resin concentration           | Control          | Densification    | Impregnation     |                 |                   | Impregnation + densification |                 |                   |
|-------------------------------|------------------|------------------|------------------|-----------------|-------------------|------------------------------|-----------------|-------------------|
|                               |                  |                  | 5%               | 10%             | 25%               | 5%                           | 10%             | 25%               |
| Density (g.cm <sup>-3</sup> ) | 0.28 ± (0.0012)  | 0.34 ± (0.011)   | 0.48 ± (0.01)    | 0.57 ± (0.01)   | 0.67 ± (0.01)     | 0.69 ± (0.01)                | 0.92 ± (0.01)   | 1.1 ± (0.01)      |
| MOE (MPa)                     | 3977.6 ± (101.7) | 3068.6 ± (125.2) | 4168.6 ± (79.37) | 4661 ± (216.41) | 5598.8 ± (303.45) | 5420.6 ± (305.75)            | 7137 ± (396.94) | 9450.4 ± (473.72) |
| MOR (MPa)                     | 29.2 ± (3.6)     | 47.5 ± (4.1)     | 53.70 ± (4.75)   | 72.95 ± (4.49)  | 37.95 ± (2.27)    | 67.46 ± (4.87)               | 81.53 ± (6.63)  | 99.55 ± (3.27)    |
| Impact resistance (J)         | 20.6 ± (1.5)     | 20 ± (1)         | 17.8 ± (1.27)    | 16.6 ± (1.34)   | 16.6 ± (1.41)     | 24.4 ± (2.27)                | 21.8 ± (1.30)   | 26.4 ± (1.52)     |
| SHC (N/mm <sup>2</sup> )      | 21.1 ± (1.2)     | 22.6 ± (2.7)     | 30.81 ± (6.50)   | 32.80 ± (1.59)  | 34.69 ± (1.93)    | 45.26 ± (1.37)               | 45.65 ± (1.37)  | 45.01 ± (2.93)    |

Values with parentheses: these represent the mean ± standard deviation (SD)

*n* = 6 for each test

**Fig. 5** Mechanical properties of date palm wood samples under various treatments (*N* = 6)

9450.4 MPa in the 25% impregnation + densification treatment, representing a remarkable 236.36% increase in bending strength. This improvement aligns with, yet exceeds, findings from Dungani et al. [8], who reported enhancements in the mechanical properties of date palm wood treated with PF resin. Similarly, MOR increased from 29.2 MPa to 99.55 MPa, indicating a 241% improvement in bending strength, consistent with the more pronounced results reported by Kashizadeh et al. [47] in their review of date palm trunk properties improved through resin impregnation.

These results clearly illustrate that MF resin impregnation, when combined with densification, significantly enhances both density and mechanical strength in date palm wood. The increasing density and weight percent gain (WPG) values indicate that the resin concentration directly influences the degree to which the resin fills the wood's porous structure, which aligns with findings from related literature. For example, Fathi et al. [16] observed similar increases in mechanical properties, such as

bending strength and elasticity, after resin treatment, although the degree of improvement was somewhat lower in their study.

Moreover, the observed reduction in WPG during densification can be attributed to resin expulsion during the compression process, mirroring findings from other studies, such as those by Shebani et al. [33]. Nevertheless, the overall retention of resin in the densified samples still contributes to the enhanced mechanical properties, with densification significantly improving both MOR and MOE. These enhancements suggest that date palm wood treated with this combination of methods could be suitable for high-strength applications in construction and furniture manufacturing, where both density and mechanical performance are critical factors.

The improvements in mechanical properties observed in this study show a comparable trend to those reported by Amirou et al. [48]. However, it should be noted that direct comparison is difficult, as their study involved different wood species, resin systems, treatment

parameters, and testing conditions. The present work highlights that substantial improvements can also be achieved in the inner part of date palm wood, which has received little attention in previous studies. Their study on Algerian date palm wood also demonstrated significant improvements in mechanical performance but not to the same degree. The higher levels of enhancement observed in the current study are likely due to the use of low molecular weight and low-viscosity MF resin, which penetrates the wood structure more effectively, further enhancing its mechanical performance when combined with densification.

In conclusion, this study provides compelling evidence that MF resin impregnation combined with densification significantly improves the physical and mechanical properties of date palm wood, with results that exceed many prior studies. Future research should focus on optimizing resin retention during densification and exploring the long-term durability of treated wood for practical applications. Furthermore, the non-linear trend observed in impact resistance presents an intriguing area for future investigation, as this behavior is not commonly reported in similar studies on palm wood or other wood species treated with comparable methods.

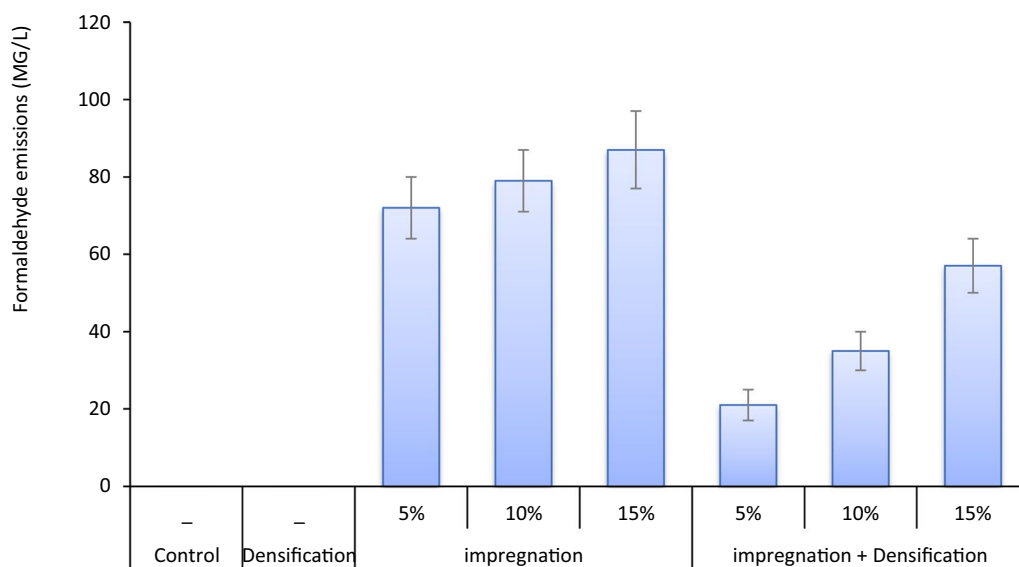
Screw-holding capacity (SHC) also showed significant improvement, rising from 21.048 N/mm<sup>2</sup> in the control to 45.014 N/mm<sup>2</sup> in the most intensive treatment, representing a 114% increase. While specific studies on SHC of treated date palm wood are limited, this improvement aligns with general trends of

enhanced mechanical properties observed in studies by ul Haq Bhat et al. [49].

#### Formaldehyde emission

The formaldehyde emission analysis revealed measurable levels in the impregnated samples and densification treatments (Fig. 6). For samples impregnated with melamine–formaldehyde (MF) resin (5% to 15%), formaldehyde emissions ranged from 0.72 to 0.87 mg/L. According to the China National Standard GB/T 17657, these values fall within the F★★ ( $\leq 1.5$  mg/L) classification. This corresponds approximately to the E1 class threshold defined in the European standard. [50]. This result represents a significant improvement compared to the study by Ahmad et al. [29], which reported formaldehyde emissions between 3.35 and 3.27 mg/L for palm wood samples impregnated with phenol–formaldehyde (PF) resin. The lower emissions observed in this study can be attributed to the reduced formaldehyde ratio in the resin formulation.

Interestingly, samples subjected to double treatments (impregnation plus densification) exhibited even lower formaldehyde emissions, ranging from 0.21 to 0.57 mg/L. This further reduction suggests that the densification process may have an additional beneficial effect on formaldehyde retention within the wood structure. There is also a possible release of formaldehyde and loss of formaldehyde during the densification process at temperature. These findings align with research by Roslinda et al. [51], who demonstrated that increasing heating temperature and extending resin curing time could further reduce formaldehyde emissions.



**Fig. 6** Formaldehyde emission of date palm wood after impregnation and densification treatments with different MF resin concentrations ( $N=3$ )

The significantly lower formaldehyde emissions achieved in this study, particularly for the double-treated samples, represent a notable advancement in developing environmentally friendly wood treatment processes for date palm wood. This improvement addresses one of the key concerns associated with resin-treated wood products, potentially expanding their applicability in indoor and environmentally sensitive applications. Furthermore, these results suggest potential avenues for future optimization of the treatment process to minimize formaldehyde emissions while maintaining or enhancing the mechanical properties of the treated date palm wood.

## Conclusions

The conclusion of this study highlights the successful application of a two-stage treatment process: impregnation with low-viscosity MF resin followed by densification in significantly enhancing the physical and mechanical properties of date palm wood. The treatment resulted in a nearly fourfold increase in density, a 136.36% improvement in modulus of elasticity (MOE), and a 241% increase in modulus of rupture (MOR), demonstrating substantial enhancement in structural performance. Additionally, the screw-holding capacity improved by 114%, while water absorption and thickness swelling were notably reduced, contributing to enhanced dimensional stability. A key aspect of this study is the reduction of formaldehyde emissions to levels compliant with stringent European standards ( $F^{***}/E1$ ), making this process environmentally sustainable and suitable for applications sensitive to chemical emissions. The synergistic combination of resin impregnation and densification yielded superior performance compared to single-treatment methods, effectively enhancing both the mechanical properties and dimensional stability of date palm wood. These findings underscore the potential of treated date palm wood for high-value applications, particularly in construction and furniture manufacturing. However, further research is recommended to assess the long-term durability and cost-effectiveness of this process, as well as to optimize resin retention during densification. Overall, this study presents a sustainable approach to valorizing date palm waste, contributing to the advancement of wood modification technologies and the development of high-performance wood products for industrial use.

## Abbreviations

|     |                            |
|-----|----------------------------|
| OSB | Oriented strand board      |
| MDF | Medium-density fiberboard  |
| PF  | Phenol-formaldehyde        |
| MF  | Melamine-formaldehyde      |
| UF  | Urea-formaldehyde          |
| MUF | Melamine-urea-formaldehyde |
| MC  | Moisture content           |
| RH  | Relative humidity          |
| SB  | Spring back                |

|       |                        |
|-------|------------------------|
| WPG   | Weight percent gain    |
| WA    | Water absorption       |
| TS    | Thickness swelling     |
| MOE   | Modulus of elasticity  |
| MOR   | Modulus of rupture     |
| SHC   | Screw-holding capacity |
| IR    | Impact resistance      |
| ANOVA | Analysis of variance   |

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## Author contributions

Peyman Ahmadi: conceptualization, methodology, investigation, data curation, formal analysis, project administration, writing—original draft preparation. Ghanbar Ebrahimi: supervision, writing—review and editing, project administration. Alireza Ashori: resources, writing—review and editing. All authors have read and approved the final manuscript.

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## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Due to confidentiality agreements with collaborators and the need to protect sensitive information related to proprietary information the data are not publicly available. However, specific datasets generated during the study can be shared with qualified researchers upon request and approval by the corresponding author.

## Declarations

## Competing interests

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 paper.

## Author details

<sup>1</sup>Department of Wood and Paper Science and Technology, Faculty of Natural Resources, University College of Agriculture & Natural Resources, University of Tehran, Karaj, Iran. <sup>2</sup>Department of Chemical Technologies, Iranian Research Organization for Science and Technology (IROST), Tehran, Iran.

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