Modification of Poplar Wood with Different Resins: A Sustainable Solution for the Furniture Industry

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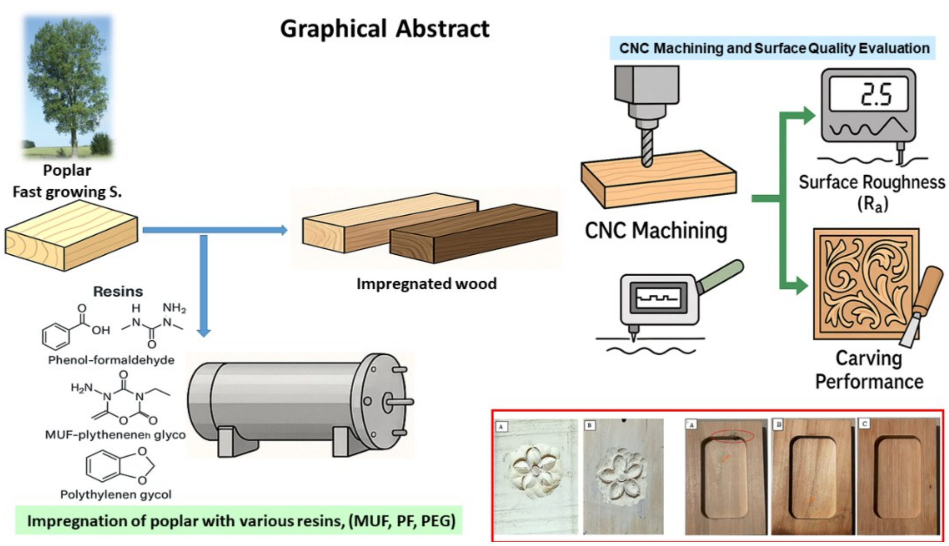
GRAPHICAL ABSTRACT



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Poplar wood (*Populus deltoides*), a fast-growing and abundant species, holds promise for sustainable material use, but its low density, poor dimensional stability, and weak strength restrict high-value applications. This study examined property enhancement through resin impregnation with phenol-formaldehyde (PF), melamine-urea-formaldehyde (MUF), and polyethylene glycol (PEG) at 5%, 10%, and 15% concentrations. Modified specimens were tested for weight percent gain, bulking, water absorption, dimensional swelling, modulus of rupture, modulus of elasticity (MOE), impact strength, and surface hardness, as well as machinability and carving performance using expert evaluation and Computer Numerical Control (CNC) surface quality. Given the laboratory-scale dimensions of the specimens, the resins achieved satisfactory penetration, as also reflected in the WPG values. The 15% PF treatment produced the greatest improvements, yielding a WPG of 26.3%, MOE above 10,000 MPa, and reduced surface roughness to 2.90 μm. Compared with untreated samples, PF-modified wood showed superior dimensional stability, machining resistance, and carving clarity, approaching the properties of hardwoods such as walnut and beech. MUF led to moderate benefits, whereas PEG mainly caused bulk increase without significant strength or moisture resistance improvements. Overall, PF impregnation effectively upgraded poplar wood, indicating its potential as a cost-effective alternative for decorative and structural applications.

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Keywords: Wood modification; Poplar wood; Phenol-formaldehyde resin; Mechanical properties; CNC machining; Furniture industry

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INTRODUCTION

Wood has long been a vital natural resource used across civilizations for toolmaking, construction, and cultural expression. In ancient civilizations, such as in Egypt, wood was employed in shipbuilding and architectural design. During the Renaissance, wood gained prominence as a valued medium in both art and architecture, symbolizing nature, beauty, and craftsmanship (Franco Taboada 2019). With industrialization, the use of wood expanded dramatically, becoming foundational in furniture manufacturing (Rame *et al.* 2023). Today, traditional hardwoods, such as beech, oak, and walnut, are extensively used in high-end furniture production, interior decoration, and other wood-based industries (Namicev and Petrovski 2019). Their superior physical and mechanical properties such as high density, surface hardness, and dimensional stability make them suitable for applications demanding both strength and aesthetics (Wisdom and Wisdom 1983; Salehi Shanjani *et al.* 2021).

Limited availability of high-quality hardwoods due to forest protection policies, environmental sustainability concerns, and increased market demand has resulted in significant pressure on natural wood resources. These challenges have led to a growing interest in fast-growing species such as poplar (*Populus deltoides*), which is widely cultivated across temperate regions. Poplar trees offer advantages such as rapid growth cycles, low cost, ease of cultivation, and adaptability to various environmental conditions (Cheng *et al.* 2022). However, its limitations include low density, high porosity, weak strength, and poor biological resistance. These restrict its use in premium furniture and structural applications (Lu *et al.* 2014; Xu *et al.* 2020; Huseyin Sivrikaya 2022). To bridge this performance gap, several wood modification strategies have been explored to improve the functional and mechanical behavior of soft and fast-growing woods (Zhang *et al.* 2023). Among these methods, resin impregnation is particularly effective, enhancing water resistance, dimensional stability, and mechanical strength through *in situ* polymerization within the wood (Sandberg *et al.* 2021).

Commonly used resins include thermosetting polymers, such as phenol-formaldehyde (PF), melamine-urea-formaldehyde (MUF), and water-soluble modifiers such as polyethylene glycol (PEG). These resins vary in terms of molecular structure, viscosity, and interaction with wood cell walls, influencing their effectiveness in performance enhancement (Rowell 2005; Ahmadi *et al.* 2024, 2025; Grinins *et al*. 2022). Earlier studies mainly have assessed modified woods at the laboratory scale, focusing on density, water absorption, and bending strength. However, little empirical data exist on how these modifications affect real manufacturing operations. In modern furniture manufacturing, processes such as Computer Numerical Control (CNC) machining and detailed carving require high precision, surface integrity, and dimensional accuracy. Consequently, evaluating the machinability and aesthetic performance of modified wood is essential for practical applications. Therefore, the present work provides a more comprehensive perspective by integrating CNC machining and artistic carving assessments with conventional mechanical testing, thereby linking laboratory-scale modification to real-world production requirements.

This study hypothesizes that impregnation of fast-growing poplar with thermosetting resins can substantially enhance its physical, mechanical, and machining properties. Such improvements are anticipated to elevate the performance of modified poplar to levels comparable with traditional hardwoods such as walnut and beech, thereby expanding its potential for high-value furniture applications, particularly in CNC machining and precision carving.

To address this hypothesis, the research integrated evaluations of machinability, carving quality, and comparative benchmarking against hardwoods with systematic assessments of PF, MUF, and PEG treatments at varying concentrations. Accordingly, the objective was to develop and evaluate an efficient and sustainable approach for enhancing fast-growing poplar wood. Treated samples were analyzed for key physical and mechanical properties and tested through manual carving and CNC machining to simulate real-world production processes. Furthermore, their performance was benchmarked against traditional hardwoods such as walnut and beech to assess industrial viability. This comprehensive approach provides new insights into the practical utilization of modified poplar as a sustainable alternative for high-value applications in the furniture industry.

EXPERIMENTAL

Wood Material

Poplar wood (*Populus deltoides*) was selected as the base material for this study due to its rapid growth, availability, and relevance to the regional wood industry. Trees with an average height of 150 cm, diameter of approximately 25 cm, and 24 annual growth rings were harvested from an industrial plantation in Malayer County, Iran. The uniform ring count ensured consistency in age and growth conditions across samples. Logs were immediately transported to the Furniture Engineering Laboratory at Malayer National University, where they were processed into standard test specimens. All samples were conditioned and stored under controlled laboratory conditions prior to modification and testing to eliminate any environmental variability in the results.

Resin Formulations

Three types of resins were used for the modification process: melamine urea-formaldehyde (MUF), phenol-formaldehyde (PF), and polyethylene glycol (PEG). Each resin was selected based on its specific chemical characteristics and suitability for improving wood properties through impregnation.

Melamine urea-formaldehyde

The MUF resin is a widely used thermosetting polymer known for its high bonding strength, dimensional stability, and moisture resistance. In this study, it was chosen for its adequate penetration capacity and post-curing hardness. The commercial MUF was procured from Samed Co. (Mashhad, Iran) and diluted with distilled water to attain a viscosity appropriate for wood impregnation.

Phenol-formaldehyde

PF is another thermosetting resin offering superior durability, chemical stability, and resistance to thermal and biological degradation. Its ability to form irreversible cross-links with the lignocellulosic matrix under heat makes it ideal for structural reinforcement. The PF was sourced from a local chemical supplier in Gorgan, Iran, and diluted prior to use.

Polyethylene glycol

PEG-1000, a medium molecular weight, water-soluble, non-reactive polyether compound, was used for its hygroscopic properties and capacity to improve dimensional stability. The PEG was obtained from Shazand Petrochemical Co. (Arak, Iran). A 30% (w/w) stock solution was first prepared using distilled water, from which working concentrations of 5%, 10%, and 15% were diluted and subsequently used for impregnation treatments. Prior to pressure treatment, wood samples were soaked in the PEG solution for 24 h to facilitate diffusion into the wood. This was followed by the Rueping empty-cell pressure impregnation process to enhance resin penetration. In this experimental framework, MUF and PF were applied as thermosetting resins with chemical reactivity, whereas PEG was used as a non-crosslinking modifier functioning mainly as a bulking and plasticizing agent to minimize shrinkage and reduce brittleness during drying and machining.

Sample Preparation

Specimens were prepared according to ISO 13061 (2014) standards (Table 1). All samples were oven-dried at 103 ± 2 °C until reaching constant weight, after which their initial dry mass (m_1) and volume (v_1) were recorded.

Table 1. Sample Dimensions Based on ISO 13061 (2014) for Different Physical and Mechanical Tests

No.	Test	Dimensions (T × R × L mm³)	Replicates	ISO Standard
1	Physical Properties (WA, S, ρ)	30 × 20 × 20	10	ISO 13061-2 (2014)
2	Hardness	50 × 50 × 50	6	ISO 13061-12 (2014)
3	Impact Resistance	20 × 20 × 300	8	ISO 13061-10 (2014)
4	MOR and MOE	20 × 20 × 300	8	ISO 13061-3 (2014)
5	Manual Carving	20 × 150 × 200	6	—*
6	CNC Machining	20 × 150 × 200	6	—*

*Note: Machining tests were conducted on treated samples to evaluate surface quality and workability. Surface roughness was measured using an SJ-201P profilometer (Mitutoyo, Japan), while surface defects, such as fiber tearing, burning, and unevenness, were assessed visually by expert evaluators.

Impregnation Process

The wood modification procedure was conducted using the Rueping empty-cell impregnation method under pressure, which allowed efficient penetration of resins into the wood structure while optimizing chemical retention. Resin solutions of MUF and PF were formulated at three different weight concentrations 5%, 10%, and 15% (w/w) by diluting the base resins with distilled water to achieve suitable viscosity for effective penetration. For the PEG treatments, a single concentration of 30% (w/w) was maintained, as it had been optimized based on prior studies and industrial recommendations. Prior to impregnation, all specimens were oven-dried to a constant weight at 103 ± 2 °C to remove residual moisture and enhance resin uptake. The dry specimens were then placed in a sealed impregnation chamber and subjected to an initial vacuum phase of 0.08 to 0.09 MPa for 30 min to evacuate air from the wood cell lumens. Subsequently, the resin solution was introduced into the chamber, and a final pressure ranging from 0.8 to 1.0 MPa was applied and maintained for 2 to 3 h, depending on resin type, to ensure deep and uniform infiltration into the wood matrix. Following the pressure treatment, different post-treatment protocols were applied based on the chemical nature of the resin.

MUF and PF treatments

Thermosetting resins require curing to initiate *in-situ* polymerization. Accordingly, the impregnated specimens were placed in a convection oven and cured at a temperature of 100 to 120 °C for a duration of 6 h. This step was essential to promote cross-linking and ensure resin fixation within the cell walls and lumens.

PEG treatments

Given the non-reactive and hygroscopic nature of PEG-1000, specimens treated with this polymer were air-dried at ambient laboratory conditions until they reached a constant weight. This approach allowed PEG to crystallize and stabilize within the wood structure without thermal degradation.

In total, 10 treatment groups were established, comprising a control group (untreated) and nine groups treated with three different resin types at three respective concentration levels. The details of each treatment configuration including resin type, concentration, and treatment code are summarized in Table 2.

Table 2. Description of Different Treatments and Resin Concentrations Used

No.	Treatment Description	Resin Type	Resin Content (%)	Treatment Code
1	Untreated (Control)	–	–	C
2	MUF-impregnated	MUF	5, 10, 15	MUF_5, MUF_{10}, MUF_{15}
3	PF-impregnated	PF	5, 10, 15	PF_5, PF_{10}, PF_{15}
4	PEG-impregnated	PEG	5, 10, 15	PEG_5, PEG_{10}, PEG_{15}

After completion of the impregnation and curing process, all specimens were oven-dried again at 103 ± 2 °C until a constant mass was achieved to eliminate residual moisture. Subsequently, the final dry weight (m_2) and dry volume (V_2) of each specimen were measured using a precision balance and a digital caliper, respectively. To quantify the effectiveness of resin uptake and volumetric expansion due to treatment, the Weight Percent Gain (WPG) and Bulking Effect (BE) were calculated using Eqs. 2 and 3

$$\mathrm{WPG}\% = \frac{\mathrm{m_2}-\mathrm{m_1}}{\mathrm{m_1}} \times 100 \quad (2)$$

$$BE\% = \frac{V_2-V_1}{V_1} \times 100 \quad (3)$$

In Eq. 3, the bulking effect (BE) refers to the relative increase in wood volume after modification compared with its initial oven-dry volume prior to treatment. Here, m_1 and v_1 are the dry weight (g) and volume (cm^3) before treatment, and m_2 and v_2 are the corresponding values post-treatment and curing.

Physical Properties

The water absorption capacity and dimensional stability of the treated and untreated wood specimens were assessed through standardized immersion tests. All samples were submerged in distilled water at ambient temperature, and measurements were taken at 2, 24, 48, 120, 192, and 264 h to monitor changes over time. Two key parameters were calculated: Water Absorption (WA %) and Volumetric Swelling (S %). Equations 4 and 5 were used,

$$WA\% = \frac{M_t-m_2}{m_2} \times 100 \quad (4)$$

$$S\% = \frac{V_t-V_2}{V_2} \times 100 \quad (5)$$

where M_t and V_t are the mass (g) and volume (cm^3) at time t post-immersion, and M_2 and V_2 are the mass and volume after treatment and curing, respectively.

Mechanical Properties

All treated and untreated wood specimens were conditioned in a climate-controlled chamber for a period of two weeks at a relative humidity of 65 ± 5% and a temperature of 22 ± 2 °C to achieve moisture equilibrium. Following conditioning, mechanical tests were performed using a universal testing machine (Instron, USA) in accordance with ISO 13061 (2014) standards (Table 1). The modulus of rupture (MOR) and modulus of elasticity (MOE) were determined *via* three-point bending tests on specimens with dimensions of 20 × 20 × 300 mm³, under a loading rate of 10 mm·min⁻¹. These tests evaluated the flexural strength and stiffness of the treated wood. Hardness was assessed using the Janka hardness test, involving the application of an 11.5-mm diameter steel ball to the radial face of 50 × 50 × 50 mm³ specimens. The force required to embed the ball halfway into the wood surface was recorded and expressed in (kN). Impact resistance was evaluated on 20 × 20 × 300 mm³ specimens using a pendulum-type impact testing machine with an impact energy of 20 J. The test was designed to simulate sudden loading conditions and assess the energy absorption capacity of the material, expressed in joules per meter (J·m⁻¹). All tests were conducted with a minimum of six replicates per treatment group. The results were statistically analyzed to determine the influence of resin type and concentration on the mechanical behavior of the modified wood.

Experimental Evaluation of Modified Wood Performance Using Expert-Based Questionnaires in Carving and CNC Machining

To assess the real-world performance and practical applicability of modified poplar wood in artistic carving and CNC machining operations, two expert-based evaluation tools were designed using structured five-point Likert-scale questionnaires from 1 ("Very Poor") to 5 ("Excellent"), (Table 3). The aim was to gather comprehensive feedback both objective and subjective from skilled professionals in each field. The questionnaires evaluated six key performance attributes: surface hardness, ease of finishing, detail accuracy, breakage resistance, color uniformity, and overall process ability. A total of 15 experienced woodcarvers and 15 CNC machine operators participated in the evaluation, each scoring the samples independently. Prior to statistical testing, the response data were assessed for normality using the Shapiro–Wilk test to determine appropriate inferential methods (Norman 2010; Boone, Jr. and Boone 2012). Statistical analyses were performed using SPSS software (version 26, IBM Corp., Armonk, NY, USA). Descriptive statistics summarized the response distributions, while Cronbach's alpha was employed to measure the internal consistency and reliability of the questionnaire items (Q1 to Q25). Reliability analysis followed the standard SPSS procedure: Analyze → Scale → Reliability Analysis.

Table 3. Five-point Likert Scale Used for Expert Evaluation of Wood Performance

Rating	Qualitative Description	Analytical Interpretation
1	Very Poor	Extremely inadequate performance in the evaluated criterion
2	Poor	Clearly observable weakness
3	Moderate	Acceptable, with evident limitations
4	Good	Technically satisfactory and industrially applicable
5	Excellent	Superior performance, comparable to or exceeding traditional hardwoods

For comparative performance analysis between resin-treated poplar and traditional hardwoods, such as walnut (*Juglans regia*) and European beech (*Fagus sylvatica*), paired t-tests or the Friedman non-parametric test were applied, depending on the distribution characteristics of the data.

CNC Machining and Surface Quality Evaluation

Following the impregnation and subsequent drying process, all treated and untreated samples underwent CNC machining to simulate real-world manufacturing conditions (Fig. 1). Surface quality was quantitatively assessed using a contact profilometric method based on needle-tracing. Surface roughness values (R_a, in micrometers) were measured perpendicular to the grain direction using a Mitutoyo SJ-201P roughness tester (Mitutoyo Corp., Japan). Dimensional accuracy was evaluated using a digital caliper, and the dimensional deviation (in mm) was calculated as the difference between the intended and actual machined dimensions. In addition to instrumental evaluation, surface finishability and defect severity were qualitatively assessed by trained woodworking professionals using standardized five-point Likert scales, as detailed in Tables 4 and 5. These assessments captured expert opinions on the practical machinability and finish quality of each treatment group. All results were compiled as mean values for each treatment. Statistical analysis was conducted using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test to identify significant differences among treatment groups at a 95% confidence level ($p < 0.05$).

Fig. 1. CNC machining of modified wood samples

Table 4. Surface Finishability Assessment Using Likert Scale

Rank	Performance Description	Qualitative Index	Rating
1	Excellent surface, ready for direct finishing	Excellent	5
2	Smooth surface, requires minimal sanding	Good	4
3	Localized unevenness, requires full sanding	Moderate	3
4	Extensive irregularities, incomplete finishing	Poor	2
5	Rough surface, requires substantial correction	Very Poor	1

Table 5. Classification of Surface Defect Severity

Rank	Surface Condition	Performance Classification	Defect Rate (%)
1	Completely clean and intact surface	Excellent	0 to 5
2	Minor, acceptable imperfections	Good	6 to 15
3	Several defective areas, needs repair	Moderate	16 to 25
4	Widespread surface defects	Poor	26 to 40
5	Unfit for final surface finishing	Very Poor	> 40

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics software, version 26. A one-way ANOVA was conducted to assess the main effects of resin type, concentration level, and their interaction on the measured physical and mechanical properties of the modified wood. *Post-hoc* comparisons were carried out using Duncan's multiple range test to identify statistically significant groupings among treatment means at a 95% confidence level ($p < 0.05$). For the analysis of expert-based questionnaire data, Cronbach's alpha coefficient was calculated to evaluate internal consistency and reliability of the instruments.

RESULTS AND DISCUSSION

Weight Percent Gain and Density

The highest WPG was observed in PEG-treated specimens at 15%, averaging 26.3% (Fig. 2). This result is consistent with Rowell (2006) and Hill (2006), who noted that PEG's low molecular weight and high solubility facilitate diffusion and lumen filling. PF and MUF treatments also increased WPG, though to a lesser extent. For example, PF at 10% reached 18.4%. It was limited by its higher viscosity but enhanced by strong chemical reactivity that forms durable bonds within the wood (Rowell 2006). MUF showed the lowest WPG values, likely due to surface-curing and elevated viscosity restricting deeper penetration. ANOVA confirmed that resin type, concentration, and their interaction had significant effects ($p < 0.001$), in line with Brischke *et al.* (2017). Similar to Ahmadi *et al.* (2024), the present findings reaffirm that WPG is a key indicator of successful resin uptake and chemical modification.

Density followed the same trend: the highest values were recorded for PEG at 10% and PF at 15%, both ~0.528 g/cm³. PEG's low viscosity allowed efficient infiltration (Hill 2006; Rowell 2005), whereas PF, despite lower diffusivity, increased the density through the formation of robust cross-linked networks during curing (Sohn and Cha 2018). A clear WPG–density correlation was evident, consistent with Esteves and Pereira (2009), who emphasized that higher resin uptake enhances compactness and strengthens the wood structure. ANOVA again confirmed significant effects of resin type, concentration, and interaction ($p < 0.001$). From a practical perspective, increased density translates into improved dimensional stability, hardness, and machining quality. Therefore, treatments yielding substantial density enhancement, particularly PF at 15% and PEG at 10%, can be regarded as promising alternatives to conventional hardwoods in high-performance furniture and carving applications.

Due to the relatively small laboratory-scale dimensions of the specimens, resin penetration was considered to be nearly uniform throughout the cross-section, which is consistent with the high WPG values obtained. This interpretation is further supported by previous microscopic investigations demonstrating cell wall penetration under comparable conditions (Ahmadi *et al.* 2024; Reinprecht, 2016). Nevertheless, it must be acknowledged that in industrial-scale treatments the penetration profile is often less homogeneous and may be concentrated in surface regions. Therefore, future research should incorporate quantitative microscopic or spectroscopic analyses of penetration depth to more accurately evaluate resin distribution in larger specimens and under practical processing conditions.

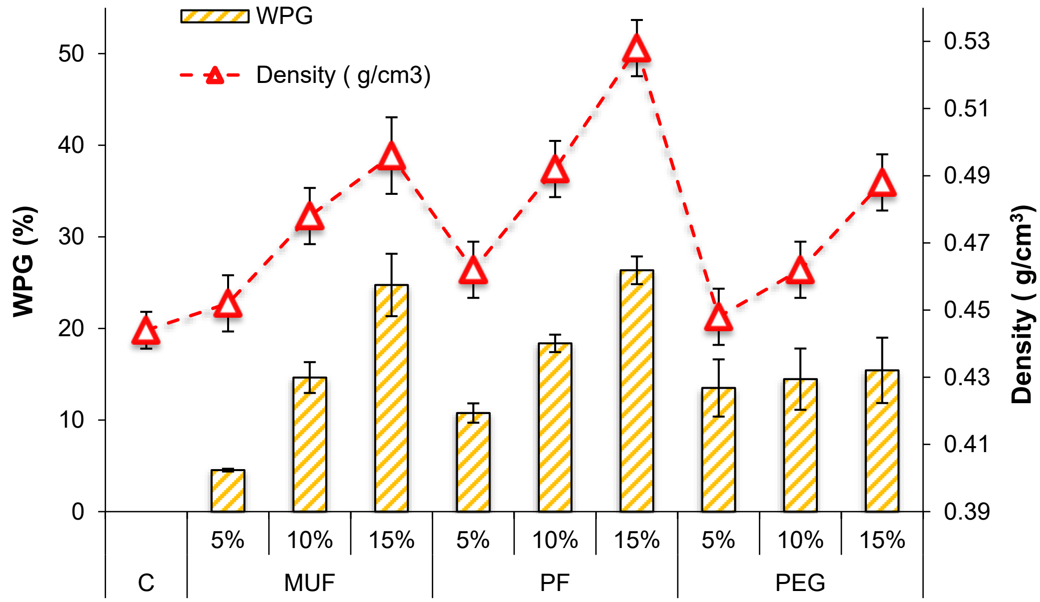

Fig. 2. WPG and density of poplar wood treated with PEG, MUF, and PF resins at different concentrations

Bulking Effect

As illustrated in Fig. 3, BE values showed a clear increasing trend with higher resin concentrations, particularly in PEG and PF treatments. The maximum BE was recorded in PEG at 15% (11.70%), consistent with Rowell (2005), Esteves and Pereira (2009), and Epmeier *et al.* (2004). These researchers reported that PEG's low molecular weight and high diffusivity enable deep penetration into cell walls, producing marked matrix expansion. Such expansion increases external dimensions while maintaining structural integrity. PF also achieved substantial BE, reaching 9.7% at 15%. Although PF penetration is more limited due to higher molecular mass and viscosity, its ability to form rigid cross-linked networks compensates for this restriction and reinforces the wood (Sohn and Cha 2018). In contrast, MUF treatments produced the lowest BE values, which was likely because of high viscosity and rapid surface curing that restrict deeper diffusion. In addition to the filling of voids, the bulking effect observed in PF and MUF treatments can be partly explained by chemical interactions between formaldehyde and wood cell walls. Formalin reacts with hydroxyl groups to form hemiacetal linkages (–O–CH_2OH), which can further condense into stable acetal bonds (–O–CH_2–O–) between adjacent wood polymers, accompanied by water release (Reinprecht, 2016). These reactions contribute to cell wall expansion and improved dimensional stability.

ANOVA confirmed that resin type, concentration, and their interaction significantly influenced BE ($p < 0.001$). From a materials engineering perspective, BE is a critical parameter that is strongly associated with apparent density, dimensional stability, and surface hardness. Prior studies (Esteves and Pereira 2009; Tsapko 2013) emphasized its correlation with reduced hygroscopicity, enhanced mechanical performance, and improved durability. These trends were also observed in this study: specimens with higher BE consistently demonstrated reduced water absorption and greater density. Therefore, BE can be regarded as a reliable indicator of treatment effectiveness and overall performance enhancement in modified poplar.

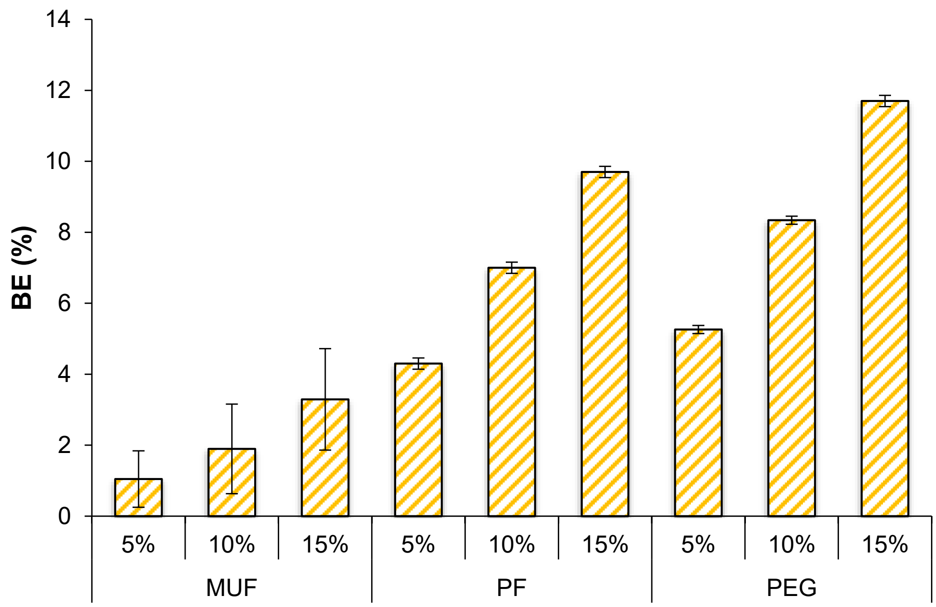

Fig. 3. The BE of poplar wood treated with PF, MUF, and PEG resins at different concentrations

Water Absorption and Dimensional Swelling

As depicted in Fig. 4 (A and B), untreated poplar specimens, representing the control group, exhibited the highest levels of water absorption and dimensional swelling. This behavior can be attributed to the inherently porous structure of poplar wood, which readily permits moisture ingress and subsequent volumetric expansion. In contrast, all resin-treated samples, particularly those impregnated with higher resin concentrations, demonstrated a marked reduction in both water uptake and swelling, indicating improved dimensional stability and enhanced resistance to moisture-induced deformation. Among the treatments, phenol-formaldehyde (PF) at a 15% concentration produced the most significant improvement, resulting in the lowest water absorption (approximately 65% after 264 h) and minimal swelling (around 4%). This superior performance can be largely attributed to PF's capacity to form dense, stable cross-linked polymer networks within the wood structure, effectively sealing voids and restricting water penetration (Rowell 2005; Hill 2006). As a thermosetting resin, PF undergoes in-situ polymerization during curing, thereby generating rigid matrices that resist both moisture absorption and cell wall expansion.

The MUF treatments also led to substantial reductions in moisture-related parameters. Although less effective than PF, MUF at 15% still yielded considerable improvements over the control, with water absorption reduced to approximately 80% and swelling maintained below 6%. The lower performance of MUF is likely due to its higher viscosity and a surface-curing tendency, which limits resin diffusion into deeper wood zones and results in less comprehensive structural modification. Conversely, PEG-treated specimens showed inferior performance in moisture resistance, despite exhibiting high resin uptake and bulking effect. At 15% concentration, PEG-treated samples still recorded significantly higher water absorption and swelling compared to PF and MUF. This is consistent with findings by Hill (2006), who noted that PEG's hygroscopic and non-curable nature prevents it from forming effective moisture barriers, thus limiting its capacity to reduce dimensional changes in humid conditions.

A statistically significant and positive correlation was observed between water absorption and swelling across all treatments, reaffirming the well-established principle that moisture-induced dimensional change in wood is closely tied to the degree of water uptake. These findings underscore the critical role of thermosetting resins, particularly PF, in improving the long-term moisture durability of poplar wood. As such, PF-impregnated wood presents a promising material for applications where high dimensional stability and resistance to environmental humidity are essential, including both indoor and outdoor furniture manufacturing.

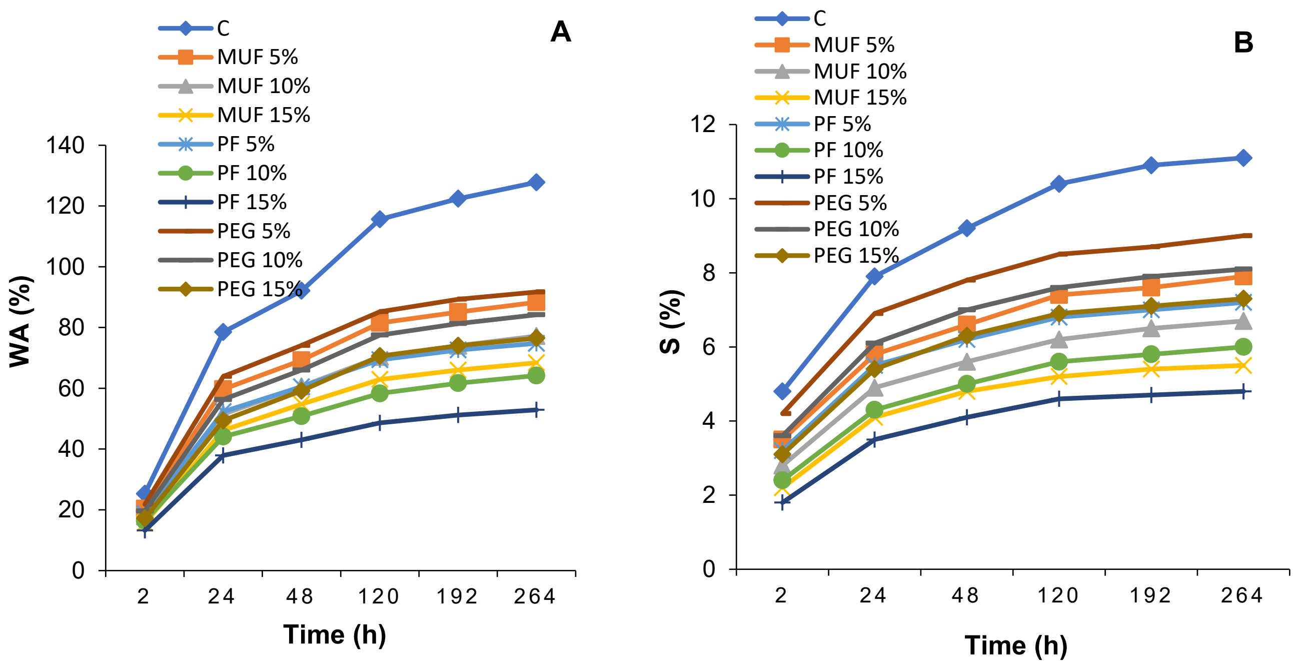

Fig. 4. (A) Water absorption and (B) Dimensional swelling of poplar wood treated with different concentrations of PF, MUF, and PEG resins

Mechanical Properties

The mechanical evaluation results (Table 6) clearly indicate that resin impregnation with PF, MUF, and PEG significantly enhanced the structural performance of poplar wood. Among the various treatments, PF at a 15% concentration yielded the most substantial improvements in mechanical strength, with the highest recorded values for MOR and MOE 81.3 MPa and 10,100 MPa, respectively. These enhancements are attributed to the formation of robust, cross-linked polymer networks between PF molecules and the lignocellulosic matrix, as highlighted by Sohn and Cha (2018) and Andersone *et al* (2012).

Following the curing process, PF becomes chemically bonded within the cell walls, reinforcing the matrix and markedly increasing its stiffness and load-bearing capacity. The MUF treatments, though less effective than PF, also showed significant improvements over the untreated control samples. At 15% concentration, MUF increased MOR and MOE to 75.9 MPa and 9,220 MPa, respectively. These gains stem from the adhesive interactions between MUF and cell wall polymers. However, the resin's relatively higher viscosity and surface-curing behavior limit its penetration depth, which may constrain mechanical reinforcement in inner wood zones (Esteves and Pereira 2009). In contrast, PEG-treated specimens exhibited moderate mechanical enhancement. At 15%, MOR and MOE reached 65.1 MPa and 7,780 MPa, respectively. These increases are primarily due to reduced internal stresses and the mitigation of micro cracking rather than genuine structural reinforcement. Because PEG does not cure or form covalent bonds with the wood, and its hydrophilic nature prevents permanent stiffening of the structure, its contribution to mechanical properties remains limited (Hill 2006).

A comparative analysis with standard hardwoods reveals that poplar impregnated with PF at 15% approaches the mechanical profile of walnut (MOR ≈ 100.7 MPa, MOE ≈ 11,600 MPa) and it enters a competitive range relative to European beech (MOR ≈ 120.6 MPa, MOE ≈ 14,800 MPa). Considering poplar's rapid growth cycle, domestic availability, and lower cost, these results underscore its potential as a sustainable alternative to imported hardwoods in high-performance applications such as furniture and fine woodworking (Gilanipoor *et al.* 2021; Cheng *et al.* 2022).

Table 6. Mechanical Properties of Poplar Wood Impregnated with PF, MUF, and PEG Resins at Different Concentrations

Treatment		MOR (MPa)	MOE (MPa)	Impact Strength (J/m)	Hardness (kN)
Resin Type	Resin Content (%)				
Control	—	55.00 (1.71)	6498 (138.09)	5.82 (0.28)	1.29 (0.03)
MUF	5	62.00 (1.05)	7360 (113.36)	6.86 (0.21)	1.60 (0.02)
MUF	10	71.34 (1.06)	8684 (106.44)	8.01 (0.16)	1.76 (0.02)
MUF	15	75.92 (0.67)	9222 (85.26)	8.94 (0.24)	1.97 (0.02)
PF	5	65.00 (0.72)	7820 (132.85)	7.36 (0.26)	1.70 (0.02)
PF	10	77.90 (0.90)	9344 (114.59)	9.14 (0.24)	1.92 (0.02)
PF	15	81.32 (0.76)	10054 (97.60)	9.26 (0.14)	2.15 (0.02)
PEG	5	58.76 (0.78)	6954 (105.97)	6.73 (0.19)	1.44 (0.02)
PEG	10	62.32 (0.93)	7418 (91.27)	7.21 (0.15)	1.55 (0.02)
PEG	15	65.06 (0.80)	7780 (94.07)	7.62 (0.15)	1.67 (0.02)
Walnut	—	100.70	11600	10.90	2.28 (0.02)
European Beech	—	120.60	14800	11.21	2.54 (0.02)

Statistical analysis using ANOVA confirmed that resin type, concentration, and their interaction had significant effects on all mechanical parameters at the 99% confidence level ($p < 0.001$). These findings are consistent with earlier works by Ahmadi *et al.* (2019, 2024), which demonstrated that resin treatments, including melamine and tannin-based systems, can substantially enhance strength, dimensional stability, and surface hardness. Furthermore, a direct and consistent correlation was observed between WPG and mechanical properties across all treatments. This supports the widely accepted principle, as reported by Hill (2006) and Rowell (2005), that higher resin uptake generally translates to improved mechanical performance. Among the tested treatments, PF stands out as the most effective modifier for engineering-grade wood enhancement where high mechanical resilience is essential. Recent studies on scrimber composites from low-value poplar peeler cores have shown that combining hydrothermal treatment with PF resin yields superior structural performance, highlighting the potential of underutilized wood resources in producing high-performance, sustainable construction materials (Arefkhani *et al.* 2024).

In summary, PF impregnation particularly at a concentration of 15% offers a highly efficient strategy for significantly improving the structural integrity of poplar wood. Its outstanding performance in terms of bending strength, stiffness, and impact resistance establishes it as a strong candidate for replacing conventional hardwoods. Additionally, its role in supporting environmental sustainability by reducing reliance on slow-growing species and lowering processing costs further strengthens its industrial appeal.

Qualitative Assessment of Carving Performance

To assess the practical applicability and aesthetic suitability of modified poplar wood, two structured questionnaires were administered, each employing a 5-point Likert scale ranging from “very poor” to “excellent.” These surveys aimed to evaluate both subjective and objective perceptions of wood quality during manual carving and CNC machining processes. Evaluated attributes included surface hardness, tool responsiveness, carving precision, finish uniformity, color consistency, and resistance to surface cracking. A total of 15 seasoned artisans and CNC operators participated in the assessment. The evaluation involved untreated control samples as well as those treated with PF, MUF, and PEG resins at concentrations of 5%, 10%, and 15%. Among all samples, poplar wood treated with 15% phenol-formaldehyde (PF15%) consistently achieved the highest mean ratings across nearly all parameters (Table 1). For instance, the average score for surface finish in PF15% samples was 4.5 out of 5, significantly higher than the control group, which scored only 2.3. Superior ratings were also recorded for crack resistance, precision in fine detail, and visual uniformity. The reliability of the assessment tool was statistically validated using Cronbach’s alpha, which yielded a value of 0.983, denoting excellent internal consistency. Based on the classification by Cao *et al.* (2021), values above 0.9 confirm outstanding reliability, reinforcing the validity of the collected data.

Table 7. Cronbach’s Alpha Coefficient

Reliability Statistics	
Cronbach’s Alpha	N of Items
0.983	50

As illustrated in Figs. 5 and 6, PF15%-treated wood exhibited exceptional performance across five major carving indicators: surface hardness, colorability, finishing quality, crack resistance, and detail sharpness. MUF15% samples also received favorable evaluations, though slightly lower in color uniformity and finish clarity. PEG15%, while offering benefits in terms of initial softness and ease of tool penetration, scored lower in maintaining fine details and achieving a polished finish.

Figure 6 further supports these findings by visually showcasing the quality of manual carvings across different treatments. Panel (a) displays untreated poplar, while panels (b), (c), and (d) show samples treated with MUF, PEG, and PF, respectively. PF-treated samples exhibit the most refined edges and consistent texture, closely resembling the aesthetic standards of traditional hardwoods.

Comparative Evaluation with Benchmark Hardwoods

To contextualize the performance of modified poplar wood, walnut and European beech were used as benchmark hardwoods. Expert evaluations indicated that untreated poplar underperformed in critical aspects such as structural firmness, surface smoothness, and detail sharpness. However, PF15%-treated samples approached and in certain cases, exceeded the performance of beech in attributes like color consistency and resistance to chipping. While walnut maintained an aesthetic advantage in terms of natural grain and visual warmth, PF15% demonstrated comparable carvability, structural integrity, and tactile response.

Given poplar's shorter growth cycle, local availability, and lower production cost, PF-treated specimens offer a compelling technical and economic alternative to traditional hardwoods. Their compatibility with both manual and automated carving processes enhances their viability for widespread use in fine furniture and artistic woodworking applications.

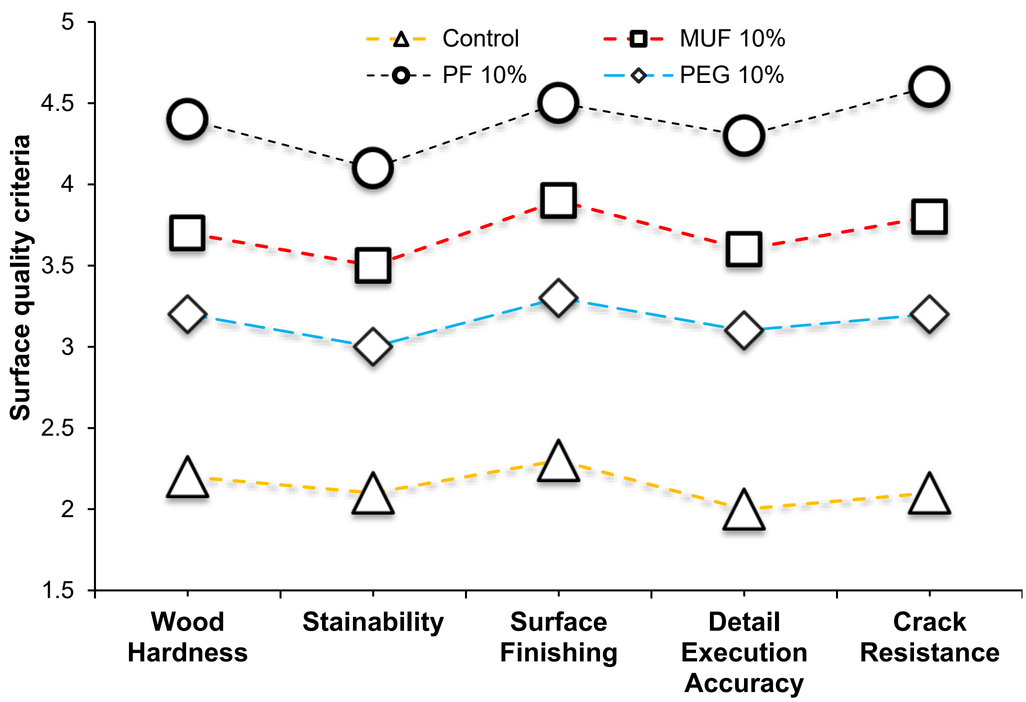

Fig. 5. Evaluation scores for surface quality indicators in carved poplar wood treated with various resins

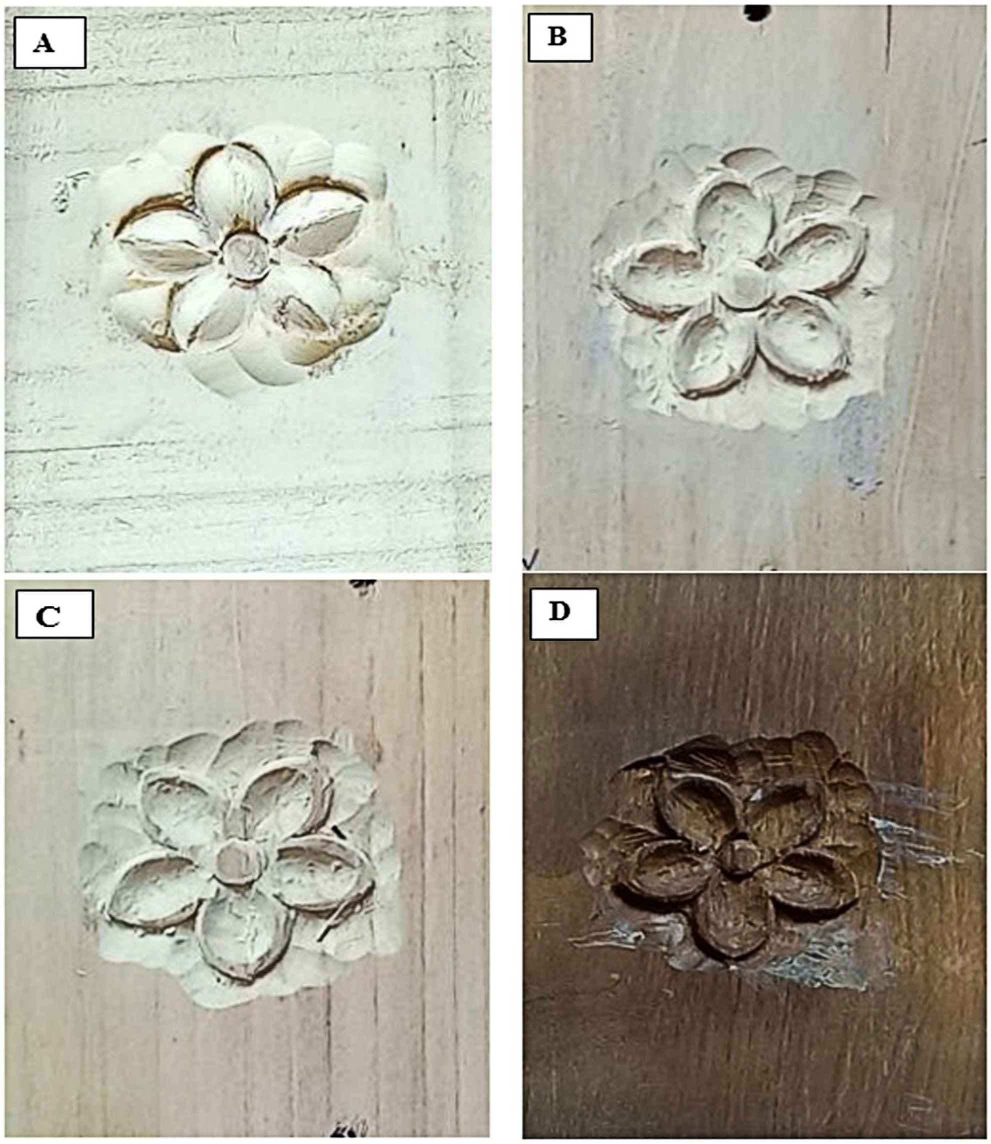

Fig. 6. Visual comparison of hand-carved poplar wood samples. (a) Control (untreated), showing coarse fiber tearing and rough surfaces; (b) MUF-treated, displaying moderate improvement with partial smoothness; (c) PEG-treated, characterized by uniform carving surfaces and reduced shrinkage cracks; and (d) PF-treated, exhibiting the smoothest and most precise carved details due to higher hardness and dimensional stability

CNC Machining Results

The CNC machining evaluations revealed that poplar wood impregnated with PF resin at a 15% concentration demonstrated superior performance across all measured technical parameters. Specifically, this treatment yielded an average surface roughness (R_a) of 2.90 µm, a substantial improvement compared to the 8.60 µm recorded for the untreated control specimens. Furthermore, the dimensional error for PF-treated samples was reduced to 0.22 mm, while the surface defect rate declined markedly to 4.2%, reflecting a significant enhancement in surface integrity and machining precision. In contrast, the control group and specimens treated with 5% PEG exhibited the poorest performance, with surface roughness values of 8.60 µm and 7.20 µm, dimensional deviations of 0.82 mm and 0.72 mm, and surface defect rates of 37.5% and 28.1%, respectively. These outcomes underscore the inadequacy of unmodified and hydrophilic PEG-treated samples in achieving acceptable surface quality and dimensional accuracy. In fact, PEG functioned primarily as a bulking and plasticizing agent rather than a cross-linking resin. By filling cell wall voids and retaining moisture, it reduced shrinkage stresses and delayed brittle failure, thereby improving dimensional stability and surface quality during drying and machining (Flaig *et al.* 2023; Yang and Mei 2023). In addition to mean performance, the PF15% group exhibited remarkably low variability, with standard deviations of 0.15 µm for surface roughness, 0.01 mm for dimensional error, and 0.6% for defect rate, indicating high repeatability and robust process stability. Conversely, untreated and PEG-treated groups demonstrated greater fluctuation in results, suggesting increased sensitivity to CNC parameters and reduced predictability in machining behavior.

Table 8. Surface Quality Characteristics of Resin-Treated Poplar Wood after CNC Machining

Treatment Type		Surface Roughness (R_a, µm)	Dimensional Error (mm)	Surface Defect Rate (%)	Machinability Class (1–5)
Resin Type	Resin Concentration (%)				
	Control	8.60 ± 0.40	0.82 ± 0.05	37.5 ± 1.2	2–3
MUF	5	6.90 ± 0.30	0.65 ± 0.04	24.3 ± 1.6	3–4
MUF	10	5.50 ± 0.20	0.47 ± 0.03	17.8 ± 1.3	3–4
MUF	15	4.80 ± 0.25	0.38 ± 0.02	12.5 ± 1.1	4
PF	5	5.10 ± 0.30	0.42 ± 0.03	13.2 ± 1.2	4
PF	10	3.70 ± 0.18	0.30 ± 0.02	7.8 ± 0.9	4–5
PF	15	2.90 ± 0.15	0.22 ± 0.01	4.2 ± 0.6	4–5
PEG	5	7.20 ± 0.40	0.72 ± 0.04	28.1 ± 1.8	3–4
PEG	10	6.00 ± 0.35	0.59 ± 0.03	21.5 ± 1.5	3–4
PEG	15	5.20 ± 0.30	0.48 ± 0.03	18.3 ± 1.3	3–4
	Walnut	2.50 ± 0.10	0.12 ± 0.01	3.5 ± 0.4	5
	European Beech	2.20 ± 0.08	0.10 ± 0.01	2.8 ± 0.3	5

The differences among treatment groups were statistically validated through one-way ANOVA, which revealed highly significant effects ($p < 0.001$) of resin type and concentration on all machining quality indicators. *Post-hoc* analysis using Duncan's test classified PF15%, along with reference hardwoods, such as beech and walnut, in the top-performing statistical groups (A or AB), while MUF, PEG, and control samples were grouped significantly lower (Groups B and below). These findings are consistent with prior literature, where thermosetting resins such as PF have been reported to form stable, *in-situ* polymer networks within the wood, thereby improving surface hardness, dimensional consistency, and overall machinability (Wang *et al.* 2019; Lang *et al.* 2022). In contrast, PEG's hydrophilic, non-curable nature limited its ability to improve machining characteristics, as evidenced by increased surface roughness and defect rates. Overall, the PF15%-treated poplar samples not only exhibited high dimensional stability and smooth surface profiles but also displayed exceptional resistance to machining-induced surface defects.

These results, supported by visual assessments and quantitative measurements (Fig. 7), position phenol-formaldehyde modified poplar wood as a viable and cost-effective alternative to traditional hardwoods in applications requiring precise CNC manufacturing such as high-end furniture, intricate carvings, and decorative wood components. This study demonstrated that impregnation with PF, MUF, and PEG resins significantly improved the density, dimensional stability, and machinability of fast-growing poplar, making it a viable alternative to conventional hardwoods in furniture and carving applications. While PF and MUF are effective in enhancing performance, their environmental limitations highlight the need for further research on bio-based and low-emission resin systems to achieve both technical and ecological sustainability.

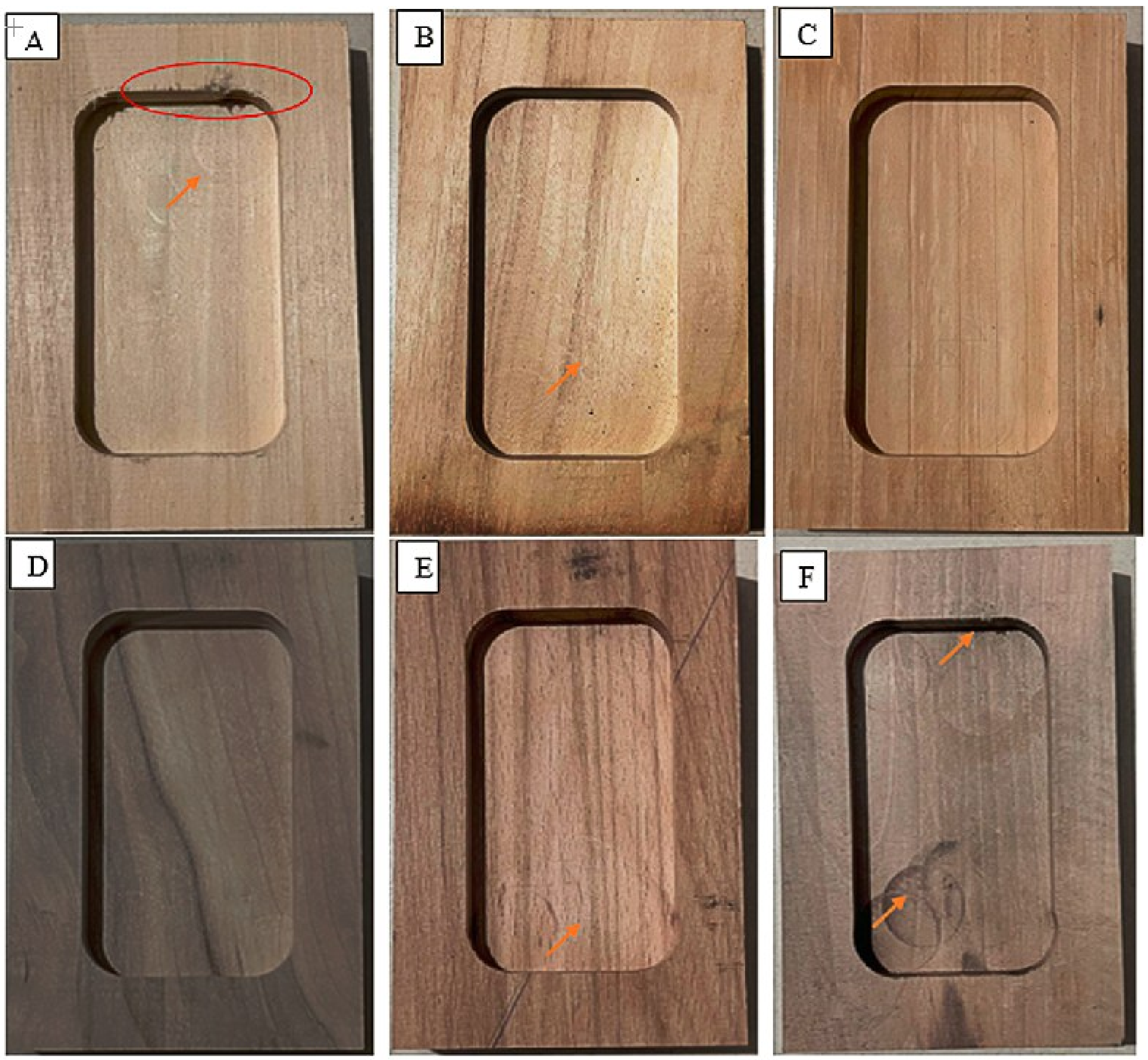

Fig. 7. Surface morphology of CNC-machined poplar and reference hardwoods. (A) Untreated poplar (Control) showing severe fiber tearing, rough texture, and poor surface definition; (B) MUF-treated poplar (15%) with moderate improvement and reduced tearing but visible unevenness; (C) PEG-treated poplar (15%) characterized by smoother surfaces and improved dimensional stability, though with slight plasticization effects; (D) PF-treated poplar (15%) exhibiting the most precise machining quality, smooth edges, and minimal fiber pull-out; (E) European beech as a reference hardwood, showing fine grain and uniform surface finish. in case, showing a slight trace of the machining path; and (F) Walnut, demonstrating high density, smoothness, and superior surface detail as a benchmark for carving and machining quality. in case, showing a slight trace of the machining path and despite the presence of partially stripped fibers

CONCLUSIONS

1. Chemical modification of fast-growing poplar wood with phenol formaldehyde (PF), melamine urea formaldehyde (MUF), and polyethylene glycol (PEG) resins significantly enhanced its physical, mechanical, and surface properties, thereby improving its industrial applicability.
2. Among all treatments, 15% PF impregnation achieved the highest improvements in weight percent gain, bulking effect, density, dimensional stability, and mechanical strength (modulus of rupture, modulus of elasticity, hardness, and impact resistance).
3. PF-treated specimens exhibited superior computer numerical control (CNC) machinability and manual carving performance, resulting in smoother surfaces, clearer details, and higher resistance to defects compared to other treatments.
4. Higher resin uptake and deeper penetration, particularly with PF and partially with MUF, were directly associated with enhanced structural integrity and improved surface quality.
5. The PEG treatment contributed to dimensional bulking and ease of machining but showed limited effectiveness in improving moisture resistance and long-term strength due to its hygroscopic and non-curable nature.
6. PF-modified poplar wood demonstrated performance levels approaching those of conventional hardwoods such as walnut and European beech, highlighting its potential as a cost-effective and sustainable substitute.
7. The successful modification of poplar supports the broader utilization of fast-growing, locally available species as alternatives to slow-growing hardwoods, aligning with circular bioeconomy and forest conservation strategies.
8. This study advances the field of wood modification by extending conventional resin impregnation research toward industrial applicability, integrating machinability and carving performance with multi-resin comparisons and benchmarking against hardwoods, thereby providing novel insights into the practical utilization of modified poplar in high-value applications.

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