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Use of rosemary (*Rosmarinus Officinalis*) plant as impregnation in wood material and retention values

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This study investigated the suitability of rosemary (*Rosmarinus officinalis*) plant extract and hydrosol for use as a preservative in Scots pine (*Pinus sylvestris* L.) and Turkish beech (*Fagus orientalis* L.) wood. The air-dry and fully dry specific gravity, tensile-shrinkage, water absorption-expansion (swelling) properties, and retention quantities of the impregnated samples were determined and statistically evaluated. Experimental applications were carried out using short, medium and long-term immersion methods; samples were soaked in water for 6, 12, 24, 48, 72, and 96 h and performance analyses were performed. The findings revealed that tree species was a statistically significant and decisive factor on specific gravity values ($F = 15.013$; $p < 0.001$). Turkish beech wood (Mean = 0.63) exhibited higher specific gravity values compared to Scots pine wood (Mean = 0.53). While the impregnation period and some factor interactions were found to be significant on air-dry specific gravity, it was determined that the effect of variables other than tree species was limited in terms of fully dry specific gravity. A significant effect of time ($F = 97.764$; $p < 0.001$), concentration ($F = 12.627$; $p < 0.001$) and impregnation time ($F = 11.713$; $p < 0.001$) factors was detected in the tensile-shrinkage behavior. In particular, it was found that hydro-sol and hydro-sol+mordant applications increased dimensional stability by reducing tensile-shrinkage values. The dominant effect of tree species ($F = 271.081$; $p < 0.001$) and time ($F = 169.730$; $p < 0.001$) on water absorption properties was noteworthy; Scots pine (67.26%) was found to have a higher water absorption rate than Turkish beech (48.87%). Among the applications, a 10% hydrolysate concentration increased the water uptake rate to 60.92%, whereas the extract+mordant combination yielded more balanced results at 55.93%. It was determined that expansion (swelling) values were particularly affected by tree species, concentration, and time factors; extract-based applications tended to increase expansion, while hydrosol applications provided more limited dimensional changes. It was found that a 10% hydrosol application yielded an average swelling value of 4.26%, representing a reduction of approximately 22% compared to the control group's value of 5.51%. Tree species was a determining factor in terms of retention values; results ranged from 0.34–1.62% in Scots pine and 0.13–0.73% in Turkish beech. In conclusion, rosemary hydrosol demonstrated more favorable performance in terms of dimensional stability in wood materials, while extract applications were found to have enhancing effects on certain physical properties. The findings suggest that rosemary extract and hydrosol could be considered as environmentally friendly alternatives in the ecological wood preservation industry, particularly for interior applications.

KEYWORDS

furniture, impregnation, natural wood protection, retention, rosemary, wood

Introduction

The increase in the world population and the related consumption habits have made the use of renewable and environmentally friendly resources mandatory. In this context, the negative effects of chemical-containing wood preservatives, which are widely used in the furniture and building sector, on human and environmental health have made it necessary to develop natural and organic alternatives. Wood, a renewable natural resource; It has been preferred throughout history due to its esthetics, easy processing and mechanical properties (Çağlayan, 2020; Karadağ et al., 2017). The increase in global warming and the decrease in forest assets have increased the importance of environmentally compatible conservation methods for longer-lasting and efficient use of wood (Bayraktar and Kesik, 2022). In this context, plant-derived extracts and natural impregnations are increasingly appearing in the literature as alternatives to chemical systems (Atılğan, 2022). There are many studies examining properties such as accelerated aging, dimensional stability, retention, mechanical properties, roughness, gloss, paint adhesion and biological resistance after the use of herbal extracts on wood surfaces (Atılğan et al., 2011; Göktaş et al., 2008; Vardanyan et al., 2015). Developments in environmentally friendly wood preservation chemicals protect wood a sustainable, low CO₂-emission construction material against biological degradation while promoting the use of renewable resources and addressing environmental concerns (Khademibami and Bobadilha, 2022).

In recent years, studies have investigated the potential of natural plant extracts for surface modification and preservative purposes in wood materials. In this context, natural substances such as pomegranate extract and gum Arabic are reported to be effective on wooden surfaces and show promise in terms of environmental sustainability (Peker et al., 2025). In recent years, there have been studies on strengthening the wooden material in a different way. FRCM-PBO composite coatings applied to wooden beams with mineral resin and quartz sand, which were used as a different reinforcement method, improved the mechanical performance of wooden structural elements by providing significant increases in load-bearing capacity and maximum bending stress compared to control examples (Atılğan and Kocaer, 2025). For nearly 200 years, creosote used in wooden railway sleepers has been recognized as harmful to human health and the environment, and its usage is entering a phase of prohibition, making it necessary to develop alternative plant-based wood protection products for wooden sleepers (Starck et al., 2022).

Wood material, which is a renewable natural resource; although it is widely used indoors and outdoors due to its esthetic, physical and mechanical properties, it has been rapidly damaged when it is not adequately protected against environmental effects (Çağlayan, 2020; Evans et al., 1996). External factors such as sunlight, ultraviolet radiation and humidity cause color change, dimensional instability and surface deterioration on wooden surfaces (Hon, 2001; Can, 2018). In the study, which investigated the protection of the surface of the wood material by forming a film layer and its effect against different physical effects, epoxy resin was applied as a protective coating material on the surfaces of wood species with different specific densities and the changes in surface properties after the hot-cold shock effect were

examined (Atılğan and Dündar Sofuoğlu, 2025). With global warming and forest fires, wood resources are becoming increasingly scarce, making it essential to develop effective and sustainable solutions for the conservation of this material.

Rosemary is also a high-potential, safe and natural antioxidant source that can replace synthetic preservatives in animal nutrition, extending food shelf life by preventing oxidation thanks to its strong phenolic compounds such as carnosic acid and carnosol (Malayoğlu, 2010). The negative effects of paints and varnishes with high solvent content used in traditional wood protection systems on human and environmental health have increased the interest in natural and ecological alternatives (Tsatsaroni et al., 1998; Jocham et al., 2011). In this context, there are many studies in the literature in which the physical, superficial and dimensional properties of wood are tried to be improved by using plant-based extracts, natural oils and resins (Atılğan et al., 2011; Vardanyan et al., 2015; Atılğan, 2022). In another study, it is reported that significant changes in color and gloss properties occur after artificial aging in ash wood coated with polyurethane-modified water-based varnishes and subjected to heat treatment at different temperatures (Ulay et al., 2025). In this study, the effect of water-based and synthetic varnishes modified with different nanomaterials on antimicrobial activity on wood surfaces was examined; The relatively lowest microorganism growth was observed in samples treated with 0.1% nano boron-added synthetic varnish. It shows that the use of nanomaterials together with varnishes applied to wooden surfaces can contribute to antimicrobial properties (Özder et al., 2024).

In the studies carried out in recent years; It has been determined that natural oils, resins, silane-siloxane-based systems and medicinal aromatic plant extracts provide water repellency, dimensional stability and antimicrobial effect in wood material, as well as improve surface performance (Atılğan et al., 2018a, 2018b; Atılğan, 2023a, 2023b). However, plant-derived impregnates are reported to have limited effect on the mechanical strength of wood in some cases, but offer positive results in terms of color, gloss, and biological resistance.

The inhibitory effect on the surface of the woodspecimens treated with rosemary oil against molds (*A. niger*, *T. viride*, and *P. chrysogenum*) was low. Pine wood treated with 10 and 100% rosemary oil showed resistance against decay fungi *G. trabeum*, *P. placenta*, and *T. versicolor*, with no weight loss of the wood samples (Yang and Clausen, 2007; Mihai and Popa, 2015). According to various research results, rosemary has been recognized as a plant that has both good antioxidant and good antimicrobial properties and is rich in chemical components (Ahmed Alrasheed et al., 2023; David et al., 2019; Golshani and Sharifzadeh, 2014). The antimicrobial and antibiofilm properties of rosemary oil against *Streptococcus mutans* and *Streptococcus pyogenes* by using it together with chlorhexidine (antiseptic, disinfectant) have been investigated *in vivo* and it has been observed that it has an inhibitory effect at all concentrations (Tas and Eğilmez, 2023; Rasooli et al., 2008). Considering the harms of traditional paint and varnish systems containing high solvents to human health and the environment, the development of natural dyes and preservatives is important for sustainability (Jocham et al., 2011; Salthammer et al., 2002). Considering that external factors such as sunlight, UV radiation and moisture cause degradation on wooden

surfaces, the investigation of the long-term durability performance of organic coatings remains up-to-date (Evans et al., 1996; Hon, 2001; Gheno et al., 2016). In another plant species study conducted by the researcher, the highest retention was obtained in red pine (2.29%) in the 30-min process with 10% yarrow hydrosol, while the lowest retention was seen in walnuts (1.17%) in the 24-h process with 10% hydrosol. Yarrow extract did not significantly affect the physical properties of the impregnated woods; however, it has been stated that hydrosol increases dimensional stability in all samples thanks to its water-repellent properties (Çetin and Kalaycı, 2025b). In a similar study, he showed that oleander extract did not have a significant effect on retention in the effects of oleander (*Nerium oleander* L.) extract and hydrosol on the physical properties of red pine, eastern beech, and walnut woods after impregnation, whereas hydrosol offers potential as an environmentally friendly wood preservative by increasing water resistance and dimensional stability (Çetin and Kalaycı, 2025b).

Another study on the rosemary plant (*rosmarinus officinalis*) examined the effect of different humidity levels (8.2, 10.8, and 15.3%) on the biotechnical properties of the plant, revealing that as the moisture content increased, leaf and stem sizes, weights, projection area, and the breaking force required to separate the leaves from the stem increased statistically significantly. On the other hand, it was determined that the essential oil content, which is the most valuable component of the plant, decreased inversely with the increase in moisture content and the highest oil yield (2.403%) was reached at the lowest humidity level (Yılmaz and Gökduman, 2016). In another similar study, after evaluating the leaves of the rosemary (*rosmarinus officinalis*) plant, it examines the potential of the idle stems to be used as raw material in the paper industry. As a result of the chemical analyzes, rosemary stems contain 63.6% holocellulose, 36.4% α -cellulose and 26.9% lignin; In morphological analysis, it was determined that the fiber length was in the “short fiber” category with 0.58 mm. The findings reveal that rosemary stalks are suitable for paper production, especially in terms of values such as felting rate and elasticity coefficient, show similar properties to hardwoods thanks to their high lignocellulosic content, and can be an alternative raw material source in preventing environmental pollution by bringing these wastes into the economy (Odabaş Serin et al., 2017). Recent research on sustainable wood modification highlights that environmentally friendly impregnation strategies can significantly improve wood performance. For example, plant-based compounds and bio-polymers have been used as natural modifying agents to enhance dimensional stability and water resistance in wood. Lignin, one of the most abundant biopolymers, was successfully incorporated into wood cell walls via impregnation, leading to remarkable anti-swelling efficiency (up to 99.4%) and reduced moisture absorption, demonstrating improved dimensional stability and durability despite minimal adverse effects on mechanical properties (Leng et al., 2024). In another study on rosemary; It has been proven that the highest essential oil content is reached in the leaves harvested in the autumn period and at low humidity levels (8.2%), that as the humidity increases, the physical dimensions of the plant and the difficulty of harvesting (breaking force) increase, and that the antioxidant capacity peaks during the full flowering period. In addition, it has been determined that the stems remaining from the leaves from which the essential oil is taken have a valuable raw material potential for the paper industry and offer an economical waste management thanks to their high cellulose content and suitable fiber structure (Ayanoglu et al., 2016).

The aim of this study is to reveal the potential of natural impregnations and coating agents of plant-based rosemary plant in the protection of wood material and to evaluate the effects of these applications (retention) on the dimensional stability, water repellency and surface performance of wood. Thus, it is aimed to contribute to the development of safer, sustainable and alternative wood protection methods in terms of human and environmental health.

Material and method

Material

Plant material

Rosemary (*rosmarinus officinalis* L.) plant, which has been used in various foods and alternative medicine from past to present, is one of the medicinal aromatic endemic plants that can grow in many parts of the world where the Mediterranean climate prevails, and is also widely found in Turkey.

Rosemary is native to the Mediterranean climate and is cultivated in its natural or cultivated environment in many countries, including Tunisia, Morocco, Algeria, Spain, France, Italy, Turkey, the United States, and China. Approximately 70% of the world's essential oil production comes from Tunisia and Morocco, but official data on production and trade is limited. In Turkey, it grows naturally, particularly along the Mediterranean and Aegean coasts. Production mainly takes place in forest areas as a non-timber product between July and September, with the harvested plants being dried and sold on the market (BAKA, 2021).

Rosemary (*rosmarinus officinalis* L.) plant is an evergreen shrub aromatic plant with a fringe root system, an upright stem, and a height of 90–200 cm. The branches are hard, the trunk is square, the structure of scaly bark on the woody outer surface, divided into numerous long and thin branches and is brown in color. The leaves are small (2–4 cm), sticky and narrow, bright green on the upper side, curled at the edges and densely hairy white on the underside (Raghavan, 2007; Charles, 2013; Sasikumar, 2004). Its flowers are small, pale purple or bluish in shape (Figure 1).

Rosemary extract (oleoresin)

Phenolic acids (rosmarinic acid), pungent diterpenes (carnosol, carnosic acid, rosmanol), triterpenes (oleanolic and ursolic acid), triterpene alcohols (α -amyrin, β -amyrin, betulin), and flavonoids and their glycosides (diosmetin, luteolin, genkwanin) (Charles, 2013).

In the preparation of rosemary plant extract and hydrosol (Atılğan, 2023a; Çetin and Kalaycı, 2025a, 2025b), the conditions under which the extraction process, which consists of dried stems and leaves in the oven, is listed in Table 1, and the proportions of mordant to be added are specified. Only natural Grape Vinegar (Vinum Acetum) was used to ensure adhesion during mordanting.

Rosemary hydrosol

Rosemary (*Rosmarinus Officinalis*), a shrub native to the Mediterranean region, is distilled to obtain essential oil from its dried leaves. The water distilled during this process yields hydrosol, which



FIGURE 1
Rosemary plant.

TABLE 1 Extraction conditions of rosemary dyestuff and dye solution-mordant mixing ratios.

Dyestuff	Water to plant ratio (g/g)	Temperature (°C)	Duration (min)	Solution type	Mordant type	Mixing ratio (%)
Rosemary	10/1	90	120	Extract	Control	0
Rosemary	10/1	90	120	Extract	Vinegar	10
Rosemary	10/1	90	120	Hydrosol	Control	0
Rosemary	10/1	90	120	Hydrosol	Vinegar	10

Atılğan (2023a), Çetin and Kalaycı (2025a, 2025b).

contains between 3 and 0.3% essential oil and pure water. Rosemary extract, phenolics, and essential oil stimulate blood circulation and have antibacterial, antifungal, antiviral, antimicrobial, antiparasitic, antiproliferative, spasmolytic, anti-inflammatory, and mild analgesic activity. Rosemary extract and essential oil have been shown to be both effective and anticholinergic. The main components of rosemary hydrosol, which remains after distillation, are 1.8-cineole, camphor, endo-borneol, verbenone, and β -phenchyl alcohol, and rosemary hydrosol generally contains about 0.1% essential oil. There are three main chemotypes of rosemary hydrosol (camphor, cineole, and verbenone), and these differences affect both the hydrosol and extract properties. Based on the hydrosol, the camphor type is softer and more floral, the cineole type is sharper and more camphor-like (with a shorter shelf life), and the verbenone type has a sweeter, greener, and more balanced character. In extracts, these chemotype differences become more pronounced due to the higher concentration of volatile and active compounds; sineol and camphor content increase sharpness and biological effect, while the verbenon type offers a more balanced and soft profile (Catty, 2001; Duke, 2000; Sasikumar, 2004; Raghavan, 2007; Charles, 2013).

A Hydrosol can be defined as a water-based solution obtained during the distillation of plants. This process aims to separate plant extracts and essential oils in a distillation machine between 90 and 100 degrees. During distillation, the sap of the plant is separated by

water vapor, and as this steam condenses, the hydrosol is formed in a separate chamber. The steam passes through a condenser (condenser) to rise upwards and be cooled. Afterwards, the steam turns into water and collects as essential oil in a large container, while the hydrosol of the plant, which carries the unique scent of the plant, accumulates in the lower part. S. S. Yerkesik Agricultural Development Cooperative (YERKOOP/MUĞLA) experimental laboratory was used to obtain Rosemary Hydrosol and extract. In Figure 2 below, the plant distillation machine boiler (Retort machine) used to obtain rosemary hydrosol is shown and workflow process Figure 3.

Method

Impregnation method

The immersion method was selected to simulate conditions that are environmentally friendly, practical, low-cost, and easy to implement, suitable for small-scale industrial applications. Additionally, the immersion impregnation method is widely used in plant-based impregnation studies and provides significant opportunities for everyone to easily perform practical applications in evaluating the retention



FIGURE 2
Distillation machine.

of natural extracts without the influence of artificial pressure conditions.

The impregnation process was carried out by immersion method, one of the methods without pressure, under the conditions specified in [ASTM-D, 1413-76 \(1976\)](#). For this, wood samples prepared in $2 \times 2 \times 3$ cm dimensions were left in oleander plant extract solution at normal atmospheric pressure for the following periods. In order to determine the adhesion rate of the impregnating agent and not to be affected by the moisture of the wood, the samples were made completely dry before and after impregnation.

Prolonged Immersion: 24 h Solution Soaking.

Medium Immersion: 3 h.

Short-Term Immersion: 30 min.

Preparation of test samples and impregnation application method

Scotch pine (*pinus sylvestris* L.) and Turkish beech (*fagus orientalis* L.) tree species, which are widely used in the wood industry, were selected. These species were selected due to their widespread industrial use and their differing anatomical and permeability characteristics, which allow meaningful evaluation of impregnation performance. Examples of experiments; It is obtained from knot-free, crack-free, smooth fibrous, reaction-free, fungus and insect damage, homogeneous in terms of color and density, first-class sapwood parts. Care has been taken to prepare the annual rings to be perpendicular to the surface (radial). Examples used in determining solution absorption and net dry matter amount; It was prepared with a length of 3 cm in the direction parallel to the fibers, a width of 2 cm in the direction parallel to the core rays, and a thickness of 2 cm in the direction tangent to the annual rings ([Bozkurt et al., 1993](#); [Akyürekli, 2003](#)). The impregnation process was carried out in a short-term (30 min), medium-term (3 h) and long-term (24 h) method by applying the immersion method to the air-dry samples. Excess solution remaining

on the surface of the samples after impregnation was removed with a paper towel and the samples were weighed in wet state. Then, the samples were dried in an oven at 50 ± 3 °C until they reached a constant weight; exact dry weight and dimension measurements were determined using 0.01 precision scales and measuring equipment ([TS 345, 2012](#)).

Dimensional stability (contraction/expansion) and water uptake rate (SAO)

Water uptake and dimensional stability (contraction/expansion) tests of the samples were performed according to [ISO, 13061-15 \(2017\)](#) standard. The samples, whose exact dry weight and dimensions were previously determined, were kept in distilled water for 6, 24, 48, 72 and 96 h under laboratory conditions ([Bozkurt et al., 1993](#)). At the end of each holding period, the samples were removed from the water, dried with a paper towel and weighed. The sizes of the samples soaked in water for 6, 24, 48, 72 and 96 h were determined. The tangential direction, radial direction, longitudinal water uptake rates (SAO) and dimensional stability (contraction/expansion) values (BS) of the samples were determined by the following formulas;

$$\text{SAO (\%)} = (M2 - M1) / M1 \times 100.$$

$$\text{BS (\%)} = (L2 - L1) / L1 \times 100.$$

Here; M1: Initial full dry weight (g).

M2: Weight of the sample removed from the water after each period (g).

L1: Full dry sample dimensions before immersion (mm).

L2: Wet sample dimensions after water immersion (mm).

Specific gravity (air dry/full dry) and retention (adhesion)

In the determination of air dry and full dry specific gravities, operations were carried out on the basis of [TS ISO 13061-1 \(2021\)](#) and

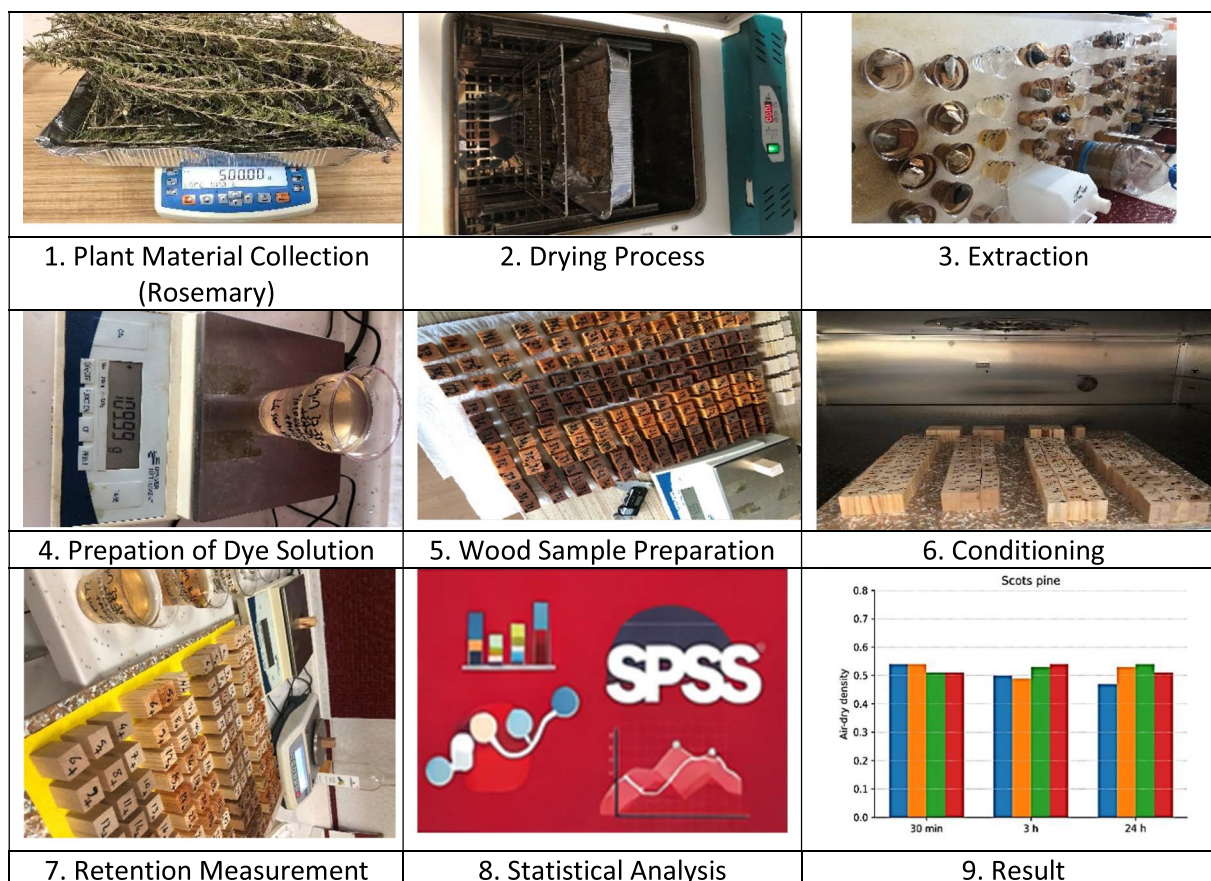


FIGURE 3
Workflow process.

TS ISO 13061-2 (2021) standards. The retention amount of rosemary extract in wood material was determined by the following formula;

$$R (\%) = \frac{\text{Moes} - \text{Moeö}}{\text{Moeö}} \times 100.$$

R (%): % retention.

Moes: Full dry weight after impregnation.

Moeö: Full dry weight before impregnation.

identified, Duncan's multiple comparison test was applied to determine which groups accounted for the differences between groups. The statistical significance level was set at $\alpha = 0.05$, and all tests were evaluated at a 95% confidence level. Results are presented as mean $\pm$ standard deviation (Mean $\pm$ SD).

Evaluation of data

The statistical analysis of the data was performed using the IBM SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA) software package. The study was designed according to a factorial experimental design that included the factors of tree species, impregnation concentration, impregnation time, and exposure time. Multi-factor analysis of variance (MANOVA) was applied for dependent variables depending on the number of factors. Main effects and interaction effects were evaluated. Three independent samples ($n = 3$) were used for each experimental condition. Measurements were performed on three independent samples for all treatment combinations. The total sample size was calculated based on the product of all factor combinations. Model assumptions were checked prior to analysis. The normality of residuals was assessed using the Shapiro-Wilk test and by examining skewness and kurtosis values. Variance homogeneity was tested using the Levene test. When significant main effects were

Findings

The results of the multiple analysis of variance to determine the effect of wood type, impregnation time and concentration on air-dry specific gravity values in samples impregnated with rosemary are presented in Table 2. According to the results of the analysis, it was determined that the tree species (A) had a statistically significant effect on the specific gravity of air dry ($F = 1468.705$; $p < 0.001$). Similarly, impregnation time (B) also showed a significant effect on specific gravity ($F = 18.149$; $p < 0.001$).

Although the effect of concentration (C) factor on air-dry specific gravity was found to be statistically significant, this effect was found to be more limited compared to other factors ($F = 2.960$; $p = 0.041$). When the interactions between the factors were examined, it was determined that $A \times B$, $B \times C$ and $A \times B \times C$ interactions had statistically significant effects on the

TABLE 2 Multiple analysis of variance (MANOVA) results of air-dried specific gravity values in samples impregnated with rosemary.

Factor	df	Sum of squares	Mean square	F	p
Tree type (A)	1	0.382	0.382	1468.705	0.000
Impregnation time (B)	2	0.009	0.005	18.149	0.000
Concentration (C)	3	0.002	0.001	2.960	0.041
A*B	2	0.005	0.002	9.554	0.000
A*C	3	0.001	0.000	0.869	0.463
B*C	6	0.014	0.002	9.283	0.000
A*B*C	6	0.015	0.003	9.742	0.000
Error	52	0.014	0.000		
Total	78	27.425			

Significant at $p < 0.05$ level.

specific gravity of air dry ($p < 0.001$). On the other hand, it was determined that the $A \times C$ interaction did not have a significant effect on specific gravity ($p > 0.05$).

The distribution of air-dried specific gravity values in samples impregnated with rosemary according to impregnation time and concentration is presented in Table 3. When evaluated in terms of tree species, it is seen that beech samples have higher air-dry specific gravity values compared to Scotch pine. Beech samples were in homogeneity group A with the highest mean value (Mean = 0.66), while Scotch pine samples showed a lower mean value and were classified in homogeneity group B (Mean = 0.51). This finding shows that the tree species has a decisive effect on the air-dry specific gravity values.

When evaluated in terms of impregnation time, the control group had the lowest mean air dry specific gravity value (mean = 0.55) and was in the C homogeneity group. In contrast, the impregnation times of 30 min and 24 h reached the highest mean values (mean = 0.60 and mean = 0.59, respectively) and were classified in the same homogeneity group (A). The 3-h application was evaluated in the B homogeneity group by being between these two groups. These results show that statistically significant changes occur in air dry specific gravity values with the increase in impregnation time.

When the concentration factor was examined, the control group (0%) showed the lowest mean air dry specific gravity value and B was in the homogeneity group (Mean = 0.55). While the 10% hydrosol application was evaluated in the AB homogeneity group with an intermediate value (Mean = 0.58), the 10% hydrosol + mordant, 10% extract solution and 10% extract solution + mordant groups reached higher mean values and were classified in the A homogeneity group. These findings indicate that mordant and extract-containing applications led to significant increases in air-dry specific gravity values compared to the control group.

The results of multiple analysis of variance to determine the effect of wood type, impregnation time and concentration on full dry specific gravity values in samples impregnated with rosemary are presented in Table 4. According to the results of the analysis,

TABLE 3 Comparison of air-dry specific gravity values in samples impregnated with rosemary according to impregnation time and concentration (Duncan test).

Variables	Groups	Avg.	Post hoc
Tree type	Scotch pine	0.51	B
	Beech	0.66	A
Impregnation time	Control	0.55	C
	30 min	0.60	A
	3 h	0.58	B
	24 h	0.59	A
Concentration	0%	0.55	B
	10% hydrosol	0.58	EU
	10% hydrosol + mordant	0.59	A
	10% extract solution	0.60	A
	10% extract solution + mordant	0.59	A

A, B, C: the difference between averages with different letters is important.

it was determined that the tree species (A) had a statistically significant effect on the full dry specific gravity ($F = 15.013$; $p < 0.001$).

On the other hand, the effects of impregnation time (B) and concentration (C) factors on full dry specific gravity values were not statistically significant ($p > 0.05$). Similarly, it was determined that the interactions between factors $A \times B$, $A \times C$, $B \times C$ and $A \times B \times C$ did not cause a significant difference on the full dry specific gravity ($p > 0.05$).

The distribution of full dry specific gravity values in samples impregnated with rosemary according to impregnation time and concentration is presented in Table 5. When evaluated in terms of tree species, beech specimens have higher fully dry specific gravity values compared to Scotch pine. Beech samples had the highest mean value and were in the A homogeneity group (Mean = 0.63), while Scotch pine samples showed a lower mean value and were classified in the B homogeneity group (Mean = 0.53). This finding suggests that the tree species has a statistically significant effect on the full dry specific gravity values.

When evaluated in terms of impregnation time variable, it was determined that all control, 30 min, 3 h and 24 h applications were in the same homogeneity group (A). However, it was observed that the mean full dry specific gravity values showed a numerical tendency to increase as the impregnation time increased, and the highest mean value was obtained in 24-h application (Mean = 0.61). Although this does not create a statistically significant difference in the impregnation time on the full dry specific gravity, it shows that there is an increasing tendency in the values with increasing duration.

When the concentration variable was examined, it was determined that the control (0%), 10% hydrosol, 10% hydrosol + mordant, 10% extract solution and 10% extract solution + mordant groups were all in the same homogeneity group (A). This result

TABLE 4 Multiple analysis of variance (MANOVA) results of full dry specific gravity values in samples impregnated with rosemary.

Factor	df	Sum of squares	Mean square	F	p
Tree type (A)	1	0.211	0.211	15.013	0.000
Impregnation time (B)	2	0.043	0.021	1.511	0.230
Concentration (C)	3	0.061	0.020	1.454	0.238
A*B	2	0.019	0.009	0.662	0.520
A*C	3	0.052	0.017	1.231	0.308
B*C	6	0.129	0.022	1.534	0.186
A*B*C	6	0.128	0.021	1.520	0.190
Error	52	0.732	0.014		
Total	78	27.553			

Significant at $p < 0.05$ level.

TABLE 5 Comparison of full dry specific gravity values in samples impregnated with rosemary according to impregnation time and concentration (Duncan test).

Variables	Groups	Avg.	Post hoc
Tree type	Scotch pine	0.53	B
	Beech	0.63	A
Impregnation time	Control	0.53	A
	30 min	0.55	A
	3 h	0.58	A
	24 h	0.61	A
Concentration	0%	0.53	A
	10% hydrosol	0.56	A
	10% hydrosol + mordant	0.57	A
	10% extract solution	0.57	A
	10% extract solution + mordant	0.63	A

A, B, C: the difference between averages with different letters is important.

reveals that different concentration applications do not create a statistically significant difference on the full dry specific gravity values. However, when the mean values are taken into account, it is seen that the 10% extract solution + mordant group has the highest mean complete dry specific gravity (Avg. = 0.63).

The air-dry and full-dry specific gravity values of the Scotch pine and beech wood samples impregnated with rosemary are presented in Table 6, Figures 4, 5, taking into account the impregnation time and concentration variables. When the specific gravity values of the air dryer were examined, it was seen that the lowest mean value was obtained in the control group (mean = 0.46) in the Scotch pine samples and this group was in the lowest homogeneity group. It was determined that the specific gravity values of air dry in Scotch pine samples generally

increased with impregnation applications, and especially in 30 min and 3 h applications, 10% hydrosol, 10% hydrosol + mordant and 10% extract solutions reached higher average values. In 24-h applications in Scotch pine, it was observed that the specific gravity values approached the control group at some concentrations.

Air-dry specific gravity values were found to be significantly higher in beech wood than in Scotch pine. The highest air-dry specific gravity value was obtained in 10% extract solution + mordant applications for 30 min and 24 h (Mean = 0.71) and these groups were in the highest homogeneity group. In general, an increasing trend in air-dry specific gravity values was observed in beech samples with increasing impregnation time and concentration.

When the full dry specific gravity values were evaluated, it was seen that the majority of the Scotch pine samples were in the same homogeneity group and the impregnation time and concentration had a limited effect on the full dry specific gravity. However, the high average value obtained in 24-h application of 10% extract solution is remarkable, and it has been determined that this group differs from other applications.

In beech samples, it was observed that the full dry specific gravity values exhibited a parallel distribution with the air dry results. The highest mean complete dry specific gravity values were obtained in 10% extract solution + mordant applications and these groups were included in the upper homogeneity groups. It can be said that impregnation applications in beech wood have a more significant effect on full dry specific gravity values compared to Scotch pine.

The results of the multiple analysis of variance to determine the effect of wood type, concentration, time and impregnation time on tensile-contraction values in samples impregnated with rosemary are presented in Table 7. According to the results of the analysis, there was no statistically significant effect of the tree species (A) on the tensile-contraction values ($p > 0.05$).

On the other hand, it was determined that concentration (B), time (C) and impregnation time (D) factors had statistically significant effects on tensile-contraction values ($p < 0.001$). In particular, the time factor was found to be the variable with the most dominant effect on tensile-contraction with its high F value ($F = 92.764$).

When the interactions between the factors were examined, it was determined that $A \times C$, $B \times D$ and $A \times B \times D$ interactions had statistically significant effects on the tensile-contraction values ($p < 0.001$). On the other hand, $A \times B$, $A \times D$, $B \times C$, $C \times D$ and other triple and quadruple interactions did not have a significant effect on pull-contraction ($p > 0.05$).

The distribution of shrinkage-contraction values in rosemary-impregnated samples according to concentration, impregnation time and time variables is presented in Table 8. When evaluated in terms of tree species, it is seen that Scotch pine and beech samples are in the same homogeneity group (A) in terms of tensile-contraction values. Although there were numerical differences between the mean values, it was determined that these differences were not statistically significant. This finding shows that the tree species does not have a decisive effect on the pull-constriction behavior.

TABLE 6 Comparison of air-dry and full-dry specific gravity values in Scotch pine and beech woods impregnated with rosemary according to wood type, impregnation time, and concentration (Duncan test).

Tree type	Impregnation time	Concentration	Air dry specific gravity			Exact dry specific gravity		
			Avg.	SS	Post hoc	Avg.	SS	Post hoc
Scotch pine	Control	0%	0.46	0.01	J	0.46	0.01	BC
	30 min	10% hydrosol	0.54	0.00	F	0.53	0.01	BC
		10% hydrosol + mordant	0.54	0.01	FG	0.53	0.01	BC
		10% extract solution	0.51	0.01	GHI	0.49	0.00	BC
		10% extract solution + mordant	0.51	0.01	GHI	0.49	0.01	BC
	3 h	10% hydrosol	0.50	0.01	HI	0.49	0.00	BC
		10% hydrosol + mordant	0.49	0.00	IJ	0.47	0.00	BC
		10% extract solution	0.53	0.01	FG	0.52	0.01	BC
		10% extract solution + mordant	0.54	0.01	FG	0.52	0.02	BC
	24 h	10% hydrosol	0.47	0.01	J	0.45	0.01	C
		10% hydrosol + mordant	0.53	0.01	FGH	0.52	0.01	BC
		10% extract solution	0.54	0.00	FG	0.87	0.60	A
		10% extract solution + mordant	0.51	0.01	GHI	0.49	0.01	BC
Beech	Control	0%	0.64	0.01	DE	0.60	0.01	BC
	30 min	10% hydrosol	0.65	0.02	CD	0.62	0.01	BC
		10% hydrosol + mordant	0.67	0.02	BC	0.63	0.03	BC
		10% extract solution	0.68	0.03	B	0.66	0.03	ABC
		10% extract solution + mordant	0.71	0.00	A	0.69	0.00	EU
	3 h	10% hydrosol	0.67	0.03	BC	0.66	0.03	ABC
		10% hydrosol + mordant	0.63	0.01	DE	0.59	0.01	BC
		10% extract solution	0.63	0.02	DE	0.61	0.02	BC
		10% extract solution + mordant	0.62	0.02	E	0.58	0.01	BC
	24 h	10% hydrosol	0.65	0.01	BCD	0.61	0.01	BC
		10% hydrosol + mordant	0.71	0.03	A	0.68	0.03	ABC
		10% extract solution	0.68	0.03	B	0.65	0.05	BC
		10% extract solution + mordant	0.67	0.01	BC	0.64	0.02	BC

A, B, C: the difference between averages with different letters is important.

In the evaluation made in terms of concentration factor, it was seen that the control (0%), 10% extract solution and 10% extract solution + mordant groups had the highest shrinkage-contraction values and were in the same homogeneity group (A). On the other hand, it was determined that the tensile-contraction values were lower in 10% hydrosol and 10% hydrosol + mordant applications and these groups were classified in homogeneity group B. These results reveal that hydrosol-based applications are effective in reducing tensile-contraction values.

When the impregnation time variable was examined, the control group was in the A homogeneity group with the highest

tensile-contraction value. The three-hour impregnation time showed the lowest tensile-contraction value and was classified in the C homogeneity group. Thirty-minute and 24-h applications exhibited intermediate values; the 30-min application was in the AB homogeneity group, and the 24-h application was in the B homogeneity group. These findings suggest that the impregnation time has a statistically significant effect on the pull-constriction behavior.

In the evaluation made in terms of time factor, it was determined that the 6-h application had the lowest tensile-contraction value and was in the C homogeneity group. With the progress of time, the tensile-contraction values increase; It was observed that 48, 72 and 96 h



FIGURE 4

Air-dry density values of rosemary-impregnated Scots pine and beech wood as affected by impregnation duration and concentration.

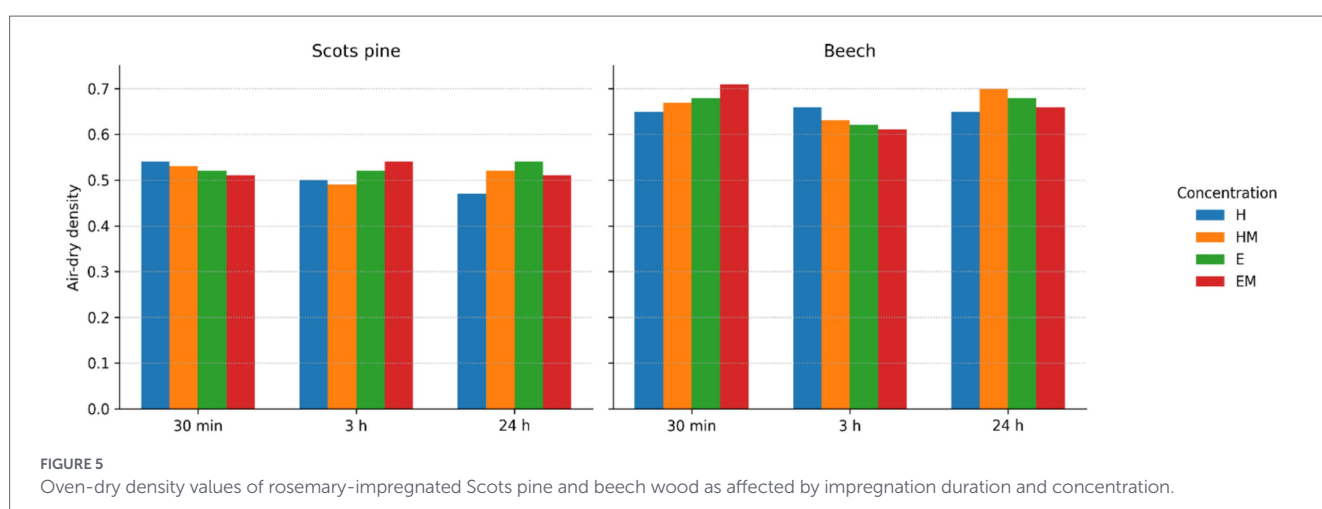


FIGURE 5

Oven-dry density values of rosemary-impregnated Scots pine and beech wood as affected by impregnation duration and concentration.

applications reached the highest values and were classified in the same homogeneity group (A). This reveals that the tensile-contraction values show a significant upward trend over time.

The time-dependent change in tensile-contraction values in Scotch pine and beech wood samples impregnated with rosemary is presented in Table 9, Figure 6. In Scotch pine samples, an increasing trend in shrinkage-contraction values was observed as time progressed. In the control group, the shrinkage-constriction values were 5.66 at 6 h, reached higher values at 48 and 72 h, and showed a limited decreasing trend at 96 h.

It was determined that the shrinkage-contraction values obtained especially at the end of the 24-h impregnation period in 10% hydrosol and 10% hydrosol + mordant applications in Scotch pine were lower than other periods and concentrations. On the other hand, in the applications of 10% extract solution and 10% extract solution + mordant, it was observed that the tensile-contraction values increased, especially at 72 and 96 h, and reached the highest values in some combinations. The highest tensile-contraction values were obtained in 96 h in 10% extract solution + mordant 24 h application in Scotch pine.

In beech wood, it was observed that the tensile-contraction values exhibited a higher and more variable distribution compared to Scotch pine. In the control group, it was determined that the tensile-constriction values increased significantly from the 48th hour onwards and

reached the highest levels at the 96th hour. It was noteworthy that in the applications of 10% hydrosol and 10% hydrosol + mordant in beech samples, low or even close to negative values were obtained, especially at the end of the 24-h impregnation period, in the early times (6 and 24 h). This shows that hydrosol-based applications can have a limiting effect on dimensional changes in beech wood.

Applications of 10% extract solution + mordant in beech wood reached the highest tensile-contraction values at 48, 72 and 96 h, especially at the end of the 24-h impregnation period, and differed significantly from other applications. In general, it was observed that the tensile-contraction values increased as time progressed in beech samples, and this increase was more pronounced especially in extract-based and mordant applications.

The results of the multiple analysis of variance performed to determine the effect of tree type, concentration, time and impregnation time on water uptake values in samples impregnated with rosemary are presented in Table 10. According to the results of the analysis, it was determined that the tree species (A) had a statistically significant effect on water uptake values ($F = 271.081$; $p < 0.001$). Similarly, it was determined that the time (C) factor had a very strong and significant effect on water intake ($F = 169.730$; $p < 0.001$).

The effect of concentration (B) factor on water uptake values was found to be statistically significant ($F = 2.898$; $p = 0.036$), but this effect was more limited compared to tree species and time factors. On

TABLE 7 Multiple analysis of variance (MANOVA) results of the effects of wood type, concentration, time and impregnation time on tensile-contraction values in samples impregnated with rosemary.

Factor	df	Sum of squares	Mean square	F	p
Tree type (A)	1	0.000	0.000	0.000	0.998
Concentration (B)	3	90.848	30.283	12.627	0.000
Time (C)	4	889.853	222.463	92.764	0.000
Impregnation time (D)	2	56.179	28.090	11.713	0.000
A*B	3	14.280	4.760	1.985	0.117
A*C	4	274.460	68.615	28.611	0.000
A*D	2	7.235	3.618	1.509	0.223
B*C	12	8.648	0.721	0.301	0.989
B*D	6	371.136	61.856	25.793	0.000
C*D	8	23.630	2.954	1.232	0.281
A*B*C	12	8.827	0.736	0.307	0.988
A*B*D	6	118.198	19.700	8.214	0.000
A*C*D	8	6.661	0.833	0.347	0.947
B*C*D	24	37.318	1.555	0.648	0.897
A*B*C*D	24	30.868	1.286	0.536	0.965
Error	260	623.526	2.398		
Total	390	23644.251			

Significant at $p < 0.05$ level.

TABLE 8 Comparison of tensile-contraction values in samples impregnated with rosemary according to concentration, impregnation time and time (Duncan test).

Variables	Groups	Avg.	Post hoc
Tree type	Scotch pine	7.41	A
	Beech	7.24	A
Concentration	0%	8.07	A
	10% hydrosol	6.81	B
	10% hydrosol + mordant	6.72	B
	10% extract solution	7.71	A
	10% extract solution + mordant	7.82	A
Impregnation time	Control	8.07	A
	30 min	7.63	EU
	3 h	6.72	C
	24 h	7.44	B
Time	6 h	4.57	C
	24 h	6.56	B
	48 h	8.39	A
	72 h	8.50	A
	96 h	8.60	A

A, B, C: the difference between averages with different letters is important.

the other hand, the effect of the impregnation time (D) factor on water intake was not statistically significant ($p > 0.05$).

When the interactions between the factors were examined, it was determined that the B $\times$ D (concentration $\times$ impregnation time) interaction had a statistically significant effect on water uptake values ($F = 13.435$; $p < 0.001$). Other double, triple and quadruple interactions did not cause a significant difference on water intake ($p > 0.05$).

The distribution of water uptake values in rosemary-impregnated samples according to concentration, impregnation time and time variables is presented in Table 11. In the evaluation made in terms of tree species, it is seen that Scotch pine specimens have higher water uptake values compared to beech specimens. Scotch pine samples were in homogeneity group A with the highest mean value (Mean = 67.26), while beech samples showed lower mean value and were classified in homogeneity group B (Mean = 48.87). This finding suggests that there is a statistically significant effect of tree species on water intake behavior.

When evaluated in terms of concentration factor, it was determined that 10% hydrosol application had the highest average water uptake value (Mean = 60.92) and was in the A homogeneity group. The 10% hydrosol + mordant and 10% extract solution groups showed intermediate values and were classified in the AB homogeneity group. In contrast, the control (0%) and 10% extract solution + mordant groups had lower mean values and were in the B homogeneity group. These results reveal that hydrosol-based applications can increase water intake values.

When the impregnation time variable was examined, it was seen that all control, 30 min, 3 h and 24 h applications were in the same homogeneity group (A). This shows that the impregnation time alone does not make a statistically significant difference on the water intake values. However, when the average values are taken into account, it has been determined that the water intake values are numerically higher in the 3-h impregnation period.

In the evaluation made in terms of time factor, it was determined that the water intake values increased significantly depending on time. The lowest mean water uptake value was obtained in 6 h (mean = 36.79) and this group was in the homogeneity group E. With the progress of time, water intake values increased; 24 h (mean = 46.66) D, 48 h (mean = 59.57) C, 72 h (mean = 71.24) B and 96 h (mean = 76.07) A were classified in the homogeneity group. These findings clearly suggest that water intake behavior is strongly influenced by the time factor.

The time-dependent change in water uptake values in Scotch pine and beech wood samples impregnated with rosemary is presented in Table 12, Figure 7. In Scotch pine samples, it was found that the water uptake values showed a marked increase with time in all combinations of concentration and impregnation time. In the control group, water intake was 45.43 at 6 h and increased to 79.38 and 82.43 at 72 and 96 h, respectively. A similar upward trend was observed in the impregnated groups.

It has been observed that in 10% hydrosol applications in Scotch pine, especially at the end of 3 h and 24 h impregnation periods, water uptake values reach higher levels as time progresses. In the 10% hydrosol + mordant group, it was determined that the water intake values were higher at 72 and 96 h in the 3-h impregnation period compared to the other times and concentrations. In 10% extract solution applications, it was noted that the water uptake values were high from the early times, especially at the end of the 24-h impregnation period, reaching approximately 89 in 96 h. In 10% extract solution +

TABLE 9 Variation of tensile-contraction values in Scotch pine and beech woods impregnated with rosemary according to concentration, impregnation time and time.

Tree type	Concentration	Impregnation time	6 h	24 h	48 h	72 h	96 h
Scotch pine	0%	Control	5.66	6.91	8.49	8.34	7.81
	10% hydrosol	30 min	6.72	7.52	8.34	8.24	8.10
		3 h	6.18	7.20	7.88	7.92	7.63
		24 h	6.14	6.54	6.08	6.28	6.42
	10% hydrosol + mordant	30 min	5.05	7.47	8.14	8.20	7.73
		3 h	5.11	6.75	7.00	7.02	6.80
		24 h	6.15	7.25	7.78	7.40	7.81
	10% extract solution	30 min	5.73	7.19	8.27	9.18	8.31
		3 h	5.02	7.57	8.13	8.03	8.24
		24 h	7.16	8.59	8.15	8.63	7.95
	10% extract solution + mordant	30 min	5.86	7.84	7.95	8.15	7.79
		3 h	5.37	7.53	6.84	7.18	6.95
		24 h	7.36	8.61	9.15	9.34	9.40
Beech	0%	Control	3.70	6.47	1.05	10.88	11.43
	10% hydrosol	30 min	5.54	7.66	10.15	10.12	10.53
		3 h	3.81	5.76	8.32	8.72	8.14
		24 h	−1.01	1.61	5.05	6.57	6.04
	10% hydrosol + mordant	30 min	1.02	4.16	9.48	9.62	9.74
		3 h	4.07	5.65	7.96	8.11	8.47
		24 h	1.69	4.64	6.92	7.04	7.41
	10% extract solution	30 min	3.23	5.64	9.82	9.79	9.99
		3 h	2.11	4.42	8.12	8.32	8.27
		24 h	6.53	9.40	9.45	10.13	9.82
	10% extract solution + mordant	30 min	2.70	5.24	9.60	9.57	9.87
		3 h	0.69	3.29	7.69	8.30	8.04
		24 h	7.28	9.71	12.35	12.60	12.38

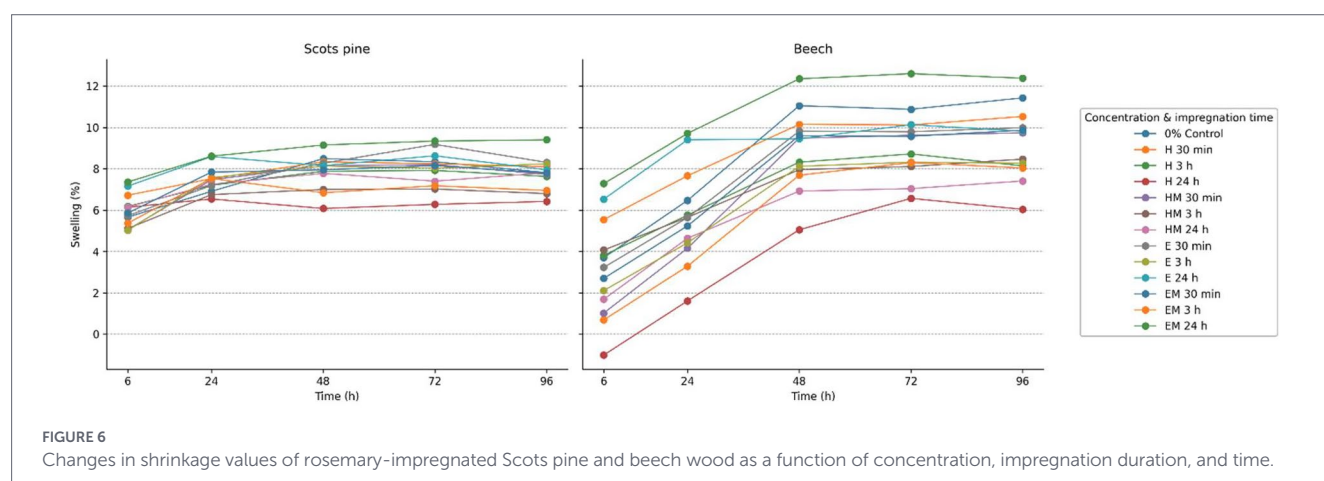


FIGURE 6 Changes in shrinkage values of rosemary-impregnated Scots pine and beech wood as a function of concentration, impregnation duration, and time.

mordant applications, it was observed that the water uptake values generally exhibited an increasing trend similar to the hydrosol groups.

Although the water uptake values in beech wood were lower in the early times compared to Scotch pine, they showed a significant increase as time progressed. In the control group, the water intake

value increased from 20.30 in 6 h to 67.26 in 96 h. In beech samples, it was observed that the water uptake values were higher than the control group, especially at the end of 30 min and 3 h of impregnation periods in 10% hydrosol and 10% hydrosol + mordant applications. In contrast, lower water uptake values were obtained early in 24-h impregnation time applications.

TABLE 10 Multiple analysis of variance (MANOVA) results of the effects of tree type, concentration, time and impregnation time on water uptake values in samples impregnated with rosemary.

Factor	df	Sum of squares	Mean square	F	p
Tree Type (A)	1	29616.410	29616.410	271.081	0.000
Concentration (B)	3	949.684	316.561	2.898	0.036
Time (C)	4	74174.130	18543.532	169.730	0.000
Impregnation Time (D)	2	558.042	279.021	2.554	0.080
A*B	3	77.880	25.960	0.238	0.870
A*C	4	923.490	230.872	2.113	0.080
A*D	2	659.471	329.736	3.018	0.051
B*C	12	196.750	16.396	0.150	1.000
B*D	6	8807.210	1467.868	13.435	0.000
C*D	8	177.954	22.244	0.204	0.990
A*B*C	12	245.190	20.432	0.187	0.999
A*B*D	6	1326.356	221.059	2.023	0.063
A*C*D	8	110.157	13.770	0.126	0.998
B*C*D	24	612.777	25.532	0.234	1.000
A*B*C*D	24	167.997	7.000	0.064	1.000
Error	260	28405.812	109.253		
Total	390	1476101.720			

Significant at $p < 0.05$ level.

TABLE 11 Comparison of water uptake values in samples impregnated with rosemary by concentration, impregnation time and time (Duncan test).

Variables	Groups	Avg.	Post hoc
Tree Type	Scotch pine	67.26	A
	Beech	48.87	B
Concentration	0%	55.04	B
	10% hydrosol	60.92	A
	10% hydrosol + mordant	58.13	EU
	10% extract solution	57.75	EU
	10% extract solution + mordant	56.47	B
Impregnation Time	Control	55.04	A
	30 min	56.78	A
	3 h	59.83	A
	24 h	58.35	A
Time	6 h	36.79	E
	24 h	46.66	D
	48 h	59.57	C
	72 h	71.24	B
	96 h	76.07	A

A, B, C: the difference between averages with different letters is important.

It was determined that the water uptake values increased over time in the applications of 10% extract solution and 10% extract solution + mordant in beech wood, but this increase was more limited compared to Scotch pine. It was observed that water uptake values became evident in extract-based applications, especially at 72 and 96 h.

The results of the multifactorial analysis of variance performed to determine the effect of wood type, concentration, time and impregnation time on the expansion (swelling) values of the samples impregnated with rosemary are presented in Table 13. According to the results of the analysis, it was determined that the tree species (A) had a statistically significant effect on the expansion values ($F = 103.227$; $p < 0.001$). Similarly, the concentration (B) factor ($F = 15.764$; $p < 0.001$) and the time (C) factor ($F = 128.942$; $p < 0.001$) also significantly affected the expansion values. On the other hand, it was observed that there was no statistically significant effect on the expansion values of impregnation time (D) ($F = 2.214$; $p = 0.111$).

When the interactions between the factors were examined, it was found that the A $\times$ B (tree species $\times$ concentration) interaction was significant on the expansion values ($F = 4.541$; $p = 0.004$). In addition, the interaction of A $\times$ C (tree species $\times$ time) ($F = 39.491$; $p < 0.001$) and the interaction of B $\times$ D (concentration $\times$ impregnation time) ($F = 16.623$; $p < 0.001$) were found to be significant. It was determined that the A $\times$ B $\times$ D interaction also made a significant difference on expansion, which was among the triple interactions ($F = 5.000$; $p < 0.001$). In contrast, A $\times$ D, B $\times$ C, C $\times$ D and other triple and quadruple interactions did not appear to have a statistically significant effect on the expansion values ($p > 0.05$).

The distribution of expansion (swelling) values in rosemary-impregnated samples according to wood type, concentration, impregnation time and time variables is presented in Table 14. When evaluated in terms of tree type, beech specimens had a higher average expansion value compared to Scotch pine. Beech had the highest mean value and was in group A homogeneity (Mean = 14.51), while Scotch pine showed a lower mean value and was classified in group B (Mean = 12.97). This finding shows that the tree species has a statistically significant effect on the expansion values.

When evaluated in terms of concentration factor, it was determined that the application of 10% extract solution had the highest average expansion value (Mean = 14.67) and was in the A homogeneity group. 10% hydrosol + mordant application was classified in group B (mean = 13.92), while 10% hydrosol application was classified in group C (mean = 13.23). The lowest mean value was observed in the control group (0%) and this group was in the D homogeneity group (mean = 12.51). The 10% extract solution + mordant group was evaluated in the BC homogeneity group (Mean = 13.57). These results show that extract-based application in particular has increased expansion; in the control group, the expansion values remained lower.

When the impregnation time variable was examined, it was determined that all of the control group, 30 min, 3 h and 24 h applications showed similar mean expansion values and were in the same homogeneity group (A) (Mean = 12.51; Mean = 13.83; Mean = 13.65; Mean = 14.05, respectively). This finding shows that the impregnation time alone does not create a statistically significant difference on the expansion values, and that the impregnation processes applied at different times lead to similar levels of expansion.

In the evaluation made in terms of time factor, it was seen that the 6-h application had the lowest average expansion value and was in the

TABLE 12 Variation of water uptake values in Scotch pine and beech woods impregnated with rosemary according to concentration, impregnation time and time.

Tree type	Concentration	Impregnation time	6 h	24 h	48 h	72 h	96 h
Scotch pine	0%	Control	45.43	55.69	65.69	79.38	82.43
	10% hydrosol	30 min	51.10	59.19	67.39	80.99	81.33
		3 h	52.73	61.59	70.27	81.10	85.41
		24 h	48.90	58.28	69.51	84.25	87.14
	10% hydrosol + mordant	30 min	42.33	52.19	64.07	76.47	81.75
		3 h	53.44	63.78	77.84	91.48	96.42
		24 h	40.28	50.33	64.40	75.53	79.04
	10% extract solution	30 min	40.90	50.63	60.30	72.37	75.67
		3 h	39.41	49.66	61.69	73.58	77.84
		24 h	66.07	74.35	82.11	89.37	89.09
	10% extract solution + mordant	30 min	51.42	59.31	68.11	78.21	81.38
		3 h	46.42	54.74	66.35	77.89	80.12
		24 h	47.09	55.94	66.75	77.81	80.37
Beech	0%	Control	20.30	29.71	46.30	58.26	67.26
	10% hydrosol	30 min	39.28	48.43	61.07	73.45	79.27
		3 h	31.49	40.53	53.19	63.67	71.05
		24 h	20.09	29.95	49.71	60.46	66.93
	10% hydrosol + mordant	30 min	19.99	28.85	40.16	56.50	64.16
		3 h	40.62	48.49	61.15	72.40	79.38
		24 h	19.66	29.27	50.32	59.08	64.41
	10% extract solution	30 min	21.65	31.24	47.45	58.84	64.97
		3 h	23.51	33.93	49.72	60.99	69.56
		24 h	32.27	44.21	56.26	65.05	69.69
	10% extract solution + mordant	30 min	23.52	34.36	51.17	63.44	68.17
		3 h	21.88	31.34	45.98	61.55	70.88
		24 h	16.77	37.26	51.99	60.03	63.99



TABLE 13 Multiple analysis of variance (MANOVA) results of the effects of wood type, concentration, time and impregnation time on expansion (swelling) values in rosemary impregnated samples.

Factor	df	Sum of squares	Mean square	F	p
Tree type (A)	1	222.621	222.621	103.227	0.000
Concentration (B)	3	101.990	33.997	15.764	0.000
Time (C)	4	1112.311	278.078	128.942	0.000
Impregnation time (D)	2	9.551	4.775	2.214	0.111
A*B	3	29.382	9.794	4.541	0.004
A*C	4	340.668	85.167	39.491	0.000
A*D	2	1.551	0.775	0.360	0.698
B*C	12	8.107	0.676	0.313	0.987
B*D	6	215.101	35.850	16.623	0.000
C*D	8	20.777	2.597	1.204	0.297
A*B*C	12	9.123	0.760	0.353	0.978
A*B*D	6	64.704	10.784	5.000	0.000
A*C*D	8	4.224	0.528	0.245	0.982
B*C*D	24	41.340	1.722	0.799	0.738
A*B*C*D	24	30.611	1.275	0.591	0.937
Error	260	560.719	2.157		
Total	390	76638.166			

Significant at $p < 0.05$ level.

TABLE 14 Comparison of expansion (swelling) values in samples impregnated with rosemary by concentration, impregnation time and time (Duncan test).

Variables	Groups	Avg.	Post hoc
Tree type	Scotch pine	12.97	B
	Beech	14.51	A
Concentration	0%	12.51	D
	10% hydrosol	13.23	C
	10% hydrosol + mordant	13.92	B
	10% extract solution	14.67	A
	10% extract solution + mordant	13.57	BC
Impregnation time	Control	12.51	A
	30 min	13.83	A
	3 h	13.65	A
	24 h	14.05	A
Time	6 h	10.70	C
	24 h	12.80	B
	48 h	14.93	A
	72 h	15.21	A
	96 h	15.07	A

A, B, C: the difference between averages with different letters is important.

C homogeneity group (Mean = 10.70). The 24-h application was classified in group B (mean = 12.80). It was determined that the 48, 72 and 96 h applications reached the highest mean values and were in the same A homogeneity group (Mean = 14.93; Mean = 15.21; Mean = 15.07, respectively). These results show that the expansion values increase as time progresses and are at higher levels, especially after 48 h.

The time-dependent change in expansion (swelling) values in Scotch pine and beech wood samples impregnated with rosemary is presented in Table 15, Figure 8. In general, it is seen that the expansion values increase significantly from 6 h to 48 h in both tree species, and after 48 h, the values remain at high levels with more limited changes.

In Scotch pine samples, the expansion value in the control group was 9.42 in 6 h and increased to 12.49 in 48 h; It was determined that the values remained at similar levels after 72 h and decreased to 11.76 in 96 h. In 10% hydrosol application, the expansion values gradually increased over time during the impregnation times of 30 min and 3 h; on the other hand, it was noted that the values remained at lower levels in the 24-h impregnation period (e.g., 10.71 in 48 h). In the 10% hydrosol + mordant group, higher values were reached at 48 h and after 30 min and 24 h (e.g., 14.41 and 13.98 at 48 h, respectively).

It was determined that the expansion values were generally higher in 10% extract solution applications, especially in the impregnation times of 3 h and 24 h. High baseline values (14.89) were observed from 6 h in 24-h extract application, and reached the highest level at 72 h, although fluctuating over time (17.50). In the 10% extract solution + mordant group, it was observed that the expansion values increased over time over all periods and the values were mostly in the range of 13–14 in the period after 48 h.

It is seen that the expansion values in beech samples are generally higher than in Scotch pine and the increase becomes evident especially after 48 h. In the control group, the expansion value increased from 8.12 in 6 h to 16.28 in 48 h and was recorded as 16.71 in 96 h. In 10% hydrosol and 10% hydrosol + mordant applications, the values after 48 h were generally in the range of 16–17; some combinations were similar to the control group, while others had higher values (e.g., 10% hydrosol + mordant–96 in 30 min at 17.60 h).

The application of 10% extract solution in beech stood out for its high expansion values, especially in the 24 h impregnation time (18.36 in 72 h; 18.02 in 96 h). In the 10% extract solution + mordant group, the values were above 16 after 48 h in 30 min and 24 h applications; on the other hand, it was determined that the values remained relatively lower in the 3-h application (e.g., 15.74 in 72 h).

The results of the multiple analysis of variance to determine the effect of wood type, impregnation time and concentration on the retention values after impregnation in the samples impregnated with rosemary are presented in Table 16. According to the results of the analysis, the effect of tree species (A) on retention values was not statistically significant ($p > 0.05$). Similarly, it was determined that impregnation time (B) and concentration (C) factors did not have a significant effect on retention values ($p > 0.05$).

When the interactions between the factors were examined, it was determined that $A \times B$, $A \times C$, $B \times C$ and $A \times B \times C$ interactions did not cause a statistically significant difference on the retention values ($p > 0.05$).

The distribution of post-impregnation retention values in rosemary-impregnated samples according to wood type, impregnation time, and concentration variables is presented in Table 17. In the evaluation made in terms of tree species, it was seen that Scotch pine

TABLE 15 Variation of expansion (swelling) values in Scots pine and beech woods impregnated with rosemary according to concentration, impregnation time and time.

Tree type	Concentration	Impregnation time		6 h	24 h	48 h	72 h	96 h
Scotch pine	0%	Control		9.42	10.81	12.49	12.32	11.76
	10% hydrosol	30 min		12.03	12.88	13.80	13.68	13.56
		3 h		11.48	12.60	13.33	13.38	13.05
		24 h		9.27	11.19	10.71	10.93	11.08
	10% hydrosol + mordant	30 min	11.01	13.66	14.41	14.46	13.95	
		3 h	10.31	12.08	12.35	12.37	12.13	
		24 h	12.20	13.41	13.98	13.56	14.00	
	10% extract solution	30 min		10.46	12.05	13.23	14.24	13.29
		3 h		11.18	13.59	14.23	14.14	14.36
		24 h		14.89	16.52	15.91	17.50	15.76
	10% extract solution + mordant	30 min		11.28	13.43	13.55	13.77	13.37
		3 h		11.67	14.04	13.28	13.66	13.39
		24 h		11.83	13.20	13.79	14.01	14.08
Beech	0%	Control		8.12	11.10	16.28	16.09	16.71
	10% hydrosol	30 min		11.07	13.38	16.13	16.12	16.57
		3 h		11.40	13.51	16.36	16.80	16.17
		24 h		8.30	11.06	14.75	16.40	15.86
	10% hydrosol + mordant	30 min		8.02	11.35	17.30	17.45	17.60
		3 h		12.60	14.30	16.88	17.01	17.41
		24 h		10.54	13.71	16.24	16.39	16.80
	10% extract solution	30 min		9.58	12.16	16.80	16.82	17.03
		3 h		10.06	12.55	16.71	16.92	16.88
		24 h		14.32	14.82	17.61	18.36	18.02
	10% extract solution + mordant	30 min		9.57	12.30	17.22	17.21	17.54
		3 h		7.47	10.21	15.06	15.74	15.44
		24 h		10.21	12.89	15.89	16.18	15.90

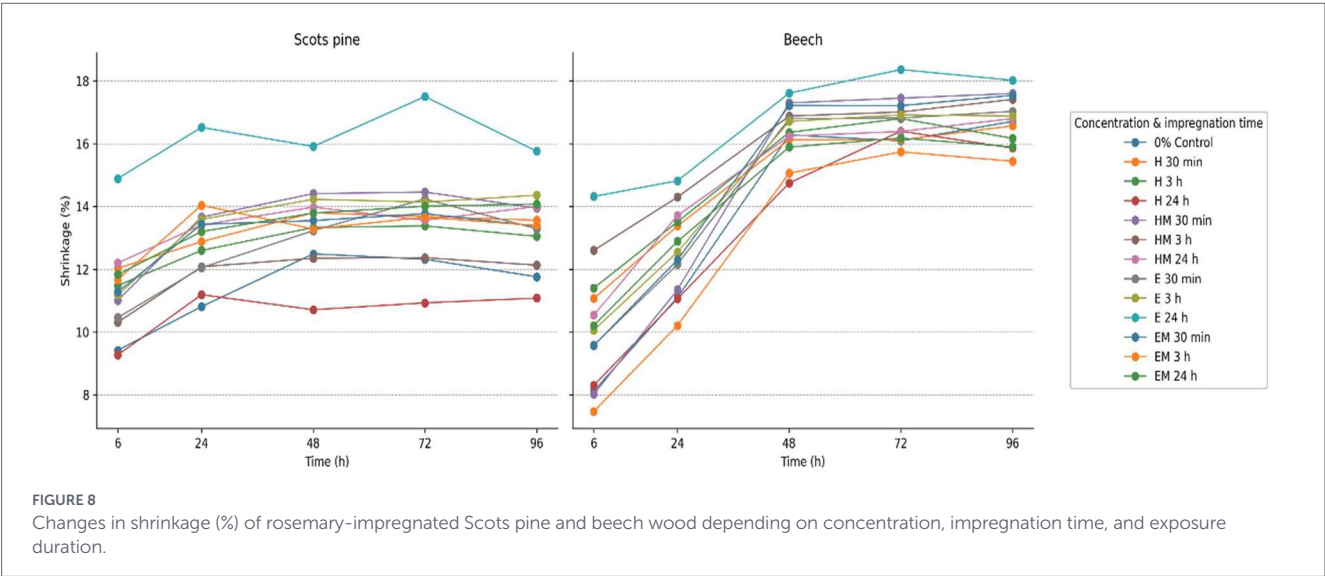


FIGURE 8 Changes in shrinkage (%) of rosemary-impregnated Scots pine and beech wood depending on concentration, impregnation time, and exposure duration.

TABLE 16 Multiple analysis of variance (MANOVA) results of the effects of wood type, impregnation time and concentration on post-impregnation retention values in samples impregnated with rosemary.

Factor	df	Sum of squares	Mean square	F	P
Tree type (A)	1	2.237	2.237	2.940	0.092
Impregnation time (B)	2	2.789	1.395	1.832	0.170
Concentration (C)	4	0.795	0.199	0.261	0.901
A*B	2	1.279	0.640	0.840	0.437
B*C	6	0.369	0.061	0.081	0.998
A*C	4	0.152	0.038	0.050	0.995
A*B*C	6	0.407	0.068	0.089	0.997
Error	52	39.580	0.761		
Total	78	78.136			

Significant at $p < 0.05$ level.

TABLE 17 Comparison of post-impregnation retention values in samples impregnated with rosemary according to impregnation time and concentration (Duncan test).

Variables	Groups	Avg.	Post hoc
Tree type	Scotch pine	0.78	A
	Beech	0.43	A
Impregnation time	30 min	0.90	A
	3 h	0.47	A
	24 h	0.37	A
Concentration	0%	1.17	A
	10% hydrosol	0.64	A
	10% hydrosol + mordant	0.52	A
	10% extract solution	0.58	A
	10% extract solution + mordant	0.49	A

A, B, C: the difference between averages with different letters is important.

samples had a higher average retention value compared to beech samples. However, the fact that both wood species are in the same homogeneity group (A) shows that the wood species does not make a statistically significant difference on the retention values after impregnation (Scotch pine Avg. = 0.78; beech Avg. = 0.43).

In terms of impregnation time, 30 min of impregnation time showed the highest average retention value (mean = 0.90), followed by 3 h (mean = 0.47) and 24-h applications (mean = 0.37). However, the fact that all times are in the same homogeneity group (A) reveals that the impregnation time does not have a statistically significant effect on the retention values.

When the concentration variable was examined, it was determined that the control (0%), 10% hydrosol, 10% hydrosol + mordant, 10% extract solution and 10% extract solution + mordant groups were all in the same homogeneity group (A). This shows that the different

concentrations applied do not produce a statistically significant difference on the retention values after impregnation.

The retention (%) values of the Scotch pine and beech wood samples impregnated with rosemary are presented in Table 18, Figure 9, taking into account the impregnation time and concentration variables. In the Scotch pine samples, it was determined that the retention values reached the highest mean in the control group (Mean = 1.62) in the 30-min impregnation period and generally tended to decrease with impregnation applications. It was observed that the application of 10% extract solution + mordant in the same impregnation time had the lowest average retention value (Mean = 0.83).

It was determined that the retention values of Scotch pine decreased significantly at the end of the 3-h impregnation period compared to the 30-min application, and the retention values were low in the 24-h impregnation period. However, the fact that all concentration groups were in the same homogeneity group (A) shows that the impregnation time and concentration variables did not make a statistically significant difference on retention in Scotch pine.

It was determined that the retention values of beech wood were generally lower than in yellow pine. In beech samples, higher retention values were obtained in 30 min of impregnation time, while it was observed that retention values decreased as the impregnation time increased. It was noted that the retention values decreased to very low levels, especially in the 24-h impregnation period. However, the fact that all applications are in the same homogeneity group (A) in beech wood reveals that concentration and impregnation time do not create a statistically significant difference on retention.

Results

Specific gravity values in wood samples impregnated with rosemary showed significant changes according to the wood species used and the application method. Air-dry specific gravity values, which were 0.46 g/cm³ for yellow pine and 0.64 g/cm³ for beech in the control groups, reached 0.71 g/cm³, the highest level in beech wood, with the combination of 10% rosemary extract and mordant. In the full dry specific gravity analysis, beech wood surpassed the value of 0.53 g/cm³ with an average of 0.63 g/cm³, while the highest full dry density was recorded as 0.63 g/cm³ in the group containing 10% extract and mordant. These data show that rosemary extract penetrates the wood structure, increasing the weight per unit volume.

Examining the dimensional stability of wood, rosemary hydrosol appears to be effective in restricting constriction and swelling movements. The tensile-contraction value, which was 8.07 in the control group, decreased to 6.81 with 10% hydrosol application; In particular, the 3-h impregnation time provided the best dimensional stability with a value of 6.72. In terms of expansion (swelling) rates, 10% hydrosol application gave an average value of 4.26%, reducing the swelling rate of the control group from 5.51% to approximately 22%. The time factor played a critical role in this process, with the average expansion amount increasing from 2.34% in 6 h to 6.42% in 96 h as the contact time of the wood with water increased.

Dimensional stability improvements, particularly under hydrosol treatments, may be attributed to partial lumen filling and reduced accessibility of hydroxyl groups to water molecules. The significant reductions in tensile-contraction and swelling values indicate a stabilizing effect on the wood structure. Similar stabilization trends were

TABLE 18 Comparison of retention (%) values in Scotch pine and beech woods impregnated with rosemary according to impregnation time and concentration (Duncan test).

Tree type	Impregnation time	Concentration	Retention (%)	Post hoc
Scotch pine	30 min	0%	1.62	A
		10% hydrosol	1.40	A
		10% hydrosol + mordant	1.01	A
		10% extract solution	1.32	A
		10% extract solution + mordant	0.83	A
	3 h	10% hydrosol	0.54	A
		10% hydrosol + mordant	0.38	A
		10% extract solution	0.45	A
		10% extract solution + mordant	0.45	A
	24 h	10% hydrosol	0.58	A
		10% hydrosol + mordant	0.56	A
		10% extract solution	0.34	A
		10% extract solution + mordant	0.65	A
Beech	30 min	0%	0.73	A
		10% hydrosol	0.62	A
		10% hydrosol + mordant	0.45	A
		10% extract solution	0.54	A
		10% extract solution + mordant	0.46	A
	3 h	10% hydrosol	0.53	A
		10% hydrosol + mordant	0.59	A
		10% extract solution	0.48	A
		10% extract solution + mordant	0.33	A
	24 h	10% hydrosol	0.16	A
		10% hydrosol + mordant	0.14	A
		10% extract solution	0.35	A
		10% extract solution + mordant	0.20	A

A, B, C: the difference between averages with different letters is important.



FIGURE 9 Retention (%) values of rosemary-impregnated Scots pine and beech wood as affected by impregnation duration and concentration (Duncan's multiple range test).

reported in recent plant-extract-based wood modification studies, including hydrosol applications derived from medicinal plants, where partial cell-wall bulking mechanisms contributed to reduced

moisture-induced deformation (Augustina et al., 2023). In our study, the 10% hydrosol treatment reduced swelling by approximately 22%

compared to the control group, confirming its potential as a dimensional stabilizer.

The anatomical structure of the trees has been decisive in terms of water intake and retention capacity. Scotch pine specimens exhibited a high water uptake average of 67.26%, while beech wood painted a more resilient picture with 48.87%. Among the applications, the 10% hydrosol achieved the highest absorption, increasing water uptake to 60.92%, while the extract and mordant group remained more balanced at 55.93%. In the retention values, which express the amount of matter retained in the wood, rates ranging from 0.34 to 1.40% were observed in Scotch pine; While the highest adhesion was found in the pure solvent group with 1.62%, these rates remained at lower levels such as 0.13 and 0.73% in beech wood.

When the studies in the literature are examined, it is seen that the retention and density values obtained in impregnation processes vary depending on the wood species and impregnation material used. [Peker et al. \(2012\)](#) reported that the highest retention value (42.43 kg/m³) was obtained by impregnating beech wood with a cement-borax mixture at 9% concentration, while the lowest value was in Scotch pine (1% ammonium tetrafluoroborate). [Sarica \(2006\)](#) stated that the highest adhesion in eastern beech wood impregnated with borax was in sessile oak (29.65 kg/m³). [Özçiftçi et al. \(2009\)](#) reported that the highest retention was in Scotch pine and the lowest in oak wood. Time and concentration were statistically significant in tensile-contraction behavior. Hydrosol-based treatments reduced shrinkage values, indicating improved dimensional stability. This may be explained by the interaction of hydrosol-derived phenolic compounds with hydroxyl groups in the cell wall, limiting moisture sorption sites. Similar antimicrobial and phytochemical profiles of rosemary extracts were documented by [Ahmed Alrasheed et al. \(2023\)](#), who highlighted the presence of bioactive compounds capable of interacting with biological and structural substrates.

In studies on density, [Kılıç and Yıldız \(2020\)](#) determined that the specific gravity values of beech and spruce woods impregnated with silicone did not show a significant change compared to the control samples. While [Gür \(2003\)](#) observed an increase in density after impregnation in Scotch pine and red pine wood, [Var and Kaplan \(2019\)](#) reported that there was no significant change in density and tangential expansion in red pine wood impregnated with geothermal waters, whereas found that the density increased by 16.64% in red pine wood impregnated with geothermal water. The significant differences observed in specific gravity values between *Pinus sylvestris* and *Fagus* are primarily attributable to anatomical structure and intrinsic density characteristics. Beech wood exhibited consistently higher air-dry and oven-dry specific gravity values, confirming that hardwoods generally possess higher density due to their fiber-rich structure and smaller lumen volumes. Similar findings were reported by [Çetin and Kalayci \(2025a, 2025b\)](#), who emphasized the decisive role of wood species in determining density-related physical properties after impregnation treatments.

As a result of the researches; the effects of impregnation on wood density and physical properties are reported to differ depending on the impregnating agent and wood species used. [Kılıç \(2012\)](#) stated that the specific gravity did not change significantly in beech and spruce woods impregnated with silicone compared to the control samples, while observed an increase in density after impregnation in Scotch pine and red pine woods. Although there are studies reporting that there is no significant change in density and tangential expansion in studies conducted with geothermal waters, it has also been stated that

the density has increased significantly in some studies ([Var and Kaplan, 2019](#)). In addition, recent studies have shown that nano and plant-derived impregnations provide positive effects on water uptake, swelling, and equilibrium moisture content of wood ([Bak et al., 2023](#)). In this context, it is considered that the current study conducted with different tree species and extract ratios contributes to the literature and serves as a reference for future research.

Discussion and recommendations

The findings confirm that wood species is a dominant factor influencing impregnation efficiency, density variation, water uptake, and dimensional stability. The higher specific gravity and lower water absorption observed in *Fagus orientalis* compared to *Pinus sylvestris* can be explained by anatomical differences between hardwood and softwood species. Hardwoods generally exhibit more complex vessel networks and reduced permeability relative to softwoods, which directly affects liquid penetration and retention behavior. Similar species-dependent impregnation differences have been reported in wood modification studies ([Hill, 2006](#); [Rowell, 2013](#)). The increase in air-dry specific gravity following rosemary extract treatments indicates effective deposition of extractive substances within the wood structure. Plant-derived phenolic compounds are known to interact with hydroxyl groups in cellulose and hemicellulose through hydrogen bonding, thereby reducing hygroscopicity and altering moisture sorption dynamics ([Rowell, 2013](#)). Previous phytochemical analyses of *Rosmarinus officinalis* have identified bioactive constituents such as carnosic acid, carnosol, and 1,8-cineole, which exhibit antioxidant and protective properties ([Burt, 2004](#); [Yesil Celiktaş et al., 2007](#)). Although detailed chemical characterization was not performed in this study, the observed density increases and retention values support the hypothesis that these compounds were successfully incorporated into the wood matrix. Retention differences between species align with established permeability trends in hardwoods and softwoods. Higher retention in Scots pine suggests deeper penetration along longitudinal pathways, whereas lower retention in beech may result from vessel occlusion and tyloses formation. Similar retention behavior has been documented in studies investigating natural preservatives and plant-based impregnation materials ([Tascioglu et al., 2013](#)).

With this research, it has been tried to reveal that the rosemary plant, which is used in food and many other areas as a result of various processes, can be included in new areas of use as a natural wood top surface protector (impregnation). It is of great importance to evaluate the rosemary plant, which has an important production potential in the world, as a wood surface protective agent in terms of ensuring its economic recycling and creating a new usage area in the woodworking industry. The reactions of wood material treated with natural preservatives, especially against combustion and decay, are presented as an important suggestion that can guide other different researches. The use of plant extracts, which are abundant in nature, in the field of wood protection can also provide economic benefits by the producers of these substances. The fact that it can be used in indoor-outdoor furniture products with herbal natural preservatives can be an important source of economic income for the sector.

In this study, the usability of the extract and hydrosol obtained from the rosemary (*Rosmarinus officinalis*) plant as an impregnating agent in Scotch pine and beech woods was examined; the effects of

applications on some physical properties of wood material were statistically evaluated. The results obtained revealed that the impregnation performance varied greatly depending on factors such as the type of wood, the form of the substance used (extract/hydrosol), concentration, impregnation time and duration of exposure to water.

When evaluated in terms of specific gravity values, it was seen that the tree species was decisive in both air-dry and fully dry conditions. Beech wood exhibited higher specific gravity values compared to Scotch pine, which may be associated with the anatomical structure and density of beech. It was determined that the impregnation time had a limited but statistically significant effect on the air-dry specific gravity, whereas the effect of factors other than the tree species on the full dry specific gravity was limited. These results show that the penetration of impregnating agents into the wood structure creates a limited change in density although it provides an increase in mass.

When the tensile-contraction values were examined, it was seen that time, concentration and impregnation time played an important role. In particular, it has been determined that hydrosol and hydrosol+mordant applications reduce tensile-contraction values and increase dimensional stability. This can be explained by the water-repellent effect of hydrosol on the wood cell walls. In extract applications, it is thought that the tensile-contraction values increase under some conditions, which may be due to the hygroscopic properties of the extract components.

Tree species and water exposure time have come to the fore as determining factors on water uptake rates. Beech wood exhibited different water intake behaviors compared to Scotch pine; this can be associated with the pore structure and fiber orientation of the wood. It was determined that hydrosol-based applications increased water uptake rates in some experimental groups, but extract+mordant combinations gave more balanced and controlled results. This finding suggests that the use of mordant strengthens the binding of the impregnating agent to the wood and limits the interaction with water.

When the expansion (swelling) values were evaluated, the effect of tree type, concentration and time factors was found to be evident. It has been determined that extract-based applications increase swelling values, whereas hydrosol applications provide more limited dimensional changes. This can be explained by the fact that hydrosol limits water penetration into the wood's cell walls thanks to its water-repellent properties. The results obtained show that hydrosol applications can be advantageous especially for usage areas where dimensional stability is important. Overall, the present findings support the potential of rosemary-based hydrosol as an effective dimensional stabilizer and rosemary extract as a density- and retention-enhancing agent. These results contribute to the expanding body of literature on sustainable, plant-based wood modification strategies and align with current trends toward environmentally responsible wood protection systems.

In general, it was concluded that rosemary hydrosol gave more positive results compared to the extract in terms of increasing dimensional stability in wood materials, while extract applications had enhancing effects on some physical properties. In this context, rosemary hydrosol has the potential to be used as an alternative use in the wood industry as an environmentally friendly and natural impregnating agent, and it is thought that it can be used especially in wood materials exposed to outdoor conditions.

Rosemary hydrosol is recommended to be considered as an environmentally friendly impregnating agent due to its effect on increasing dimensional stability in wood materials. In order to better understand

the effects of mordant use in impregnation applications, comparative studies should be conducted with different mordant types and concentrations. The industrial applicability of the findings obtained through research involving different wood species and long-term strength tests should be revealed.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TC: Investigation, Software, Data curation, Conceptualization, Resources, Writing – original draft, Visualization, Validation, Methodology, Project administration, Writing – review & editing, Formal analysis, Supervision.

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Conflict of interest

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