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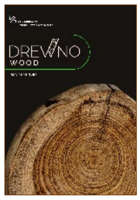

The Impact of an Ultrasound-Assisted Mixing Method for Varnish Systems on The Varnish Layer's Surface Hardness and Surface Scratch Resistance

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The objective of this study was to determine the effects of mechanical and ultrasound-assisted stirring methods for varnish systems on the varnish layer's surface hardness and surface scratch resistance. The study focused on polyurethane, acrylic, and polyester varnish systems, which were applied to three distinct wood types: Scots pine (*Pinus sylvestris* L.), Turkish beech (*Fagus orientalis* Lipsky), and African mahogany (*Khaya ivorensis* A. Chev.). The mixing processes included mechanical stirring for 3 and 5 minutes, as well as ultrasound-assisted stirring with differing power levels (80 W and 120 W) for 3 and 5 minutes. The highest surface hardness (175.10) was achieved using polyester varnish obtained by mechanical stirring for 3 minutes and applied to Turkish beech, while the lowest surface hardness (66.80) was observed for acrylic varnish obtained by 120 W ultrasound-assisted stirring for 5 minutes and applied to African mahogany. The highest surface scratch resistance (0.760 N) was observed with polyester varnish obtained by mechanical stirring for 5 minutes and applied to Scots pine, and also with acrylic varnish obtained by 80 W ultrasound-assisted stirring for 3 minutes and applied to Turkish beech. Overall, the findings suggested that the ultrasound-assisted mixing method generally fell short in terms of enhancing the varnish properties compared with the mechanical mixing technique.

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Introduction

Varnishing stands out as a highly favored method for safeguarding and beautifying wooden surfaces, paintings, and a range of decorative items. Typically, varnishes comprise a mixture of resin, drying oil, drier, and volatile solvent. During the drying process, the solvent component of the varnish evaporates, leaving the remaining elements to undergo oxidation or polymerization, resulting in the creation of a resilient, see-through protective layer. This protective film not only shields but also elevates the visual appeal of wooden floors, interior wood paneling and trim, as well as furniture.

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Varnishes can be formulated using one or multiple compounds. Multi-component varnishes are applied by incorporating and blending each individual component in specified proportions as per the manufacturer's guidelines. The effectiveness of the final dried varnish coat hinges on the accurate amalgamation of the varnish liquid, which comprises all of the constituent elements. Despite varnish manufacturers' providing instructions on the appropriate procedures and timing for these mixtures, there are instances where the process falls short of perfection, leading to substantial and costly defects in the varnish layer in both the short and long term [Westsystem, 2019; Baykan et al., 2000].

The surface hardness and scratch resistance of varnished wood play a pivotal role in ensuring the optimal performance of the final product across various applications. However, there exist certain factors that impose limitations on the longevity of varnishes when applied to wood surfaces. Among these factors, cavitation during the mixing of varnish components stands out as a significant contributor. Cavitation is a phenomenon wherein the static pressure of a liquid drops below the liquid's vapor pressure, resulting in the formation of minuscule vapor-filled voids within the liquid. Under elevated pressure, these voids, often referred to as "bubbles," collapse and have the potential to induce defects in the varnish layer. During the varnishing process, applicators commonly utilize propeller mixers, which can induce cavitation in the varnish liquid and consequently impact the properties of the varnish layer. As indicated in the literature, ultrasonic cavitation has been recognized for its potential to intensify the breakdown and deterioration of compounds, particularly those with partially stable carbon chains [Effendi and Wulandari, 2019]. Essentially, this process generates micro-cavities within the liquid, leading to a porous structure in the dried layer, thus adversely affecting key quality attributes such as the surface hardness and scratch resistance of the varnish. Moreover, non-uniform mixing can result in cracks due to disparate elastic behaviors across different sections of the varnish surface layer.

A recently emerging technique employed to mitigate cavitation and facilitate material mixing is the application of ultrasonic waves. Ultrasound refers to sound waves that exist beyond the range of human auditory perception and propagate within a medium through alternating phases of expansion and compression. The occurrence of cavitation bubbles is prompted during the expansion phase when a significant negative pressure is generated [Gungoren et al., 2019]. Leveraging ultrasonic technology, various substances can be thoroughly mixed within sealed plastic or metallic containers (or bottles) without necessitating their opening or manual agitation. The disruptive action of ultrasonic energy, characterized by the collapse of cavitation bubbles and the propagation of shockwaves, is known to break down aggregated materials [Povey and Mason, 1999].

Through ultrasound-assisted mixing, Nejad et al. (2015) investigated the quality of nanoparticle dispersion within a bio-based coating. He et al. (2018) used ultrasonic stirring to effectively blend metal composites. Masri et al. (2018) conducted a comparative study of acidic ionic liquids based on dicationic ammonium and diazabicyclo octane (DABCO) that had been functionalized with SO_3H, as well as ultrasonic cavitation and traditional mechanical stirring. Effendi and Wulandari (2019) used ultrasonic energy to remove petroleum hydrocarbons from polluted low-permeability soils. Using a variety of surface chemistry methods, Gungoren et al. (2019) thoroughly investigated the effect of ultrasound (US) on a quartz–amine flotation system. To obtain optimum results, Zanghellini et al. (2021) used a solvent-free ultrasonic dispersion method for nanofillers within an epoxy matrix. Cheng and Wang (2022) used ultrasound-assisted mixing to improve the dispersion and distribution of composite particles inside a rubber matrix. Their research showed that ultrasonic waves had a beneficial effect on both dispersive and distributive mixing, thus improving the overall quality and performance of rubber products. All of the aforementioned researchers agreed that the ultrasound-assisted mixing technique had positive effects.

Currently, there is a scarcity of information regarding the impact of ultrasound-assisted varnish component mixing on the surface hardness and scratch resistance of varnish layers applied to wood materials. This study aimed to address this gap through experiments that compared the effectiveness of mechanical and ultrasound-assisted mixing methods for varnish systems, considering different mixing durations and ultrasonic power levels.

Experimental design

The research was structured around three different wood types, utilizing three distinct varnish types and six different stirring procedures. Two distinct tests were conducted, with ten repetitions for each test specimen. An overview of the study's overall framework is presented in Table 1.

Table 1. The overarching framework of the study

Wood type	Varnish type	Stirring method			Tests	Repetition
		Stirring method	Ultrasound Power (watt)	Stirring time (Min)		
Scots pine Turkish beech African mahogany	Polyurethane Acrylic Polyester	Mechanic	-	3	surface hardness surface scratch resistance	10
				5		
		Ultrasonic	80 watt	3		
				5		
			120 watt	3		
				5		

Materials and methods

1. Wood materials

Three distinct wood types were employed as test samples in this study: Scots pine (*Pinus sylvestris* L.) (0.49 g/cm^3), Turkish beech (*Fagus orientalis* Lipsky) (0.70 g/cm^3), and African mahogany (*Khaya ivorensis* A. Chev.) (0.50 g/cm^3). These particular wood varieties were chosen due to their extensive utilization within the wood products sector. Wood samples were selected randomly, being sourced from timber merchants located in İzmir, Turkey.

The wood samples were subjected to conditioning at a temperature of 20±2 °C and a relative humidity of 65±5% until they reached a stable mass. For each wood species, test samples (totaling 1080, comprising 3 wood types x 3 varnish types x 6 stirring methods x 2 tests x 10 repetitions) were prepared. These test samples, possessing an average moisture content of 12% and dimensions of 100 mm × 100 mm × 10 mm, were fashioned following the guidelines contained in TS 2470 (1976).

2. Varnishing

The experimental wood samples were treated with polyester, acrylic, and polyurethane varnishes, adhering to the conditions laid down in ASTM D 3023 (1998). These varnishes were sourced from companies located in Muğla, Turkey. Details regarding the varnishes and their constituent elements are provided in Table 2.

The sanded test samples underwent varnishing through spray application using three distinct varnish types: polyurethane, acrylic, and polyester, in accordance with the ASTM D 3023 (1998) specifications. The recommended proportions for solvent composition and hardener ratio were adhered to as per the manufacturer's instructions. The varnish mixtures were subjected to two mixing methods: ultrasound-assisted stirring and conventional mechanical stirring. Mechanical stirring was executed using a power mixer at 700 rpm, while ultrasonic stirring was achieved utilizing an ultrasonic device (Kudos HP 53 kHz) with ultrasound energy set at 80 and 120 W. Two different mixing durations were used in the study: 3 and 5 minutes.

Table 2. Varnishes and components mixing

Varnish type	Filling coat		Top coat	
	Varnish /hardener/ accelerator	Solvent	Varnish/hardener/ accelerator	Solvent
Polyurethane	2/1	Polyurethane thinner (%5-10)	1/1	Polyurethane thinner (%5-10)
Acrylic	5/1	Acrylic thinner (%40-50)	5/1	Acrylic thinner (%50-60)
Polyester	1kg/20 ml/20 ml	Monostirol (%15-20)	1kg/20 ml/20 ml	Monostirol (%15-20)

Table 3. Varnish application conditions

Type of varnish	Viscosity DIN Cup/4mm	Amount used (g/m^2)	Nozzle gap (mm)	Air pressure (bar)
Polyurethane	18-20	120-150 (filling) 100-120 (top)	1.8	2
Acrylic	15-18	100-120	1.8	
Polyester	32-40	100	2.5	

For the polyurethane and acrylic varnish mixtures, a resting period of 10 minutes was observed before their application on the wooden test samples (Megep, 2012). No resting time was provided for the polyester varnish system, which tends to gel rapidly upon mixing. Subsequent to each application of the varnish coating, the dried layer was meticulously sanded using abrasive papers (220–320–400). The interval between the application of successive varnish layers was six hours for polyurethane, three hours for acrylic, and 25 minutes for polyester. A comprehensive description of the application conditions is given in Table 3.

3. Determination of surface hardness

To determine the hardness of the varnish coating, samples were subjected to the König pendulum hardness test in accordance with ASTM D 4366-95 (1984), after conditioning. Test panels were placed on the panel table, and a pendulum was carefully placed on the surface of each panel. The pendulum was then deflected by 6° before being let go, which concurrently started the oscillation counter. The König hardness value was calculated as the number of oscillations necessary for the amplitude to drop from 6° to 3°. Ten tests were performed on various samples from each treatment group to verify accuracy.

4. Determination of surface scratch resistance

The varnished samples' scratch resistance was assessed in accordance with the TS 4757-86 standard. A diamond bit (radius: 0.090±0.003 mm) scratch tester was used to create a discernible scratch on the test sample's surface. A spirit level was used to align the diamond bit with the horizontal plane, and a pressure screw rotating at a speed of 5±1 minute was used to secure the experimental sample to a supporting disc.

The device was positioned horizontally when the supporting handle made contact with the diamond bit on the sample. After careful modifications were made with a sensitivity of ±0.01 N, the experiment started. The initial applied force was 5 N, and the force was decreased in 0.5 N steps until a continuous scratch appeared and could be seen on the sample surface. If a continuous scratch appeared at 5 N, the force was then decreased in 0.5 N steps to 2 N, then in 0.25 N steps to 1 N, and lastly in 0.1 N steps to 1 N, until a dotted scratch was produced.

After using a soft cloth and alcohol to clean the sample surface, a visual inspection was carried out under 100 lux illumination. The value corresponding to the continuous scratch mark prior to the appearance of dotted scratches is considered to be a good indicator of the sample's scratch resistance.

5. Statistical evaluation

The results were subjected to analysis of variance (ANOVA), followed by Duncan's multiple range test to determine whether there were any statistically significant differences between the average variable values, in order to determine the effects of wood species, varnish type, and stirring technique on surface hardness and surface scratch resistance. The tests' p-value cutoff for significance was established at 0.05.

Results and discussion

Table 4 presents arithmetic means and standard deviations of the results for surface hardness and surface scratch resistance.

The analysis of variance results were utilized to ascertain the impact of wood type (WT), varnish type (VT), and stirring method (SM) on varnish layer surface hardness and surface scratch resistance, as indicated outlined in Table 5. As the data in Table 5 show, all variables and interactions demonstrated a significant effect ($p \leq 0.05$) on both surface hardness and surface scratch resistance.

In Table 6, the results of the Duncan test are presented, where superscript letters (a, b, c) are conventionally used to denote statistical significance. These symbols aid in ranking differences between groups based on the level of significance, typically set at $p < 0.05$ or $p < 0.01$.

Table 4. Surface hardness and surface scratch resistance means

Wood Type	Varnish type	Stirring method	Surface hardness (number of oscillations) Mean	Surface hardness (number of oscillations) Standard Deviation	Surface scratch resistance (N) Mean	Surface scratch resistance (N) Standard Deviation
Scots pine	Polyurethane	Mechanic / 3	115.300	6.767	0.667	0.301
		Mechanic / 5	76.400	10.309	0.200	0.000
		Ultrasonic 80 W / 3	115.500	7.678	0.200	0.000
		Ultrasonic 80 W / 5	96.600	9.180	0.200	0.000
		Ultrasonic 120 W / 3	108.200	12.164	0.200	0.000
		Ultrasonic 120 W / 5	93.200	13.879	0.200	0.000
	Acrylic	Mechanic / 3	96.200	11.282	0.267	0.103
		Mechanic / 5	75.700	9.719	0.200	0.000
		Ultrasonic 80 W / 3	86.100	18.266	0.343	0.098
		Ultrasonic 80 W / 5	76.000	18.469	0.457	0.190
		Ultrasonic 120 W / 3	83.300	12.623	0.200	0.000
		Ultrasonic 120 W / 5	69.100	8.439	0.200	0.000
	Polyester	Mechanic / 3	166.400	25.242	0.333	0.163
		Mechanic / 5	172.100	27.469	0.760	0.219
		Ultrasonic 80 W / 3	148.800	27.975	0.267	0.115
		Ultrasonic 80 W / 5	119.100	17.477	0.200	0.000
		Ultrasonic 120 W / 3	138.200	17.517	0.200	0.000
		Ultrasonic 120 W / 5	134.600	25.631	0.200	0.000
Turkish be-ech	Polyurethane	Mechanic / 3	133.900	14.185	0.533	0.115
		Mechanic / 5	82.200	5.978	0.700	0.352
		Ultrasonic 80 W / 3	97.800	8.203	0.200	0.000
		Ultrasonic 80 W / 5	91.400	9.721	0.200	0.000
		Ultrasonic 120 W / 3	97.500	7.472	0.300	0.167
		Ultrasonic 120 W / 5	92.400	7.763	0.680	0.179
	Acrylic	Mechanic / 3	113.500	12.295	0.500	0.115
		Mechanic / 5	91.900	8.925	0.300	0.115
		Ultrasonic 80 W / 3	108.300	11.954	0.760	0.219

Wood Type	Varnish type	Stirring method	Surface hardness (number of oscillations) Mean	Surface hardness (number of oscillations) Standard Deviation	Surface scratch resistance (N) Mean	Surface scratch resistance (N) Standard Deviation
		Ultrasonic 80 W / 5	120.800	16.758	0.400	0.141
		Ultrasonic 120 W / 3	104.000	13.840	0.300	0.115
		Ultrasonic 120 W / 5	94.600	14.668	0.360	0.089
	Polyester	Mechanic / 3	175.100	24.551	0.200	0.000
		Mechanic / 5	167.500	30.631	0.200	0.000
		Ultrasonic 80 W / 3	133.500	31.402	0.200	0.000
		Ultrasonic 80 W / 5	100.500	19.637	0.200	0.000
		Ultrasonic 120 W / 3	127.300	24.350	0.200	0.000
		Ultrasonic 120 W / 5	148.700	25.513	0.200	0.000
African mahogany	Polyurethane	Mechanic / 3	104.500	9.407	0.200	0.000
		Mechanic / 5	74.200	4.614	0.200	0.000
		Ultrasonic 80 W / 3	104.700	4.001	0.200	0.000
		Ultrasonic 80 W / 5	103.700	5.794	0.200	0.000
		Ultrasonic 120 W / 3	116.889	6.882	0.200	0.000
		Ultrasonic 120 W / 5	106.100	7.490	0.200	0.000
	Acrylic	Mechanic / 3	84.300	12.970	0.240	0.089
		Mechanic / 5	76.300	16.813	0.240	0.089
		Ultrasonic 80 W / 3	77.700	13.013	0.200	0.000
		Ultrasonic 80 W / 5	89.800	11.213	0.200	0.000
		Ultrasonic 120 W / 3	93.500	12.076	0.200	0.000
		Ultrasonic 120 W / 5	66.800	6.941	0.200	0.000
	Polyester	Mechanic / 3	164.200	19.651	0.200	0.000
		Mechanic / 5	156.100	31.956	0.200	0.000
		Ultrasonic 80 W / 3	140.800	13.481	0.200	0.000
		Ultrasonic 80 W / 5	121.700	12.746	0.200	0.000
		Ultrasonic 120 W / 3	130.900	31.413	0.200	0.000
		Ultrasonic 120 W / 5	144.778	16.138	0.200	0.000

Table 5. Interactions between factors on surface hardness and surface scratch resistance

Statistical analysis (p value) (surface hardness)						
WT	VT	SM	WT+ VT	WT+ SM	VT+ SM	WT + VT + SM
0.000*	0.000*	0.000*	0.000*	0.000*	0.000	0.006*
Statistical analysis (p value) (surface scratch resistance)						
WT	VT	SM	WT+ VT	WT+ SM	VT+ SM	WT + VT + SM
0.000*	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*

* = Significant according to α ≤ 0.05; WT: Wood Type; VT: Varnish type; SM: Stirring method

Table 6. Results of the Duncan tests for the wood type. varnish type and stirring method average and standard of mean on surface hardness and surface scratch resistance

	Surface hardness		Surface scratch resistance	
		Mean		Mean
Wood type	Scots pine [b]	109.48	Scots pine [b]	0.30
	Turkish beech [a]	115.60	Turkish beech [a]	0.35
	African mahogany [b]	108.47	African mahogany [c]	0.20
Varnish type	Polyurethane [b]	100.49	Polyurethane [a]	0.31
	Acrylic [c]	89.32	Acrylic [a]	0.30
	Polyester [a]	143.89	Polyester [b]	0.24
Stirring method	Mechanic / 3 [a]	128.15	Mechanic / 3 [a]	0.34
	Mechanic / 5 [bc]	108.04	Mechanic / 5 [a]	0.34
	Ult / 80W / 3 [b]	112.57	Ult / 80W / 3 [b]	0.28
	Ult / 80W / 5 [d]	102.17	Ult / 80W / 5 [bc]	0.26
	Ult /120W / 3 [b]	111.02	Ult / 120W / 3 [c]	0.22
	Ult /120W / 5 [cd]	105.14	Ult / 120W / 5 [bc]	0.27

1. Surface hardness

Hardness, a crucial characteristic of coatings, is closely tied to durability and long-term performance [Vardanyan et al., 2014; Gurleyen, 2021]. Hardness values can vary between different wood types and varnish formulations [Sanivar and Zorlu, 1980]. Harder surfaces tend to exhibit more oscillation, while less hard surfaces exhibit reduced oscillation [Sonmez, 1989]. In the context of this study, the highest surface hardness value (175.10) was observed for polyester varnish obtained using mechanical stirring for 3 minutes and applied to Turkish beech, while the lowest value (66.80) was recorded for acrylic varnish subjected to ultrasound stirring at 120 W for 5 minutes and used on African mahogany. Cakicier et al. (2011) applied various varnishes to heat-treated woods and investigated varnish hardness properties. Their study identified the highest surface hardness in cellulose lacquer (79.1) applied to limba wood. Comparing our study's highest and lowest varnish hardness values with those from that similar study [Cakicier et al., 2011], our results are found to be higher. This may be attributed to our practice of mixing varnish components for a standardized period before application to wood test panels. In Figure 1, the data on surface hardness are presented graphically.

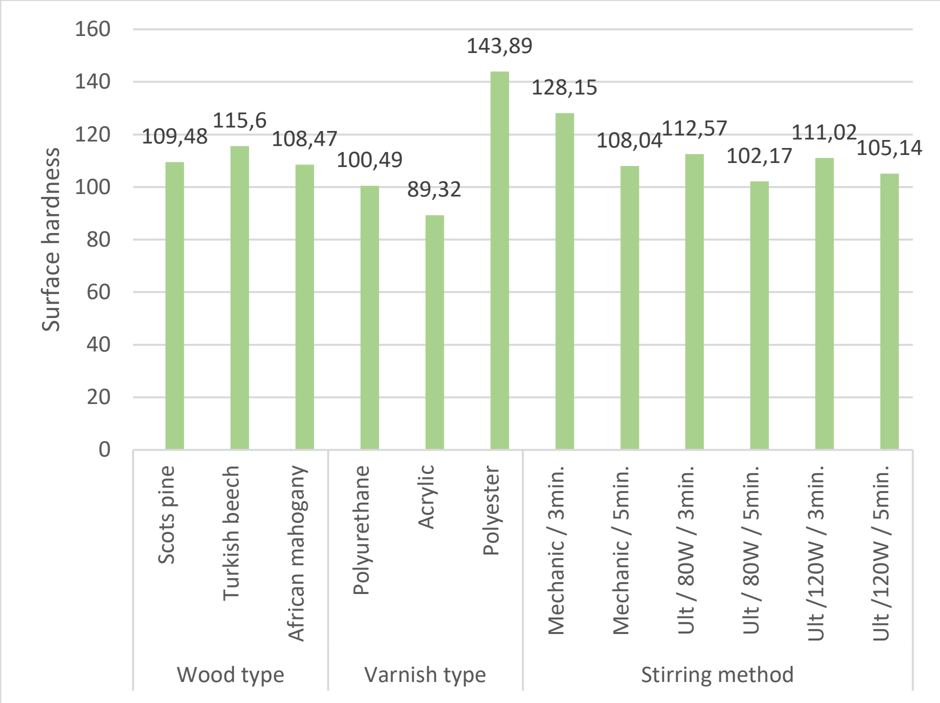

Fig. 1. Surface hardness of wood species

The surface hardness was measured in direct proportion to the density of the samples, respectively, as follows: Turkish beech (0.70 g/cm^3) 115.60, pine (0.49 g/cm^3) 109.48, and African mahogany (0.50 g/cm^3) 108.47. This ranking may be attributed to the density variations among wood species. These findings align with earlier research, indicating that hardness fluctuations are influenced by wood species, treatment conditions, and even the orientation of testing (Shi et al., 2007).

Although the ultrasound-assisted stirring method was expected to enhance varnish hardness, it did not yield the expected improvements. Instead, in this study, the ultrasound-assisted stirring method generally led to a reduction in surface hardness.

The ordering of varnishes by surface hardness was found to be as follows: polyester (143.89), polyurethane (100.49), acrylic (89.32). Consistently with earlier studies, these results reflect the tendency for polyurethane varnish to exhibit higher surface hardness, while water-based varnishes typically display lower hardness values than their synthetic counterparts [Sonmez et al., 2004; Gurleyen, 2021]. Sonmez et al. (2004) attributed the lower surface hardness of water-based varnishes to the small size of molecules in their structure, facilitating easy penetration into wood fibers and the formation of a thin layer.

The surface hardness values obtained in our study exceeded those reported by Cakicier et al. (2011). This disparity is believed to be a result of the longer duration of varnish component mixing in our study. Notably, the lowest hardness value among acrylic varnishes aligns with prior findings reported by Gurleyen (2011).

Comparing the impact of mixing methods on surface hardness, mechanical stirring for 3 minutes led to the highest value (128.15). Conversely, ultrasound-assisted mixing at 80 W for 5 minutes yielded the lowest surface hardness (102.17). The trend indicates that increased stirring time has a detrimental effect on surface hardness, possibly attributable to the flotation effect induced by ultrasound waves [Gungoren et al., 2019]. It is suggested that this outcome adversely influenced varnish curing and hardening, potentially due to the removal of hydrophobic components from the varnish liquid through foam generated by the flotation effect of heat and air bubbles produced by ultrasound.

2. Scratch resistance

The impact of stirring methods on scratch resistance is summarized in Table 4. Notably, the highest surface scratch resistance value (0.70 N) was achieved using Turkish beech wood, polyurethane varnish, and mechanical stirring for 5 minutes (0.28 N). The ordering of wood species in terms of surface scratch resistance was found to be as follows: Turkish beech (0.35 N), pine (0.30 N), African mahogany (0.20 N). Generally, our scratch resistance values were lower than those reported by Cakicier et al. (2011) and Gurleyen (2021). The data from scratch resistance testing are presented graphically in Figure 2.

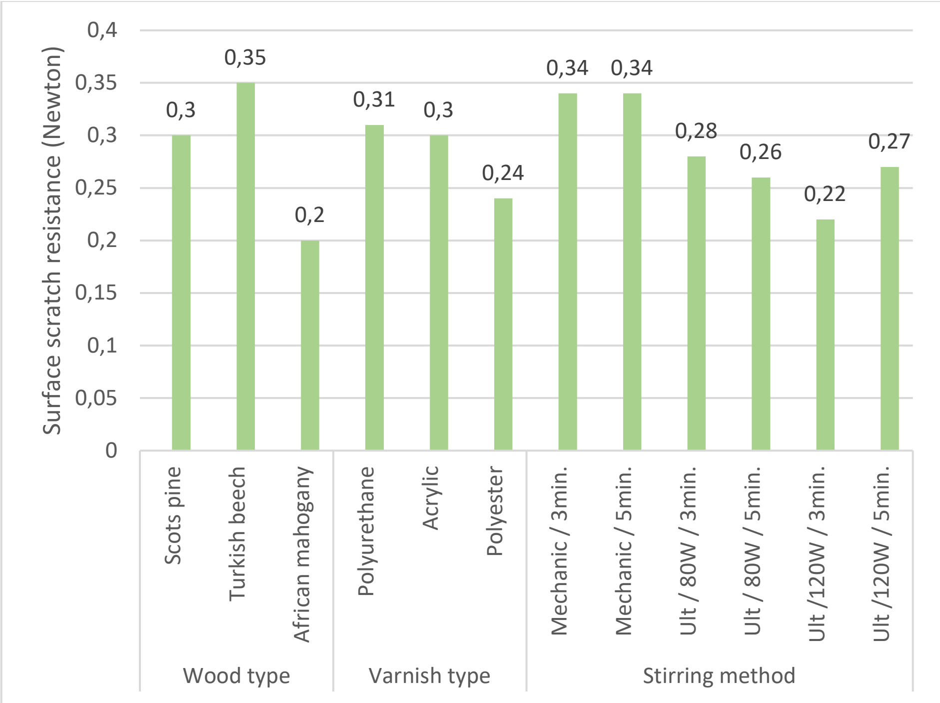

Fig. 2. Scratch resistance of wood species

When varnishes are ranked from highest to lowest surface scratch resistance, the sequence is as follows: polyurethane (0.31 N), acrylic (0.30 N), polyester (0.24 N). It is noteworthy that polyurethane and acrylic varnishes form a single homogeneous group. The elevated scratch resistance observed with polyurethane varnish aligns with the results reported by Gurleyen (2021).

Comparing the effects of mixing methods on surface scratch resistance, the ordering from highest to lowest is as follows: mechanical stirring for 3 and 5 minutes (0.34 N), ultrasound-assisted mixing at 80 W for 3 minutes (0.28 N), and ultrasound-assisted mixing at 120 W for 3 minutes (0.22 N). The success of the ultrasonic method may be influenced by such factors as material type, solid–liquid ratio, temperature, wave frequency, and energy/power employed [Kim and Wang, 2003].

In our study, we observed that increasing ultrasound power had a negative impact on surface hardness. Throughout the experiment, it became evident that higher ultrasound energy led to elevated temperatures in the varnish mixture. This is in agreement with findings reported by Effendi and Wulandary (2019) regarding the removal of pollutants from contaminated soil. While their process was successful with high ultrasound power, in our case, the elevated ultrasound wave power resulted in increased temperatures within the varnish mixture. This outcome is consistent with prior research by Gungoren et al. (2019). Once again, this may be attributed to the previously mentioned flotation effect.

In future investigations, consideration should be given to exploring separate and hybrid approaches for ultrasonic and mechanical mixing methods, such as employing solely mechanical shaking or combining mechanical shaking with ultrasonic irradiation, similarly to the procedure proposed in a prior study (Effendi and Wulandari, 2019).

Consequently, future studies exploring the impact of the ultrasound-assisted mixing method on varnish chemistry may lead to a deeper understanding and potential utilization of this method in the field of wood varnishing.

Conclusions

This study investigated the impact of ultrasound-assisted and mechanical mixing methods on the varnish component mixture in terms of surface hardness and surface scratch resistance. The specific conclusions drawn from this study may be summarized as follows:

1. Turkish beech (*Fagus orientalis* Lipsky) exhibited higher surface hardness than Scots pine (*Pinus sylvestris* L.) and African mahogany (*Khaya ivorensis* A. Chev.) wood. This ordering may be attributed to density variations among the wood species.
2. In terms of surface hardness performance, the varnishes used in this study are ordered as follows: polyester, polyurethane, acrylic. For surface

scratch resistance performance, the sequence was polyurethane, acrylic, polyester.

3. Among the stirring methods, the mechanical stirring method demonstrated greater success than the ultrasound-assisted stirring method. Overall, the ultrasound-assisted method, particularly when using high ultrasound power and a 5-minute mixing time, led to a deterioration in varnish layer properties.
4. Based on our findings, we cannot endorse the use of ultrasound-assisted mixing as a viable method for enhancing surface hardness and surface scratch resistance performance in varnish component mixing.

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