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Resistance of Three Commonly Used Wood Species Treated with Selected Plant-Based Oil to Fungi Infestation

Otpornost na gljivice triju često upotrebljavanih vrsta drva zaštićenih odabranim biljnim uljem

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ABSTRACT • *Using wood as a construction material comes with the problem of degradation due to material resistance and exposure to favourable conditions conducive to fungal growth. This study investigated the resistance of treated commonly used wood species (Triplochiton scleroxylon, Gmelina arborea, and Terminalia superba) to fungal decay in construction in Nigeria. The selected wood species were treated with neem oil, moringa seed oil, and castor oil as preservatives. The treatability and physical properties of the treated wood samples were assessed, including moisture content, density, absorption, and retention of preservatives, to ascertain the suitability of oil preservatives. An accelerated fungi infestation test was carried out on the treated wood samples by inoculating them with Gilbertella persicaria for 7 weeks, and visual observation was done every week. The weight loss due to infestation was calculated after the 7th week of exposure to fungi. The wood species exhibited varying moisture content and density with Afara having (27.66 % and 508.61 kg/m³), Gmelina wood (21.00 % and 528.07 kg/m³), and Obeche (16.83 % and 531.75 kg/m³), respectively. For the rate of absorption, Afara recorded (5.06 %, 4.18 %, and 6.58 %), Gmelina wood (9.35 %, 7.61 %, and 8.50 %) and Obeche (0.95 %, 4.22 %, and 8.15 %) when treated with neem oil, moringa seed oil, and castor oil, respectively. Treated wood samples demonstrated significantly lower volumetric swelling and weight loss compared to untreated samples. Castor oil treatment, especially on Gmelina wood, emerged as effective in minimizing dimensional changes and fungi infestation, making it a promising choice for applications requiring stability, leaching resistance, and protection against fungi infestation.*

KEYWORDS: *oil treatment; resistance; physical properties; fungal decay; plant based-oil*

SAŽETAK • *Pri upotrebi drva kao građevnog materijala veliki je problem propadanje drva zbog izloženosti uvjetima koji pogoduju rastu gljiva. U ovoj studiji istraživana je otpornost često upotrebljavanih vrsta drva u graditeljstvu Nigerije (Triplochiton scleroxylon, Gmelina arborea i Terminalia superba) koje su prethodno zaštićene od propadanja uzrokovanoga gljivama. Odabrane vrste drva premazane su uljem nima, uljem sjemenki moringe i ricinusovim uljem kao zaštitnim sredstvima. Procijenjena je mogućnost zaštitnog postupka i fizička svojstva zaštićenih uzoraka, uključujući sadržaj vode, gustoću drva te apsorpciju i retenciju zaštitnog sredstva kako bi se utvrdila prikladnost uljnih zaštitnih sredstava. Ubrzani test zaraze gljivama proveden je na tretiranim uzorcima*

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drva inokulacijom gljivom Gilbertella persicaria tijekom sedam tjedana, a uzorci su vizualno promatrani svaki tjedan. Nakon sedam tjedana izloženosti gljivama izračunan je gubitak mase. Vrste drva pokazale su različit sadržaj vode i gustoću, pri čemu je drvo limbe imalo (27,66 % sadržaj vode i gustoću 508,61 kg/m³), bijelog tika (21,00 % sadržaj vode i gustoću 528,07 kg/m³), a abahe (16,83 % sadržaj vode i gustoću 531,75 kg/m³). Brzina apsorpcije ulja nima, ulja sjemenki moringe i ricinusova ulja za uzorke drva limbe bila je 5,06 %, 4,18 % i 6,58 %, bijelog tika 9,35 %, 7,61 % i 8,50 %, a abahe 0,95 %, 4,22 % i 8,15 %. Tretirani uzorci drva pokazali su znatno niže volumno bubrenje i gubitak mase u usporedbi s netretiranim uzorcima. Tretman ricinusovim uljem, posebno na drvu bijelog tika, pokazao se učinkovitim u smanjenju dimenzijskih promjena i zaraze gljivama, što ga čini prikladnim izborom za primjene na drvu kad se zahtijevaju stabilnost, otpornost na ispiranje i zaštitu od zaraze gljivama.

KLJUČNE RIJEČI: *tretiranje uljem; otpornost; fizička svojstva; propadanje uzrokovano gljivama; prirodna ulja*

1 INTRODUCTION
1. UVOD

Wood, a fundamental resource intertwined with human civilization, serves diverse purposes, notably in construction, where over 80 % of Nigerian timber products are used for building, furniture, and various applications (Tolunay *et al.,* 2008; Ekundayo *et al.,* 2022). Its versatility and resilience make it invaluable, yet its variable nature necessitates the selective use of durable species due to concerns about long-term endurance (Oluwafemi and Adegbenga, 2007; Kayode, 2007). Wood deterioration caused by biological agents such as fungi, poses a significant issue in protecting the structural integrity and durability of wooden structures and furniture (Ligne *et al.,* 2022). This is especially noticeable when using wood species like *Triplochiton scleroxylon, Gmelina arborea,* and *Terminalia superba* due to their lightweight composition (Akanbi and Ashiru, 2002).

Fungal deterioration remains a challenge, leading to significant economic and social costs (Goktas *et al*., 2007). Decay fungi are multicellular filamentous microorganisms that feed on wood structural components by germinating on moist parts and disseminating their hyphae (mycelial filaments) throughout the wood. The resultant effect of this notable deterioration in wood is that its strength decreases as it varies depending on the kind of fungus, wood species, and lumber dimensions (Shupe *et al*., 2008). The use of chemical preservations to enhance wood resilience against bio-deteriorating agents is a traditional technique of wood preservation that has demonstrated limits in providing long-term solutions while also creating significant environmental problems (Khademibami and Bobadilha, 2022).

Addressing these challenges, eco-friendly wood preservatives, particularly plant-based oils, have gained attention (Woźniak *et al*., 2022; Kwon *et al.,* 2023). It has been demonstrated through various findings that the impregnation of wood with eco-friendly materials such as linseed oil, castor oil, basil oil, moringa oil, and other vegetable oil-based hydrophobic liquids significantly reduces cracking in load-bearing timber elements, and reduces water absorption, increasing durability and reducing costs and material consumption in timber structures (Shkarovskiy *et al.,* 2022; Sharaf *et al.,* 2022; Kachel *et al.,* 2023).

Neem oil, derived from the neem tree (*Azadirachta indica*), is known for its antifungal properties attributed to bioactive compounds such as azadirachtin, nimbin, and salannin, which inhibit fungal growth through various mechanisms, including disruption of fungal cell membranes and interference with enzyme activity (Zhang *et al.,* 2016; Brunner *et al.,* 2018). Similarly, Moringa seed oil, extracted from *Moringa oleifera*, shows promising antifungal effects, although its precise mode of action remains incompletely understood. Studies suggest that bioactive constituents like isothiocyanates, flavonoids, and phenolic compounds contribute to its antifungal properties (Deshmukh *et al.,* 2018). Castor oil, obtained from the seeds of the Ricinus communis plant, has been extensively researched for its diverse properties, including its potential as a treatment for fungal resistance in wood species (Kusch and Panstruga, 2017; Kwon *et al.,* 2023). Ricinoleic acid, found in castor oil, exhibits antifungal properties (Kusch and Panstruga, 2017). These oils offer potential avenues for enhancing wood species resistance against fungi, providing diverse mechanisms to combat fungal infestations in wood (Thirkell *et al.,* 2017).

Despite this, there is a research gap in understanding their efficacy in wood preservation, necessitating a push towards traditional organic techniques for environmental sustainability. Therefore, this study investigates the use of selected plant-based oil to enhance *Triplochiton scleroxylon, Gmelina arborea*, and *Terminalia superba* wood resistance against fungal deterioration.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The study was carried out at the Federal University of Technology Akure situated at Latitude 7.2629° N and Longitude 5.1924° E in Ondo State, Nigeria, in the Akure South Local Government Area. The three wood samples were collected from *Triplochiton scleroxylon, Gmelina arborea,* and *Terminalia superba* wood obtained from a reputable industrial sawmill in Akure, Ondo State, Nigeria. For the physical properties and durability test, wood samples (Plate 1) with dimensions of 20mm × 20mm × 60mm and 20mm × 20mm × 20mm were used, respectively. After that, they were oven-dried at about 100°C until constant weight. All samples were prepared and tested according to the modified test of the ASTM 2019 test method for solid woods.

Figure 1 Prepared wood samples of the three selected wood species
Slika 1. Pripremljeni uzorci triju odabranih vrsta drva

2.1 Treatment of wood samples
2.1. Tretiranje uzoraka drva

The treatment of *Triplochiton scleroxylon, Gmelina arborea,* and *Terminalia superba* wood samples was performed using three plant-based oils: neem oil, moringa seed oil (MSO), and castor oil. Oven-dried wood samples were fully immersed in the oils at their original, undiluted concentrations for 24 hours. The oils were applied hot at approximately 60 °C to maximize flowability and penetration into the wood structure, ensuring adequate absorption. During the immersion, no pressure or vacuum was applied. Following this treatment, the wood samples were removed from the oils, allowed to drain excess oil, and subsequently dried in the oven at a temperature of (102±3) °C until constant weight was attained. The weight of each sample before and after immersion was recorded to estimate absorption efficiency. This procedure facilitated uniform distribution of the oils within the cellular structure of wood, preparing the samples for subsequent testing.

2.2 Fungi inoculation process
2.2. Postupak inokulacije gljivama

The *Gilbertella persicaria* (soft rot fungi) for the accelerated fungi infestation test was stored in the refrigerator at 4 ºC. Twelve sample plates were sterilized with ethanol to accommodate the infected samples. After being sterilized, the plates were placed in the oven for 25 minutes to dry, and 39 g of potato dextrose agar (PDA) was dissolved in 1000 ml of water and heated to dissolve the medium completely using an autoclave at 121 °C and pressure of 151 lbs for 15 minutes. An Amoxicillin capsule was also poured into the PDA to avoid bacteria contamination. After this, a 10 mm cork borer was used to inoculate the fungal isolate to the centre of the prepared PDA and incubate it under aseptic conditions.

2.3 Determination of basic physical properties of the selected wood
2.3. Određivanje osnovnih fizičkih svojstava odabranog drva

The physical properties of the three wood species were determined on defect-free wood samples of dimensions of 20 mm × 20 mm × 60 mm for both treated and untreated samples according to the American Society for Testing Materials (2009).

2.3.1 Percentage moisture content
2.3.1. Postotak sadržaja vode

The moisture content of the wood samples was determined using the weight (Plate 3A) of the samples before drying and after drying in the oven to attain a constant weight.

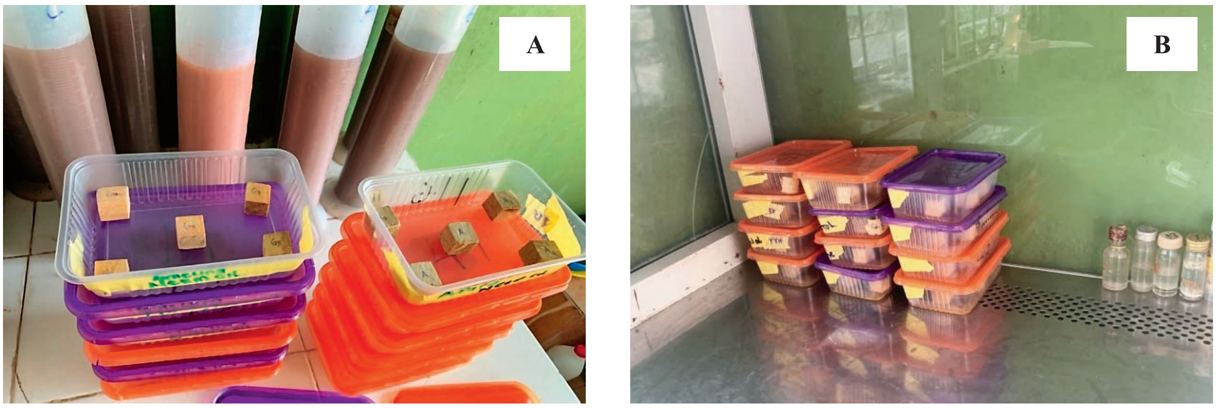

Figure 2 (A) Fungi Inoculation process; (B) Inoculated wood samples
Slika 2. (A) Postupak inokulacije gljivama; (B) inokulirani uzorci drva

$$Moisture\ content\ (\%) = \frac{W_g - W_o}{W_o} \cdot 100 \quad (1)$$

Where: W_g – Weight of green samples (g); W_o – Weight of dried samples (g).

2.3.2 Density
2.3.2. Gustoća

The density of the wood samples after oven drying was determined using the mass and volume of the oven-dried wood samples. After oven drying, the density of the wood sample was calculated as follows:

$$Density\ (\rho) = \frac{Mass\ of\ oven\ dried\ sample}{Volume} \quad (2)$$

2.3.3 Volumetric shrinkage (VS)
2.3.3. Volumno utezanje (*VS*)

The volumetric shrinkage of the samples was determined by recording the volume of the wood samples at the green stage and at the end of the drying period. The initial volume of the samples (L × B × H) was taken at the green stage using the vernier calliper, and at the end of the drying process. The final volume attained was measured. The volumetric shrinkage of the samples is estimated as follows:

$$VS\ (\%) = \frac{D_1 - D_2}{D_1} \cdot 100 \quad (3)$$

Where: VS – volumetric shrinkage (%); D_1 – green dimension (mm); while D_2 – final dimensions after oven-drying (mm).

2.3.4 Volumetric swelling (VSW)
2.3.4. Volumno bubrenje (*VSW*)

The volumetric swelling of the three selected wood samples (Plate 3B) treated with oil was determined by taking the oven-dried dimensions of the wood, soaked in water for 24, 48, and 72 hours, respectively, and taking the final dimensions. The following formula was used:

$$VSW\ (\%) = \frac{D_2 - D_1}{D_1} \cdot 100 \quad (4)$$

Where: VSW – volumetric swelling (%); D_1 – oven-dried dimensions (mm), while D_2 – final dimensions after soaking (mm).

2.3.5 Weight loss due to leaching after continuous soaking in water
2.3.5. Gubitak mase zbog ispiranja nakon kontinuiranog namakanja u vodi

After 72 (Plate 3C) hours of continuous soaking of both the treated and untreated samples in water, samples of each wood species were oven-dried till a constant weight was obtained. The weight loss due to leaching was calculated using the formula:

$$\%\ Weight\ loss = \frac{W_2 - W_3}{W_2} \cdot 100 \quad (5)$$

Where: W_2 – weight before oven drying (g); W_3 – weight after oven drying (g).

2.4 Treatability of wood samples with oil preservatives
2.4. Obrada uzoraka drva uljnim zaštitnim sredstvima

2.4.1 Oil preservative absorption
2.4.1. Apsorpcija uljnih zaštitnih sredstava

This is the amount of preservation chemical the wood samples absorb. The percentage absorption was calculated by using the following formula:

$$\%\ Absorption = \frac{W_2 - W_1}{W_1} \cdot 100 \quad (6)$$

Where: W_1 – Oven dry weight of the sample (g), W_2 – Initial weight after treatment (g), and W_3 – Final weight after treatment (g).

2.4.2 Oil preservative retention
2.4.2. Retencija uljnih zaštitnih sredstava

The amount of each preservative retained in the wood after the treatment period or cycle was calculated using the equation below:

Figure 3 Experimental procedures for physical properties test: A) weighing of wood samples B) extracted samples prepared for test C) soaking of samples in water
Slika 3. Eksperimentalni postupci ispitivanja fizičkih svojstava: A) vaganje uzoraka drva, B) izdvojeni uzorci pripremljeni za ispitivanje, C) namakanje uzoraka u vodi

Table 1 Assessment of mould growth
Tablica 1. Procjena rasta plijesni

Mould grade *Ocjena plijesni*	**Description** / *Opis*
0	No visible mould growth / *nema vidljivog rasta plijesni*
1	Small amount of mould growth: some doubt about mould *mala količina plijesni: postoji sumnja u postojanje plijesni*
2	Sparse mould growth without a doubt / *nesumnjivo vidljiva plijesan*
3	Moderate mould growth: most of the surfaces are not covered with mould *umjeren rast plijesni: većina površine nije prekrivena s plijesni*
4	Heavy mould growth: surfaces entirely covered with fluffy mycelia and spores *intenzivan rast plijesni: površine su potpuno prekrivene pahuljastim micelijem i sporama*
5	Sever mould growth: multicolour mould with black mould *vrlo izrazit rast plijesni: uz crnu plijesan pojavila se i višebojna plijesan*

$$Retention\ (kg/m^3) = \frac{G \cdot C}{V} \cdot 10 \qquad (7)$$

In Eq. 7, *G* is the amount of the oil preservatives absorbed by the wood samples at the initial and final weight of each sample in grams; *C* is the preservative solution in 100 g of the oil preservative; and *V* is the volume of the wood sample.

2.5 Resistance to fungi infestation test
2.5. Test otpornosti na gljive

2.5.1 Assessment of fungi mould growth
2.5.1. Procjena rasta gljiva i plijesni

The rate of fungi mould growth was calculated during the period of 7 weeks of exposing the wood samples to fungi infestation with visual observation every week using the parameters in Table 1 (Ahmed *et al.,* 2013).

2.5.2 Weight loss due to fungi infestation
2.5.2. Gubitak mase zbog zaraze gljivama

The weight of the wood samples after exposure to the fungi species was calculated using the following equaton:

$$Weight\ Loss\ (\%) = \frac{W_i - W_f}{W_i} \cdot 100 \qquad (8)$$

Where: W_i – oven-dried weight (g) after treatment; W_f – oven-dried weight (g) after exposure to fungi attack of samples treated.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Basic physical properties of the three selected wood species
3.1. Osnovna fizička svojstva triju odabranih vrsta drva

3.1.1 Moisture content and density
3.1.1. Sadržaj vode i gustoća drva

The result of the initial moisture content (*MC*, %) distribution presented in Table 2 showed that the *MC* among the three selected wood species differed significantly, with Afara having the highest moisture content at (27.66 ± 3.58) %, followed by Gmelina (21.00 ± 8.36) %, and Obeche with the lowest value of (16.83 ± 7.08) %. Also, Density distribution (Table 2) showed that Obeche had the highest density of (531.75 ± 49.70) kg/m^3, followed by Gmelina (528.07 ± 20.27) kg/m^3, while Afara recorded the lowest density of (508.61 ± 34.65) kg/m^3. There was a significant difference in moisture content distribution and no significant difference in density among the species. A strong correlation was observed between density and moisture content, indicating that density increased as moisture content decreased. The variation in moisture content and density among the wood species may be attributed to inherent differences in their cellular structures according to Wodzicki (2001). Afara's higher moisture content might be due to its porous structure, influencing its density. There was an inverse relationship between moisture content and density – densities increased as moisture content decreased (Altuntaş and Yıldız, 2007).

3.1.2 Volumetric shrinkage
3.1.2. Volumno utezanje

The descriptive statistics illustrated in Table 2 revealed the distribution of percentage volumetric shrinkage (*VS*) among the three selected wood species, with Gmelina exhibiting the highest *VS* at (10.31 ± 2.61) %, followed by Obeche at (7.67 ± 3.59) %, and Afara recording the lowest value at (3.72 ± 1.79) %. Analysis of variance ($\alpha = 0.05$) for *VS* distributions revealed significant differences among the selected wood species (Table 2). Afara's lower shrinkage may indicate its suitability in applications where minimal dimensional changes are critical (Yildiz *et al*., 2006).

3.2 Treatability of the selected wood species with oil preservatives
3.2. Mogućnost tretiranja odabranih vrsta drva zaštitnim uljnim sredstvima

3.2.1 Treatment absorption
3.2.1. Apsorpcija zaštitnih sredstava

The absorption results (Figure 4) showed clear variation across wood species and treatment types. Afara ex-

Table 2 Descriptive statistics of the basic properties of the selected wood species
Tablica 2. Deskriptivna statistika osnovnih svojstava odabranih vrsta drva

Species *Vrsta drva*	**Moisture content, %** *Sadržaj vode, %*	**Density, kg/m³** *Gustoća, kg/m³*	**Volumetric shrinkage, %** *Volumno utezanje, %*
Obeche / *abahi*	27.66 ± 3.58[a]	508.61 ± 34.65[a]	3.72 ± 1.79[c]
Afara / *limba*	16.83 ± 7.08[b]	531.75 ± 49.70[a]	7.67 ± 3.59[b]
Gmelina / *bijeli tik*	21.00 ± 8.36[b]	528.06 ± 20.27[a]	10.31 ± 2.61[a]

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

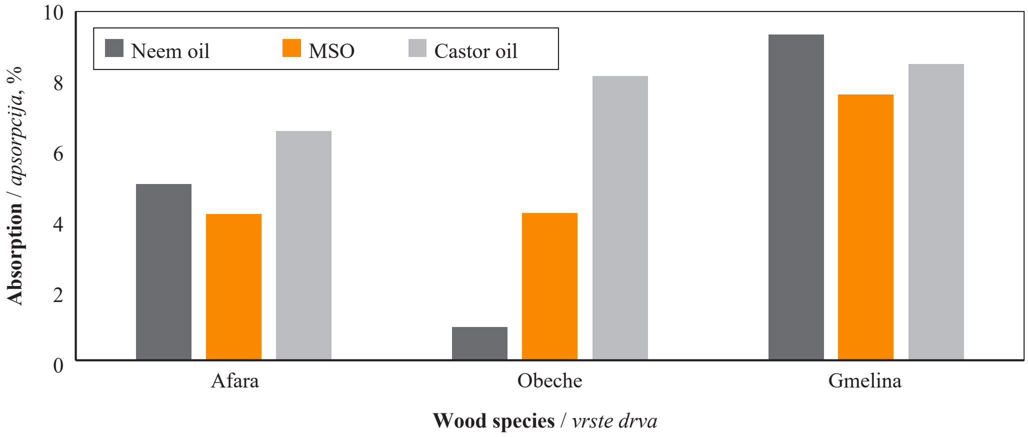

Figure 4 Absorption of varying treatments of the selected wood species
Slika 4. Apsorpcija različitih zaštitnih uljnih sredstava na odabranim vrstama drva

hibited absorption values of (5.06 ± 2.23) %, (4.18 ± 2.70) %, and (6.58 ± 2.51) % when treated with neem oil seed, moringa seed oil (MSO), and castor oil, respectively. Obeche recorded (0.95 ± 0.58) %, (4.22 ± 3.02) %, and (8.15 ± 1.48) % for the same treatments, while Gmelina showed the highest overall absorption, with values of (9.35 ± 3.20) %, (7.61 ± 2.36) %, and (8.50 ± 3.04) % in response to neem oil seed, MSO, and castor oil, respectively. These variations align with earlier findings by Adeduntan and Olusola (2008), who noted that preservative retention in cellulosic materials is strongly influenced by the anatomical structure of different wood species.

Duncan's Multiple Range Test for the treatment absorption (Table 3) also revealed that there are significant differences among both species and treatment types. Among the species, Gmelina (8.48 ± 2.77) % was assigned to group *a*, showing significantly higher absorption than Afara (5.28 ± 2.52) % and Obeche (4.44 ± 3.55) %, both placed in group *b*. This indicates that Afara and Obeche did not differ significantly from each other but absorbed significantly less than Gmelina. For the treatment types, castor oil (7.74 ± 2.41) % formed group *a* and produced significantly higher absorption than neem oil (5.12 ± 4.13) % and MSO (5.34 ± 5.01) %, which were grouped under *b* and showed no significant difference between them. The finding showed that Gmelina demonstrated superior absorption capacity across treatments, while castor oil proved to be the most effectively absorbed preservative.

3.2.2 Retention of oil preservative
3.2.2. Retencija zaštitnih uljnih sredstava

The oil retention results presented in Figure 5 for different treatments, demonstrated varied retention values across the wood species: Afara recorded values of (26.42 ± 10.07) kg/m³, (22.57 ± 14.03) kg/m³, and (33.24 ± 12.14) kg/m³; Obeche (5.50 ± 2.99) kg/m³, (21.95 ± 14.09) kg/m³, and (45.65 ± 8.17) kg/m³ and Gmelina recorded (54.70 ± 19.75) kg/m³, (40.79 ± 11.20) kg/m³, and (46.09 ± 16.32) kg/m³ when treated with Neem oil seed, Moringa seed oil, and Castor oil respectively. Duncan's Multiple Range Test (Table 4) revealed significant

Table 3 Duncan's multiple range tests for treatment absorption
Tablica 3. Duncanovi testovi višestrukog raspona za apsorpciju zaštirnog sredstva

Species *Vrsta drva*	**Absorption, %** *Apsorpcija, %*	**Treatment** *Zaštitno sredstvo*	**Absorption, %** *Apsorpcija, %*
Obeche / *abahi*	5.28 ± 2.52[b]	Neem oil	5.12 ± 4.13[b]
Afara / *limba*	4.44 ± 3.55[b]	MSO	5.34 ± 5.01[b]
Gmelina / *bijeli tik*	8.48 ± 2.77[a]	Castor oil	7.74 ± 2.41[a]

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

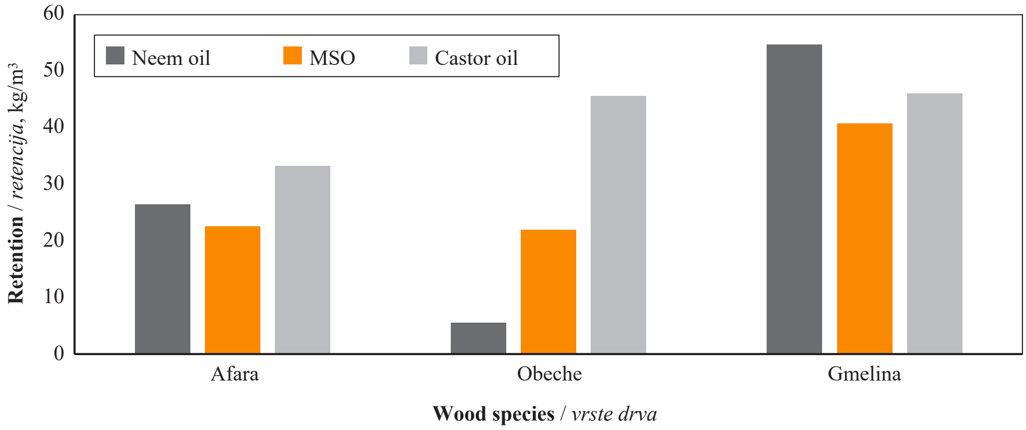

Figure 5 Retention of varying treatments of the selected wood species
Slika 5. Retencija različitih zaštitnih uljnih sredstava na odabranim vrstama drva

Table 4 Duncan's multiple range tests for retention
Tablica 4. Duncanovi testovi višestrukog raspona za retenciju

Species *Vrsta drva*	**Retention, kg/m³** *Retencija,* kg/m³	**Treatment** *Zaštitno sredstvo*	**Retention, kg/m³** *Retencija,* kg/m³
Obeche / *abahi*	24.37 ± 19.22[b]	MSO	28.44 ± 15.18[b]
Afara / *limba*	27.41 ± 12.14[b]	Neem oil	28.87 ± 24.05[b]
Gmelina / *bijeli tik*	47.19 ± 16.08[a]	Castor oil	41.66 ± 13.21[a]

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

differences in retention among both the wood species and treatment types. Among the species, Gmelina recorded the highest mean retention value (47.19 ± 16.08) % and was assigned to group *a*, indicating that it retained significantly more preservative than the other species. Afara (27.41 ± 12.14) % and Obeche (24.37 ± 19.22) % were both placed in group *b*, showing no significant difference between them, but significantly lower retention compared to Gmelina. This trend suggests that the anatomical characteristics of Gmelina enhance its capacity to retain preservatives more effectively. Similarly, significant differences were observed among the treatment types. Castor oil (41.66 ± 13.21) % formed group *a*, demonstrating the highest and significantly greater retention compared to MSO (28.44 ± 15.18) % and neem oil (28.87 ± 24.05) %, both grouped under *b*. The similarity between MSO and neem oil indicates that these two treatments were absorbed and retained at comparable levels, but far less effectively than castor oil. However, Gmelina exhibited superior preservative retention among the three selected wood species, while castor oil proved to be the most efficient treatment in terms of retention capacity.

3.2.3 Volumetric swelling
3.2.3. Volumno bubrenje

Table 5 presents the descriptive statistics of the volumetric swelling of the three selected wood species

Table 5 Descriptive statistics of volumetric swelling of the selected wood species
Tablica 5. Deskriptivna statistika volumnog bubrenja odabranih vrsta drva

Treatment *Zaštitno sredstvo*	**Time** *Vrijeme*	**Afara** – *Limba* %	**Obeche** – *Abahi* %	**Gmelina** – *Bijeli tik* %
Neem oil / *ulje nima*	24 hours	7.76 ± 1.98	5.60 ± 1.96	7.53 ± 3.97
	48 hours	13.72 ± 4.36	12.05 ± 1.15	10.20 ± 3.52
	72 hours	16.05 ± 3.94	14.26 ± 1.81	14.40 ± 3.60
MSO / *ulje sjemenki moringe*	24 hours	7.48 ± 1.62	8.28 ± 2.97	7.37 ± 1.85
	48 hours	10.86 ± 1.50	12.18 ± 1.70	10.58 ± 1.87
	72 hours	14.71 ± 2.53	15.20 ± 2.54	12.53 ± 2.12
Castor oil *ricinusovo ulje*	24 hours	7.10 ± 2.91	11.13 ± 1.20	8.52 ± 6.84
	48 hours	8.72 ± 1.92	12.27 ± 1.02	11.31 ± 5.85
	72 hours	10.26 ± 3.23	15.71 ± 1.95	13.15 ± 5.89
Control *kontrolni uzorak*	24 hours	4.86 ± 3.07	7.67 ± 4.21	5.16 ± 1.50
	48 hours	8.77 ± 2.62	9.99 ± 3.07	6.51 ± 1.99
	72 hours	10.84 ± 3.10	11.35 ± 3.68	9.28 ± 1.74

Values are mean ± standard deviation. / *Vrijednosti su srednja vrijednost ± standardna devijacija.*

Table 6 Duncan's multiple range tests for volumetric swelling
Tablica 6. Duncanovi testovi višestrukog raspona za volumno bubrenje

Species *Vrsta drva*	**Volumetric swelling, %** *Volumno bubrenje, %*	**Treatment** *Zaštitno sredstvo*	**Volumetric swelling, %** *Volumno bubrenje, %*	**Time** *Vrijeme*	**Volumetric swelling, %** *Volumno bubrenje, %*
Gmelina *bijeli tik*	9.71 ± 3.66[b]	Control	8.27 ± 2.75[b]	24 hours	7.37 ± 2.80[c]
Afara *limba*	10.09 ± 2.90[b]	Castor oil	10.91 ± 3.23[a]	48 hours	10.60 ± 2.76[b]
Obeche *abahi*	11.31 ± 2.46[a]	MSO	11.02 ± 2.11[a]	72 hours	13.15 ± 3.56[a]
		Neem oil	11.28 ± 2.92[a]		

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

(Afara, Obeche, and Gmelina) subjected to various oil treatments at different immersion durations. Table 4 shows that, on average, Afara, Obeche, and Gmelina recorded volumetric swelling values of (10.09 ± 2.90) %, (11.31 ± 2.46) %, and (9.71 ± 3.66) %, respectively. Table 6 showes that, based on the varying oil treatments, for Afara, samples treated with Neem oil (12.51 ± 3.41) % had the highest swelling, followed by Moringa seed oil (11.02 ± 2.11) %, Castor oil (8.60 ± 2.69) %, and the control (8.61 ± 2.62) %. Similarly, for Obeche, samples treated with Castor oil (13.04 ± 1.39) % showed the highest swelling, followed by Moringa seed oil (11.89 ± 2.04) %, Neem seed oil (10.64 ± 1.64) %, and the control (9.67 ± 3.00) %. For Gmelina, samples treated with Castor oil (11.00 ± 5.54) % recorded the highest swelling, followed by Neem seed oil (10.71 ± 3.70) %, Moringa seed oil (10.16 ± 1.95) %, and the control (6.99 ± 1.74) %. The results indicate that the oil treatments did not bring about a statistically significant improvement in the dimensional stability of the wood species. Nevertheless, the swelling values were closely related across treatments, suggesting that oil impregnation maintained a comparable performance to untreated samples. This observation showed that after 72 hours of water soaking, the volumetric swelling did not differ significantly between the treated and untreated specimens, indicating that the treatments contributed to modest stabilization without detrimental effects on wood structure.

3.2.4 Weight loss due to leaching after soaking in water
3.2.4. Gubitak mase zbog ispiranja tijekom namakanja u vodi

The weight loss due to leaching of the three selected wood treated with varying oil treatments, presented in Figure 6, showed that Afara, Obeche, and Gmelina had (10.43 ± 3.68) %, (15.61 ± 5.22) %, and (7.07 ± 2.14) %, respectively. Based on treatment, for Afara, the untreated samples recorded the highest value of (11.51 ± 5.94) %, followed by Moringa seed oil (11.38 ± 4.50) %, Neem seed oil (10.05 ± 0.42) %, and castor oil (8.79 ± 1.57) %. Likewise, for Obeche, the samples treated with Neem oil recorded the highest value of (19.84 ± 1.49) %, followed by castor oil (16.55 ± 1.49) %, followed by moringa seed oil with (15.66 ± 5.49) % and the control had the lowest value of (10.37 ± 6.09) %, while, for Gmelina the untreated samples recorded the highest value of (9.43 ± 1.97) %, followed by moringa seed oil (7.19 ± 1.91) %, followed by castor oil with (5.88 ± 1.28) % and the wood treated with neem. There is no significant difference in the varying treatments, but the three wood samples are significantly different in terms of weight loss, as samples obtained from Gmelina per-

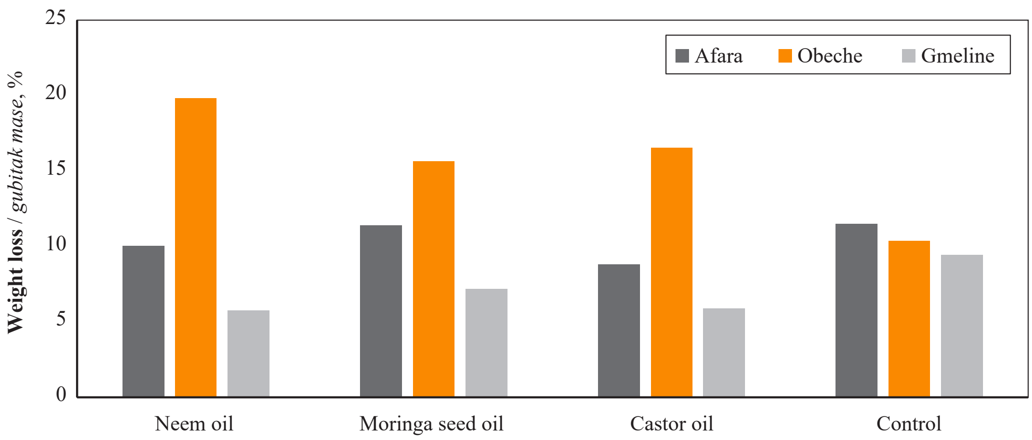

Figure 6 Descriptive statistics of weight loss due to leaching of the selected wood species
Slika 6. Deskriptivna statistika gubitka mase odabranih vrsta drva zbog ispiranja

Table 7 Duncan's multiple range tests for weight loss
Tablica 7. Duncanovi testovi višestrukog raspona za gubitak mase

Species *Vrsta drva*	**Weight loss, %** *Gubitak mase, %*	**Treatment** *Zaštitno sredstvo*	**Weight loss, %** *Gubitak mase, %*
Gmelina / *bijeli tik*	7.07 ± 2.14[a]	Castor oil	10.41 ± 4.85[a]
Afara / *limba*	10.44 ± 3.68[b]	Control	10.44 ± 4.75[a]
Obeche / *abahi*	15.61 ± 5.22[c]	MSO	11.41 ± 5.32[a]
		Neem oil	11.88 ± 6.19[a]

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

formed best, which was significantly different from samples obtained from Afara and Obeche.

Duncan's Multiple Range Test (Table 7) revealed significant differences in weight loss among the wood species but not among the treatment types. Among the species, *Gmelina* recorded the lowest weight loss (7.07 ± 2.14) % and was placed in group *a*, indicating significantly greater resistance to deterioration. Afara (10.44 ± 3.68) % was assigned to group *b*, showing moderate weight loss, while Obeche (15.61 ± 5.22) % exhibited the highest weight loss and was assigned to group *c*, indicating significantly lower durability compared to both Gmelina and Afara. This pattern suggests that Gmelina possesses inherently superior natural resistance to degradation, while *Obeche* is the most susceptible to weight loss. In contrast, the treatment types showed no significant differences in weight loss. Castor oil (10.41 ± 4.85) %, the control (10.44 ± 4.75) %, MSO (11.41 ±

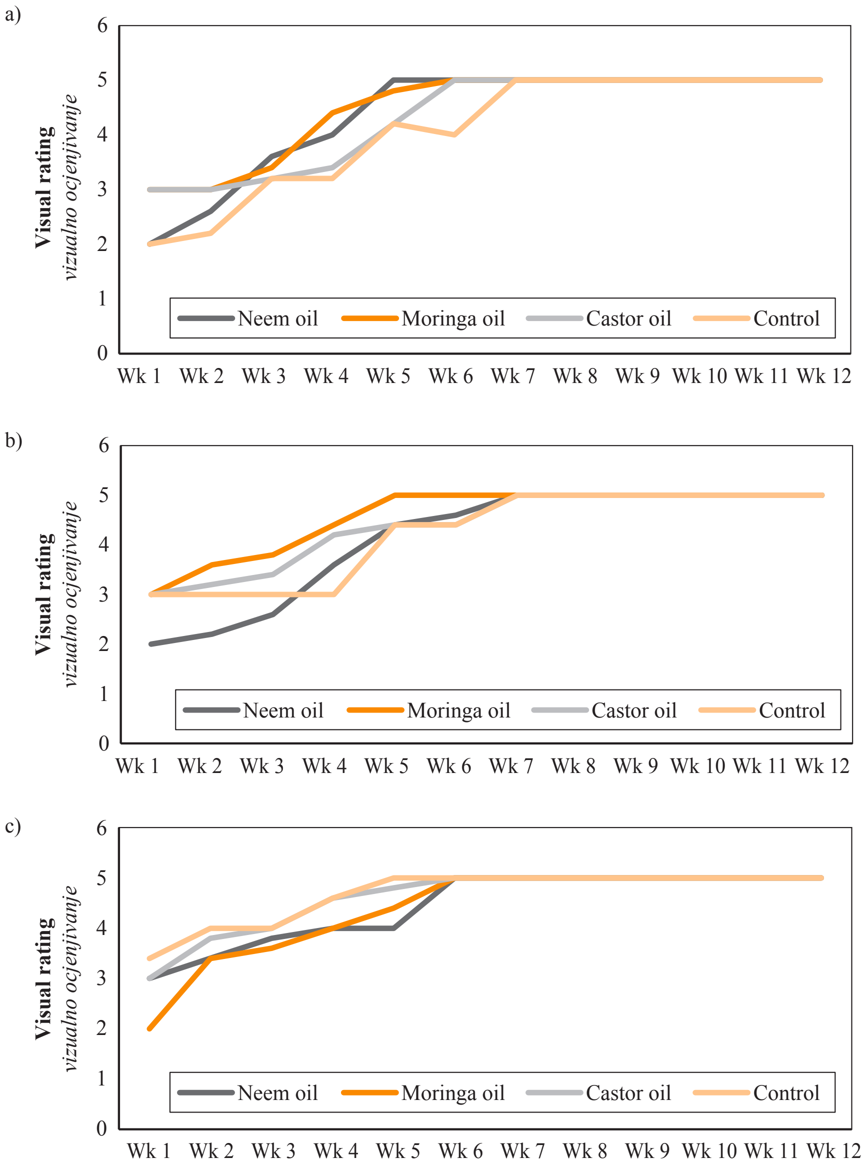

Figure 7 Resistance of treated wood against fungi infestation; a) Afara, b) Gmelina, c) Obeche
Slika 7. Otpornost tretiranog drva na zarazu gljivama: a) drvo limba, b) drvo bijelog tika, c) drvo abahija

5.32) %, and neem oil (11.88 ± 6.19) % all belonged to the same statistical group, indicating that none of the treatments provided a significantly different level of protection under the conditions of this study. This suggests that treatment type had little influence on weight loss compared to inherent species characteristics.

3.3 Resistance of wood treated against fungi infestation
3.3. Otpornost tretiranog drva na zarazu gljivama

3.3.1 Fungi mold growth
3.3.1. Rast plijesni

Figure 7a shows the resistance of Afara wood treated with varying oil treatments against fungi infestation. It showes that the untreated samples of Afara and samples treated with Neem oil recorded moderate infestation after exposure to fungi from week 1 to week 3 and complete infestation at week 8 and week 5, respectively, owning that the untreated Afara wood tended to sustain more resistance against fungi, while Afara wood treated with moringa oil and castor oil showed heavy infestation from week 1 of exposure and complete infestation from week 5 and 6, respectively. Also, Figure 7b shows that the Gmelina wood treated with neem seed oil recorded the best resistance against fungi infestation after showing slight infestation from week 1 to week 4 of exposure to fungi infestation. In contrast, untreated wood samples and those treated with moringa oil and castor oil showed moderate infestation from week 1 of exposure and were completely infested from week 5 of exposure. Likewise, Figure 7c shows that the Obeche wood treated with moringa oil recorded the best resistance against fungi infestation after showing slight infestation from week 1 to week 2 of exposure to fungi infestation. In contrast, wood samples treated with neem seed oil and castor oil showed moderate infestation from week 1 of exposure, and were completely infested from week 6 of exposure, while the untreated Obeche, which showed the least performance, was heavily infested from week 1 and showed complete infestation at week 5 of exposure to fungi.

3.3.2 Weight loss due to fungi infestation
3.3.2. Gubitak mase zbog zaraženosti gljivama

Weight loss of oil-treated wood species due to fungal infestation (Figure 8) varied across species and treatments. Among the wood species, Gmelina exhibited the lowest overall weight loss (4.29 ± 2.46) %, followed by Afara (7.56 ± 3.84) % and Obeche (9.02 ± 6.80) %, indicating differences in inherent resistance to biodeterioration. Within species, weight loss also varied depending on the treatment. For Afara, neem oil-treated samples showed the highest weight loss (8.97 ± 4.69) %, followed by untreated samples (7.51 ± 1.60) %, moringa seed oil (MSO) (7.43 ± 4.58) %, and castor oil (6.31 ± 4.48) %. In Obeche, untreated samples exhibited the greatest weight loss (15.99 ± 8.85) %, followed by neem oil (8.79 ± 6.85) %, castor oil (6.17 ± 1.83) %, and MSO (5.13 ± 1.08) %. For Gmelina, the highest weight loss was recorded in neem oil-treated samples (6.80 ± 3.28) %, followed by the control (4.14 ± 1.87) %, MSO (3.55 ± 1.26) %, and castor oil (2.67 ± 1.06) %. Overall, preservative-treated wood experienced less heavy infestation, while Afara wood showed moderate damage even in oil-treated samples from the first week of exposure.

Duncan's Multiple Range Test (Table 8) confirmed these observations, revealing significant differences in weight loss among wood species. Gmelina (4.29 ± 2.46) % was placed in group *a*, demonstrating significantly greater resistance compared to Afara (7.56 ± 3.84) % and Obeche (9.02 ± 6.80) %, both in group *b*, which did not differ significantly from each other. This highlights the inherently superior durability of Gmelina. Significant differences were also observed among the treatments. Castor oil (5.05 ± 3.17) % and MSO (5.37 ± 3.08) % formed group *a*, representing the

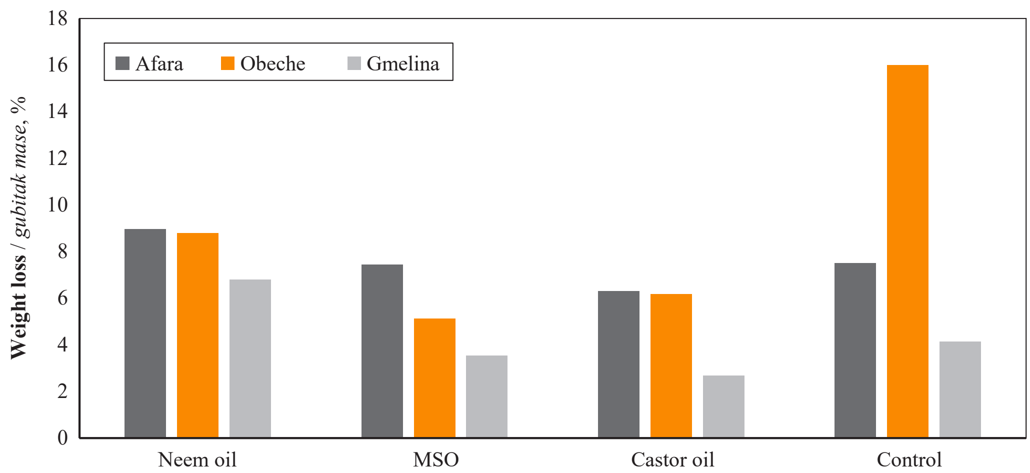

Figure 8 Percentage weight loss of wood species to fungal infestation
Slika 8. Postotni gubitak mase drva zbog zaraženosti gljivama

Table 8 Duncan's multiple range tests for weight loss
Tablica 8. Duncanovi testovi višestrukog raspona za gubitak mase

Species *Vrsta drva*	**Weight loss, %** *Gubitak mase, %*	**Treatment** *Zaštitno sredstvo*	**Weight loss, %** *Gubitak mase, %*
Gmelina / *bijeli tik*	4.29 ± 2.46[a]	Castor oil	5.05 ± 3.17[a]
		MSO	5.37 ± 3.08[a]
Afara / *limba*	7.56 ± 3.84[b]	Neem oil	8.18 ± 4.88[b]
Obeche / *abahi*	9.02 ± 6.80[b]	Control	9.21 ± 7.13[b]

Note: Alphabets with the same letter indicate no significant difference; alphabets with different letters indicate a significant difference.
Napomena: Vrijednosti s istim slovima nisu značajno različite, dok se vrijednosti s različitim slovima značajno razlikuju.

most effective treatments for minimizing weight loss, while neem oil (8.18 ± 4.88) % and the untreated control (9.21 ± 7.13) % were grouped in *b*, indicating lower protective efficacy. Although neem oil reduced weight loss slightly relative to the control, it was not significantly more effective under the conditions tested. These findings are consistent with previous studies demonstrating that untreated wood is more susceptible to fungal attack (Schmidt, 2006; Owoyemi *et al*., 2020; Salami *et al*., 2020) and that plant oil treatments can enhance the biological resistance of wood (Akhtar and Ahmad, 2011). The results also align with Carlquist (2012) report that variation in preservative efficacy and wood resistance depends on species and inherent anatomical characteristics. Gmelina exhibited the highest resistance to fungal degradation, while castor oil and MSO proved to be the most effective preservatives across the tested wood species.

As previously noted, neem oil contains bioactive compounds such as azadirachtin, nimbin, and salannin, which are known to disrupt fungal cell membranes and interfere with enzyme activity (Zhang *et al.,* 2016; Brunner *et al.,* 2018). Moringa seed oil similarly contains isothiocyanates, flavonoids, phenolics, and chitin-binding proteins that may inhibit fungal growth through membrane destabilization, oxidative stress induction, and interference with vital metabolic pathways (Deshmukh *et al*., 2018; Batista *et al*., 2014). Castor oil, rich in ricinoleic acid, has been documented to impair fungal cell membrane structure and function, leading to reduced nutrient uptake and suppressed growth (Kusch and Panstruga, 2017; Kwon *et al*., 2023). These mechanisms collectively provide a biological basis for the partial protection observed in treated wood samples.

The results obtained in this study demonstrate that neem, moringa, and castor oils enhance wood resistance primarily by delaying fungal colonization and reducing the rate of degradation, rather than by achieving complete protection. This is supported by two observations: (a) treated samples exhibited lower weight loss and slower onset of visible decay compared to untreated controls, and (b) most samples were eventually colonized under prolonged exposure. Thus, the oils behaved mainly as fungistatic agents, suppressing fungal activity without fully preventing growth.

The mechanistic properties reported in the literature also align with this pattern. For instance, neem limonoids and flavonoids have been shown to reduce mycelial growth and inhibit fungal enzymes, often resulting in slowed but not entirely halted fungal development (Wylie and Merrell, 2022). Similarly, moringa-derived proteins such as Mo-CBP3 can block spore germination and disrupt plasma-membrane organization, but their action becomes fully fungicidal only at higher concentrations than those typically achieved in wood impregnation (Batista *et al.,* 2014). Castor oil's ricinoleic acid disrupts fungal membranes but generally provides growth inhibition rather than total eradication at low application rates (Nitbani, 2022; Suurbaar *et al.,* 2017). These mechanistic insights explain why treated samples in this study exhibited slowed decay yet were still susceptible under extended exposure.

When compared with conventional preservatives such as copper-based systems or borates, the plant oils tested here do not provide the same level of long-term or systemic protection. Chemical preservatives form stable, leach-resistant deposits within the wood matrix, making them more effective at completely preventing colonization over long periods, particularly under high-moisture conditions (Rahman *et al*., 2019). By contrast, plant oils tend to remain within surface layers and lumina, where they act by creating temporary chemical and physical barriers to fungal establishment. However, their advantages, including low toxicity, biodegradability, and reduced environmental impact, support their value as eco-friendly alternatives for low-risk applications or as supplementary treatments within integrated protection systems.

The scatter plot in Figure 9 illustrates the relationship between the rate of fungal infestation and treatment absorption. The data points are widely dispersed with no clear upward or downward trend, indicating that there is little to no meaningful correlation between the two variables. Treatment absorption varies substantially across all levels of infestation, suggesting that factors other than infestation rate likely play a stronger role in determining absorption levels. The dotted horizontal line represents the average treatment absorption, which appears to be around seven units, and the distribution of points above and below this line fur-

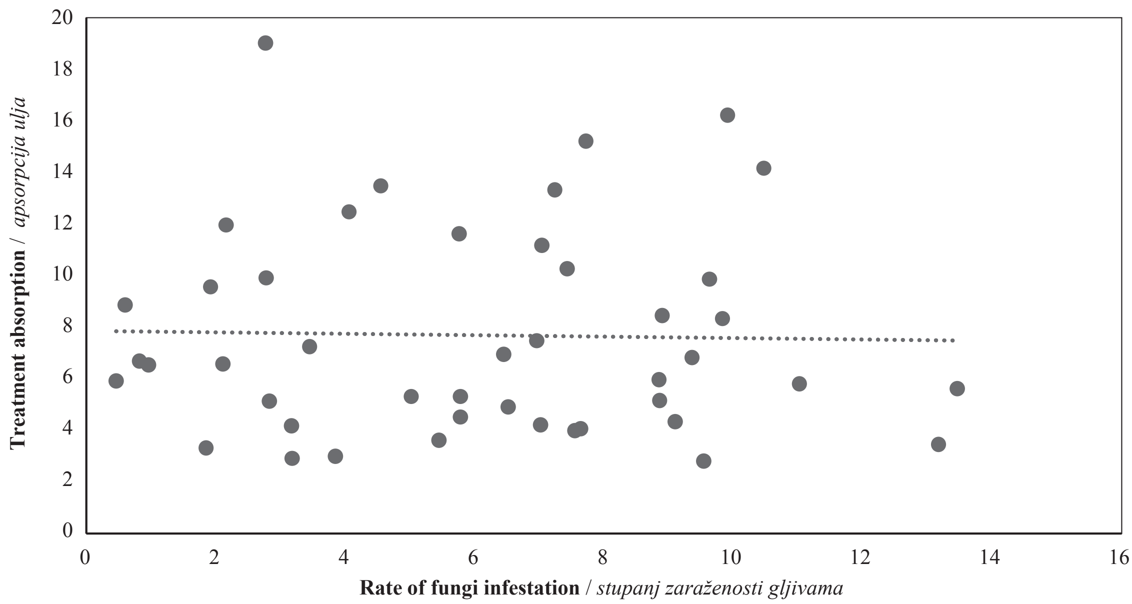

Figure 9 Correlation between oil absorption and resistance against fungal attack
Slika 9. Korelacija između apsorpcije ulja i otpornosti na gljivične napade

ther highlights the high variability in the data. Overall, the figure suggests that the rate of fungal infestation is not a reliable predictor of treatment absorption.

4 CONCLUSIONS
4. ZAKLJUČAK

The study confirms that untreated wood is highly vulnerable to infestation and deterioration, particularly evident in Afara, Gmelina, and Obeche wood species. Density influences absorption levels and resistance to infestation, with denser woods exhibiting lower absorption and greater resistance. Wood treated with castor oil shows reduced swelling and weight loss, highlighting its effectiveness in mitigating fungi infestation. The need for understanding the differences in wood properties is crucial for informed selection and application. Gmelina, especially with castor oil treatment, emerges as a promising option for applications requiring dimensional stability and protection against infestation.

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