Environmentally Friendly Chemical Modification of Four Wood Species by Glycerol–Maleic Anhydride Treatment: Physical, Mechanical, and Biological Assessment

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ABSTRACT

This research aimed to assess the improvements in dimensional stability and resistance to wood decay by treating the wood with a solution of glycerol–maleic anhydride mixture (GLY-MA) without a catalyst, at four concentrations (10%, 15%, 20%, and 25%), followed by heat treatment at 170 °C for 4 h. Four wood species were selected for property testing: two locally grown in Egypt, namely Tree of heaven (*Ailanthus altissima*, heartwood) and Cypress (*Cupressus sempervirens*, sapwood), and two imported species, European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*), both heartwood. The treatment conditions reported here proved the effectiveness in enhancing the stabilization against water absorption for all four wood species. All four concentrations improved dimensional stability, with the highest improvement observed with the 25% treatment for all wood species. Although the treatments had a slight effect on decreasing compressive strength and hardness, a clear significant difference was observed at a concentration of 25% compared to untreated samples. The hardness at a 25% concentration was 4434.7 N, 2440 N, 5220 N, and 1440 N for Tree of heaven, Cypress, Beech, and Spruce, respectively. Across all species studied, the use of the four concentrations demonstrated a shift in wood resistance against white rot and brown rot fungi from non-resistant to moderately resistant. Therefore, in terms of cost-effectiveness, it is recommended to use the low concentration, 10% to enhance decay resistance, as this concentration effectively achieves the desired outcome without the need for higher concentrations, in addition to being environmentally friendly.

Keywords: Hygroscopicity, White rot fungi, Hardness, Compression parallel to grain, Chemical modification.

INTRODUCTION

The development of sustainable materials has become increasingly important in light of environmental issues and the depletion of natural resources such as timber trees. Wood, owing to its renewable nature and wide range of applications, has drawn the attention of numerous researchers and wood producers interested in analyzing its characteristics to ascertain the best use for each wood species. However, certain woods are sold at high prices due to specific properties or limited availability, necessitating the search for alternatives for certain applications (Hassan, 2019). Despite its versatility, wood does have drawbacks such as low dimensional stability due to fluctuating moisture in the surrounding environment, susceptibility to fungal decay organisms and insect infestations, and vulnerability to weathering when exposed to outdoor conditions for extended periods (Walker, 2006).

Over the last two decades, one strategy has been adopted to find alternatives to common woods used for specific applications (Hassan and Tippner, 2019), particularly in outdoor environments or places prone to termite or fungal decay attacks (Barnett and Jeronimidis, 2009). Another strategy involves modifying the properties of wood through various techniques to imbue specific advantages for particular wood species, such as enhancing resistance to fungal attacks or termite infestations or increasing hygroscopicity. This is accomplished through thermal methods, thermo- mechanical methods, or chemical methods (Hill, 2007 and Mohareb and Badawy, 2017).

Among these, chemical methods have proven to be the most significant, with some commercially available solutions marketed worldwide as alternatives to traditional wood preservatives, such as furfurylation and acetylation (Sandberg *et al.,* 2021). This shift is attributed to the move away from traditional preservatives, some of which have clear negative effects on the environment and human health (Hill, 2007). Developing a wood preservation approach that is environmentally friendly and does not rely on biocides is a crucial issue. Previous studies have utilized carboxylic acids and their derived compounds or along with glycerol, polyglycerol, and glycidyl methacrylate, specifically focusing on beech, poplar, and teak woods (Li *et al.*, 2012; L'Hostis *et al.*, 2017; Martha *et al.*, 2021; Basri *et al.,* 2022 and Mubarok *et al.,* 2022). Generally, glycerol is an organic compound having several applications in the food and pharmaceutical industries. Moreover, it is the principal byproduct of the process of producing biodiesel, which is derived from animal fats and vegetable oils (Pirzadi and Meshkani, 2022). In an attempt to improve the properties of Beech wood, Mubarok *et al.* (2019) used glycerol or

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polyglycerol with malic acid anhydride, followed by heat treatment at three temperatures: 150, 200, and 220°C in the presence of an inert gas, nitrogen, for 20 hours. This treatment improved resistance against soft rot fungus and termites. Most of the studies involved chemical treatment with glycerol with carboxylic acids followed by heat treatment, typically in the presence of an inert gas such as nitrogen for extended durations. It is noteworthy that using ovens for heat treatment in the absence of oxygen may be costly, as most sawn wood plants, such as those in Egypt, utilize conventional kilns, which may limit the feasibility of this method on a commercial scale. Additionally, the literature does not thoroughly cover the effect of concentration solutions. It is noteworthy to mention that not all woods will behave the same manner when it chemically treated as they have different microstructures. Accordingly, this study aimed to explore the utilization of various concentrations of a glycerol and maleic anhydride mixture on four different wood species, two locally sourced wood species (Tree of heaven and Cypress, sapwood) and two imported species (European beech and Spruce), coupled with heat treatment in the presence of oxygen for a fairly short period (4 h). Subsequently, the study involved hygroscopicity examination of these wood types along with an analysis of selected mechanical properties such as hardness, compressive strength, and resistance to wood-decomposing fungi.

MATERIALS AND METHODS

Four wood species were used for this experiment two locally grown and two imported, they are Tree ofheaven (*Ailanthus altissima*, heartwood), Cypress (*Cupressus sempervirens,* sapwood), European beech (*Fagus sylvatica*, heartwood), and Norway spruce (*Picea abies*, heartwood). The Tree of heaven and Cypress woods were extracted from trees locally grown in Alexandria and Monufia governorate, respectively. The two imported boards were purchased from a local wood market. The four wood species were identified based on their gross and anatomical features. All wood samples for the treatment were prepared with a size of 20 x 20 x 60 mm^3 (T x R x L). The wooden samples were clear from any obvious defects.

Glycerol-maleic anhydride (GLY-MA) solution preparation

To prepare the glycerol-maleic anhydride (GLY-MA) impregnation solution (molar ratio of 1:2), 1 mol of glycerol and 2 mol of maleic anhydride were mixed. The mixture was then heated while stirring for 3 hours at 80°C, following the method described by Roussel *et al.* (2001). The produced solution of GLY-MA was dissolved in distilled water to obtain a desired concentration of 10%, 15%, 20%, or 25% w/w.

GLY-MA wood impregnation

The impregnation apparatus is shown in Figure (1). The process begun by subjecting the prepared wooden samples with the aqueous GLY-MA solution to a vacuum at 0.01 $N.mm^{-2}$ for 30 min in a laboratory reactor, followed by pressure sustained at 1 $N.mm^{-2}$ for 60 min for Tree of heaven and Beech wooden samples, and for 90 min for Cypress and Spruce.

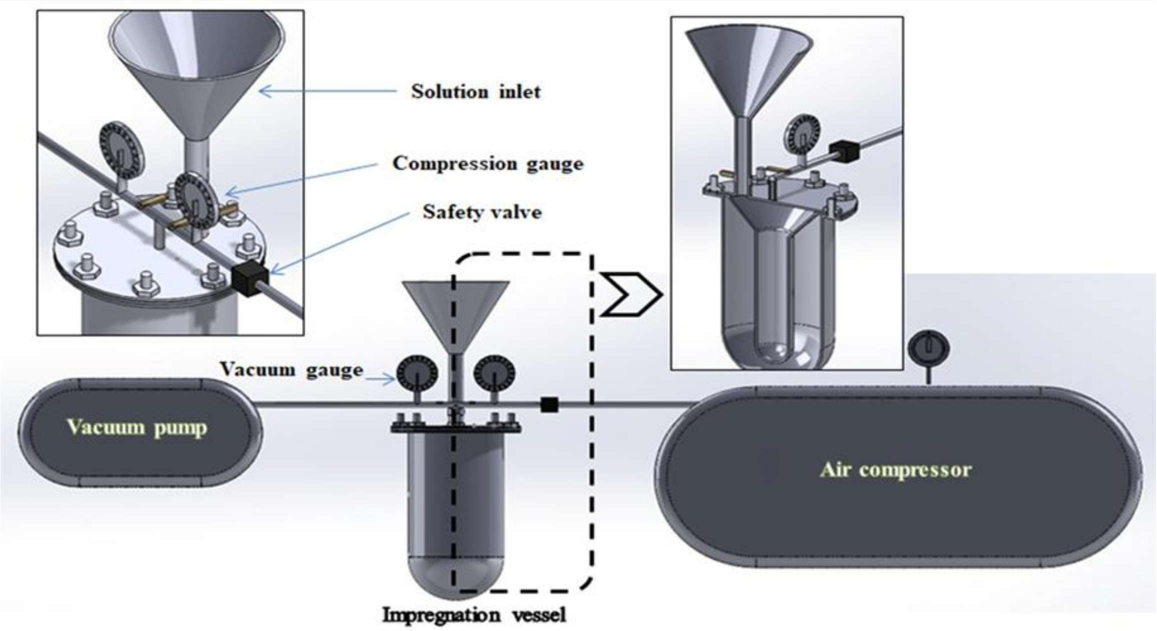

Fig. 1. Impregnation process apparatus utilizing GLY-MA solution

Post chemical treatment with heat

The impregnated samples were left at 25 °C and 65% RH for a sufficient time, allowing the excess water to evaporate. The oven temperature was maintained at 40 °C ±3 for 10 h. After the end of the impregnation process, the wood samples were subjected to heat treatment at 90°C for 4 h, followed by an increase to 170°C for an additional 4 h to complete the reaction of the GLY-MA with wood chemical constituents.

Physical properties assessment

Wood density ($\rho_{mod\ or\ un}$) was performed following ASTM D2395-17 (2017) based on gravimetric method and calculated according to Eq (1),

$$\rho_{mod\ or\ un} = \frac{M_o}{V_o} \qquad (1)$$

where, M_o and V_o are the oven-dried mass and volume, respectively for all wood samples (modified or control)

In this study, the following equations (2-4), derived from (Hill, 2007 and Sandberg *et al.*, 2021), were employed to assess various parameters related to the treatment of wood specimens with GLY-MA. Prior to and subsequent to every GLY-MA treatment, specimens were subjected to a 24-hour period inside the oven to calculate weight percent gain (WPG) by the differences in oven dry weight of samples before modification) W_{un}) and after modification (W_{mod}) according to Eq. (2),

$$WPG_{10,15,20,or25}(\%) = \frac{W_{mod} - W_{un}}{W_{un}} \times 100 \qquad (2)$$

The anti-swelling efficiency of the GLY-MA treated wood expressed in percentage calculated using Eq. (3),

$$ASE_{10,15,20,or\ 25}(\%) = \frac{S_{un} - S_{mod}}{S_{un}}\ x100 \qquad (3)$$

where ASE is the percentage of anti-swelling efficiency of GLY-MA modified wood samples, S_{un} and S_{mod} is volumetric swelling of unmodified and modified wood samples, respectively.,

Total volumetric shrinkage ($S_{V\ 10,15,20,or\ 25}$) for the modified woods was calculated according to Eq. (4),

$$S_{V\ 10,15,20,or\ 25}(\%) = \frac{S_s - S_o}{S_o}\ x100 \qquad (4)$$

where, S_s is the swollen volume and S_o is the oven-dried volume.

Mechanical behavior

The mechanical behavior of both the modified and unmodified wood samples was assessed through compression parallel to grain and side hardness tests (on the tangential surface) in accordance with British Standard (BS 373, 1957). These mechanical tests were conducted using an Amsler Universal Testing Machine. Prior to the mechanical tests, all wood samples (both control and GLY-MA treated) were conditioned at 25°C and 65% relative humidity in a controlled climatic chamber.

Resistance of wood to fungal attack test

The resistance to decay from the brown rot fungus *Tyromyces palustris*, denoted as (TYP), and the white-rot fungus *Irpex lacteus*, denoted as (IRL), was conducted through a mini-block fungal exposure test (Mohareb *et al.*, 2012). The dimensions of the samples were 30 × 10 × 5 mm³ (length × width × thickness), with eight replications for each treatment, and their oven-dried weights (M_i) were recorded. Petri dishes filled with sterile malt-agar medium were inoculated with mycelium from the freshly grown TYP and IRL fungi. Each dish contained two treated specimens and one untreated sample, exposed to fungal decay for 12 weeks. The oven-dried masses (M_f) after the test were then recorded. The moisture content after the incubation was also calculated. The durability class was determined according to the EN 350-1 (1994) standard.

The decay resistance was measured by weight loss according to Eq. (5),

$$M_{TYP\ or\ IRL}(\%) = \frac{M_i - M_f}{M_i}\ x100 \qquad (5)$$

where $M_{TYP\ or\ IRL}$ is the percentage of mass loss ratio caused by the respective fungus types (*Tyromyces palustris* and *Irpex lacteus*), M_i and M_f are the oven-dried initial mass before and after infection, respectively.

Statistical analysis

One-way analysis of variance was used to investigate the effect of the four concentrations (10, 15, 20, and 25%) of GLY-MA on the physical, mechanical, biological properties. The significance level was 0.05. The ANOVA is followed by Fisher's LSD test to detect the differences among the means. Given that the four studied species have different structures (Panshin and De Zeeuw, 1970), it is preferable to analyze how the GLY-MA solution affects each wood species individually. Therefore, conducting separate analyses for each species would be appropriate.

RESULTS AND DISCUSSION

Figure (2) shows the appearance of wooden samples after treatment for each wood species. From left to right, the sequence includes the control followed by other GLY-MA treatments. It is evident that the treatments influenced the colors, with variations observed based on the type of wood used.

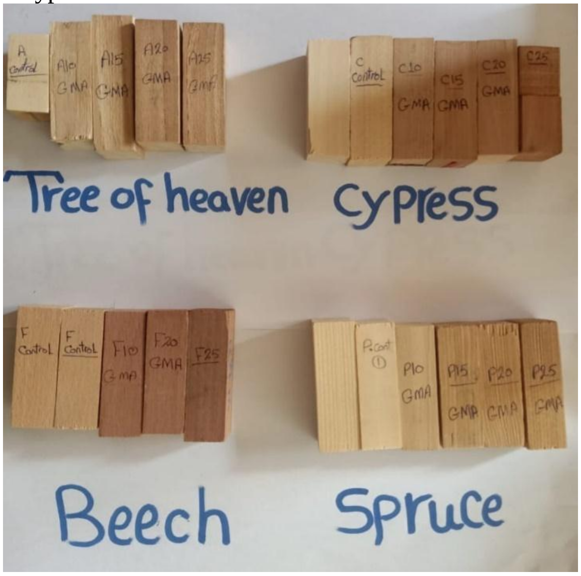

Fig. 2. Appearance of the samples after GLY-MA treatments

The density of tree of heaven, Cypress, Beech, and Spruce woods was investigated with various treatments. Statistical analyses, particularly notable with the 25% treatment concentration, revealed significant variations between the untreated samples and those treated with various concentrations (Figure 3).

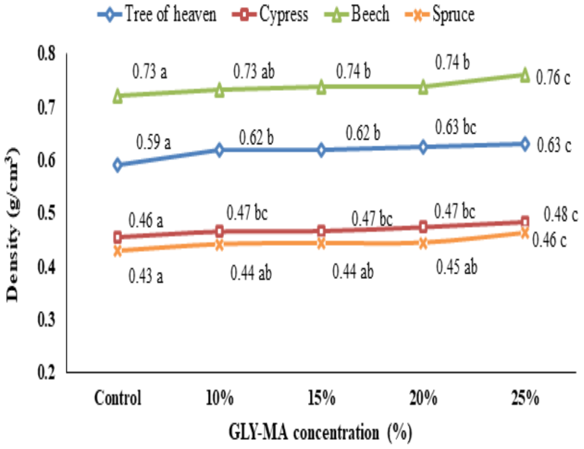

Fig. 3. Densities of all studied wood species untreated and treated with GLY-MA solution. For each wood type, means that do not share a letter are significantly different (α =0.05)

Beech wood treated with GLY-MA exhibited an increase in density, where the highest density was observed at a concentration of 25%. The mean density value for the control was 0.73 g/cm³, while for the four concentrations, it ranged between 0.73 and 0.76 g/cm³. For Tree of heaven wood, the mean density value for the control was 0.59 g/cm³, whereas for the four concentrations, it ranged from 0.62 to 0.63 g/cm³. Fisher's LSD tests indicated neither significant differences between the 25% and 20% concentrations, nor between 10%, 15%, and 20%. Cypress wood recorded a mean density of 0.46 g/cm³, with the four concentrations ranging between 0.47 and 0.48 g/cm³. Similarly, the average density value of untreated Spruce wood was 0.43 g/cm³, while with the four concentrations it ranged from 0.44 to 0.46 g/cm³. Howevere, the effect of the 10%, 15%, and 20% GLY-MA concentrations on density did not exhibit significant variations among them. The results indicated that the average density values for the untreated and treated samples can be ranked as follows: Beech wood had the highest density, followed by Tree of heaven wood, then Cypress wood, and finally Spruce. Schorr *et al.* (2018) reported significant density increase in lodgepole pine wood treated with a mixture of glycerol and citric acid. Figure (4) shows the weight percentage gain (WPG) of the four different wood species. Fisher's LSD test revealed significant differences at 0.05 significance level between the four treatments (concentrations) for each of the four investigated species. The results of this study revealed the WPG is increased with the increase in the solution concentration. However, it was observed that all wood species treated with a 25% GLY-MA solution exhibited the highest WPG values compared to the other treated wood samples, while those treated with 10% showed the lowest WPG.

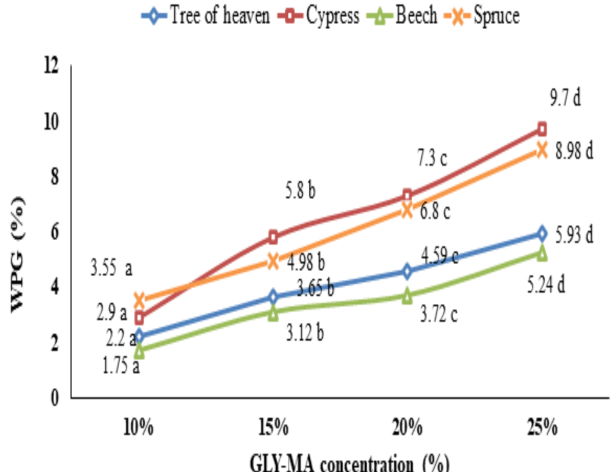

Fig. 4. WPG of all studied wood species treated with the GLY-MA solution. For each wood type, means that do not share a letter are significantly different (α =0.05)

In a study by L'Hostis *et al.* (2017) on Beech wood treated with citric acid and glycerol at various temperatures, they found that the WPG ranged from 25.5 to 39.7 %, yet when the same wood was treated with tartaric acid and glycerol, the WPG ranged between 17.6-34%. Despot *et al.* (2008) found that when treating Beech wood with citric acid and a catalyst followed by heat treatment for 10 h, the average WPG obtained was 6.11 %.

Generally, the ability of wood to tolerate changes in size and shape in various environmental circumstances is known as dimensional stability. The antiswelling or shrinkage efficiency and swelling behavior are physical parameters that are used to judge the efficiency of the modification process used for wood (Sandberg *et al.*, 2021). The antiswelling efficiency (ASE) of the four different wood species is illustrated in Figure (5).

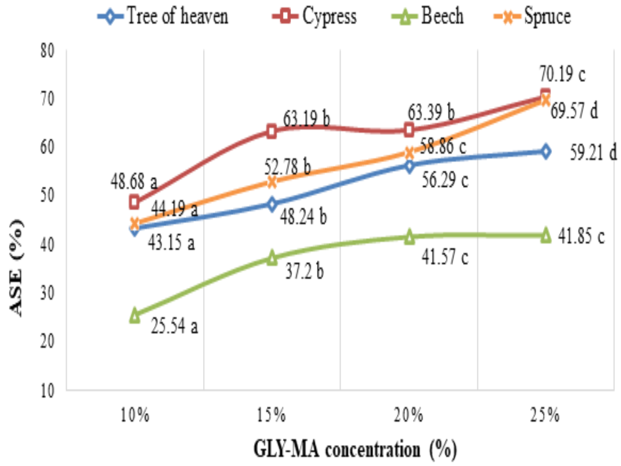

Fig. 5. ASE of all studied wood species treated with GLY-MA solution. For each wood type, means that do not share a letter are significantly different (α =0.05)

For Cypress wood, the ASE values were ranged from 48.68% (conc.10%) to 70.19% (conc.25%). For Spruce wood, the values ranged between 44.19% (conc.10%) and 69.57% (conc. 25%). For Tree of heaven wood, the values ranged from 43.15% to 59.21%. For Beech wood, the values ranged from 25.52% (conc.10%) to 41.85% (conc.25%). Based on the presented results, it is evident that the effect of GLY-MA concentration on the ASE is varies depending on the wood species. Specifically, there was a significant increase in the ASE with increasing GLY-MA concentration for Spruce and Tree of heaven. However, for Beech, there were non-significant differences between the 20% and 25% treatment concentrations. Similarly, in the case of Cypress, there was non-significant difference between the impact of 15% and 20% concentration. These findings are crucial to be considered, particularly due to the potential cost implications associated with increasing the concentration unnecessarily for these species. As it depicted in Figure (5), the ASE values ranked in descend order were for Cypress, Spruce, Tree of heaven, and then Beech. The volumetric swelling, a critical parameter for assessing wood's dimensional stability (Walker, 2006). As it illustrated in Figure (6), there is a notable decrease in volumetric swelling with increasing solution concentration. Cypress wood exhibits the lowest swelling values, while Beech demonstrates the highest. These results collectively indicate an enhancement in decrease volumetric swelling for all wood species following the treatment.

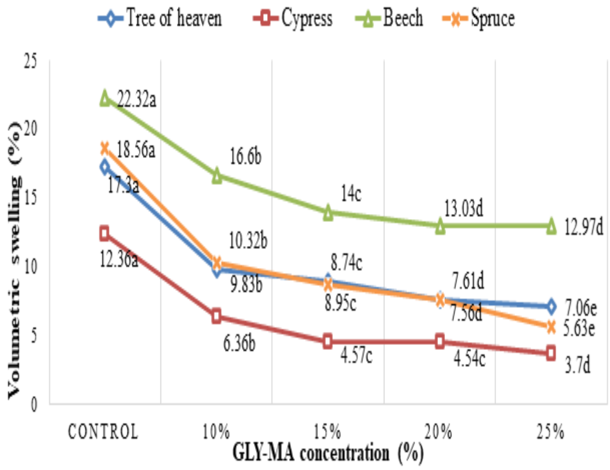

Fig. 6. Volumetric swelling plotted against GLY-MA concentrations. For each wood type, means that do not share a letter are significantly different (α =0.05)

Based on the results of the ASE and volumetic swelling, this observation aligns with previous studies, such as that of Soulounganga *et al.* (2004), who found that a mixture of polyglycerol and glycidyl methacrylate increased dimensional stability compared to untreated wood. Similarly, Schorr *et al.* (2018) reported significant improvement in lodegepole pine wood using glycerol and citric acid mixture treatment, reaching an ASE of approximately 49%. Chabert *et al.* (2022) observed an enhanced dimensional stability in Beech wood which treated with glycerol and maleic acid, achieving an ASE of 63%. Additionally, Mubarok *et al.* (2019) investigated the effect of glycerol and polyglycerol combined with glycidyl methacrylate or maleic anhydride on Beech wood properties. Their treatments, particularly at a 10% concentration, led to a remarkable enhancement in dimensional stability, reaching approximately 80%. Martha *et al.* (2021) explored impregnating short rotation teak sapwood with a GLY-MA solution (10%), followed by thermal modification at different temperatures. Their findings indicated a significant increase in ASE, suggesting improved dimensional stability. Moreover, He *et al.* (2020) demonstrated a reduction in water absorption through wood modification using maleic anhydride, highlighting a potential avenue for improving dimensional stability.

Compressive strength values for Tree of heaven, Cypress, Beech, and Spruce were recorded across various treatment groups and detailed in Figure (7).

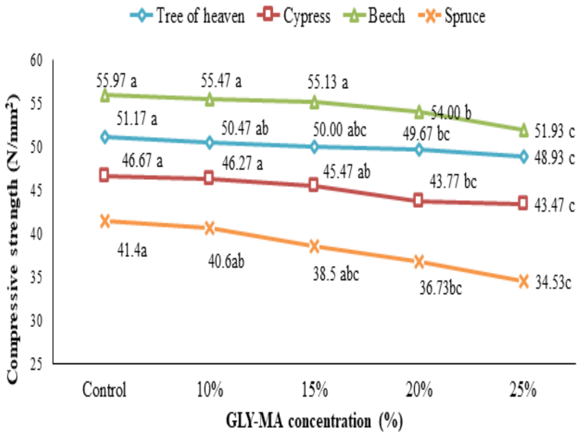

Fig.7. Compressive strength plotted against GLY-MA concentrations. For each wood type, means that do not share a letter are significantly different (α =0.05)

A decrease in compressive strength was observed with an increase in the concentration of the impregnating solution. Significantly, the highest concentration (25%) demonstrated a notable decrease compared to the untreated samples. The results indicate that the compressive strength values were highest in Beech wood, followed by Tree of heaven, Cypress, and finally Spruce. Additionally, Spruce wood exhibited a more significant decrease of 25% compared to the other three types of wood. Figure (8) shows the mean hardness values in Newtons for the control and the four treatments. When compared to other treated wood samples, it is evident that all four species' untreated wood samples had the highest hardness values, whilst wood treated with a 25% GLY-MA solution had the lowest hardness values.

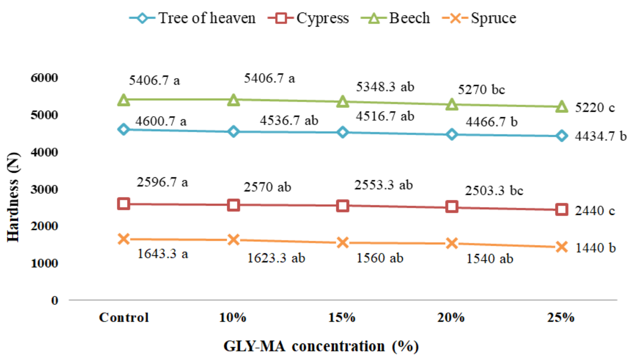

Fig. 8. Hardness plotted against GLY-MA concentrations. For each wood type, means that do not share a letter are significantly different (α =0.05)

Among the four wood species examined, Beech wood exhibited the highest hardness values. Tree of heaven, Cypress, and Spruce wood followed in second, third, and fourth level, respectively. On the contrary to the results of this study, Schorr *et al.* (2018) reported that the hardness values of lodgepole pine treated with a glycerol-citric acid mixture were higher than those of untreated wood.

The reduction in the values of hardness and compressive strength may be attributed to the acidic conditions during the modification process (Dong *et al.*, 2021). Generally, it is known that when wood is heat-treated, especially in the presence of oxygen, there is a loss in its mass, which adversely affects its mechanical properties (Hill, 2007 and Sandberg *et al.*, 2021). However, with the presence of chemical treatment, there is no severe reduction, and this occurs in all four species.

In a study performed by Feng *et al.* (2014) on poplar wood, it was found that the citric acid treatment alone can cause a significant reduction in the impact strength. Yan and Chen (2018) performed a study on poplar wood which underwent treatment involving glycerol and heat at different temperatures. The mechanical properties, including the loss tangent, were subsequently assessed. They noted that the samples influenced the relaxation processes and molecular mobility of both the main chain and side chains of wood polymers (cellulose, hemicellulose, and lignin).

In a study performed by Mubarok *et al.* (2019) on Beech wood treated with polyglycerol coupled with maleic anhydride or glycerol and maleic anhydride followed by heat treatment under inert condition at various temperature (150, 200, and 220°C), they found a reduction on the static bending properties (MOE and MOR) compared to untreated samples. Mubarok *et al.* (2022) utilized a combination of polyglycerol or glycerol with or without maleic anhydride for wood treatment. They employed various temperatures. Their results indicated that treated wood exhibited an increase in modulus of elasticity (MOE) and a decrease in modulus of rupture (MOR) compared to the control.

Durability against white- and brown rot fungi

Figures (9 and 10) show the mass loss percentages which attributed to decay caused by the specified fungi, with M_{IRL} representing *Irpex lacteus* and M_{TYP} representing *Tyromyces palustris*.

It is noteworthy that the control samples exhibited the highest mass loss values for both fungal species compared to the treated wood samples. Particularly, wood treated with GLY-MA at a concentration of 25% demonstrated the lowest mass loss compared with the rest species. Based on the mass losses and in accordance with EN 350-1 (1994) for durability classifications, the control samples for all four species are categorized under group 5 (non-durable).

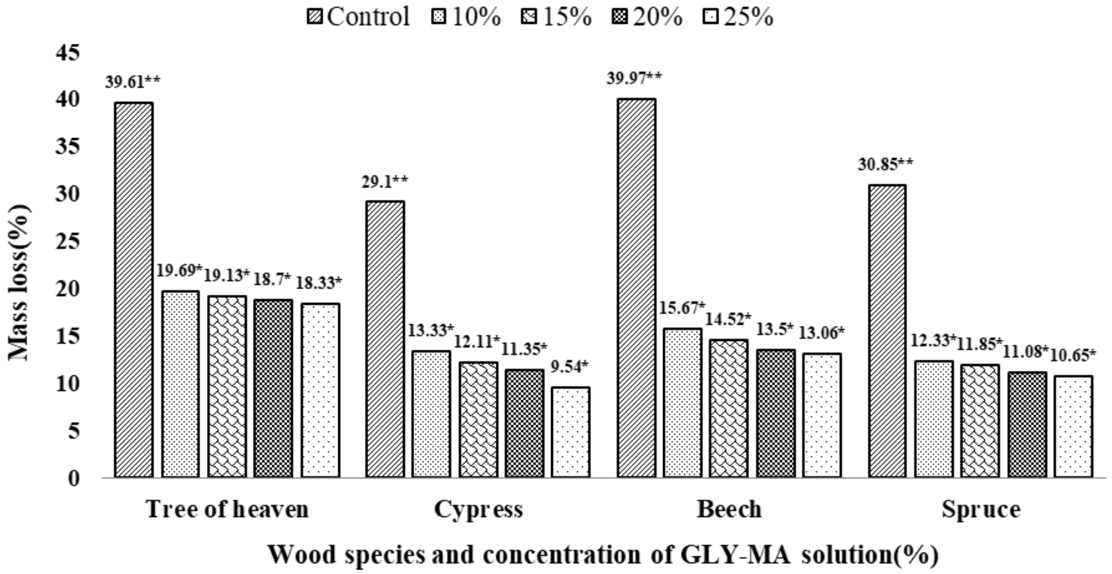

Fig. 9. Mass loss (%) due to decay by Irpex lacteus at different concentrations, with * representing durability class 3 and ** representing durability class 5

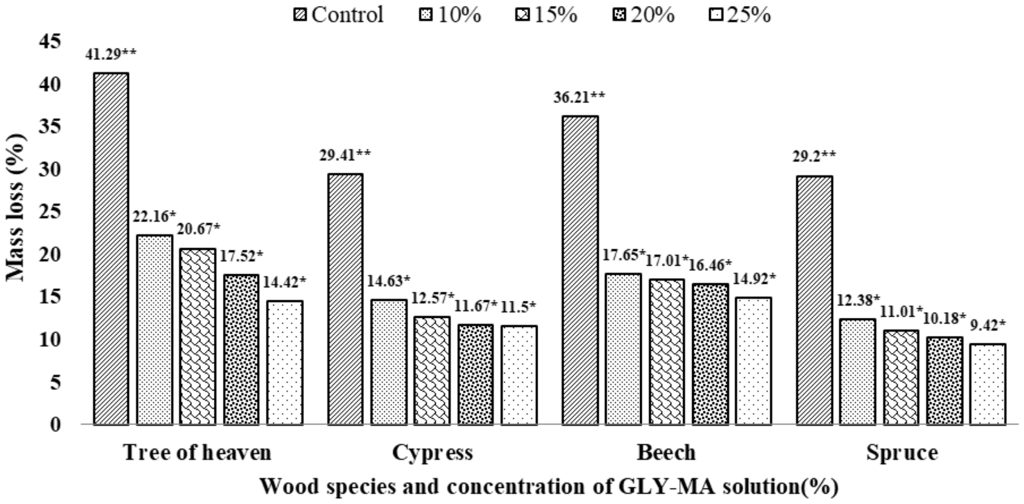

Fig. 10. Mass loss (%) due to decay by Tyromyces palustris at different concentrations, with * representing durability class 3 and ** representing durability class 5

Importantly, all wood samples of the four species treated with GLY-MA across different concentration levels were classified under durability class 3 (moderately durable). Martha *et al.* (2021) explored the impregnation of short rotation teak sapwood with a solution of GLY-MA (10%), followed by thermal modification at treating temperatures of 150 and 220 °C. Their findings revealed an improved fungal resistance against the three fungi: *Coriolus versicolor*, *Pycnoporus sanguineus*, and *Coniophora puteana*, with the treatment at 220°C exhibiting the lowest mass loss.

Mubarok *et al.* (2022) assessed the decay resistance of wood samples after leaching in a soil bed test against soft-rotting microfungi. They found that almost all modified woods were classified as durable to very durable.

Yan and Morrell (2015) noted that treatment of Douglas fir wood (completely from heartwood) with glycerol followed by heat treatment, reduced mold resistance and had no effect on degradation by decay fungi. Despot *et al.* (2008) observed that citric acid, when used as a cyclic compound with a catalyst to treat Beech wood, increased its resistance to the brown rot fungus *Poria placenta*. Soulounganga *et al.* (2004) utilized a mixture of polyglycerol and glycidyl methacrylate, finding that wood resistance increased against *Coriolus versicolor* as a white rot fungus and *Poria placenta* as a brown rot fungus. In a study by Mubarok *et al.* (2019) on Beech wood treated with polyglycerol coupled with maleic anhydride or glycerol and maleic anhydride, followed by heat treatment under inert conditions at various temperatures, they observed increased resistance against the fungus *Coriolus versicolor*.

The effectiveness of the treatment described in the current study on strengthening these wood species' resistances to weathering and termite attack needs to be tested in further research.

CONCLUSION

In this study, four wood types were treated with varying concentrations (10%, 15%, 20%, and 25%) of a glycerol and malic acid mixture, followed by oxygen-assisted heat treatment. Results indicated improved dimensional stability, evidenced by decreased volumetric swelling and ASE. The highest enhancements in WPG and ASE were observed at the 25% concentration. Mechanical properties (compressive strength and hardness) showed a decrease with increasing concentration, notably at 25%, compared to the control. The treatment also enhanced resistance against white and brown rot fungi, with all concentrations providing medium resistance (durability class 3 according to EN 350-1). Since all four concentrations have increased the durability class to the same level, it is recommended to use the lower concentration (10%) for cost-effectiveness.

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الملخص العربي

التعديل الكيميائي الصديق للبيئة لأربعة أنواع من الأخشاب عن طريق المعالجة بالجليسرول–انهيدريد حامض الماليك: التقييم الفيزيائي والميكانيكي والبيولوجي

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يهدف هذا البحث الي تقدير مدي التحسن في الثبات البعدي ومقاومة الخشب للتحلل بواسطة الفطريات لنوعين من الأخشاب النامية محلياً هما شجره السماء والسرو ونوعين من الأخشاب المستوردة هما الزان الأوروبي والاسبروس والتي تم معالجتهم بأربع تركيزات مختلفة (١٠%، ١٥%، ٢٠% و٢٥%) من مخلوط محلول الجليسرول وأنهيدريد حامض الماليك في غياب أي عامل محفز ثم معالجة الخشب حرارياً في وجود الاكسجين لمدة أربع ساعات على درجة حرارة ١٧٠ درجه مئوية. أشارت النتائج المتحصل عليها ان ظروف المعالجة المستخدمة اثبتت فعاليتها في تحسين ثبات الأبعاد ضد الماء لجميع الأنواع الخشبية المستخدمة. من الجدير بالذكر ان جميع التركيزات المستخدمة في تلك الدراسة قد أدت إلى تحسن واضح في ثبات الأبعاد تجاه الرطوبة، وقد وجُد ان أعلى معدل تحسن في جميع الأنواع الخشبية كان عند المعالجة بتركيز ٢٥ %. ومن ناحية أخرى كان للمعاملات تأثير طفيف في تقليل قوة الانضغاط والصلادة، إلا أنه هناك فرق معنوي واضح في الاخشاب المعالجة بتركيز ٢٥% مقارنة بالأخشاب غير المعالجة. وكانت قيم الصلادة عند تركيز ٢٥% هي ٤٤٣٤,٧ نيوتن، ٢٤٤٠ نيوتن، ٥٢٢٠ نيوتن، ١٤٤٠ نيوتن لكل من شجرة السماء، السرو، الزان والاسبروس على التوالي. وقد أوضحت نتائج الدراسة ان استخدام التركيزات المختلفة من مخلوط الجليسرول وانهيدريد حامض الماليك في جميع الأنواع التي تمت دراستها اظهرت تحولًا في مقاومة الخشب ضد فطريات العطب الأبيض والعطب البني من غير المقاومة إلى متوسطة المقاومة. ومن ثم توصى الدراسة باستخدام اقل تركيز (١٠%) لتعزيز مقاومة الاخشاب محل الدراسة تجاه الفطريات المحللة للأخشاب حيث إن هذا التركيز يحقق النتيجة المرجوة بشكل فعال دون الحاجة إلى استخدام تركيزات أعلى بالإضافة إلى كونه منخفض التكلفة وصديق للبيئة.