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Investigation of Impregnation Approach of Zinc Oxide Nano-Dispersions for Potential UV Stabilization in *Abies alba* and *Fagus sylvatica*

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Abstract: As biological material, wood is distinctly affected by to various environmental influences during use. Reductions in durability can come from ultraviolet (UV) radiation, insects, fungi, and microorganisms in both exterior and interior applications. Wood can be easily protected from living organisms via the control of moisture content; however, UV radiation is not so easily managed. Wood components subject to this degradation are damaged and decomposed at a molecular level leading to deterioration of surface quality, especially in visible application areas. A potential remedy to this is using the UV-stabilizing properties of zinc oxide nanoparticles. Zinc oxide nano-dispersions based on propylene glycol (PG) were introduced into the microscopic structure of fir (*Abies alba*) and beech (*Fagus sylvatica*) wood by whole-cell impregnation to overcome problems associated with surface coatings. In this work the material uptake of ZnO nano-dispersions in concentrations of 1%, 2%, and 3% *w/v* were investigated and their effect on the stability of the optical appearance to UV exposure in short-term weathering were evaluated. Untreated reference samples showed significant photo-yellowing. A 1% *w/v* ZnO dispersion significantly increased the UV stability of treated surfaces. It was found that the uptake of the nano-dispersions was independent of the proportion of ZnO, and that the impregnating agents penetrated fir wood (about 200%) stronger than beech wood (about 70%). Already, a 2% *w/v* ZnO nano-dispersion led to a saturation of ZnO in the cell structure of the treated wood, for fir as well as beech, and no further ZnO uptake was achieved with 3% *w/v* nano-dispersions. Scanning electron microscopy shows an agglomeration of ZnO-NP in the cellular pathways impacting penetration, reducing leachability at higher concentrations.

Keywords: zinc oxide; nanoparticles; impregnation; UV-stabilization; wood degradation

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1. Introduction

Increasing the durability of wood has long been the subject of research because wood as a biological material is always exposed to environmental degradation and its natural durability may not be sufficient for the intended service life. In light of sustainability, it is necessary to keep wood in use for as long as possible and to conserve natural resources. Environmental factors such as UV radiation, moisture, insects, fungi, and other microorganisms play a particularly important role in wood degradation [1]. The natural degradation mechanisms by living organisms can be easily reduced in a targeted manner by means of moisture content regulation [2]. However, the influence of UV radiation cannot be so easily avoided and is a consistent agent of deterioration, especially as wood is commonly used in visible areas exposed to sunlight.

At the molecular level, UV radiation has the effect of splitting lignin into smaller units due to its high energy [3]. The UV radiation produces radicals which leads to partial energetic imbalances within the lignin molecule and changes in its polymeric structure due to free radical reactions, liberation of phenolics, and condensation of lignin compounds [4,5]. Furthermore, this results in reactions among the degradation products [6].

The effects of UV radiation occur in different forms depending on the site of application of the wood. Outdoors, degradation of lignin associated with leaching from weathering leads to graying of the wood surface [7] as the cell wall polymers lignin and holocellulose are degraded by UV light and the degradation products are leached by rainwater. The damaged surface is then further prone to fungal colonization [8,9]. Indoors, UV radiation causes lightening and frequently yellowing of the surface [10]. This color change is associated with changes on wood extractives and the production of quinones [11,12]. The main difference to outdoor degradation is the lack of rainwater action and fungal colonization, which lead to modified compounds like carbonyl and carboxyl chromophore groups with different light absorbance and therefore a change in color [13,14]. In both cases, outdoors and indoors, these changes negatively affect the visual appearance in particular because it is less preferred in visible applications though the structural integrity is not significantly reduced.

The rise of wood constructions in recent years has led to an increase in the use of wood in visible applications. As a result, methods are needed to preserve the initial appearance of the natural surfaces for a long time. Research has been conducted to increase the durability of wood and stabilize it against UV radiation [15–17]. This has focused on use of surface treatments, which form a thin protective layer that can be easily damaged by abrasion as they only penetrate the surface cell layer [18] and maintenance is required during the service life to ensure the protective effect [19]. Impregnations could represent an improved option, as introduction of the protective agent deeper into the wood cells can maintain a longer-lasting protection over lifetime of the optical appearance of the material used.

The UV protective capabilities of organic metal oxides as UV absorbers such as TiO_2 or ZnO have been known for some time. For example, zinc oxide nanoparticles (ZnO-NP) are already used in sunscreens as UV blockers, but also to increase the UV stability of food [20–24]. As mentioned, there are other nanoparticles besides ZnO, such as CuO and TiO_2, which are suitable for use as UV protection, but ZnO, for example, shows higher dispersion stability than CuO [25]. Also, Titanium dioxide can be used as a very effect agent to prevent photoprotection in paints but in applications of wood it can lead to increased degradation of wood polymers due its UV-induced photoactivity. Zinc oxide nanoparticles are more preferrable in the regard that they have an equal UV-filtering effect to titanium dioxide at lower concentrations and a lower whitening on the surface color [26].

In addition, the effects on biological properties of impregnation with ZnO-NP in concentrations of 2.5% to 5% aqueous dispersion into Rubberwood *Hevea brasiliensis* have been investigated, showing a positive effect on biological resistance against *Trametes hirsuta* and *Polyporus meliae* [25]. Other studies also tested fungal decay resistance against another white-rot fungus *Ganoderma applanatum* using a zinc oxide concentration of 1–5% in a water:ethanol (1:1) solution in pine wood and showed improved pine wood decay resistance with similar protection compared to traditional wood preservatives [27].

Further, the influence of ZnO-NP on the water repellency and dimensional stability of beech wood in submerged aqueous solution at concentrations of 0, 1, 2, and 4% was investigated, indicating that the dimensional stability increased and reduced hygroscopicity occur. Additional FTIR analysis suggested a strong interaction between the ZnO-NP and the chemical components of wood [28]. Another study shows that ZnO impregnation reduced water uptake even with low concentrations of 0.5% [21]. Clausen et al. vacuum-treated southern pine with aqueous ZnO-NP dispersions at concentrations of 1, 2.5, and 5% and evaluated leaching resistance and UV protection [29]. The authors showed that no leaching occurred in treated specimens in a laboratory leaching test, even at high retention of 13 kg/m^3. However, at high concentrations a chemical depletion occur after 12 months of outdoor exposure. At concentrations of 2.5% or greater, ZnO provides substantial

resistance to water absorption. Due to the issue of ZnO nanoparticles not being soluble in water, experiments were conducted to use other carrier media, such as polypropylene, polyethylene glycol, or propylene glycol to improve the material uptake even more [22,23].

Propylene glycol was shown to have high stability without additional surfactant or dispersant [23,24]. Another approach for protecting wood surfaces was tested with a 2% ZnO-based acrylate coating and also showed reduced yellowing and improved optical properties [30]. *Wrightia tinctoria* was coated with 1% and 2.5% *w/v* ZnO nano dispersions in propylene glycol and exposed to accelerated weathering whereby rapid yellowing was observed in uncoated specimens and a strong reduction in photo-yellowing and restricted lignin degradation for nano dispersion coated specimens was observed [24].

In this work, whole-cell impregnation treatment of ZnO-NP dispersions with propylene glycol as carrier medium was investigated. The aim was to gain knowledge about how ZnO-NP dispersions penetrate wood and how the impregnating agent is distributed within the cell structure. The protective effect of the ZnO-NP treatment wood was elaborated by UV stability and chemical changes in the material. By determining those properties, we examine if this whole-cell impregnation approach delivers a deeper penetration and therefore a potential advantage over coating treatments. A deeper penetration could result in a long-lasting protective layer and further a longer service life of the treated material, which could reduce material consumption and save natural resources.

2. Materials and Methods

Fir (*Abies alba*) and beech (*Fagus sylvatica*) wood were provided by Stefl Holz (Kuchl, Austria). Zinc oxide nanoparticles (ZnO-NP) < 100 nm as well as propylene glycol (PG) were provided by Sigma Aldrich Chemicals Pvt. Ltd. (Merck, Kennborough, NJ, USA).

2.1. Specimen Pretreatment

The wood was cut into clear, defect free specimens measuring 25 × 15 × 5 mm^3. After cutting, the samples were conditioned in a standard climate at 20 °C and 65% relative humidity for one week. Prior to use, the samples were dried until the weight was constant (±0.3 mg).

2.2. Dispersion Preparation

The preparation of the ZnO nano-dispersion followed that of Nair et al. [24]. The nano-dispersions were prepared by mixing 1%, 2%, 3% (*w*/*v*) of ZnO nanoparticles in PG without adding any additional dispersant (BZ1, BZ2, BZ3 in beech wood, and TZ1, TZ2, TZ3 in fir wood, respectively). Blends were mixed for 10 min under rapid stirring (4000 min^{-1}) at room temperature to obtain a homogenous solution. To prevent agglomeration of the nanoparticles, the dispersion was subsequently sonicated for 60 min at 35 kHz at 20–25 °C in an ultrasonic bath (Bandelin, Berlin, Germany)

2.3. Impregnation and Penetration Behaviour

Ten specimens were used for each impregnation. The samples were placed in beakers using glass beads and wire netting to avoid contact between specimens. The loading process was carried out with the beakers in a steel vessel. The impregnation process consisted of a vacuum phase at 70 mbar for 30 min, then the addition of the impregnating agent and immediate pressure phase at 5 bars for 2 h. The vacuum was not broken. After impregnation, the samples were taken out of the vessel and surfaces were wiped off from excess impregnating agent before drying at 103 ± 2 °C until the weight was constant (±0.3 mg).

The solution uptake (L_A) and the final material uptake (M_A) of the ZnO nano-dispersions after drying were determined by the following formulas:

Formula (1). Solution uptake

$$L_A\ [\%] = \frac{m_{ui} - m_0}{m_0} \times 100 \quad (1)$$

where m_0 is the dry mass (u = 0%) of the wood sample prior treatment and m_{ui} is the wet mass of the wood sample after impregnation.

Formula (2). Material uptake

$$M_A\ [\ \%] = \frac{m_{0i} - m_0}{m_{0i}} \times 100 \quad (2)$$

where m_0 is the dry mass (u = 0%) of the wood sample prior treatment and m_{0i} is the dry mass (u = 0%) of the wood sample after impregnation.

2.4. Scanning Electron Microscopy

One specimen was used for investigation of impregnation retention for each dispersion type using a Zeiss Ultra Plus field emission scanning electron microscope (SEM) with an annular backscatter electron detector (Carl Zeiss AG, Oberkochen, Germany). The treated specimens were cut in 1 mm layers and the determination was carried out with layers 2 mm underneath the initial surface of the specimens. The SEM working distance was set between 4 mm and 6 mm with an acceleration voltage of 5 kV. Prior to imaging, samples were coated with a thin layer of gold using a Sputter Coater 108 (Cressington Scientific Instrument Ltd., Watford, UK) with a current of 40 mA and coating time of 60 s.

2.5. Leaching Resistance

The leaching resistance (*LR*) was determined by following Sommerauer et al. [31]. In brief, ten impregnated specimens were soaked in a flask with the 10-fold the volume of the samples of water and kept under moderate mechanical shaking (60 min^{-1}) for cycles of 1, 2, 4, 8, and 16 h. The water was changed after every intermediate step. The samples were oven-dried after leaching and weight after leaching was registered.

Leaching resistance was calculated according to the following formula:

Formula (3). Leaching resistance

$$LR[\ \%] = \frac{m_{aL} - m_0}{m_{Oi} - m_0} \times 100 \quad (3)$$

where m_{aL} is the dry mass (u = 0%) of the wood sample after leaching, m_{0i} is the dry mass (u = 0%) of the wood sample after impregnation, and m_0 is the dry mass (u = 0%) of the wood sample.

2.6. Short-Term Weathering and CIELab Color Measurement

For the elaboration of the UV stability a short-term weathering procedure with focus on UV exposure was applied on six specimens for each dispersion with a circle of 4 h conditioning phase and 2 h UV-radiation for a total of 216 h in a QUV/Spray-Accelerated Weathering Tester (Q-Panel Lab Products, Cleveland, OH, USA) using UVA lamps at a wavelength of 430 nm. Conditioning phases were applied to prevent overheating of samples.

The UV stability was assessed by means of colorimetry, which is an efficient technique for characterizing the surface color of wood samples. This method used standards established by Commission International de L'E'clairage to take measurements of the parameters L^* (lightness), a^* (green–red chromaticity coordinate), b^* (blue–yellow chromaticity coordinate) possible. The change in coordinates corresponds to a change in color and is therefore a suitable approach to measure the influence of UV radiation on the optical appearance of wood. ΔE^* is a general term for the total change in the color coordinate and the higher it is, the stronger was the shift in color in terms of lightness, green–red, and blue–yellow color.

Single point color measurements were performed on the respective specimens before and after impregnation, as well as after UV exposure with the Mercury 2000 spectrophotometer (Datacolor, Lawrenceville, NJ, USA) with CIE standard Illuminates D65 and a 10° standard observer, according to the CIELab color space system. Ten untreated specimens were used as reference.

Color change (ΔE) was calculated using the formula below:

Formula (4). Color change

$$\Delta E_{ij} = \sqrt{(L_i - L_j)^2 + (a_i - a_j)^2 + (b_i - b_j)^2} \quad (4)$$

where x_i is the initial $L^*/a^*/b^*$ value of the sample and x_j is the $L^*/a^*/b^*$ value of the sample after impregnation or UV exposure.

2.7. Chemical Changes

The chemical changes due to short-term weathering were analyzed for all samples by Fourier Transform Infrared Spectroscopy (FT-IR) using a "Miracle" diamond-attenuated Total Reflection (ATR) unit (Perkin Elmer, Waltham, MA, USA) with a round crystal surface of 1.8 mm. Samples were tested in the wavelength range between 4000 and 600 cm^{-1} with results reported in absorbance and were applied directly to the diamond lens in without further treatment (32 scans, 4 cm^{-1} resolution). The treated specimens were cut in 1 mm layers to determine the penetration of inner cells of the specimens. The determination was carried out with those layers 2 mm underneath the surface of the specimens. Three spectra per sample were averaged for each formulation with ATR and baseline correction using Bio Rad KnowItAll 2023 Software (BioRad Laboratories, Hercules, CA, USA).

2.8. Statistical Analysis and Data Processing

Statistical analyses were performed using OriginPro 2023 Software (OriginLab, Northampton, MA, USA). Within groups a Shapiro–Wilk normality and a Levene´s test and further an ANOVA and Tukey's post hoc test were performed at a significance level of $\alpha = 0.05$.

3. Results

3.1. Impregnation Behaviour

After the treating process, the weight of each impregnated specimen was measured and showed that ZnO-NP dispersion uptake differed between treated wood species. The dispersion uptake of beech wood was about 70% based on sample weight (Figure 1) with fir wood showing a higher uptake of the dispersions (190.75–198.97%).

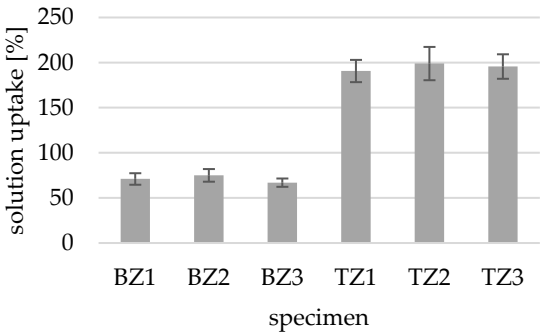


Figure 1. Dispersion uptake of beech (BZ1–BZ3) and fir (TZ1–TZ3); $n = 10$. Fir wood has a far higher dispersion uptake than beech—more than twice as high. The dispersion uptake is not influenced by ZnO-NP concentrations.

There was a significant difference in solution uptake between the species beech and fir at a significance level of $\alpha = 0.05$ ($p \leq 0.01$). However, no significant difference was observed between 1%, 2%, or 3% ZnO-NP with each used species or interaction of both factors. Propylene glycol seems to be suitable as an impregnating agent for softwoods, but for hardwoods the uptake was unexpectedly low despite larger pores.

Similarly, material uptake (Figure 2*)* was roughly twice as high in fir wood treated with the 1% ZnO-NP dispersion as in beech wood. For this characteristic a significance difference ($p \leq 0.01$) was obtained for species, ZnO-NP concentration, and interaction of both factors. With 2% ZnO-NP, saturation occurred regardless of the wood species, so that

the material absorption did not exceed 12%. Dispersion with 3% ZnO-NP did not lead to any further increase in sample weight.

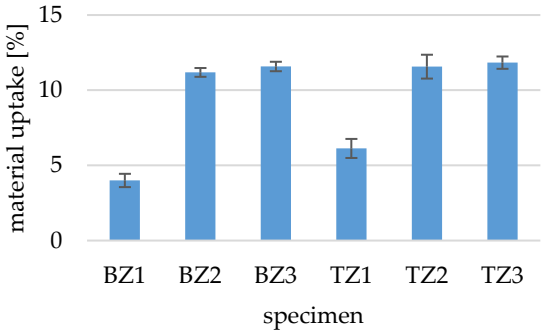


Figure 2. Material uptake of beech (BZ1–BZ3) and fir (TZ1–TZ3); n = 10. Material uptake did not increase with higher ZnO-NP concentrations over 2% *w/v* of ZnO-NP. This behavior was present in both beech and fir wood. For fir wood, a higher material uptake was observed even at 1% *w/v* ZnO-NP concentration, roughly 200%.

3.2. Scanning Electron Microscopy

An accumulation of ZnO-NP in wood cellular structure was seen, with variation between wood species. In beech, ZnO-NP deposits accumulated on vessel walls but did not form a uniform layer, and not all vessels were infiltrated (Figure 3).

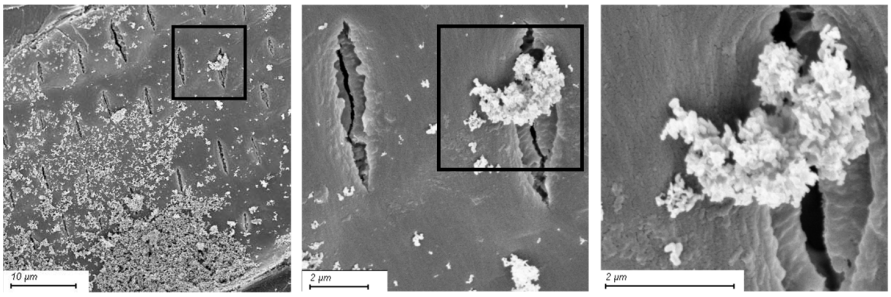


Figure 3. SEM images of impregnated beech samples with 2% *w/v* ZnO-NP dispersion (BZ2). ZnO-NP layers present in beech pores with agglomerates present at cell-to-cell interconnections.

However, ZnO-NP showed the ability to reach vessels in inner wood regions due to the bigger pores in beech in all dispersion concentrations. As the amount of ZnO-NP in the formulation increased, more material accumulates, which is independent from the wood species, because of the blocking of pits also occurring in fir (Figure 4). This behavior of ZnO agglomeration was also seen by de Peres et al. [27].

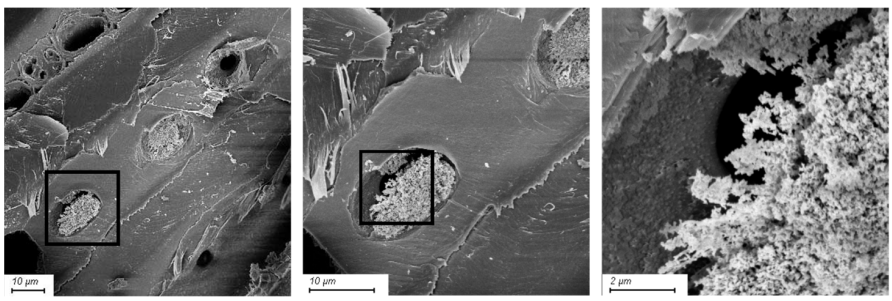


Figure 4. SEM images of impregnated fir samples with 3% *w/v* ZnO-NP dispersion (TZ3). Inside cells (2 mm) of fir wood treated with of ZnO-NP dispersions with blocking of penetration pathways by ZnO-NP agglomerations.

For fir, the same phenomenon of ZnO-NP accumulation took place but has a higher impact on further penetration. The cell-to-cell connections were smaller than in beech and the ZnO-NP agglomerates primarily were visible on those important penetration pathways. However, ZnO-NP were still detectable in 2–3 mm depth of all wood specimens which could represents a deeper treatment than surface applications.

3.3. Leaching Resistance

After impregnation, the samples were tested for their leachability. In beech, the majority of the impregnated material was shown to be lost in leaching testing (Figure 5). This indicates that there was no stable fixation of the impregnating agent in the wood structure. At higher dispersion concentrations, the percentage of loss decreased (approx. 5% for beech wood). This behavior was likely due to the easily penetrable microstructure of beech wood. Water can easily penetrate and dissolve impregnated material, but partial blockages occur due to agglomeration of ZnO-NP. For leaching resistance, a significance difference ($p \leq 0.01$) was obtained for species and ZnO-NP concentration. Interaction between species and ZnO-NP concentration was not significant different.

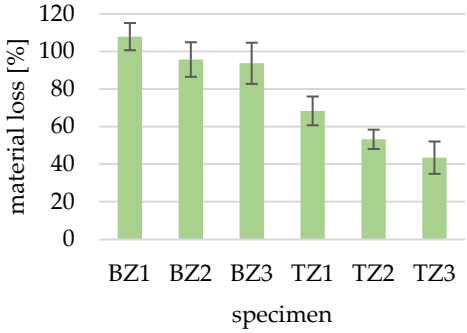


Figure 5. Material loss of beech (BZ1–BZ3) and fir (TZ1–TZ3); n = 10. The material loss decreases slightly for increasing ZnO-NP concentration for both beech and fir wood. The high material loss for beech wood with 1% *w/v* ZnO-NP dispersion (BZ1) means that all of the loaded ZnO-NP is lost due to leaching. A relatively low material loss at fir wood with 3% *w/v* ZnO-NP dispersion (TZ3) was observed.

Similar behavior was observed in fir wood, although here the proportion of material loss is much lower. In fir wood, a stronger blocking and mechanical anchoring of the ZnO-NP lumps was seen, which may have led to less water entering the cell structure and less material leaching. These results were consistent with the findings of the SEM analysis and could be seen in other studies, whereas ZnO-NP concentrations up to 4% led to higher dimensional stability a reduced hygroscopicity [28].

3.4. Short-Term Weathering and CIELab Color Measurement

The color change (ΔE, Table 1) due to UV exposure was significantly reduced by using the 1% ZnO-NP dispersion in both beech wood, and fir, in comparison to an unimpregnated sample. The higher the ΔE value the stronger the change in color and thus a lack in color or UV stability. Untreated specimens demonstrated a strong photo-yellowing. Beech wood experienced a color change of 19.26; fir wood color changed by 22.17. An increasing proportion of ZnO-NP in PG was not associated with further increases in the UV protection effect, with only a slight reduction occurring compared to untreated reference samples. This may be caused by an agglomeration of ZnO-NP at concentrations above 1%. The trends seen in the color change values indicate that all samples became darker (L^*), more reddish (a^*), and turned strongly to a yellow color (b^*), whereby the ZnO-NP dispersion reduced color change for the treated specimens.

Table 1. Color change (ΔE^*) due to impregnation and UV treatment in short-term weathering. Increasing ZnO-NP concentrations increased the lightness (L^*) of the specimens. The UV treatment caused darkening ($-L^*$) of all samples and shifted the color to the more reddish ($+a^*$) and more yellow color ($+b^*$) coordinates. The biggest change was observed in specimens without ZnO-NP dispersion treatment (BZR, TZR).

Specimen	State	L^* [b]		a^* [b]		b^* [b]		ΔE
BZR	beech untreated	69.79	(1.43)	6.27	(0.83)	16.22	(1.83)	-
BZR UV [a]	beech untreated	60.70	(2.04)	13.25	(0.93)	31.70	(1.21)	19.26
BZ1	beech impr. ZnO 1%	63.86	(2.66)	9.24	(2.14)	24.26	(2.78)	-
BZ1 UV [a]	beech impr. ZnO 1%	60.87	(3.36)	12.49	(0.67)	31.97	(0.81)	8.88
BZ2	beech impr. ZnO 2%	66.55	(6.32)	6.21	(1.69)	17.19	(3.04)	-
BZ2 UV [a]	beech impr. ZnO 2%	54.13	(3.08)	10.94	(1.23)	25.95	(2.29)	15.92
BZ3	beech impr. ZnO 3%	70.45	(1.13)	6.25	(1.73)	15.41	(2.82)	-
BZ3 UV [a]	beech impr. ZnO 3%	56.39	(1.48)	9.70	(1.18)	24.62	(2.77)	17.16
TZR	fir untreated	78.14	(3.66)	5.36	(1.14)	22.20	(1.05)	-
TZR UV [a]	fir untreated	66.61	(2.12)	14.00	(0.39)	39.05	(0.77)	22.17
TZ1	fir impr. ZnO 1%	66.68	(1.89)	10.01	(1.15)	34.32	(2.30)	-
TZ1 UV [a]	fir impr. ZnO 1%	60.38	(1.59)	12.67	(1.10)	33.15	(2.00)	6.93
TZ2	fir impr. ZnO 2%	79.06	(3.04)	3.77	(0.84)	22.69	(2.63)	-
TZ2 UV [a]	fir impr. ZnO 2%	61.70	(2.65)	12.04	(0.73)	32.08	(1.89)	21.40
TZ3	fir impr. ZnO 3%	79.54	(3.17)	3.23	(0.74)	17.46	(2.05)	-
TZ3 UV [a]	fir impr. ZnO 3%	64.07	(3.96)	10.07	(1.38)	29.37	(2.77)	20.69

$n = 10$; [a] $n = 6$; [b] standard deviation in brackets.

3.5. Chemical Changes

Generally, the UV stability of wood is always associated with the stability of the lignin component. In the range 3100 cm^{-1} (Figures 6 and 7), there was a connection of bands of the wood substance, as well as PG. In Figures 8 and 9 peaks in the fingerprint region (1800 to 800 cm^{-1}) includes several bands of lignin, especially at 1643 cm^{-1}, where conjugated C=O and C=C aromatic ketones of lignin units respond; at 1595 cm^{-1} aromatic skeletal vibration of syringyl lignin and C=O stretch occurs. Further bands at 1505 to 1506 cm^{-1} are related with the aromatic skeletal vibration of lignin and at 1455 cm^{-1} aromatic CH deformation and asymmetric bending of CH3 in lignin is present. Syringyl ring movements with CO stretch and C1–O vibration in syringyl derivatives of lignin were observed at 1324 cm^{-1}. C–O-stretching behavior also occurs at 1234 cm^{-1} due to lignin-syringyl rings. At 1110 cm^{-1} an aromatic skeletal and C–O stretch in lignin is present [4,32–39].

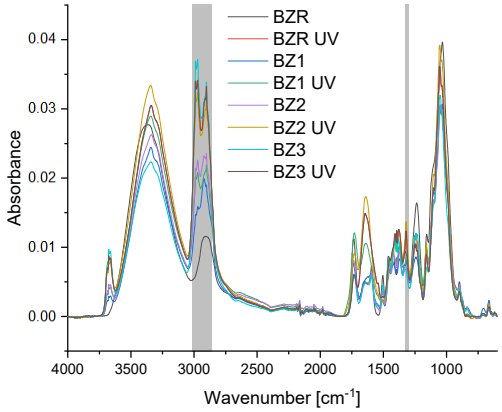


Figure 6. FT-IR spectra of beech unimpregnated (BZR) and impregnated (BZ1–BZ3) specimen in the range 4000–600 cm^{-1}, with comparison of UV-treated aliquots. Bands of the beech wood substance, as well as PG around 3100 cm^{-1}.

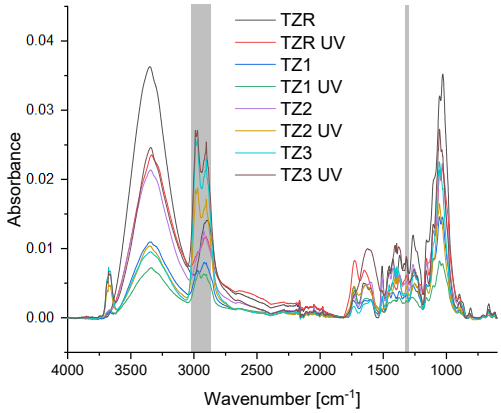


Figure 7. FT-IR spectra of fir unimpregnated (TZR) and impregnated (TZ1–TZ3) specimen in the range 4000–600 cm^{-1}, with comparison of UV-treated aliquots. Bands of the fir wood substance, as well as PG, around 3100 cm^{-1}.

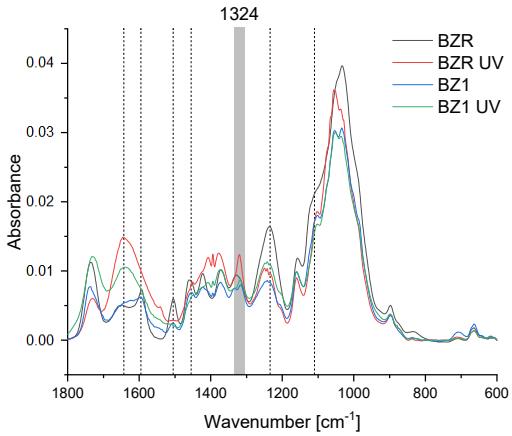


Figure 8. FT-IR spectra of beech unimpregnated (BZR) and impregnated (BZ1) specimen in the range 1800–600 cm^{-1}, with comparison of UV-treated aliquots. Syringyl ring movements with C–O stretch and C1–O vibration from syringyl derivatives of lignin at 1324 cm^{-1} was still recognizable after UV treatment indication a stabilization effect of ZnO-NP dispersion.

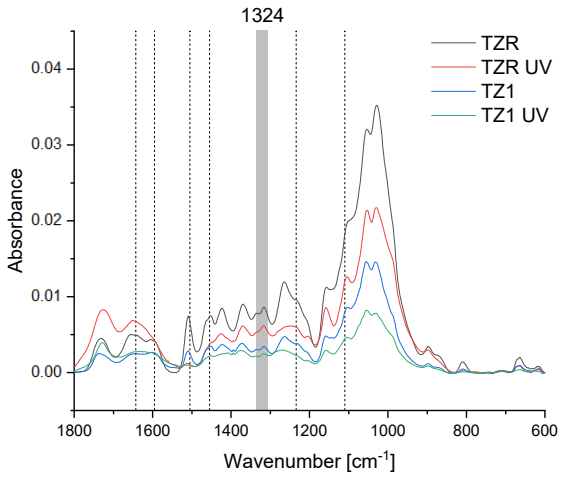


Figure 9. FT-IR spectra of fir unimpregnated (TZR) and impregnated (TZ1) specimen in the range 1800–600 cm^{-1}, with comparison of UV-treated aliquots. Same stabilization effect as in beech was visible when ZnO-NP dispersion was used wood at a wavelength of 1324 cm^{-1} where syringyl derivative movements of lignin are active.

Differences in molecular bands attributable to lignin breakdown because of UV treatment can be seen in Figures 8 and 9. These include a strong reduction at 1505 cm^{-1} (lignin aromatics–skeletal vibration) and an increase at 1650 cm^{-1}, indicating a cleavage of acetyl-groups occurs as a result.

The band at 1324 cm^{-1} at low concentrations of ZnO-NP in beech wood, as well as in fir wood, was less affected by UV treatment than in the other samples. At this wavelength, syringyl ring movements with CO stretch and C1–O vibration are known to occur in syringyl derivatives of lignin [39,40]. This implies that less chemical change in this compound occurred, indicating the ZnO treatment led to partial stabilization. This corroborates with the color changes of the surfaces, since here, too, a stronger stabilization effect was present at low concentrations of ZnO-NP.

4. Conclusions

In this work, the impregnation characteristics and UV-stabilizing properties against short-term weathering of ZnO NP propylene glycol dispersions in fir and beech wood were tested. Dispersion and material uptake, SEM analysis, as well as measurements of color and chemical change by FT-IR were investigated. It was found that the uptake of the nano-dispersions did not increase with increasing ZnO-NP concentration in treatment solution and that the impregnating agents were better taken up by fir wood (roughly 200%) than by beech wood (roughly 70%). A 2% ZnO nano-dispersion led to a saturation of ZnO-NP in the cell structure of the treated wood in both species. The SEM investigation showed that ZnO-NP was able to penetrate the inner regions of the wood cells in beech but accumulated on the cell walls in a non-uniform manner. Higher ZnO-NP concentrations lead to more accumulation, which may have caused blocking of penetration pathways and prevention of further treatment deposition. This behavior may also explain the reduction in leachability with increasing amount of ZnO-NP because more cells were blocked thus preventing water entering the cells. Even if the impregnating substance had not been fixed in the wood substance, whole cell impregnation shows the potential for a higher protective effect than surface application due to deeper penetration. CIELab and FT-IR analysis showed stabilization effects against UV exposure, significantly at lower concentrations of 1% *w/v* ZnO-NP which can be attributed to the stabilization of C–O compounds in lignin-syringyl rings.

The results of this work demonstrate the potential for long-lasting UV stabilization of visible wood applications using ZnO-NP dispersions with PG as a whole-cell impregnation agent and represent a promising alternative to conventional surface applications.

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