An X-ray CT assessment of fungal growth in spruce, poplar and thermally-modified poplar

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ABSTRACT
Poplar has been gaining attention as a potential material for use in engineered wood products (EWPs). However, poplar wood is not durable against fungal degradation, which is an important factor that needs to be investigated. Previous studies on degradation have mostly focused on evaluating mass loss (ML), while lacking information on the progress of degradation. In this study a recently developed non-destructive X-ray computed tomography (CT) technique was used to investigate the degradation progress within poplar, thermally modified (TM) poplar, and spruce during a 10-weeks fungal degradation experiment. The results showed that degradation led to a significant decrease in density, particularly after 15 days. Based on the X-ray CT scans, it was observed that spruce showed a higher mass loss at the end grain while poplar showed a homogeneous pattern throughout the entire block. Thermally modified poplar specimens were less degraded even at moist conditions. The density of the wood was found to affect the fungal susceptibility of both poplar and TM poplar: a higher density resulted in a lower mass loss of poplar. The use of X-ray CT scanning allowed for a detailed micro- level insight into fungal decay, which can potentially help in protecting poplar in future industrial use for constructions.

1. Introduction
Poplar (*Populus*) is widely recognized as a fast-growing tree species. As a considerable resource, it has potential to be increasingly used for high-end engineered wood products (EWPs) such as glued-laminated timber (GLT) and cross-laminated timber (CLT) (Balatinecz *et al.* 2014, Humar 2020). While poplar has a low density and hardness, its mechanical properties have been shown to be sufficient for use in CLT (Kramer *et al*. 2014). Recent research has also demonstrated that the moisture dynamics of poplar are comparable to that of Norway spruce (*Picea abies*) for CLT (Jiang 2022). However, in practical applications, biological durability is still a critical factor to consider, as for construction uses, poplar CLT could be susceptible to fungal degradation in a fungus-favoured environment. During construction (due to rain) as well as during the use phase (due to condensation or water infiltration), high relative humidity and moderate temperatures can promote wood degradation by rot fungi. To address this, use classes (UCs) are applied in the wood industry based on different environmental exposures that can cause biological deterioration (CEN 2013). In most cases, EWPs are expected to be used mainly in UC2 and sometimes UC3 situations, which involve occasional or limited wetting and no biodeterioration of the products. In the past, efforts to enhance the longevity of non-durable wood types typically involved modifying their chemical characteristics through the use of preservatives. However, due to environmental restrictions, several biocidal substances have been prohibited in the European Union thus the future of wood preservation methods is directed towards more sustainable alternatives. Thermal modification is considered as an effective method for protecting wood against fungal decay, especially for non-durable wood species like poplar (Wang 2020). It is well-established and commercialized. According to literature, TMT is a sustainable alternative to traditionally treated wood products, and its superior weathering resistance and cost-effectiveness make it a preferred choice over chemically modified woods (Esteves and Pereira 2009, Willems *et al.* 2013, 2015, 2020, Willems and Altgen 2019, Wang 2020, Hill *et al.* 2021). However, the brittleness of TMT makes it not optimal for load- bearing applications. To make the best use of its durability feature, thermally modified wood could be used for cladding or decking or be added as an outer layer to engineered wood products such as GLT and CLT.
Natural durability is one of the critical aspects that affect the service life of wood species. However, there

is a lack of detailed understanding about the complex relationship between materials and fungal decay, particularly with regards to how the structure of wood and other components impact the process of degradation. Most studies use a standard fungal test to measure the mass loss of wood, which links to the corresponding DCs in service conditions as described for mainly UC3 & UC4 in EN 335 (CEN 2013, Bollmus 2018, Brischke and Alfredsen 2020). Although being useful for evaluating the durability of wood, conventional tests do not provide sufficient insight into the ongoing degradation process within the material. Typically, investigations into the progress of wood decay rely on destructive approaches, which make the examination of the same wood sample at subsequent time points not feasible. In some laboratories, isothermal calorimetry has been used as a successful non-destructive method for assessing fungal activity over time by measuring heat production resulting from biochemical processes (Wadsö 2013, 2017). However, this technique does not provide any information on the spatial distribution of fungal activity.

The use of X-ray computed tomography (CT) is shown to be a highly promising method for investigating fungal decay in a laboratory environment, which offers numerous benefits, including its fast-speed, non-destructiveness, and ability to produce 3D images of the internal structure of the material (Van den Bulcke 2009). With X-ray CT, researchers can visualize the degradation progress as well as the density changes over time and examine the effects of fungal decay activity on materials without causing any damage, while also gaining a comprehensive understanding of the material's internal composition through detailed imaging (Withers 2021). Various studies have previously been conducted to visualize the fungal activity inside wood. In a recent work by Martin (2021), X-ray imaging was utilized to investigate moisture migration in wood, with the aim of evaluating its hygroscopicity, wettability, and related characteristics. In 2022, a 3D X-ray CT set-up and analysis pipeline was developed and successfully used to track the spatial and temporal changes in decayed wood during a fungal decay lab test (De Ligne 2022). The findings of previous studies also demonstrate a high degree of agreement between X-ray CT results and mass loss data derived from the EN standards (Macchioni et al. 2007, Hervé 2014).

This study utilized X-ray CT imaging to monitor the degradation process by *Trametes versicolor* over time in untreated and TM poplar and spruce specimens exposed in a mini-block fungal test. By comparing poplar and TM poplar with spruce, commonly used in GLT and CLT, a more comprehensive understanding of durability and service life prediction for poplar and TM poplar in EWPs for future load-bearing constructions is obtained.

2. Materials and methods

2.1 Test material

The wood species used in the fungal decay test were poplar (*Populus deltoides* × *nigra*), thermally modified poplar (treated by vacuum technology aimed at durability DC2-3, provided by company Lignius) and Norway spruce (*Picea abies*). The poplar wood used was obtained from a polyclonal stand in Grimminge, Belgium. Poplar specimens were taken with varying densities, ranging from 380 to 520 kg/m^3, representing a range of properties commonly present in (hybrid) poplar plantations. European beech (*Fagus sylvatica L.*) was included in the test as a reference wood species for checking the validity of the fungal decay test through virulence assessment. 80 mini- block specimens (30 (L) × 10 (W) × 5 (T) mm^3) were prepared for the fungal decay test on poplar and modified poplar (of which 16 specimens of each were assessed with X-ray CT over time) and 20 specimens for beech and spruce. All specimens were free from stains and defects as indicated in CEN (2013).

2.2 Decay test

A fungal decay test was performed according to a mini-block fungal test (Bravery 1978, Deklerck 2020, De Ligne 2021), adapted from EN 113–2 (CEN 2021). All specimens were conditioned at 20 ± 2°C, 65 ± 2% relative humidity (RH) for 15 days and weighed (to the nearest 0.001 g) prior to the decay test

(EMC, poplar ~12.5%, TM poplar ~7.7%, spruce ~12.1%). The wood blocks for fungal decay test were all sterilized using gamma irradiation (25–50 kGy, Cobalt 60 radiation, Synergy Health Ede B.V.) before being placed on a fungus grown on a 4% agar/2% malt culture medium (Thermo Fisher Diagnostics B.V., Landsmeer, The Netherlands). The wood blocks were placed on a plastic mesh (to avoid direct contact with the agar/malt medium) as soon as the surface was completely covered by the fungal mycelium. The white rot basidiomycete fungus *Trametes versicolor* was used, which is an obligatory test fungus for hardwoods in EN 113-2 (CEN 2021). The Petri dishes were sealed with parafilm and incubated at 20 ± 2°C, 65 ± 2% RH for 10 weeks. After 10 weeks, the mini-blocks were removed from the Petri dishes, carefully cleaned, oven- dried and weighed ($m_{\text{final, dry}}$). To estimate the initial oven-dry mass ($m_{0,\text{ dry}}$) of all the test specimens, 10 additional test specimens for each group were oven-dried (48 h at 103°C) after conditioning at 20 ± 2°C, 65 ± 2% RH.
The mean moisture content (MC) of the 10 test specimens, was used to calculate the initial dry mass and mean density of each specimen using:

$$m_{0,dry} = \frac{m_1}{1+MC} \quad (1)$$

$$D_{estOD} = \frac{m_{0,dry}}{V} \quad (2)$$

where $m_{0,\text{dry}}$ is the initial dry mass of the specimen, m_1 is the initial conditioned mass, *MC* is the mean moisture content, D_{estOD} is the estimated oven dry density, *V* is the volume of the mini-block.

The mass loss (*ML*) of each test specimen was calculated using the equation:

$$ML = \frac{m_{0,dry} - m_{final,dry}}{m_{0,dry}} \quad (3)$$

where $m_{\text{final, dry}}$ is the final dry mass after 10 weeks of fungal degradation.
During the fungal decay test, 16 of the 80 specimens of poplar and thermally modified poplar and 4 of the 20 specimens of spruce were assessed over time with X-ray CT.

2.3 X-ray CT

2.3.1 Experimental set-up

Over a period of 10 weeks, the Petri dishes were subjected to regular scans (after 5, 15, 35 and 70 days of fungal degradation as well as the oven-dry scan) using the Nanowood scanner at the UGent Centre for X-ray Tomography (UGCT, www.ugct. ugent.be). The scanner control software platform was based on LabView®. In addition, the scanner utilized a closed-type Hamamatsu directional tube and a large area Varian flat-panel detector (Dierick 2010, 2014). The scan settings were chosen to fulfil the requirements of sufficient observation for the actual material size. Due to the limited field view of the detector, it was not possible to scan the entire stack of Petri dishes at once. Thus, the Petri dishes were organized in stacks of seven and secured with surgical paper tape as can be seen in Figure 1. For each scan, a reference material with a constant density value of 1.4 kg/m^3 was attached to the edge of the stack. With the reference material, the attenuation coefficients can be converted to the approximate density values Equation (4).

Figure 1. Schematic of the X-ray CT set-up (left), poplar mini-blocks after 5 days of fungal decay by *Trametes versicolor* (middle) and poplar mini-blocks after 70 days of fungal decay with water droplets due to condensation (right).

2.3.2 Image acquisition and reconstruction

All the stacks of the petri dishes were scanned at an average tube voltage of 80 kV, a tube power of 8 W and a voxel size of 100 µm. The exposure time was set to 500 ms per projection, 2401 projections in total, thus the scanning process took approximately 21 min per stack. The same scan settings were applied for all the scans at the 5th, 15th, 35th, 70th day as well as for the oven-dry scans by the end of the decay test.

After the image acquisition, X-ray CT images were reconstructed in batch and beam hardening correction was applied (De Muynck 2015). The segmentation of mini-blocks from the resulting greyscale volumes was done in Fiji (Schindelin *et al.* 2012). Subsequently, the grey values of the mini-block volumes were converted to density values by using the grey values of the reference material and air (De Ridder *et al.* 2010):

$$D_i = D_{ref}\left(\frac{GV_i - GV_{air}}{GV_{ref} - GV_{air}}\right) \quad (4)$$

where D_i is the density of voxel i (kg/m^3), D_{ref} is the density of the reference material (1.4 kg/m^3), GV_i is the grey value of voxel i, GV_{air} is the grey value of air and GV_{ref} is the grey value of the reference material. The calculation was done with Python 3.7.5 (Python Software Foundation, https://www.python.org/).

2.4 Data analysis

2.4.1 Mean density change over the entire block

To determine the relative mean density changes of the mini- blocks during the experiment, the average density was calculated at four-time steps for each mini-block based on its grey values. As the mini-blocks had different densities at the beginning of the experiment, the relative changes of each mini-block in density were calculated as below:

$$Mean\ density\ change = D - D_{estOD} \quad (5)$$

where D is the average density value of the entire mini-block (kg/ m^3) and D_{estOD} is the estimated oven-dry density value calibrated from the reference samples before the test Equation (2).

It is worth noticing that the estimated oven-dry density before the decay test (based on estimated dry mass) as well as the oven-dry density after the decay test (based on X-ray CT scan of dried wood samples) correspond to the actual density values of the mini-blocks. The density values obtained from the scans during the decay test represent wood density including moisture, which is actually the 'moist wood density'. The water in the wood includes: the moisture absorption from the proximity to the agar medium, the fungal hyphae in the wood blocks (mainly water) and the water transported or produced by fungi. Therefore, once the decay progresses, the 'moist wood density' may decrease because of the fungal

degradation becoming more dominant than the effect of wetting, or increase when wood wetting is more dominant.

2.4.2. Mean density change

To better understand the degradation progress within the mini- blocks, each mini-block (with a length of 30 mm on average) is divided into five regions and the greyscale profile was analysed in the longitudinal direction (Figure 4). This profile represented the average grey value per slice and was obtained by analysing 300 slices that were 100 μm thick. By using this greyscale profile, the density of each slice was calculated (Equation 3).

$$Mean\ density\ change\ = D_i - D_{estOD} \quad (6)$$

Where D_i is the average density value of a slice i (kg/m^3) and D_{estOD} is the estimated oven-dry density value calibrated from the reference samples before the test (kg/m^3).

The density values obtained for five regions were compared to the estimated oven-dry density before the test (based on estimated dry mass) which is an average density value that is identical for each slice. Mini-blocks are expected to have a homogeneous density profile before decay, as was also observed in similar experiments (De Ligne 2022).

2.4.3. Statistical data analysis

A one-way analysis of variance (ANOVA) was performed, followed by a Tukey's multiple comparison test to determine whether the mean density change of each region along the longitudinal direction of the mini-blocks differed significantly for poplar and spruce.

In order to visually capture and analyse certain degradation phenomena that occur at a submillimetre scale, the greyscale volumes obtained from X-ray computed tomography (CT) were transformed into colour images. This was done by assigning colours to different density ranges of voxels. The colour scale used for this purpose ranged from 100 to 900 kg/m^3 and had an interval of 100 kg/m^3. By using this colour mapping scheme, the density information from the greyscale volumes could be effectively conveyed in a visual format, enabling easier interpretation and analysis of the underlying data.

3. Results and discussion

3.1 Fungal development in (thermally modified) poplar

The density change of poplar and thermally modified poplar over the period of 70 days fungal testing is presented in Figure 2. The mass-loss level of each scanned block is indicated by a colour scale and mini-blocks originating from the same wood beams are marked in the same line styles. The durability of the specimens was rated between 1 (very durable) and 5 (not durable) based on the percentage of mass loss due to fungal degradation, as described in EN113-2 (CEN 2021). It should be noted that, although this rating scale is intended for larger block sizes (5 × 2.5 × 1.5 cm) exposed for 16 weeks, Deklerck (2020) reported that there is adequate variation in mass loss for mini-blocks of various wood species, exposed for 8 and 12 weeks, to compare the durability of the wood species using the same classification as in CEN (2016). Additionally, the durability ratings of mini-blocks were similar for many wood species tested (Deklerck 2020, 2020, De Ligne 2021). The fungus was virulent, as the reference beech specimens had a median mass loss of 30%. The mass loss of unmodified poplar was above 15%, corresponding to DC 4 (slightly durable) and DC5 (non-durable). In contrast, most of the thermally modified poplar blocks had a mass loss below 15%, corresponding to DC1-3 (very durable to moderately durable). Three specimens had a mass loss between 15% and 30% (green lines in Figure 2, DC4, slightly durable) and one specimen (in blue) had a ML above 30%, which already showed a density decrease after 15 days. It is most likely that thermal modification of the timber beam these less-durable specimens originated from was suboptimal, thus a higher mass loss and a lower durability was observed compared with other specimens.

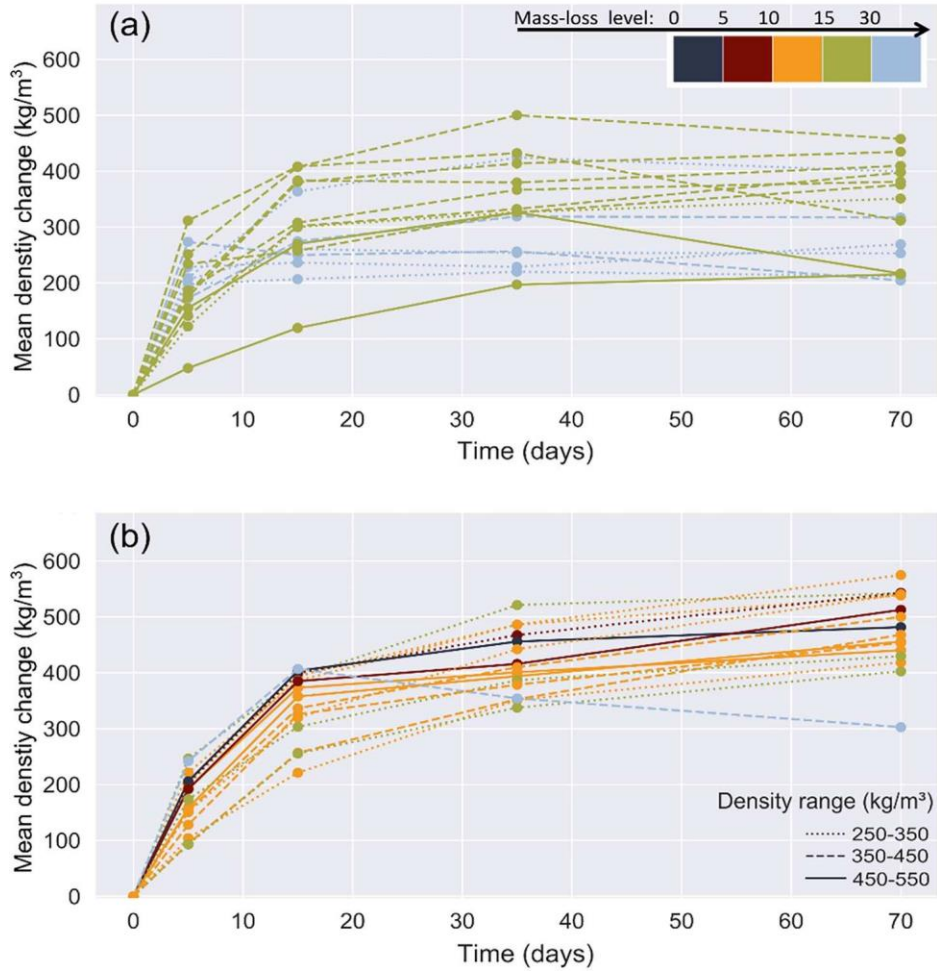

Figure 2. Density change over time (kg/m^3) relative to the oven-dry density of (a) specimens of poplar and (b) thermally modified poplar during 10 weeks of degradation by *Trametes versicolor*, as assessed with X-ray CT. The colour of the curve gives an indication of the amount of mass loss (ML) after 10 weeks of degradation.

The pattern of decreasing density was also observed for highly degraded beech and spruce by De Ligne 2022. The lower density-change value, occurring for several well- degraded samples (>15% ML) after 15 or 35 days of degradation, is likely associated with severe fungal degradation within the wood block. This appeared to be significant for the fungal degradation of poplar wood with a low density. For other specimens with >15% ML, this decrease in density change value could not (yet) be observed. Presumably the density increases from water transport and water 'production' by the fungus masked the density decrease or mass loss due to degradation. Indeed, De Ligne (2022) conducted an experiment without fungi as a reference to investigate the moisture sorption progress and density change of mini-blocks in an agar medium. During the initial 15 days, the density of the mini- blocks increased as they absorbed moisture from the agar medium. However, the experiment with fungi showed a larger increase in density, indicating a likely correlation between fungal metabolization, moisture production, and moisture transport by the fungus (Stienen *et al.* 2014, Thybring 2017). In addition, the experimental data strongly suggests the occurrence of water transfer or production as a result of fungal activity, which is evident from the generation of water droplets during the test (as depicted in Figure 1). The observed loss in wood mass can be attributed to fungal degradation, while the increase in mean density change primarily arises from water metabolization and transport facilitated by the fungus. It is important to note that the density observed through CT scanning fluctuates due to the interplay between wetting effect and degradation. Consequently,

a reduction in density observed through CT scanning indicates that the degradation effect surpasses the wetting effect, and vice versa.

The thermally modified poplar mini-blocks exhibited less variation in density change compared to the unmodified poplar. These findings align with a previous study by Jiang (2022), which also reported similar results regarding the moisture dynamics of poplar and TM poplar. Thermally modified wood is commonly utilized as a high-value product for outdoor construction applications, such as cladding, as it is expected to exhibit lower wettability and improved resistance against fungal decay (Hakkou 2005, Van Acker *et al*. 2011, Hill 2013, 2021, Javed 2015, Altgen and Militz 2016, Fredriksson 2019, Willems and Altgen 2019). However, the density increased after 5 days, resulting from water uptake and moisture transport by the fungus. Surprisingly this increase did not significantly differ between thermally modified poplar and unmodified poplar (p-value = 0.29, Mann–Whitney U test). This lack of significant difference can be attributed to the moist conditions in the experimental set-up that prevented the modified wood from drying out. Nevertheless, the fungal degradation was less severe in the thermally modified specimens, indicating a clear effect of the thermal modification, even in the presence of moisture (with moisture contents ranging between 28% and 76% after five days for TM poplar, while between 10% and 90% for unmodified poplar). According to the literature, high-temperature thermal modification induces significant structural modifications in wood, including hemicelluloses degradation and lignin modification (Hill 2006, Kocaefe *et al*. 2008). These changes result in a more condensed lignin structure and reduced hemicelluloses content, making the wood less susceptible to decay. The altered chemical composition, particularly the low hemicelluloses content and modified lignin structure, make the wood less favourable as a substrate for decay-causing organisms. Additionally, thermal modification reduces nutrient availability for microbial growth, impairs enzymatic activity, and limits the ability of decay fungi to efficiently degrade and utilize the wood as a nutrient source (Lekounougou *et al.* 2009, Thybring and Fredriksson 2021). The modified chemical composition, condensed lignin structure, and cell-wall changes inhibit microbial activity, reduce colonization and proliferation of decay-causing fungi, and hinder enzyme penetration into the cell wall. The formation of new extractives and degraded extractive residues further contribute to cell-wall bulking and potentially affect the sorption properties of the wood (Hill *et al.* 2021). In summary, the combined chemical and biological factors contribute to the observed reduction in biodegradation and improved durability of thermally modified poplar. These findings have significant implications for the utilization of thermally-modified timber in various outdoor applications, where its enhanced resistance to fungal decay and reduced biodegradation make it a valuable and sustainable option.

3.2 Density variation along the longitudinal direction

The primary means of hyphal penetration into a wooden block is through the major longitudinal pathways. These pathways are primarily vessels for hardwoods, whereas for softwoods, tracheids serve as the primary channels of penetration (Bravery 1975). Despite significant anatomical differences between the two studied hardwood and softwood species, the density change pattern for the entire mini-block displayed a similar pattern for poplar and spruce as shown in Figure 2. To visualize the density profile along the mini-blocks over the entire period, representative examples of side views along the longitudinal direction of one poplar and one spruce specimen are presented in Figure 3. Poplar seemed to have homogeneous density profiles for all the scans including the oven- dried scan while spruce had an increased density in the middle region after 35 and 70 days. It is worth noticing that the earlywood and latewood of spruce were clearly distinguishable, and that the latewood area seemed to have a higher density increase than the early wood which indicated that more moisture or water was accumulated in the latewood zones. This was also observed by Sedighi-Gilani (2012, 2014) and De Ligne (2022), i.e. the moisture uptake varies between earlywood and latewood, and the moisture uptake in the latewood cells not only saturated earlier but also presented higher values of saturation.

To obtain a more profound understanding of the impact of the internal structure of the examined blocks on the fungal degradation process, the scanned blocks were virtually divided into five subzones (longitudinally) and the density of each subzone was determined. This was done for all scanned specimens

as illustrated in Figure 4. The results indicate that, in comparison to spruce, poplar exhibited a more homogeneous pattern of density changes across the entire block. There were no statistically significant differences observed between the three regions (=5 subzones) of poplar and thermally modified poplar (Figure 4). However, it is worth noting that the mean-density changes in the outer (left and right) regions was consistently higher than the middle region at the 5th, 15th, 35th and 70th day. This may be attributed to the fact that capillary water uptake occurred at the cross sections of the blocks, and in the case of poplar, which contains vessel elements that provide easy access for fungal hyphae, degradation occurred evenly throughout the entire block over time.

The cross-section regions (L&R) of the spruce specimens had lower density values as compared to the middle region, indicating a higher amount of degradation at the sides, especially at the 35th and 70th day, suggesting that fungi were not able to decompose the middle zone immediately. During the first week, the longitudinal moisture uptake from the end grain was the primary process, followed by fungal degradation only from the second week onwards. Due to the anatomical difference, it makes spruce more difficult for fungal hyphae to penetrate its core through the end-grain. However, a recent study by De Ligne (2022) on fungal decay of various wood species demonstrated a uniform degradation pattern for spruce, which differs from the findings in this study. The discrepancy in observations may be due to the use of the brown rot fungus *Coniophora puteana* in that experiment, whereas white rot fungi *Trametes versicolor* was used in the present study. Considering the common knowledge that brown-rot fungi are known to degrade softwoods more than hardwoods, we hypothesize that the type of fungus used may have an impact on this observation.

3.3 Effect of density

Wood density is a crucial factor in the characterization and quality evaluation of wood products, as it has been widely established that wood with higher density typically demonstrates better performance compared to wood with lower density. The rationale for this observation is grounded in the direct correlation between wood density and its mechanical properties, including strength, stiffness and toughness (Bekhta and Niemz 2003, Windeisen 2009, Lesar 2013, Bao 2017, Li 2018, Monteiro 2020). However, it is imperative to note that the fungal susceptibility of wood, despite its vital significance, is often overlooked in the context of wood density analysis. The presented regression plot in Figure 5 shows the relationship between wood density and mass loss of poplar mini-blocks with a density range of 250–550 kg/ m^3. Both the X-ray CT scanned specimens and non-scanned specimens were included. The findings suggest that the mass loss of poplar decreases with increased density, indicating a negative correlation between wood density and mass loss. This correlation is consistent with previous studies which have suggested that denser wood species generally exhibit better durability due to their greater resistance to degradation fungi (Guilley 2004, Humar 2008). Similar results have been shown Humar (2008) for oak, one of the most durable European wood species, with lower density oak specimens being more susceptible to fungal decay than denser specimens.

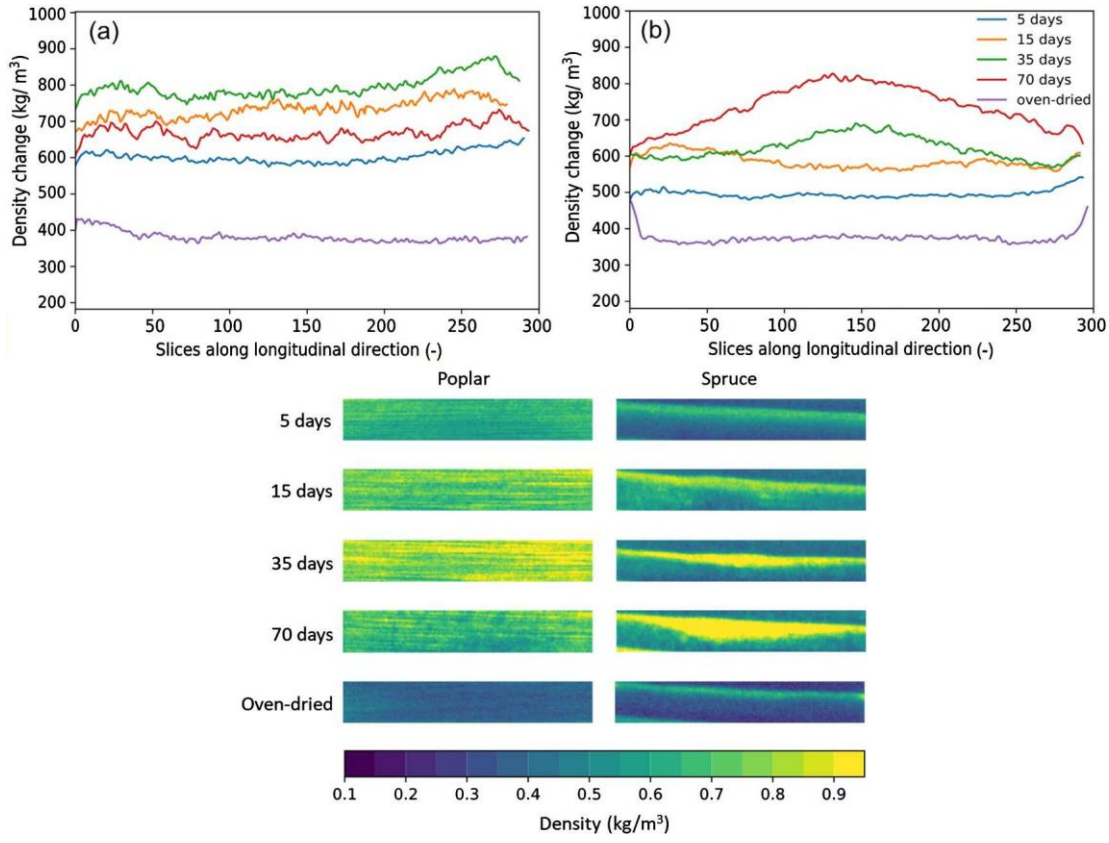

Figure 3. Density change along the longitudinal direction of a (a) poplar (with a mass loss of 23%) and a (b) spruce (with a mass loss of 11%) mini-block specimens as example (1 slice = 100 µm); (c) density visualization of 14 slices (located in the middle) of the corresponding specimens showing water production and mass loss related to fungal activity throughout the entire experiment. Figure 3(c) is the corresponding visualization of Figure 3(a,b) over time.

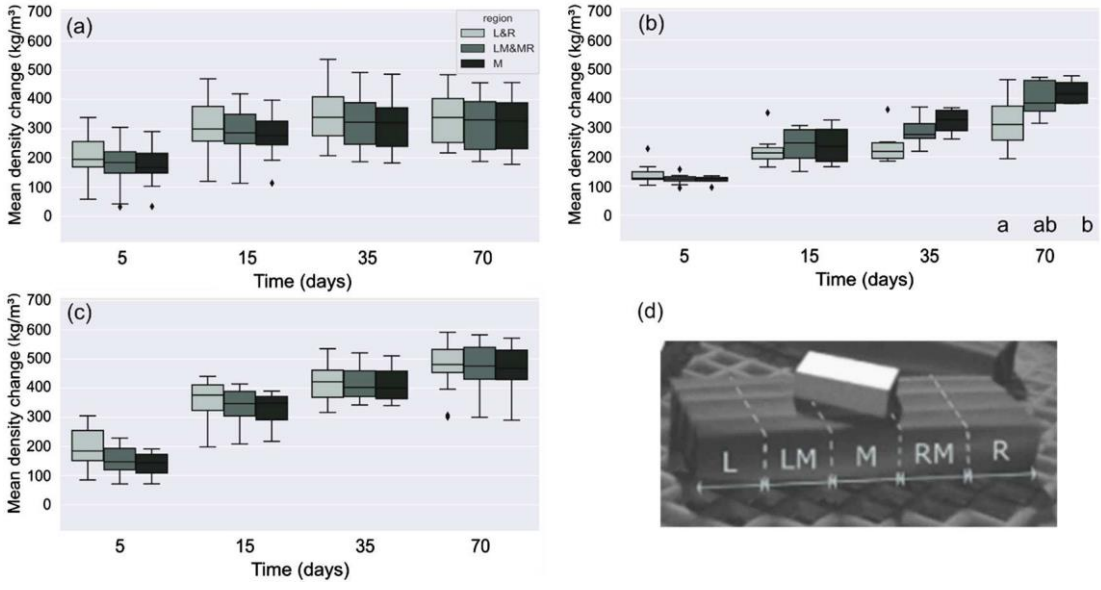

Figure 4. Mean-density change over time averaged over three zones (1.00 × 0.50 × 0.52 cm) along the longitudinal direction of the wood blocks: outer left and right zone (L&R), middle zone (M) and the zone between the left and

middle zone and the middle and right zone (LM&MR). For those regions where the density was significantly different (one-way analysis of variance (ANOVA) p-value <0.05) between regions, a letter (a, b) was assigned based on Tukey's multiple comparison.

The same trend could be observed for TM poplar, with a similar wood density resulting in about 15% less mass loss than unmodified poplar. Note that the outlier samples with a ML of 25% and higher were excluded from the regression for TM specimens. Since all the TM specimens that had a ML of >25% originated from the same thermally modified wood beam (Figure 5, orange circles), it seems that this wood beam was not homogenously modified. As a result, several specimens from this beam experienced a higher mass loss and a lower durability compared to the other specimens, which contributed to a higher variability of mass loss observed in the TM poplar. It is worth noting that this variation is not unusual in thermally modified timber studied, as the modification process can often result in significant changes in wood properties including mass loss, due to the complex interactions between wood components and thermal-treatment parameters (Hill *et al.* 2021). Fungal susceptibility of thermally modified poplar is influenced by environmental factors such as relative humidity and temperature, is a key determinant of wood decay and can significantly impact the durability and lifespan of wood products (Van den Bulcke 2011, Bollmus 2018, Wang 2018, Cappellazzi 2020, Marais 2020, Ayanleye *et al.* 2022).

Since density is correlated to fungal susceptibility, it is crucial to integrate wood density analysis to obtain a comprehensive understanding of the performance and longevity of wood products, particularly for species such as poplar, which exhibit a broad range of quality. Therefore, further research is needed to better understand the relationship between wood density and mass loss for thermally-modified wood and careful classification of poplar is essential to ensure a thorough evaluation of its fungal susceptibility and subsequent impact on the durability of wood products.

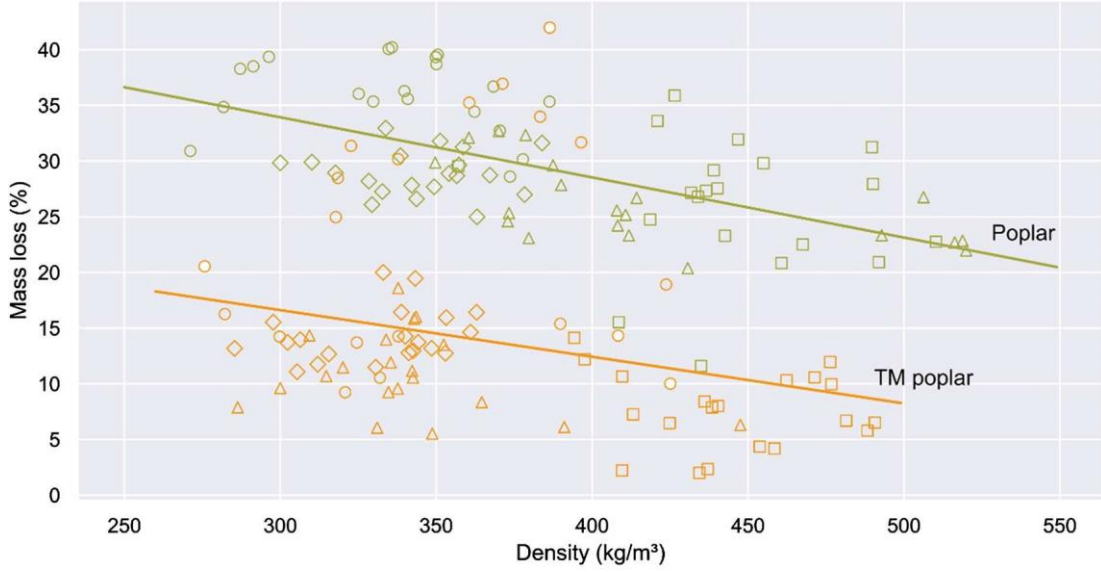

Figure 5. Distribution of density value and the corresponding mass loss of all (TM) poplar mini-blocks from the fungal degradation test (both from X-ray CT scanned samples and non-scanned samples). Same symbols indicate that the specimens are originally from the same wood beams. Symbols in green represent the mass loss of poplar and symbols in orange represent the corresponding mass loss of TM poplar from the same beams. Note that all the TM specimens that have a ML of >25% originated from the same wood beam. The coefficient of determination (R^2) for the linear regression line of poplar was 0.334 and for TM poplar (excluding the samples with a ML of more than 25%, which are presumed not properly modified) was 0.306.

4. Conclusions

X-ray CT has emerged as a versatile and non-invasive analytical technique for evaluating the extent of fungal degradation on a variety of wood species. This imaging modality allows for the real-time visualization and quantification of internal structural changes within the specimens and providing valuable insights into the underlying mechanisms of fungal degradation over time. This research studied the degradation patterns of poplar, thermally modified poplar and spruce, revealing valuable insights into the degradation progress in the wood specimens: the fungal degradation progress in TM poplar is significantly slower than in unmodified poplar even though the MC after five days did not significantly differ between TM and unmodified poplar; unlike poplar or TM poplar, the degradation pattern of spruce showed a higher mass loss from the two cross-sectional sides and lower in the middle whereas with poplar degradation was homogeneous; this study also uncovered a positive correlation between density of poplar and its resistance to fungal degradation, both for unmodified and TM poplar. It is reasonable to conclude that thermal modification has a significant impact not only on the mass loss of wood but also on the progress during the entire degradation period. Consequently, it is important for researchers and industry professionals to carefully consider the potential effects of thermal modification when assessing the long-term durability and environmental impact of poplar wood. The outcomes of this study show the intricate dynamics of wood degradation in (thermally-modified) poplar and spruce and underline the importance of considering density as a crucial factor in the design and selection of poplar as a suited alternative species for spruce in GLT and CLT products for constructions. The findings of this study can also be used to inform strategies for the classification and protection of wooden structures, e.g. thermal modification, and thus may potentially contribute to the development of fast-growing poplar.

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