International Biodeterioration & Biodegradation 104 (2015) 231–237

Contents lists available at ScienceDirect

International Biodeterioration & Biodegradation

journal homepage: www.elsevier.com/locate/ibiod

Comparison between degradation capabilities of the white rot fungi *Pleurotus ostreatus* and *Trametes versicolor* in beech wood

Ehsan Bari [a, b, *], Nouredin Nazarnezhad [a], Seyed Mahmoud Kazemi [a], Mohammad Ali Tajick Ghanbary [c], Behbood Mohebby [d], Olaf Schmidt [e], Carol A. Clausen [f]

[a] Department of Wood and Paper Sciences, Faculty of Natural Resources, University of Agriculture Sciences and Natural Resources, Sari, Iran
[b] Department of Wood Science and Engineering, Technical Faculty of Sari No 2, Sari, Iran
[c] Department of Mycology and Plant Pathology College of Agronomic Sciences, Agriculture and Natural Resources University, Sari, Iran
[d] Department of Wood and Paper Sciences, Faculty of Natural Resources, Tarbiat Modares University, Noor, Iran
[e] Department of Wood Biology, University of Hamburg, Leuschnerstr. 91, 21031 Hamburg, Germany
[f] USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726, USA

ARTICLE INFO

Article history:
Received 5 December 2014
Received in revised form
24 March 2015
Accepted 24 March 2015
Available online 26 June 2015

Keywords:
Pleurotus ostreatus
Trametes versicolor
Fagus orientalis
Mass loss
Compression strength
Hardness
Impact load resistance
FT-IR spectroscopy
Chemical analysis
Microscopy

ABSTRACT

The degradation capabilities of two white rot fungi, *Pleurotus ostreatus* and *Trametes versicolor*, obtained from natural stands of *Fagus orientalis* (beech) in Northern Iran were studied. Fruiting bodies of *P. ostreatus* and *T. versicolor* were collected from fallen beech in the Alamdardeh forest, Iran. Beech wood samples were exposed to both fungi for 120 days according to EN113. Mass loss, resistance to compression parallel to grain, impact load resistance, as well as lignin, cellulose and hemicellulose content were determined in the samples before and after fungal exposure. FT-IR spectroscopy was used to collect spectra after fungal decay. Light and electron microscopy were used to study white-rot decay patterns in wood and compare the mechanism of attack for both fungi. Both fungi reduced wood mass and chemical constituents in similar quantities. Chemical analyses indicated similar reductions in cellulose, lignin and total carbohydrates. Both fungi had negligible affect on the hemicelluloses, arabinan, galactan, and glucan. Patterns of white decay were the same for both fungi. Thinning of the cell walls, colonization of fungal hyphae as well as formation of bore holes on the cell wallswere also similar for both fungi. The results demonstrated that both fungi produced a simultaneous white rot in beech wood.

1. Introduction

In nature, wood undergoes biological decay, primarily by white-, brown- and soft-rot fungi (Eriksson et al., 1990; Zabel and Morrell, 1992; Mohebby, 2003; Schmidt, 2006). Basidiomycetes are responsible for the majority of wood decay. Soft-rot fungi (ascomycetes and deuteromycetes) degrade wood under wet conditions (Findlay and Savory, 1954; Liese, 1955). Fungi use enzymatic and non-enzymatic systems to attack wood cell walls (Zabel and Morrell, 1992; Eaton and Hale, 1993; Schmidt, 2006). Wood undergoes a number of changes during decay; such as mass and strength losses. Significant changes occur in the chemical composition of cell wall during exposure to fungal attack (Schmidt, 2006; Maresi et al., 2013; Bari et al., 2014). Fungal attack is responsible for significant decreases in mechanical and physical wood properties, influencing moisture content, electrical conduction, acoustics, convection, elasticity and plasticity in wood (Cowling, 1961; Schmidt, 2006). The changes cause significant losses in mechanical properties even before measurable weight loss (Curling et al., 2000, 2002). Former studies have already shown a close relationship between the degradation of hemicellulose components and losses in mechanical properties (Wilcox, 1978; Winandy and Morrell, 1993).

White rotting fungi use all the chemical components of wood cell walls. Ecologically, the two fungi evaluated in the study have somewhat different modes of attack. *Pleurotus ostreatus* not only

* Corresponding author. Department of Wood and Paper Sciences, Faculty of Natural Resources, University of Agriculture Sciences and Natural Resources, Sari, Iran.
E-mail addresses: bari_lenzites@yahoo.com, e.bari@sanru.ac.ir (E. Bari), m.tajick@sanru.ac.ir (M.A. Tajick Ghanbary), mohebbyb@modare.ac.ir (B. Mohebby), olaf.schmidt@uni-hamburg.de (O. Schmidt), cclausen@fs.fed.us (C.A. Clausen).

http://dx.doi.org/10.1016/j.ibiod.2015.03.033
0964-8305/

causes saprophytic rot in dead and fallen trees, it also acts as a wounding parasite in living trees. *Trametes versicolor* causes massive saprophytic degradation in dead wood in the forests of Northern Iran. The objective of this study was to compare wood degradation and influence on wood strength properties of *P. ostreatus* and *T. versicolor* to determine if *P. ostreatus* could be a suitable substitute for the EN standard test fungus *T. versicolor*.

2. Material and methods

2.1. Fungal isolation

The fruiting bodies of *P. ostreatus* (Jacq.: Fr.) Kummer and *T. versicolor* (L.: Fr.) Pilát were collected from living beech trees (*Fagus orientalis* Lipsky.) at Alamdardeh forest (located in Sari, Iran). For molecular verification of the fungal species, pure cultures obtained from the fruiting bodies of the fungi were identified by rDNA-ITS analysis according to Schmidt et al. (2012). Fungal DNA was extracted, amplified by polymerase chain reaction (PCR) of the ITS region and sequenced. Identification was done by sequence comparison with sequences deposited in the DNA databases using the BLAST program (Bari, 2014). Pure fungal cultures were maintained on malt extract agar in Petri dishes.

2.2. Sample preparation

Disks were cut from trunks of five beech trees (*F. orientalis* Lipsky.) at breast height and were then air-dried. Wood samples were cut from the prepared disks for related experiments; light microscopy (8 × 8 × 8 mm), mass loss determination (25 × 20 × 15 mm) according to EN 113 (1997), hardness (60 × 20 × 20 mm) according to ASTM-D143-94 for (ASTM, 2000), impact load resistance (60 × 20 × 6 mm) according to ASTM-D256-04 (ASTM, 2004), and compression parallel to grain (50 × 20 × 20 mm) according to ASTM-D143-94 (ASTM, 2000). Ten specimens were cut for each test as replicates. Samples were initially conditioned at 25 °C and RH 40% and then exposed to test fungi for different periods of time.

2.3. Biological resistance

In order to evaluate the degradation capabilities of both fungi, beech wood blocks were cut according to EN 113 and then they were initially oven dried at 103 ± 3 °C and weighed prior to fungal exposure. The wood blocks were then sterilized at 121 °C for 20 min and exposed to fungi grown in Kolle-flasks according to EN113. They were incubated for 120 days at 22 ± 2 °C and relative humidity of 65 ± 5%. Ten replicate specimens were prepared for each treatment. At the end of the incubation the wood samples were taken out and mycelia were removed from the block surfaces. The blocks were oven dried and weighed to calculate the mass loss according to EN 113 (1997).

2.4. Chemical analysis

Changes in the chemical constituents of the wood cell walls following exposure to the test fungi were evaluated according to TAPPI standards test methods as well as a modified method for carbohydrate analysis (Davis, 1998). Decayed wood samples were oven dried, milled and sieved to pass through a mesh size of 40 to determine contents of Klason lignin according to T 222 om-98 (TAPPI, 1998), cellulose according to T 17 wd-70 (TAPPI, 1997), and hemicelluloses according to T 249 cm-85 (TAPPI, 1992). The amounts of hemicellulose, arabinose, galactose, glucose, xylose and mannose, were determined in the decayed wood.

2.5. FT-IR spectroscopy

FT-IR spectra were obtained directly from wood powder, using a Shimadzu 8400s FT-IR Spectrometer equipped with DLATGS detector. All samples were examined at a spectral resolution of 4 cm^{-1} with 30 scans per sample. Background scans were also carried out using a blank collector. A rubber band method was used for each spectra with baseline correction. The band for CO_2 was removed to make a suitable baseline correction (Mohebby, 2003).

2.6. Light and SEM microscopy

2.6.1. Light microscopy

The wood blocks (8 × 8 × 8 mm) were prepared from the degraded wood specimens and sectioned (10–15 μm) using a sliding microtome (GSL_1 Microtome). The sections were stained using a mixture of Safranin 0.5% and Astrablue 0.3% in 1:1 ratio (Mohebby, 2003; Schweingruber et al., 2011; Bari et al., 2015). The stained samples were washed with distilled water for 1–3 min, dehydrated with a 95% and absolute ethanol series for 2–3 min. After rinsing with xylol for 1–2 min, the sections were mounted on slides with Mountalan glue. To avoid buckling of the sample, a 50 g weight was placed on the cover glass while the slide was drying at 60 °C for 12 h. The sections were studied under a light microscope (Olympus E-450) to determine patterns of fungal decay.

2.6.2. Scanning electron microscopy

The specimens (5 × 5 × 5 mm) were fixed with 3% glutaraldehyde in 0.1 M phosphate cacodylate buffer overnight. They were then washed with the same buffer three times for 30 min. Post-fixation was carried out with 1% osmium tetra-oxide in 0.1 M phosphate cacodylate buffer for 4 h. Specimens fixed with osmium tetra-oxide were rinsed in distilled water three times each for 30 min and then dehydrated with an ethanol series (10, 30, 50, 70, 80, 90 and three times 100%) for 30 min each. Critical point drying was applied with CO_2 at 42 °C. The specimens were coated with Au/Pd at 0.4 torr pressure and 20 mA for 3 min. Finally, they were examined under a Jeol JSM-6400 SEM at 15–20 kV (Mohebby, 2003).

3. Results and discussion

3.1. Losses in mass and strengths

Losses in mass and mechanical properties due to both white-rot fungi are shown in Table 1. According to the results, both fungi caused 26% mass loss in beech wood after 120 days of exposure. The mass loss obtained for both *T. versicolor* and *P. ostreatus* are in range of the minimum mass loss of 20% which is necessary for beech wood, according to EN 113 (1997) and ENV 12038 (2002), to demonstrate that the fungus is an aggressive strain (virulence).

Both fungi reduced compression parallel to grain in beech wood to similar degrees as shown in Table 1. The loss in compression

Table 1
Losses in beech wood properties due to white rot fungal attacks after 120 days of exposure.

Fungus	Properties loss in (%)			
	Mass	Compression$_{\parallel}$[a]	Hardness	Impact
P. ostreatus	26.7 ± 2.7	45.97 ± 1.69	18.33 ± 2.31	95.51 ± 0.15
T. versicolor	26.4 ± 1.2	56.03 ± 1.03	32.54 ± 1.35	90.12 ± 0.06

[a] Compression parallel to grain.

strength within the incubation period is quite high and it is an indication of severe degradation.

It should be noted that any decrease in compression parallel to grain was a result of fungal attack and changes in the chemical components of the cell walls, especially decrease in lignin content (Shwarze et al., 2004; Schmidt, 2006) resulting in a reduction in wood density that can also affect strength properties (Kollmann and Côté, 1975).

Hardness of the wood samples was also reduced following exposure to both fungi (Table 1). However, the loss following exposure to *P. ostreatus* was approximately half of the loss following exposure to *T. versicolor*. This result indicates the high decay capability of the fungus *T. versicolor*.

According to previous reports (Curling et al., 2000, 2002), decrease in hardness could be due to loss of hemicellulose. In general, hemicelluloses are responsible for the compression strength perpendicular to grain. The arabinan and galactan are side chain elements of xylan and mannan, the two main hemicellulose polymers (Timell, 1967) and may be either more vulnerable to degradation or may have to be removed before the main chain of the polymer can be attacked (Curling et al., 2002). Reduction in hemicellulose affects integrity of the cell wall polymers and decreases the strength against mechanical loads.

As shown in Table 1, both fungi could reduce the impact load resistance in beech more than 90% which indicates capability of the fungi to attack wood aggressively. Cleaved ether bonds in cellulose are responsible for reduction in impact load resistance (Kubicek, 2013). It is also reported that cell wall thinning, bore holes and appearance of micro-cracks in the cell walls due to fungal degradation are other reasons for strength losses; especially impact load resistance (Kollmann and Côté, 1975). Schwarze et al. (2004) indicated that simultaneous white-rot leads to a brittle fracture of the infected wood because of the progressive degradation of the cellulose-rich secondary wall.

3.2. Chemical analysis and FT-IR spectroscopy

Table 2 shows the average cellulose, lignin, and hemicellulose content, and total carbohydrates in beech wood samples after white-rot decay fungi. As shown in Table 1, both fungi were able to attack cellulose. Hemicelluloses were also used by fungi. Any remaining cellulose and lignin after fungal attack indicates similar capabilities of both fungi to degrade wood. Both fungal species belong to the group of the simultaneous white-rotting fungi which are able to degrade carbohydrates and lignin to a similar extent (Schmidt, 2006). Reduction in cellulose content and increase of the lignin in wood indicate cellulolytic mechanism of the fungi which was used during the degradation of beech wood, although reports indicate both cellulolytic and ligninolytic mechanisms in wood for these fungi (Schmidt, 2006; Kubicek, 2013).

Hemicellulose was the most degraded polymer in beech wood exposed to both fungi. Determination of the total carbohydrate showed similar reduction for beech exposed to both fungi.

Chemical assessments of the decayed wood indicate that the lignin content remaining in the beech wood after 120 days of exposure to *P. ostreatus* was very similar to that of the *T. versicolor*. It was described in the literature that white-rot fungi, such as *T. versicolor*, attack all wood components during initial stages of decay and cause simultaneous white-rot (Cowling, 1961; Kirk, 1973) and fungal species belonging to the genus *Pluerotus* act as lignin-selective delignifiers (Camarero et al., 1994; Martínez et al., 2005; Boddy et al., 2008; Kubicek, 2013). However, the chemical analyses in this study revealed non-selective white-rot decay in both fungi.

The FT-IR spectra of the decayed beech wood by *P. ostreatus* and *T. versicolor* demonstrated changes in wood spectrum; especially peaks of the fingerprint region (Fig. 1). Comparison between the spectra obtained from wood decayed by both fungi revealed the appearance of new peaks and increases in some of the peaks due to fungal enzymatic attacks. There are many well-defined peaks in the fingerprint region of 1800–600 cm^{-1}. The assigned peaks in the region mentioned are unconjugated C=O matching xylan at 1735 cm^{-1} which is increased in wood decayed by both fungi (Mohebby, 2005; Zhang et al., 2013). The increase of the C=O might be related to changes in wood lignin and cleaving aromatic skeletal structures from hemicelluloses due to enzymatic attacks. There was also a new peak which was appeared at 1596 cm^{-1}. This peak is assigned for conjugated C–O stretching (Mohebby, 2005; Zhang et al., 2013). It is an indication of cleavage in lignin structure (Mohebby, 2005). There was also a peak increasing at 1365 cm^{-1} that was assigned for C–H deformation in cellulose and hemicelluloses (Mohebby, 2005; Zhang et al., 2013). Another peak was increased at 1234 cm^{-1} which is assigned for syringyl ring; C–O stretch in lignin and xylan. This result indicates that the bonds between lignin and hemicelluloses are cleaved during the fungal attack. A peak appears at 617 cm^{-1} that is assigned for C–H out of plane. This is an indication of cleavage between lignin and hemicellulose due to fungal attack.

The increases or appearance of the peaks indicate that new bands occurred due to breakdown of hemicellulose and lignin polymers. During fungal attack, different types of hydrolyzing enzymes could be liberated to alter and break linkages in the cell-wall components and release them as small molecules (Mohebby, 2005). During this period, many chemical changes occurred in the cell wall constituents, indicating that both fungi could assimilate them as carbon sources.

The white-rot fungus could remove most of the hemicelluloses, lignin and some cellulose, according to the spectra and assigned peaks (Fig. 1). The results of the chemical analysis as well as the FT-IR spectroscopy confirm ability of the fungi to remove all types of the cell-wall constituents, suggesting that *T. versicolor* is a non-selective white-rot fungus. Chemical analyses and microscopy in other studies have also indicated that this species is a non-selective or simultaneous type and that it removes lignin, hemicelluloses and cellulose (Eriksson et al., 1990; Anagnost, 1998; Highley and Dashek, 1998; Mohebby, 2003, 2005). Chemical changes in beech wood were studied by Pandey and Pitman (2003) and showed a

Table 2
Chemical compositions of beech wood after fungal attack after 120 days exposure.

	Cellulose (%)	Lignin (%)	Hemicelluloses[a]					
			Arabinan (%)	Galactan (%)	Glucan (%)	Xylan (%)	Mannan (%)	Total carbohydrates (%)
Beech wood	39.56 ± 3.19	22.23 ± 0.76	0.62 ± 0.01	2.90 ± 0.03	53.35 ± 1.00	10.10 ± 0.00	0.76 ± 0.06	67.60 ± 1.13
P. ostreatus	31.67 ± 2.85	9.67 ± 0.38	0.63 ± 0.01	2.27 ± 0.02	48.60 ± 0.35	11.20 ± 0.00	0.73 ± 0.00	63.05 ± 0.04
T. versicolor	30.63 ± 4.18	9.47 ± 0.25	0.55 ± 0.00	1.79 ± 0.02	48.35 ± 0.48	11.15 ± 0.13	0.86 ± 0.09	62.65 ± 0.30

[a] Hemicelluloses were calculated according to the total amounts in wood.

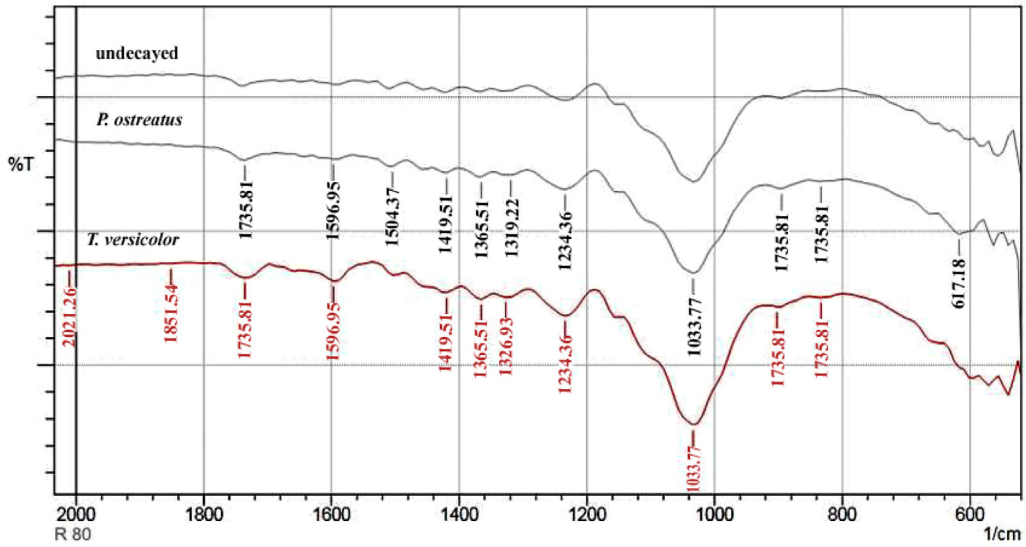

Fig. 1. FT-IR spectra of beech wood (*Fagus orientalis*) after 120 days of exposure to white rot fungi. (1) undecayed, (2), *Pleurotus ostreatus*, (3) *Trametes versicolor*.

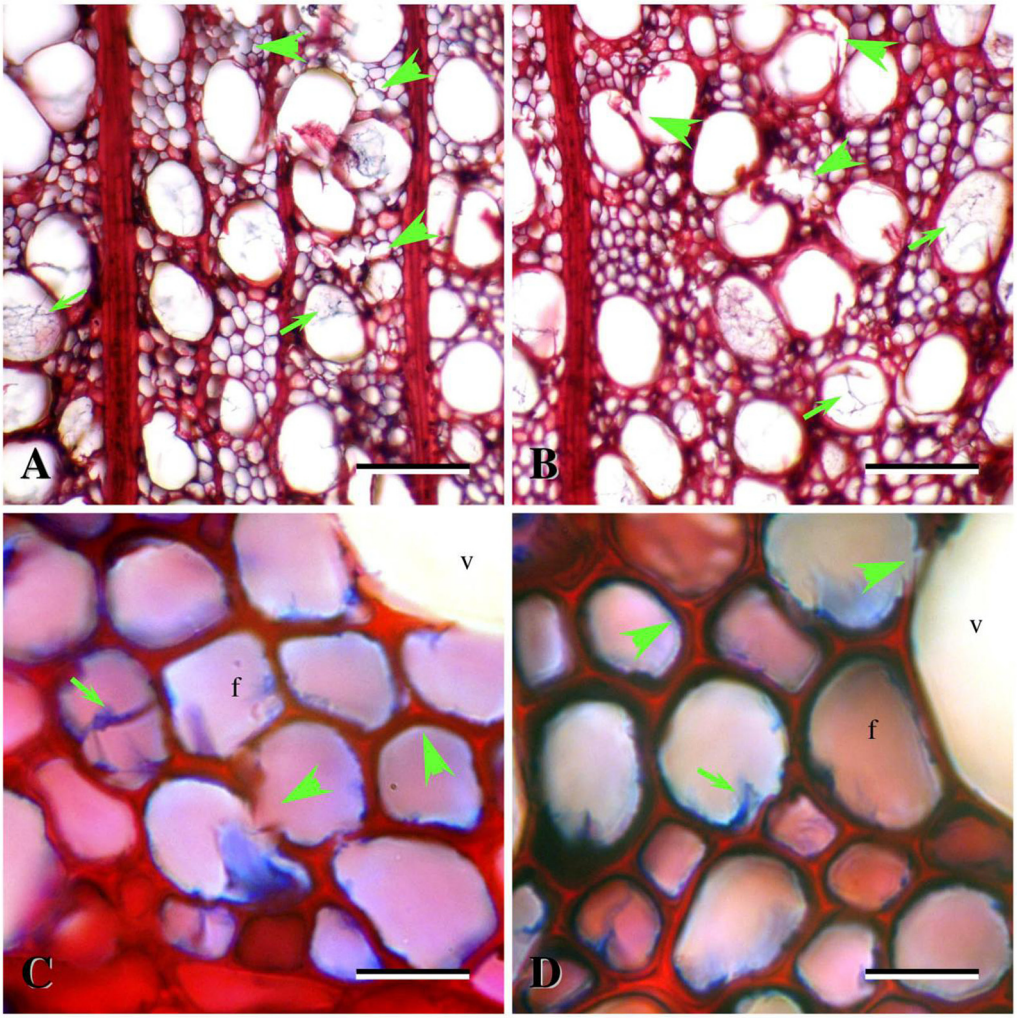

Fig. 2. Light microscopy of white rot decay in beech after 120 days of exposure to the fungi; *Pleurotus ostreatus* (A&C) and *Trametes versicolor* (B&D). A–D: Cross section. Hyphal colonization in vessel lumina (v) and fibers (f); especially vessels (*arrow*). Eroding and rupture in cell walls (*arrowheads*). A&B: bar 70 μm; C&D: bar 20 μm.

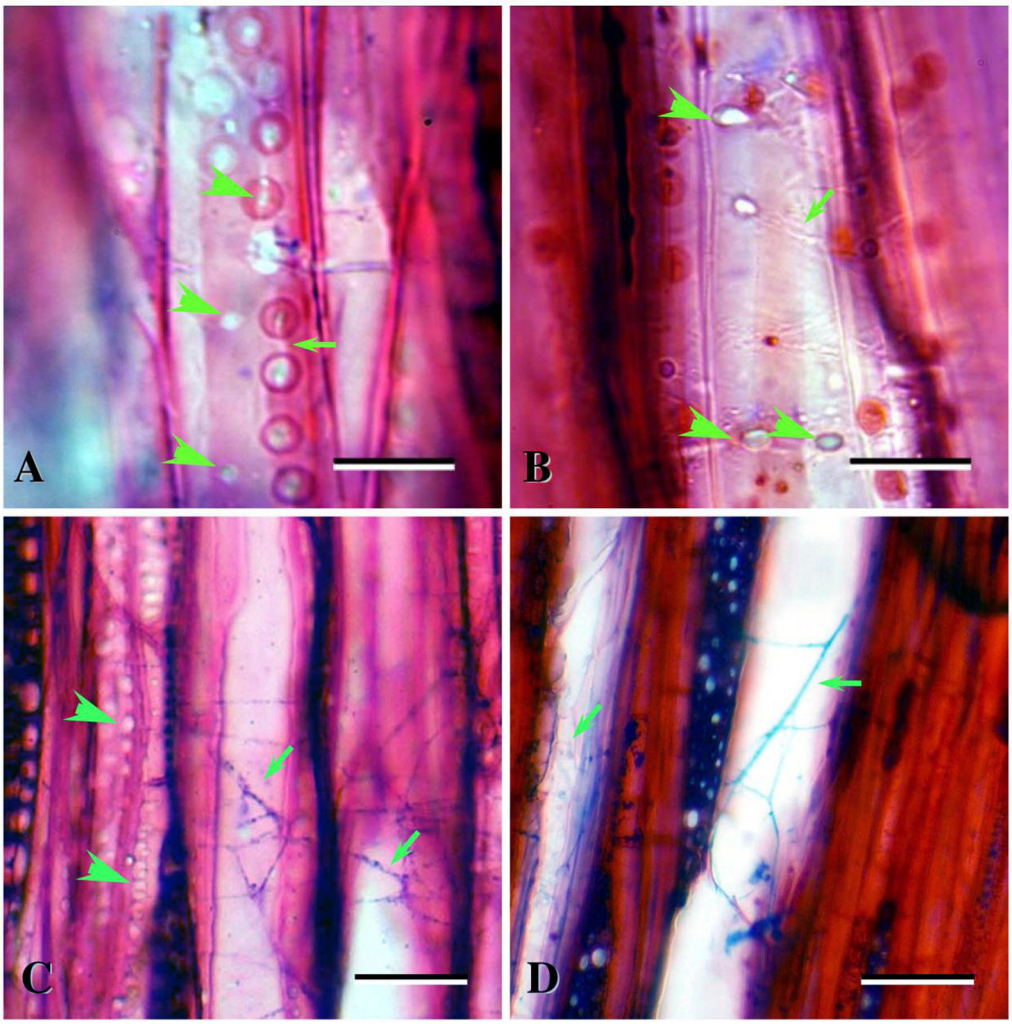

Fig. 3. Light microscopy of white rot decay in beech after 120 days of exposure to the fungi; *Pleurotus ostreatus* (A&C) and *Trametes versicolor* (B&D). A&B: radial sections; C&D: tangential section. Presence of hyphae in vessels lumina (*arrows*) and opening of vessel pits and bore holes on vessel walls (*arrowheads*). A&B: bar 25 μm; C&D: bar 70 μm.

decrease in intensity of bands for lignin and carbohydrate, particularly hemicelluloses. The study indicated that hemicelluloses are preferentially attacked by *T. versicolor*, rather than cellulose. Faix et al. (1993) also studied chemical changes in beech wood decayed by *T. versicolor* using FTIR-spectroscopy and recorded complex bands between 1200 and 900 cm^{-1}; due mainly to changes in polysaccharides and hemicellulose.

The results from this study indicate that the fungi attack the cell-wall components non-selectively and assimilate lignin, hemicelluloses and cellulose, in agreement with the work of previous authors who have used IR spectroscopy (Mohebby, 2005).

3.3. Light and SEM microscopic evaluations

Microscopic evaluations of the attacked beech wood are shown in Figs. 2–4. It was observed that both fungi colonize in cell lumina and attack cell walls by thinning the cell walls and making bore holes on the walls to penetrate through the lumina into the wood. The microscopy revealed similar strategies of attack for both fungi.

In the cross section, it was observed that both fungi colonized their hyphae in vessel members and penetrated into the neighboring cells to develop the degradation mechanism (Fig. 2A–D and Fig. 4A&B). In the case of white-rot decay, it has been shown that hyphae tend to colonize in vessel lumen of infected hardwoods (Wilcox, 1968; Rayner and Boddy, 1988), then, ramify through simple or bordered pits to open pits and ease the hyphal penetration (Cowling, 1961; Wilcox, 1968, 1970; Schwarze, 2007; Bari et al., 2014, 2015).

In the radial views of the attacked wood, it was observed that formation of bore holes in the vessel walls and formation of the bore holes on the cell walls followed nearly the same patterns for both fungi (Fig. 3A&B and Fig. 4C&D). Reports indicate that the bore holes on the cell walls are formed by specialized hyphae with the initial diameter of 0.5 μm or less (Liese, 1970; Schwarze et al., 2004). The mechanism of bore-hole formation by decay fungi has been investigated by several researchers. It has been reported that the hyphae either swelled slightly before penetration (Bayliss, 1908), and constricted into a fine thread to perform the first actual penetration (Nutman, 1929; Sen, 1948), or that there was no change in diameter upon penetration (Cartwright, 1930; Bailey, 1934).

In the tangential view of the attacked wood, colonization of hyphae in vessel members was observed for both fungi (Fig. 3C&D and Fig. 4E&F). Rays and fibers were also deeply eroded by both fungi. Generally, in advanced stages of simultaneous white-rot decay, the cross sections show that cell walls intensively attacked by fungi and fibers become hollow pores after white-rot decay in the same patterns. The reports also indicate severe degradation of rays and fibers due to white-rot attack (Blanchette, 1984a,b;

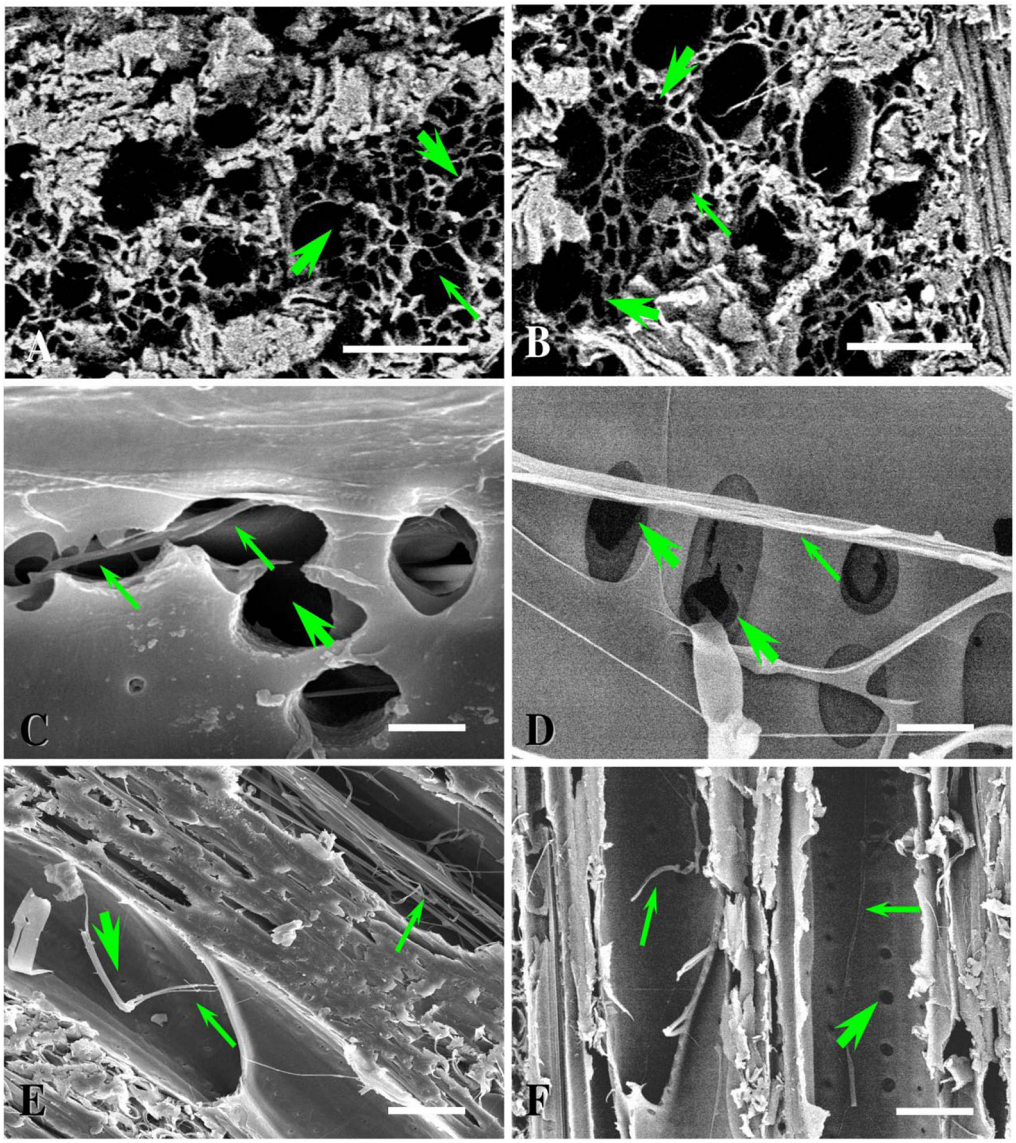

Fig. 4. Scanning electron micrographs of beech wood degradation after 120 days of exposure to the white-rot fungi; *Pleurotus ostreatus* (A,C&E); *Trametes versicolor* (B,D&F). A&B: cross sections: Eroded cell walls (*arrowheads*) as well as colonization of hyphae in cell lumina (*arrows*). C&D: radial sections: Presence of hyphae in vessels (*arrows*) and hyphal attacks in vessel pits and bore holes in vessel walls (*arrowheads*). E&F: tangential section: hyphae in vessels pit (*arrows*) and bore holes in vessel walls (*arrowheads*). A&B: bar 100 μm; C&D: bar 5 μm; E&F: bar 10 μm.

Eriksson et al., 1990; Blanchette and Biggs, 1992; Bari et al., 2014, 2015). According to the results, it can be concluded that both fungi follow similar decaying patterns and decaying mechanisms.

4. Conclusion

Assessments and comparing the degradation capabilities and with rot decay patterns in beech wood due to fungi *P. ostreatus* and *T. versicolor* indicated that both fungi have similar degradation capabilities and they are able to decay beech wood in the same manner and with the same or similar mechanisms. Mass loss, strength loss and reduction in chemical constituents of beech wood were quite similar for both test fungi. The FT-IR spectroscopy confirmed similar changes in wood due to fungal attack. It can be concluded that *P. ostreatus* is comparable in decay capacity with the standard fungus *T. versicolor*.

Acknowledgments

The authors express their sincere gratitude to Fred Matt, Forest Products Laboratory, Madison, USA, for cooperation in extraction of hemicellulose sugars, Mr. Soleyman Zaheri and Mrs. Fatemeh Bavaneghi Sari Natural Resources Faculty's lab director, and Dr. Hamid Reza Naji in Institute of Tropical Forestry and Forest Products, University of Putra Malaysia for the electron microscopy.

References

American Standard for Testing and Material (ASTM International), 2004. Standard Methods for Testing Determining the Izod Pendulum Impact Resistance of Plastics. Standard D 256–4.
American Standard for Testing and Material (ASTM International), 2000. Standard Methods for Testing Small Clear Specimens of Timber. Standard D 143–94.
Anagnost, S.E., 1998. Light microscopic diagnosis of wood decay. IAWA J. 19, 141–167.

Bailey, A.J., 1934. The penetration of fungi through wood. J. For. 32, 1010–1011.
Bari, E., 2014. Potential of Biological Degradation of Oriental Beech Wood by the White-rot Fungus *Pleurotus ostreatus* and the Effects on Mechanical and Chemical Properties There of and its Comparison with Standard the White-rot Fungus *Trametes versicolor*. Sari Agriculture and Natural Resources University, Sari, Iran. Dissertation.
Bari, E., Schmidt, O., Oladi, R., 2015. A histological investigation of Oriental beech wood decayed by *Pleurotus ostreatus* and *Trametes versicolor*. For. Pathol. http://dx.doi.org/10.1111/efp.12174.
Bari, E., Taghiyari, H.R., Mohebby, B., Clausen, C.A., Schmidt, O., Vaseghi, M.J., 2014. Mechanical properties and chemical composition of beech wood exposed for 30 and 120 days to white-rot fungi. Holzforschung. http://dx.doi.org/10.1515/hf-2014-0057.
Bayliss, J.S., 1908. The biology of *Polystictus versicolor* fries. J. Econ. Biol. 3, 1–24.
Blanchette, R.A., 1984a. Screening wood decayed white rot fungi for preferential lignin degradation. Appl. Environ. Microbiol. 48, 647–653.
Blanchette, R.A., 1984b. Selective delignification of eastern hemlock by *Ganoderma tsugae*. Phytopathology 74, 153–160.
Blanchette, R.A., Biggs, A.R., 1992. Defense Mechanisms of Woody Plants against Fungi. Springer-Verlag, New York.
Boddy, L., Frankland, J.C., Van West, P., 2008. Ecology of Saprotrophic Basidiomycetes. Academic Press, London.
Camarero, S., Galletti, G.C., Martínez, A.T., 1994. Preferential degradation of phenolic lignin units by two white rot fungi. Appl. Environ. Microbiol. 60, 4509–4516.
Cartwright, K.S.T.G., 1930. A Decay of Sitka Spruce Timber, Caused by Trametes Serialis, Fr. A Cultural Study of the Fungus. Deptartment of Scientific and Industrial Research. Forest Products Research, London, p. 26. Bulletin, No 4.
Cowling, E.B., 1961. Comparative Biochemistry of the Decay of Sweetgum Sapwood by White-rot and Brown-rot Fungi. USDA Forest Service, Washington, DC. Technical Bulletin–1258.
Curling, S.F., Winandy, J.E., Clausen, C.A., 2000. An Experimental Method to Simulate Incipient Decay of Wood by Basidiomycete Fungi. IRG/WP/00–20200. International Research Group on Wood Protection, Stockholm, Sweden.
Curling, S.F., Clausen, C.A., Winandy, J.E., 2002. Relationships between mechanical properties, weight loss, and chemical composition of wood during incipient brown-rot decay. For. Prod. J. 52, 34–39.
Davis, M.W., 1998. A rapid modified method for compositional carbohydrate analysis of lignocellulosics by high pH anion-exchange chromatography with pulsed amperometric detection (HPAEC/PAD). J. Wood Chem. Technol. 18 (2), 235–252.
Eaton, R.A., Hale, M.D.C., 1993. Wood: Decay, Pests and Protection. Chapman and Hall, London.
Eriksson, K.E.L., Blanchette, R.A., Ander, P., 1990. Microbial and Enzymatic Degradation of Wood and Wood Components. Springer- Verlag, New York.
EN 113, 1997. Wood Preservatives-determination of the Toxic Values against Wood Destroying Basidiomycetes Cultured on Agar Medium.
ENV 12038, 2002. Durability of Wood and Wood-based Products – Wood-based Panels – Method of Test for Determining the Resistance against Wood-destroying Basidiomycetes. Beuth Verlag, Berlin.
Faix, O., Bremer, J., Schmidt, O., Stevanovic, T., 1993. Monitoring of chemical changes in white-rot degraded beech wood by pyrolysis gas chromatography and Fourier transform infrared spectroscopy. J. Anal. Appl. Pyrolysis 21, 147–162.
Findlay, W.P.K., Savory, J.G., 1954. Moderfäule. Die Zersetzung von Holz durch niedere Pilze. Holz Werkst. 12, 293–296.
Highley, T.L., Dashek, W.V., 1998. Biotechnology in the study of brown- and white-rot decay. In: Bruce, A., Palfreyman, J.W. (Eds.), Forest Products Biotechnology. Taylor and Francis, London, pp. 15–36.
Kirk, T.K., 1973. The chemistry and biochemistry of decay. In: Nicholas, D.D. (Ed.), Wood Deterioration and its Preservation by Preservative Treatments, vol. 1. Syracuse University Press, Syracuse, pp. 149–181.
Kollmann, F.F.P., Côté Jr., W.A., 1975. Principles of wood science and technology. In: Solid Wood, vol. 1. Springer – Verlag, New York.
Kubicek, C.P., 2013. Fungi and Lignocellulosic Biomass. John Wiley & Sons, Inc, India.
Liese, W., 1955. On the decomposition of the cell wall by micro-organisms. In: Record of the Annual Convention British Wood Preservation Association, Cambridge, pp. 159–160.
Liese, W., 1970. Ultrastructural aspects of woody tissues disintegration. Annu. Rev. Phytopathol. 8, 231–258.
Maresi, G., Oliveira Longa, C.M., Turchetti, T., 2013. Brown rot on nuts of *Castanea sativa* mill: an emerging disease and its causal agent. iForest Biogeosciences For. 6, 294–301.
Martínez, A.T., Speranza, M., Ruiz-Dueñas, F.J., Ferreira, P., Camarero, S., Guillén, F., Martínez, M.J., Gutiérrez, A., del Río, J.C., 2005. Biodegradation of lignocellulosics: microbial, chemical, and enzymatic aspects of the fungal attack of lignin. Int. Microbiol. 8, 195–204.
Mohebby, B., 2003. Biological Attack of Acetylated Wood. Göttingen University, Germany. PhD thesis.
Mohebby, B., 2005. Attenuated total reflection infrared spectroscopy of white-rot decayed beech wood. Int. Biodeterior. Biodegrad. 55, 247–251.
Nutman, F.J., 1929. Studies of wood-destroying fungi. I. *Polyporus hispidus* (Fries). Ann. Appl. Biol. 16, 40–64.
Pandey, K.K., Pitman, A.J., 2003. FTIR studies of the changes in wood following decay by brown-rot and white-rot fungi. Int. Biodeterior. Biodegrad. 52, 151–160.
Rayner, A.D.M., Boddy, L., 1988. Fungal Decomposition of Wood: its Biology and Ecology. Wiley, Chichester.
Schmidt, O., 2006. Wood and Tree Fungi: Biology, Damage, Protection, and Use. Springer- Verlag, Germany.
Schmidt, O., Gaiser, O., Dujesiefken, D., 2012. Molecular identification of decay fungi in the wood of urban trees. Eur. J. For. Res. 131, 885–891.
Schwarze, F.W.M.R., Engels, J., Mattheck, C., 2004. Fungal Strategies of Wood Decay in Trees, second ed. Springer- Verlag, New York.
Schwarze, F.M.W.R., 2007. Wood decay under the microscope. Fungal Biol. Rev. 21, 133–170.
Schweingruber, F.H., Börner, A., Schulze, E.D., 2011. Atlas of Stem Anatomy in Herbs, Shrubs and Trees, vol. 1. Spinger- Verlag, Germany.
Sen, J., 1948. Orientation of cellulose and its relation to decay cavities in the secondary walls of ehir (*Pinus longifolia*) tracheids. Sci. Cult. (Calcutta) 14, 163–164.
Technical Association of Pulp and Paper Industry (TAPPI), 1998. Standard Methods for Acid-insoluble Lignin in Wood and Pulp. Standard T 222 Om–98.
Technical Association of Pulp and Paper Industry (TAPPI), 1992. Standard Methods for Carbohydrate Composition of Extractive-free Wood and Wood Pulp by Gas-liquid Chromatography. Standard T249 Cm–85.
Technical Association of Pulp and Paper Industry (TAPPI), 1997. Cellulose in Wood. Standard T 17 Wd–97.
Timell, T.E., 1967. Recent progress in the chemistry of wood hemicelluloses. Wood Sci. Technol. 1, 45–70.
Wilcox, W.W., 1968. Changes in Wood Microstructure through Progressive Stages of Decay. U.S. Forest Service Research Paper FPL–70.
Wilcox, W.W., 1970. Anatomical changes in wood cell walls attacked by fungi and bacteria. Botanical Rev. 36, 1–28.
Wilcox, W.W., 1978. Review of literature on the effects of early stages of decay on wood strength. Wood Fiber 9, 252–257.
Winandy, J.E., Morrell, J.J., 1993. Relationship between incipient decay, strength, and chemical composition of Douglas-Fir heartwood. Wood Fiber Sci. 25, 278–288.
Zabel, R.A., Morrell, J.J., 1992. Wood microbiology. Academic Press, New York.
Zhang, S.Y., Wang, C.G., Fei, B.H., Yu, Y., Cheng, H.T., Tian, G.L., 2013. Mechanical function of lignin and hemicelluloses in wood cell wall revealed with microtension of single wood fiber. BioResources 8, 2376–2385.