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Influence of xylem ray integrity and degree of polymerization on bending strength of beech wood decayed by *Pleurotus ostreatus* and *Trametes versicolor*

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ABSTRACT

The scope of this research was to evaluate the influence of xylem ray (XR) and degree of polymerization (DP) of holocellulose in Oriental beech wood (*Fagus orientalis* Lipsky.) on impact bending strength against two white-rot fungi. Beech wood specimens, exposed to *Pleurotus ostreatus* and *Trametes versicolor*, were evaluated for impact bending strength at 15-day intervals for 120 days. Microscopic evaluations at each time interval indicated that both fungi degraded marginal ray parenchyma at early stages of decomposition causing a drastic loss in impact bending strength. However, the two fungi differed in their ability to reduce DP; DP and xylem ray integrity (without precedence) were the most important factors in mechanical stability of beech wood.

1. Introduction

Lignocellulosic biomass is renewable, and huge amounts of lignocellulose are annually synthesized and degraded in nature. White-rot fungi are a heterogeneous group of fungi that usually belong to basidiomycetes (Zabel and Morrell, 1992; Blanchette, 1995; Liers et al., 2006; Schmidt, 2006). Basidiomycete white-rot fungi and some related litter-decomposing fungi are the only organisms which are capable of mineralizing lignin efficiently (Kirk and Cullen, 1998; Hatakka, 2001). More than ninety percent of all wood-rotting basidiomycetes are of the white-rot type and they are predominantly found in hardwoods (Gilbertson, 1980; Bari and Tajick Ghanbari, 2015). Many white-rot fungi colonize cell lumina and cause cell wall erosion. Eroded zones coalesce as decay progresses and large voids filled with mycelium are formed. This type of rot is referred as non-selective or simultaneous rot (Eriksson et al., 1990; Blanchette, 1995; Schmidt, 2006; Bari et al., 2014, 2015b).

Ray parenchyma cells are ribbon-like structures that occur in various arrangements. These cells function for water conduction, support, and transport and storage of nutrients (Erikson et al., 1990; Ilvessalo-Pfäffli, 1995; Carlquist, 2001). In hardwoods, average ray volumes range from about 7% to about 30% (Ilvessalo-Pfäffli, 1995). Rays occupy about 20–27 % of beech wood by volume. Ray cells vary in size and shape, and have simple (more common) or bordered pits (Zabel and Morrell, 1992; Ilvessalo-Pfäffli, 1995). The fact that microfibril angles are assumed to be high in ray cells suggests a mechanical role of these cells beyond their water and nutrient transport and storage capacity (de Borst and Bader, 2014). Actually, the rays are a critical factor in the strength of wood. A significance role of rays, from the mechanical viewpoint is their

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elasticity against horizontal load (Mattheck and Kubler, 1997). The contribution of ray cells to some mechanical properties like radial stiffness has already been shown (Burgert et al., 2001). High fractions of ray cells in hardwoods appears to contribute to stem mechanical stability (Fonti and Frey, 2002; Zheng and Martínez-Cabrera, 2013). However, the role of rays in relation to mechanical behavior of decayed wood has not been studied in detail (e.g. Schwarze, 1995).

The source of strength in solid wood is the wood fiber. Wood is basically a series of tubular fibers or cells cemented together. Each fiber wall is composed of various quantities of three polymers: cellulose, hemicelluloses, and lignin. Cellulose is the strongest polymer in wood and, thus, is highly responsible for strength in the wood fiber because of its high degree of polymerization and linear orientation (Winandy and Rowell, 2005). On the molecular level, aggregations of cellulose chains are hydrogen bonded into a long, thin chain (microfibril) encrusted in the lignin-hemicellulose matrix (Sweet and Winandy, 1999). Changes in temperature, pressure, humidity, pH, chemical adsorption from the environment, UV radiation, fire, or biological degradation can have significant effects on the strength of wood (Winandy and Rowell, 1984; Rowell, 2005). Cellulose has long been thought to be primarily responsible for strength in the wood fiber because of its high degree of polymerization and linear orientation. Hemicellulose may act as a link between the fibrous cellulose and the amorphous lignin. Hemicellulose definitely acts as a matrix for the cellulose and also to increase the packing density of the cell wall (Lebow and Winandy, 1999; Winandy and Lebow, 2001). Lignin is thought to serve as a stiffener for the fiber. It has often been speculated that the long, linear cellulose molecules are primarily responsible for the strength of the fiber. However, a single microfibril or a group of microfibrils cannot entirely account for the strength of an entire fiber (Winandy and Rowell, 1984). The chemical-mechanical linkages between the cellulose microfibril and the lignin-hemicellulose matrix and the adjacent microfibril allow a lateral load to be shared among both microfibrils. When the cellulosic microfibrils and lignin-hemicellulose matrix act as a continuum, internal stress can be efficiently distributed across the cell wall and throughout the entire fiber. It is this ability for intrafiber stress distribution and load sharing that enables wood fibers to functionally act as a composite material (Sweet and Winandy, 1999).

Toughness or impact strength is the ability of wood to absorb the force of impact bending and characterizes the ability of material to withstand impact loads. Impact strength is expressed as the energy consumed while breaking wood with defined dimensions. This mechanical property is most sensitive to decay and unlike other strength properties that decrease gradually as decay progresses, impact strength declines rapidly during incipient wood decay (Rowell, 2005). We hypothesized that this decline in mechanical properties of wood - especially impact bending-is related to anatomical and/or chemical alteration in xylem. Therefore, the objectives of this research were to investigate the influence of xylem ray integrity and the degree of polymerization on impact bending strength of decayed and undecayed beech wood, and to determine the relationship between impact bending strength and changes in the DP of cellulose and chemical composition.

2. Materials and methods

2.1. Specimen preparation

Wood blocks were obtained from beech trees (*Fagus orientalis* Lipsky) at breast height and air-dried to reach 23 ± 2% moisture content. Specimens of $25_l \times 20_r \times 15_t$ mm according to the EN113 (1997) were used for determination of mass loss (ML), and $60_l \times 20_r \times 6_t$ mm according to ASTM-D256-04 (ASTM, 2004) for testing impact bending strength. The specimens used to evaluate impact bending strength were cut in cross section. Ten replicate specimens were prepared from different disks for each test. They were kept in a conditioning chamber (25 °C, and 40 ± 3% RH) for 4 weeks before testing because wood has a thermo-hygromechanical behavior and its properties depend on the combined action of temperature, relative humidity, and mechanical load variations (Figueroa et al., 2012).

2.2. Source of fungi

Two white-rot fungi, *Pleurotus ostreatus* and *Trametes versicolor* were used in this research. The sources of fungi are described in previous publications (Bari et al., 2015c). Fungi had been verified in accordance with Schmidt et al. (2012).

2.3. Fungal degradation

Wood samples were oven dried at 103 ± 2 °C and weighed. The wood blocks were sterilized at 121 °C for 20 min and exposed to the test fungi in Kolle-flasks. Wood specimens were incubated for 120 days at 24 ± 2 °C and 65 ± 5% RH. Ten samples were harvested at 15 day intervals, brushed clean of mycelia, oven dried and weighed to calculate ML according to EN113 (EN113, 1997) and moisture content.

2.4. Mechanical experiments

2.4.1. Unnotched impact bending strength

Impact bending strength was determined according to ASTM-D256-04 using Equation (1).

$$I = \frac{F_{max}}{A} \quad (1)$$

Where; I is resistance to impact (J/m^2), F_{max} = force (J), A = cross section area (m^2).

2.5. Chemical analyses

2.5.1. Extractives free wood preparation

After the mechanical tests, the samples were ground to pass a 40-mesh (0.4 mm) screen to obtain same sizes of particles. Then, wood extractives were removed by a mixture of ethanol-acetone (1:2) for 8 h, ethanol 95% for 4 h and hot water for 1 h according to T 264 cm-97 (TAPPI, 1997) to prepare extractive free wood for extraction of holocellulose.

2.5.2. Extraction of holocellulose

Holocellulose was prepared according to the method of Mohebby (2003). About 2 g extractive free wood was placed in a 100 ml Erlenmeyer and 80 ml distilled water was added. Also, 0.25 ml acetic acid (100%) and 0.75 g sodium chlorite ($NaClO_2$) were added into the Erlenmeyer flasks and closed with a glass bubble. The flasks were held at 80 °C for 1 h in a hot water bath. Extractions were repeated three times at 80 °C. Extracted samples were cooled in an ice-water bath, filtered with a glass filter, and washed with 100 ml distilled ice-water and 25 ml acetone. The filtered samples were dried at 105±3 °C and weighed.

2.5.3. Degree of polymerization

Degree of polymerization (DP) of holocellulose of sound and decayed beech wood was determined according to the method of Straus and Levy (1942). For each sample, 10 mg of holocellulose

weighed with 0.001 g precision was dissolved in 10 ml cupri-ethylene diamine for 30 min at 25 °C before measuring viscosity of the resulting solution using a #300 Canon-Fenske capillary viscosimeter in a constant temperature bath at 25 °C. Relative viscosity is a ratio of the efflux time for the solution and the efflux time of the solvent. Average DP values were calculated from the intrinsic viscosity measurements on a per gram basis (ASTM, 2012).

2.6. Light and electron microscopic imaging

2.6.1. Light microscopy

Mini blocks (8 × 8 × 8 mm) were cut from degraded wood specimens and sectioned (10–15 μm) using a sliding microtome equipped with high quality removable blades (GSL_1 microtome, WSL). All sections were triple-stained with 0.5% aqueous Safranin, 0.3% aqueous Astrablue and 1% aqueous Picrin-Anilinblue mixed in 1:1:1 ratio for 3–5 min (Gartner and Schweingruber, 2013; Bari et al., 2015b). Samples were mounted on microscopic slides via Mountalan glue. To avoid buckling of the sample, a 50 g weight was placed on the cover glass edges while the slide was drying at 60 °C for 12 h. Dried sections were examined microscopically and photographed with the Olympus microscope and an Olympus E-450, camera.

2.6.2. Scanning electron microscopy

Small blocks (5 × 5 × 5 mm) were cut from degraded and sound wood specimens and the fixed overnight with 3% glutaraldehyde in 0.1 M phosphate cacodylate buffer. They were rinsed in 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. Fixed specimens were washed with distilled water three times each for 30 min followed by dehydration with an increasing ethanol percentage (10, 30, 50, 70, 80, 90 and three times 100%) for 30 min (each step). Critical point drying was applied with CO_2 at 42 °C. Sections were then mounted on SEM stubs, sputter coated to a thickness of 30 nm with gold. A SEM micrograph (VEGA\\TESCAN-LMU) was used for observation (Mohebby, 2003).

3. Results and discussion

3.1. Mass loss determination

The average mass loss (ML) percentage for wood samples exposed to *P. ostreatus* and *T. versicolor* at different incubation times is summarized in Table 1. A general ascending trend and a similar final ML for two studied fungi can be deduced from this table. However, after forty five and ninety days, the average ML caused by both fungi showed a slight decrease. This is attributed to a temporary dysfunction in the incubator resulting in decreased humidity or probably due to the natural variation among the different sets of samples. Controlled moisture content is important for white-rot fungal metabolism (Cowling, 1961). Since the amount of enzyme secretion in white-rot fungi is highly related to the environmental moisture content (Eriksson et al., 1990; Kubicek, 2013), even a few days of decline in access to substrate water, especially in *T. versicolor*, may inhibit the decay process.

3.2. Moisture content due to fungal activity

The results demonstrated that the moisture contents (MC) of the decayed wood blocks correlated with the mass losses for both decay fungi (Fig. 1). It seems that ML and MC have a mutual relationship: the metabolic activities of any fungus leads to the formation of energy-rich adenosine triphosphate (ATP) which is necessary to produce as well as release fungal enzymes (Zabel and Morrell, 1992; Eaton and Hale, 1993; Schmidt, 2006). These fungal activities by themselves increase the moisture content of wood. However, fungi do not get the total water, which is measured in degraded wood, from the respiration of wood cellulose. It has to be considered that cellulose is not completely degraded to CO_2 and 56% water, instead intermediate metabolites for the synthesis of fungal biomass are produced and about 40% of the consumed cellulose is used for those metabolites (Schmidt, 2006). Thus, a great part of water in degraded wood is due to the capability of wood decay fungi to transport water from a wet source (e.g. growth medium) to dry wood, as it occurred with several indoor wood decay basidiomycetes (Stienen et al., 2014). On the other hand, the major cell-wall constituents of wood are large macropolymers that are insoluble in water. Hence, any increase in the mass losses (due to fungal activity) could change the chemical composition of the

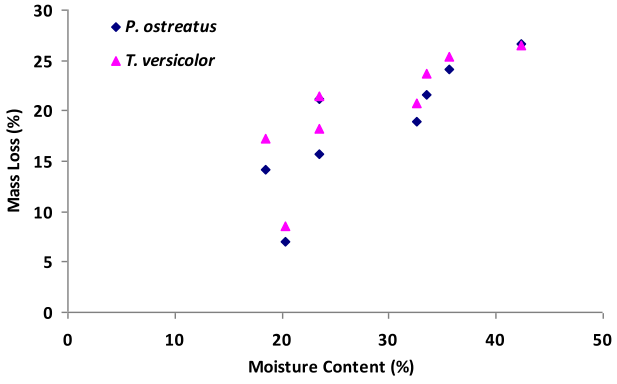

Fig. 1. Correlation between moisture content and mass loss due to the white-rot fungi *P. ostreatus* (◆) and *T. versicolor* (▲).

Table 1
Average of percent properties losses in decayed Oriental beech wood samples by white-rot fungi.

Fungus	Wood property	Exposure time (days)								
		0	15	30	45	60	75	90	105	120
P. ostreatus	Mass[a]	0	7.03 ± *0.51*	15.65 ± *0.44*	14.15 ± *0.02*	18.88 ± *0.09*	21.57 ± *0.30*	21.18 ± *0.02*	24.10 ± *0.10*	26.66 ± *2.70*
	Density[b]	0	31.07 ± *0.87*	28.25 ± *2.63*	37.35 ± *0.67*	28.27 ± *1.32*	27.68 ± *4.55*	31.11 ± *2.47*	28.00 ± *1.06*	26.73 ± *1.70*
	Impact bending[a]	0	70.20 ± *0.03*	82.17 ± *0.01*	77.22 ± *0.06*	83.43 ± *0.39*	87.11 ± *0.24*	82.73 ± *0.08*	92.29 ± *0.01*	95.51 ± *0.15*
	DP	0	57.17 ± *1.67*	81.16 ± *0.60*	70.13 ± *0.16*	75.06 ± *0.50*	73.31 ± *0.50*	63.93 ± *0.95*	70.00 ± *0.73*	74.98 ± *0.66*
T. versicolor	Mass[a]	0	8.50 ± *0.63*	18.21 ± *0.64*	17.21 ± *0.64*	20.74 ± *0.63*	23.73 ± *0.12*	21.46 ± *0.50*	25.32 ± *0.67*	26.43 ± *1.20*
	Density[b]	0	36.20 ± *0.18*	39.99 ± *3.22*	44.51 ± *0.92*	33.07 ± *3.86*	35.59 ± *9.22*	37.27 ± *8.07*	30.05 ± *2.08*	26.42 ± *3.44*
	Impact bending[a]	0	67.26 ± *0.04*	87.86 ± *0.8*	84.10 ± *0.12*	88.64 ± *0.69*	89.50 ± *0.33*	79.40 ± *0.21*	90.35 ± *0.45*	90.12 ± *0.06*
	DP	0	38.28 ± *0.15*	20.98 ± *0.40*	52.75 ± *0.06*	42.83 ± *0.11*	37.73 ± *0.24*	44.99 ± *0.28*	26.90 ± *0.35*	36.03 ± *0.16*

± values represent standard deviations of the means.
[a] Bari et al., 2015d.
[b] The determination of wood samples density is based on oven dry condition (D_o).

wood and result in an increase in MC. However, it should be considered that a great share of the final wood moisture content is due to fungal water transport from a wet source (Schmidt, 2006; Stienen et al., 2014), e.g. from agar in Kolle flasks.

3.3. Impact bending strength

The impact strength showed a sharp decrease after the first 15 days of exposure for both fungi (Table 1). This is agreement with other studies which also showed a rapid loss in the wood impact bending strength at the initial phase of exposure to white rot fungi (Armstrong and Savory, 1959; Henningsson, 1967; Wilcox 1978; Fengel and Wegner, 1989; Bari et al., 2015d). The strength values continued to significantly decrease until the 30th day of exposure for both fungi. Following this the strength loss values were somewhat erratic, exhibiting a slight additional decrease after 120 days exposure. The average density of sound beech wood samples was about 0.76 g/cm^3 which, in parallel with the high strength loss, dramatically decreased after just 15 days of exposure to the fungi. This synchronization indicates the close correlation between wood density and impact bending strength (Kollmann and Côté, 1968; Eaton and Hale, 1993).

3.4. Chemical analyses

The two test fungi differed in their ability to decompose cellulose; *P. ostreatus* degraded the chains of cellulose at a greater intensity and decreased DP more severely than *T. versicolor* (Table 1).

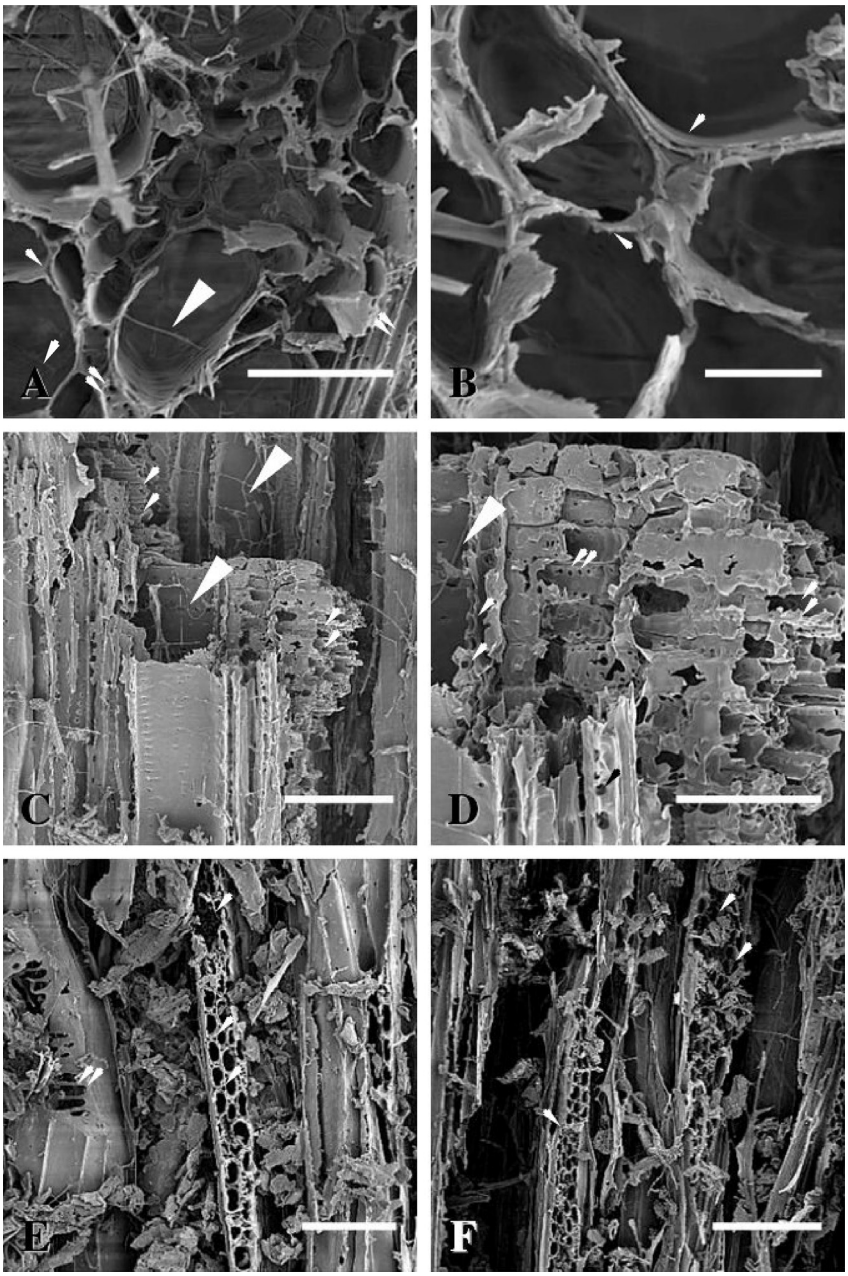

Fig. 2. Scanning electron micrographs of decay patterns in Oriental beech wood after 120 days of exposure to *Pleurotus ostreatus*. A–B: Cross views show the eroded and ruptured cell walls as well as hyphae colonizing the cell wall; C–D: Radial views show the presence of hyphae on vessel wall and completely decomposition of parenchyma; C–D: Tangential section show hyphae in vessel lumen and bore holes in vessel walls as well as decomposition of the ray walls. Scale bars in A, D, E: 50 μm; B: 10 μm; C, F: 100 μm.

Former studies (Bari, 2014; Bari et al., 2014, 2015a, b, c, d) demonstrated that both fungi consume all chemical cell wall components at approximately the same rate. However, at the molecular level, there were obvious differences.

The white-rot fungi which produce simultaneous decay in wood consume all components of xylem including carbohydrates as well as lignin (Eriksson et al., 1990; Schmidt, 2006). However, the mechanical properties, especially MOE, MOR, and impact bending are highly influenced by the cellulose component (Kollmann and Côté, 1968; Parsapajouh, 2000). It is believed that the cellulose is primarily responsible for strength in the wood fiber because of its high degree of polymerization and linear orientation (Lebow and Winandy, 1999; Winandy and Lebow, 2001). Fungi use a hydrolysis system for degradation of cellulose bonds (Kubickek, 2013). They degrade cellulose by hydrolyzing the β-1,4-glycosidic bonds using extracellular enzymes (endoglucanases), which break down crystalline cellulose to cellobiose (Sweet and Winandy, 1999; Kubickek, 2013).

3.5. Anatomical evaluation of decayed beech wood

Microscopic images showed similar decaying patterns for both fungi (Figs. 2–5). Generally, *T. versicolor* and *P. ostreatus* caused a simultaneous decay of the beech wood (Bari et al., 2014, 2015a, b, d).

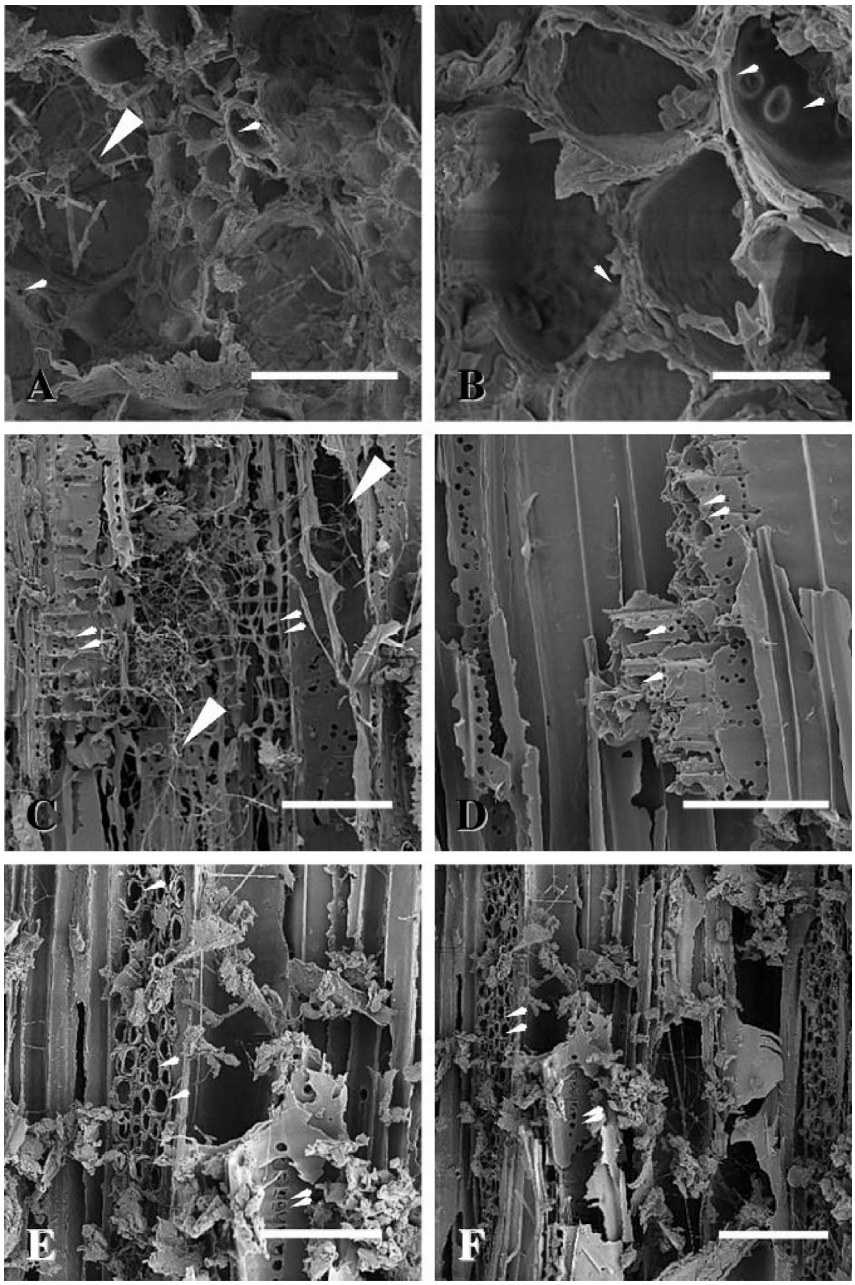

Fig. 3. Scanning electron micrographs of decay patterns in Oriental beech wood after 120 days of exposure to *Trametes versicolor*. A–B: Cross-sectional views show the decomposition of cell walls as well as hyphae colonizing the cell lumen; C–D: Radial views show the accumulated of hyphae on vessel wall and completely decomposition of xylem rays; C–D: Tangential section show tumble of cell element and hyphae colonization in vessel lumen and bore holes in vessel walls as well as decomposition of the ray walls. Scale bars in A, D, E: 50 μm; B: 10 μm; C, F: 100 μm.

In cross section, both fungi decreased the cell wall thickness gradually. At the early stages of decomposition, the thinning and rupture of fiber cell walls were not severe and S_2 layers of the most fibers have not been removed yet. However, the contacting cells between large rays and fibers were appreciably deteriorated (Fig 5A and B; Figs. 2, 3F and 4 E, F). With increasing incubation time, the progressive thinning of fiber cell walls continued until only middle lamella of fibers remained intact (Figs. 2, 3B and 4 A, B). Total separation of large rays from ground tissue was observed at this phase (Fig 4E). At the very advanced stages of decay, even middle lamellae were affected and voids were formed (Fig 2A; 5C).

3.6. The effect of molecular, microscopic, and macroscopic alteration of wood on impact bending strength during decomposition courses

During incipient wood decay, serious strength loss can occur before it is visually detected (Rowell, 2005). This can be more severe in wood species with several-millimeters-long rays like beech and when exposed to brown-rot fungi. Mattheck and Kubler (1997) explained that in both cases, the potential of a brittle fracture in wood is higher; large rays act as “radial rigid boards” and make wood inelastic. This is the same for woods decayed by a fungus which preferably degrade cellulose (brown-rot), since the

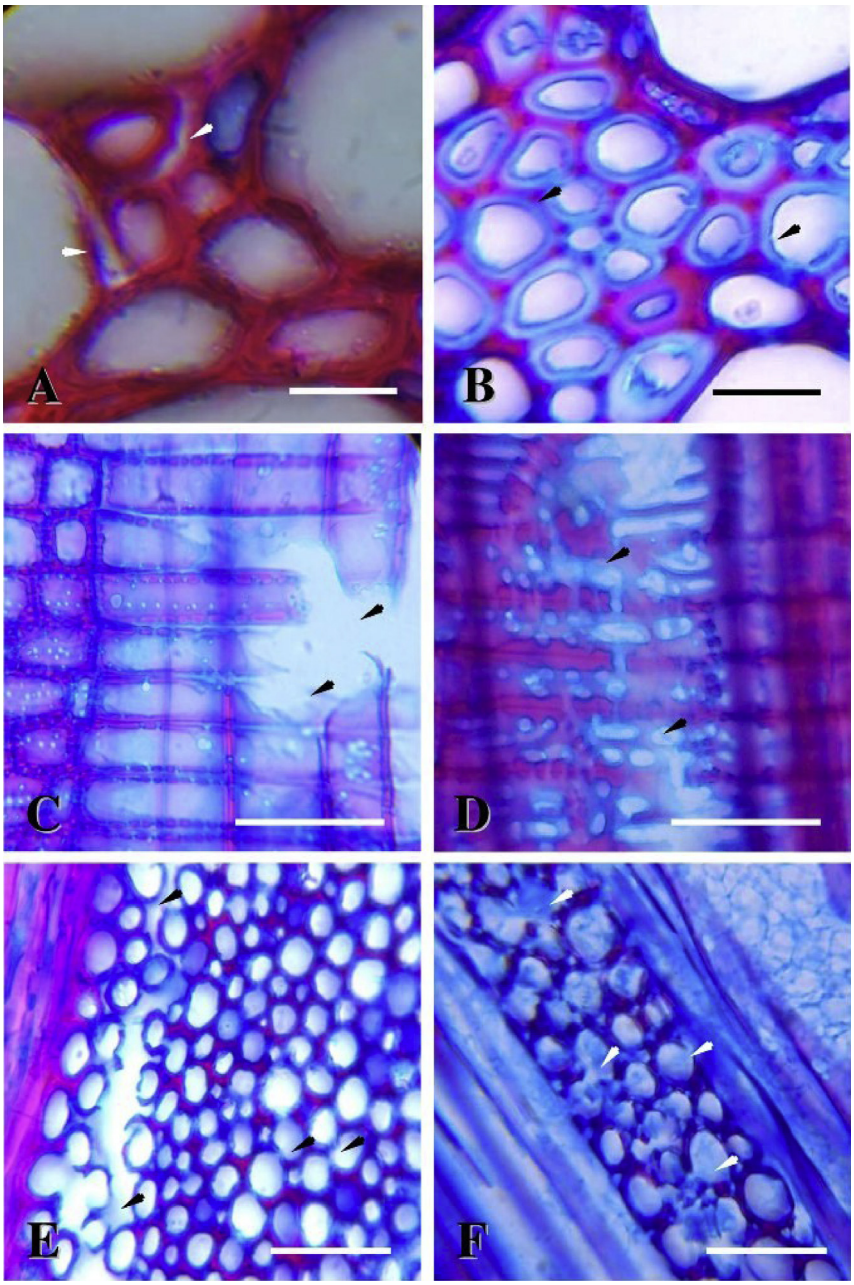

Fig. 4. Light microscopic images showing the hyphal activity of two white-rot fungi in Oriental beech wood after 120 days of exposure. A, C, & E: *Pleurotus ostreatus*; B, D, & F: *Trametes versicolor*. A–B: Cross-sectional views show the thinning and eroded as well as delignified cell walls; C–D: Radial section show the bore holes decomposition of xylem rays caused by enzymatic activity; E–F: Tangential section show thinning as well as delignified and decomposition of xylem rays; Scale bars in A, B: 30 μm; C, D: 20 μm; E, F: 30 μm.

remaining lignin is much more fragile than consumed cellulose. On the other hand, selective white-rot which preferably degrades lignin can cause a ductile fracture in wood. Accordingly, simultaneous white-rot, as studied here, is anticipated to stand somewhere between these two extremes. However, a swift loss in mechanical properties was observed in this study even in the early stages of decomposition. After 15 or 30 days of exposure, wood samples seemed to become brittle and unable to disperse the load energy. Consequently, since *Pleurotus ostreatus* and *T. versicolor* caused simultaneous decay in beech, something more than degraded cellulose might be responsible for the early loss in strength. On the other hand, fiber erosion was not severe after 15–30 days exposure and the only microscopically notable alteration in xylem tissue was the deterioration of marginal ray parenchyma. Hence, it appears that rays are an important factor affecting strength in beech wood.

The contact areas between wood rays and longitudinally oriented cells are assumed to be weak points (Keunecke et al., 2006). Hence, detaching large rays from ground tissue in the early stages of wood decomposition would further debilitate this weak area which finally leads to total separation of rays and formation of tiny cracks. Since impact strength shows the shock resistance of wood and rays play an important role in dispersion of imposed mechanical stress (Rowell, 2005), these tiny cracks, in turn, will interrupt elastic stress transfer enabling cracks to propagate.

Ray cells have been shown to act as reinforcing elements in wood (de Borst and Bader, 2014). They are radial bracings which delay longitudinal cleavage as well as cross-bolts which interlock adjacent tree rings against axial shear (Mattheck and Kubler, 1997). The role of ray parenchyma in wood is similar to horizontal I-beams in a reinforced brick wall. When the rays are decomposed, the remaining structure is stiff and resists bending, but breaks under insignificant loading (Mattheck and Kubler, 1997). The contribution of rays in the mechanical stability of woods is even greater in species with larger rays like plane (*Platanus*) and beech (*Fagus*) (Mattheck and Kubler, 1997; Zheng and Martínez-Cabrera, 2013). Generally, all species with broad rays like beech and oak wood can be considered as anti-shock (Mattheck and Kubler, 1997). It has been shown that rays are about 3 times stiffer and stronger than in solid beech wood (Burgert and Eckstein, 2001). Hence, even slight degradation of these large rays will instantly decrease the mechanical stability of wood as has been shown in this research.

Regarding the fibers, the source of mechanical strength of wood at the molecular, microscopic, and macroscopic levels will all be affected during biological decomposition: white-rot fungi have a complete cellulase complex (Rowell, 2005) and when wood is exposed to white-rot fungi, chemical intra-polymer bonds of cellulose are broken during early stages of decomposition. As decay continues, at the microscopic level, secondary wall layers will gradually degrade, resulting in the failure of S_2–S_3 and S_1–S_2 bonds. When decay is advanced, the middle lamella which acts as an adhesive keeping fibers together will partly be destroyed. Major impact bending losses coincided with a great initial loss in DP after only 15–30 days of incubation, especially in the case of *P. ostreatus*. The low variation in DP during moderate or advanced stages of

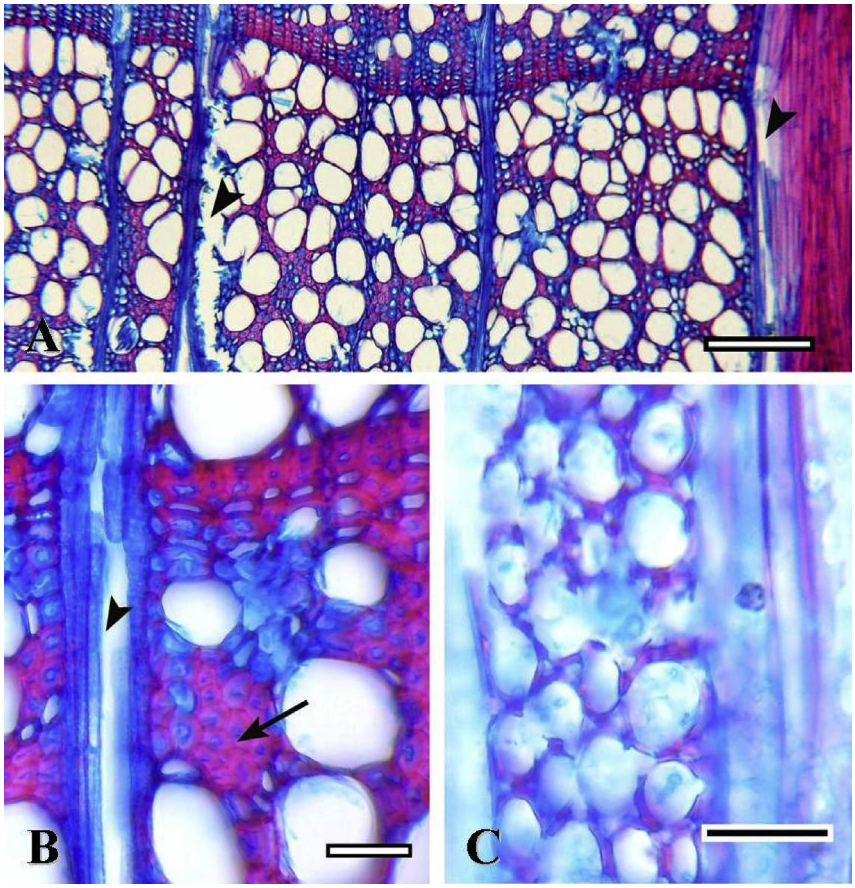

Fig. 5. Degradation of xylem rays exposed to white rot fungi in cross (A and B) and tangential (C) sections. A–B: separation of rays from ground tissue (arrowheads) while the adjacent fibers (arrow) are still highly lignified and intact (*Pleurotus ostreatus*). C: disintegration of ray parenchyma in a sample exposed to *Trametes versicolor*. Scale bars in A: 200 μm; B, C: 20 μm.

decay indicates that along with ray detaching, degradation at the molecular level (reduction in cellulose chain) can be a contributing factor for loss of mechanical strength in wood.

4. Conclusion

Oriental beech wood, exposed to two white-rot fungi in 15 days intervals up to 120 days was evaluated for the relationship between molecular, chemical and anatomical alteration with mechanical instability. Results showed that although *P. ostreatus* and *T. versicolor* both caused simultaneous decay and final wood strength loss was almost similar, their initial ability to degrade holocellulose was different. During the course of decay, the moisture content increased rapidly in samples decayed by both fungi and similar deteriorating patterns were observed in micrographs, substantiating the similarity in the decay pattern of the two fungi. The dramatic loss in impact bending strength of beech wood at early stages of decay was related to the role of large xylem rays in mechanical stability as well as reduction in degree of polymerization of holocellulose (DP). Overall, it was concluded that although mass loss, wood density reduction, and fiber cell wall erosion can affect wood mechanical strength, detachment of rays from wood tissue and loss of DP are the key factors in leading to reduced impact bending strength.

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