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ORIGINAL ARTICLE

Impact of fungal decay on the structural integrity of wood

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Abstract

Wood-destroying fungi induce different types of decay, which cause significant reductions in elastomechanical properties of wood when the mass loss is not yet gravimetrically detectable. Particularly difficult to define is incipient decay since the reduction of elastomechanical properties is highly dependent on the heterogeneity of wood species. Early-stage effects of incipient decay on impact behavior remain insufficiently understood. The aim of this study was to clarify how different rot types affect structural integrity in relation to mass loss. Therefore European beech (*Fagus sylvatica*) and Scots pine (*Pinus sylvestris*) sapwood specimens were incubated with white-rot (*Trametes versicolor*), brown-rot (*Coniophora puteana*) or soft-rot fungi. After incubation, moisture content and relative mass loss were measured. Mass loss (ML) increased linearly over time across all fungi-wood combinations, reaching a maximal reduction of 67% in European beech wood and 39% in Scots pine sapwood with *Trametes versicolor*. For *Coniophora puteana*, ML in European beech peaked at 26%, while Scots pine sapwood reached 24%. Soft-rot fungi caused the least degradation reaching 9% ML for European beech wood and 4% for Scots pine sapwood after 99 days. High-Energy Multiple Impact (HEMI) – tests were performed to evaluate the effect of mass loss by fungal decay on the structural integrity of wood, expressed as the Resistance to Impact Milling (RIM). The RIM decreased with increasing ML at early-stages proving the high sensitivity of the test to detect incipient decay, especially with brown rot. The reduction of structural integrity was compared with the reduction of different strength properties of wood depending on the mass loss, where RIM values exhibited less variability compared to other strength properties, suggesting higher measurement stability in case of white and brown-rot decay.

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1 Introduction

Wood offers several advantages over other construction materials as a natural and renewable biopolymer. These include renewability, ease of workability, a favorable strength-to-density ratio, good thermal insulation, and aesthetic appeal (Reinprecht 2016). Wooden products and constructions made from wood and wood-based composites are commonly exposed to diverse environmental factors. As a result, they are subject to deterioration caused by both abiotic and biotic agents. Environmental and biological agents significantly affect a wide range of wood's mechanical and physical properties. The extent and nature of these changes vary depending on the wood species, environmental conditions, and organisms involved (Zabel and Morrell 2020). According to Zabel and Morrell (2020), approximately 10% of harvested wood globally replaces wood that has decayed during service. Wood-destroying fungi degrade the polymers of the wood cell wall - hemicellulose, cellulose, and lignin - leading to substantial changes in mechanical and physical characteristics and structural failures of wood. Based

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on their decay mechanisms, fungal species are traditionally categorized into three rot types: brown rot, white rot, and soft rot. Decay significantly reduces the mechanical properties of wood, often before measurable mass loss occurs (Wilcox 1978; Curling et al. 2002b), making early detection essential to prevent further structural damage. However, although methods such as drilling resistance measurements (Sharapov et al. 2020; Nutto and Biechele 2015) or Pilodyn indentation tests (Gao et al. 2017) are frequently used in practice, they present several limitations in detecting incipient decay. The High-Energy Multiple Impact (HEMI) test was originally developed to assess the structural integrity of thermally modified wood (Rapp et al. 2006) and has also proven suitable for detecting fungal decay (Brischke et al. 2006). Resistance to Impact Milling (RIM) measures structural integrity and, by extension, the brittleness of wood. It is calculated from the degree of integrity (I), defined as the ratio of the mass of the 20 largest fragments to the total mass of all fragments, and the fine fraction (F), defined as the ratio of the mass of fine fragments (< 1 mm) to the total mass of all fragments. RIM values can be reliably obtained with few repetitions and can detect fungal decay even before any mass loss is measurable (Brischke et al. 2008). This was validated for both brown-rot and white-rot fungi (Brischke et al. 2006). In addition, the HEMI test is largely insensitive to weathering effects because the specimens are crushed much more severely than natural cracks would occur, allowing reliable detection of structural changes even after long-term exposure. In contrast, the effects of soft-rot decay on wood's structural integrity are not yet fully understood. Tests involving soft-rot fungi are typically conducted as field trials or in so-called terrestrial microcosms using unsterile soil, making it difficult to isolate the influence of specific biotic agents. However, previous studies have demonstrated that single-species soft-rot tests with microfungi are feasible and were successfully conducted under controlled laboratory conditions (Nilsson 1973). Results from previous studies suggest that the correlation between mass loss due to fungal decay and RIM values is dependent on rot type and, in some cases, even on the specific fungal species (Brischke et al. 2008). In conclusion, the impact of fungal decay on the structural integrity of wood should be assessed individually for each of the three main rot types. To achieve this, carefully controlled testing under pure-culture conditions and the consideration of test-specific parameters are required. Therefore, this study aimed to (i) determine how different rot types affect the fracture pattern and structural integrity (RIM) of wood specimens after HEMI testing, and (ii) evaluate whether rot-type-dependent correlations exist between mass loss (ML) and changes in RIM, and how these relationships compare with correlations between ML and conventional strength properties.

2 Materials and methods

2.1 Wood specimens and provenance

Six thousand specimens, each measuring 10 (axial) × 5 × 20 mm³, were cut from rectangular strips prepared from 10 Scots pine (*Pinus sylvestris*) sapwood (sw) and 10 European beech (*Fagus sylvatica*) boards. As a result, replicate samples of 20 axially matched specimens each were prepared for subsequent experiments.This ensured that replicate test specimens with maximally similar initial properties were used for each test combination. Both wood species were purchased as untreated, kiln-dried sawn timber from a local timber market. The wood showed no visible signs of decay or blue staining, and no growth anomalies such as knots and resin canals were present.

3 Decay tests

For each material-rot type combination, 50 × 20 specimens were labeled, oven-dried at 103 °C for 36 h until constant mass (moisture content (MC) = 0%), weighed to the nearest 10^{-3} g, and sterilized in an autoclave (Tuttnauer Systec 5075 ELVC, Breda, Netherlands) at 121 °C for 20 min, while wrapped in aluminum foil, as prescribed by the standard EN 113-2 (2020). For the basidiomycete decay tests with both wood species, the wood-destroying fungi *Trametes versicolor* (Lloyd F., CTB 863 A) (*T.v.*), which causes white rot, and *Coniophora puteana* ((Schumach.) P. Karst., Eberswalde 15) (*C.p.*), which causes brown rot, were used. Kolle flasks were used as culture vessels. Each flask was filled with a malt-agar solution (1.875 g agar + 75 g of 4% malt solution per vessel), which served as the nutrient medium for the test fungi, and then autoclaved. After cooling, one inoculum (Ø 10 mm) was extracted using a cork borer from each fungal culture (*T.v.* and *C.p.*), no older than 30 days, and placed at the center of the medium. The vessels were sealed with cotton plugs and incubated at 22 °C and 70% relative humidity (RH), under reduced light to allow the mycelium to grow. After seven days, the sterile specimens (20 per Kolle flask) were inserted into the culture vessels in direct contact with the mycelium and evenly distributed on the surface (Fig. 1). The culture vessels were then re-incubated under the same conditions.

Soft-rot tests were performed with modifications based on the procedure prescribed in EN 807 (2001) using *Chaetomium globosum* Kunze (ATCC 6205), *Humicola grisea* Traaen (MG 28), *Petriella setifera* (Alf. Schmidt) Curzi (MG 50), and *Trichurus spiralis* Hasselbr (MG 31). Unlike EN 807 (2001), *Lecythophora mutabilis* was not used in this study. At the time of inoculation, the fungal cultures

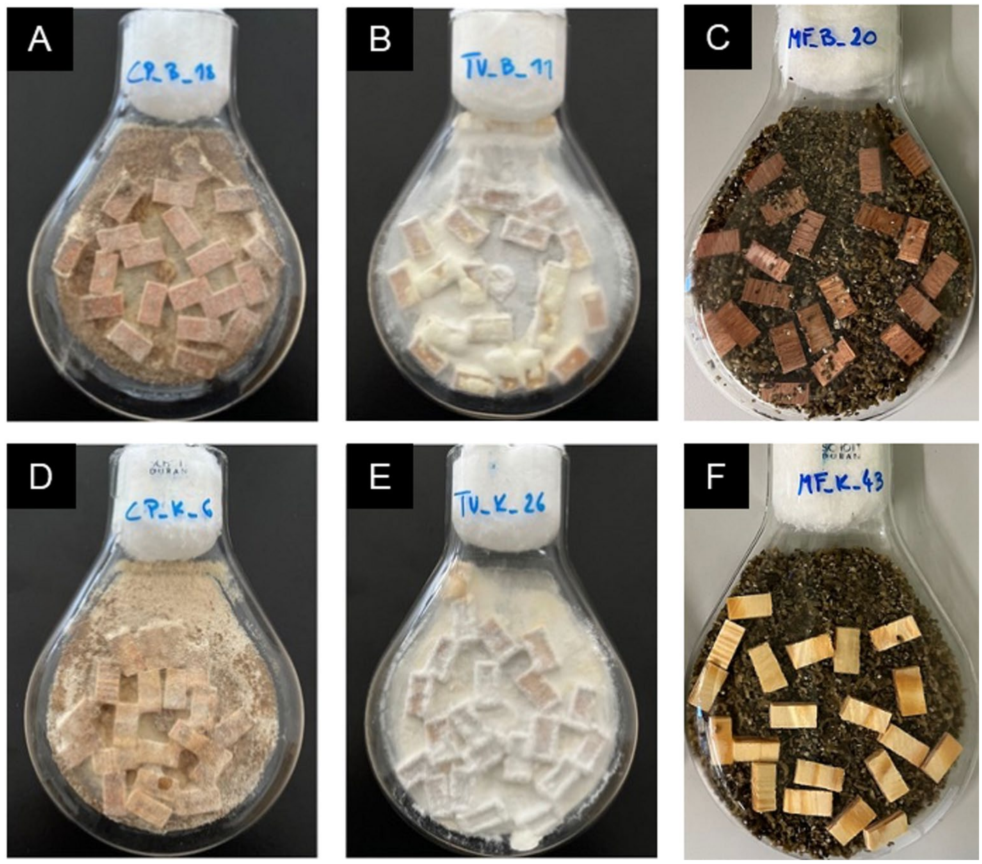

Fig. 1 Kolle flasks containing wood specimens (20 per flask) with dimensions of 10 mm (axial) × 5 mm × 20 mm during incubation. (A) *C. puteana* on European beech, (B) *T. versicolor* on European beech, (C) Soft-rot fungi on European beech, (D) *C. puteana* on Scots pine sw, (E) *T. versicolor* on Scots pine sw, (F) Soft-rot fungi on Scots pine sw. One replicate sample consisted of 20 single specimens

were between 14 and 28 days old. Kolle flasks were filled with 150 mL of dry vermiculite (anhydrated aluminum-iron-magnesium silicate) and 75 mL of deionized water, sealed with cotton plugs, and autoclaved. The spore suspension for the soft-rot fungi was prepared following EN 807 (2001). The specimens were placed on the vermiculite surface and evenly distributed (Fig. 1). After placement, the specimens and substrate were inoculated with the prepared spore suspension. In each culture vessel, 15 mL of the suspension was injected to ensure contact with all specimens and the substrate. The vessels were sealed with cotton plugs and incubated at 27 °C and 70% RH, under reduced light conditions.

3.1 Evaluation of mass loss and wood moisture content

After various incubation periods, the specimens were removed from the vessels, and the adhering mycelium was carefully removed using a sharp scalpel and a soft kitchen sponge to avoid damaging the wooden structure. The samples (consisting of 20 single specimens) were labeled, and their mass immediately after fungal incubation (m_i) was determined to the nearest 10^{-3} g. Subsequently, the specimens were oven-dried at 103 °C for 36 h until a constant mass was achieved (MC = 0%) and weighed again to the nearest 10^{-3} g ($m_{i,0}$). The wood moisture content after incubation (MC_i) was calculated according to Eq. (1). The percentage mass loss of the specimens (ML) was calculated according to Eq. (2).

$$MC_i = \frac{(m_i - m_{i,0})}{m_{i,0}} \times 100\ [\%] \tag{1}$$

MC_i = Wood moisture content after incubation [%].
m_i = Mass after incubation [g].
$m_{i,0}$ = Oven-dry mass after incubation [g]

$$ML = \frac{(m_0 - m_{i,0})}{m_0} \times 100\ [\%] \tag{2}$$

ML = Wood mass loss [%].
m_0 = Oven-dry mass before incubation [g].
$m_{i,0}$ = Oven-dry mass after incubation [g].

3.2 High energy multiple impact (HEMI) test

The detection of fungal decay using the High-Energy Multiple Impact (HEMI) test was described by Brischke et al. (2006). In this study, the following procedure was applied:

each replicate sample consisting of 20 single specimens, measuring 10 (axial) × 20 × 5 mm³, was placed in a steel bowl along with seven stainless steel balls of various diameters (1 × 35 mm, 3 × 12 mm, and 3 × 6 mm). The specimens were then crushed under defined conditions for 60 s at a rotary frequency of 23.3 s^{-1}. After crushing, all fragments were placed on a slit sieve with a defined slit width of 1 mm, following ISO 5223 (1995), and shaken for 2 min on an orbital shaker at a rotary frequency of 200 min^{-1}. In addition to the decay-exposed samples (each consisting of 20 specimens), reference samples of each wood species were tested as controls. The degree of integrity (*I*), defined as the ratio of the mass of the 20 largest fragments to the total mass of all fragments (m_{all}) after crushing was calculated as:

$$I = \frac{m_{20\ biggest}}{m_{all}} \times 100\ [\%] \tag{3}$$

I=Degree of integrity [%].

$m_{20\ biggest}$=Mass of the 20 biggest fragments [g].

m_{all}=Mass of all the fragments [g].

The fine fraction (*F*) is the ratio between the mass of the fine fragments ($m_{fragments\ <\ 1\ mm}$ with particles < 1 mm) and the mass of all fragments (m_{all}) after crushing (adapted from Emmerich et al. 2019):

$$F = \frac{m_{fragments<1mm}}{m_{all}} \times 100\ [\%] \tag{4}$$

F= Fine fraction [%].

$m_{fine\ fraction}$= Mass of the fine fraction (< 1 mm) [g].

m_{all}= Mass of all the fragments [g].

Finally, the resistance to impact milling (*RIM*) as a measure of the structural integrity of the material, was calculated using the values *I* (degree of integrity) and *F* (fine fraction):

$$RIM = \frac{(I - 3 \times\ F) + 300}{4}\ [\%] \tag{5}$$

RIM=Resistance to impact milling [%].

I=Degree of integrity [%].

F=Fine fraction [%].

3.3 Data processing and statistical analysis

Mass loss resulting from fungal decay was determined for each sample, with each sample consisting of 20 individual specimens, by comparing the oven-dry mass before and after incubation and expressing the loss as a function of incubation time. The measurements obtained from the HEMI test — degree of integrity (I), fine fraction (F), and resistance to impact milling (RIM) — were presented in relation to mass loss. Each data point therefore represents the relative value for one sample of 20 specimens. Regression curves were fitted using the method of least squares, and the corresponding coefficients of determination (R^2) were calculated in Microsoft Excel (Microsoft Corporation, USA).

4 Results and discussion

4.1 Mass loss due to fungal decay

Mass loss (*ML*) increased linearly over time for all fungi–wood combinations (Fig. 2), with the most pronounced degradation observed in European beech exposed to *Trametes versicolor*, reaching up to 67% after 82 days (R^2 = 0.905). In comparison, Alfredsen et al. (2021) reported a maximum *ML* of 30% in European beech caused by *T. versicolor* after 16 weeks of incubation (specimen dimensions: 15 × 25 × 50 (axial) mm³), which was substantially lower than the values observed in the present study. A more similar result was reported by Meyer and Brischke (2015), who found a *ML* of 57% for the same wood–fungus combination after 16 weeks. In contrast, Scots pine sw incubated with *T. versicolor* exhibited considerably lower *ML* under identical conditions, with a maximum of 39% (R^2 = 0.957). This aligns with the generally higher susceptibility of hardwoods to white-rot fungi, as previously reported by Zabel and Morrell (2020) and Schwarze (2007). The lower degradation of softwoods may be attributed to the higher content of phenolic compounds such as p-coumaryl alcohol in softwood lignin, which are more resistant to fungal enzymatic attack (Ridout 2000). *ML* for *C. puteana* in European beech peaked at 26% (R^2 = 0.933), while Scots pine sw reached 24% (R^2 = 0.857). Brischke et al. (2006) reported *ML* values of up to 50% in Scots pine sw after 68 days of incubation with *C. puteana*, indicating a considerable difference in decay severity. This disparity likely resulted from variations in fungal virulence, as well as differences in specimen volume and geometry. Brischke et al. (2020) observed *ML* values of approximately 8–9% after 28 days in Scots pine sw specimens of identical volume but varying geometry incubated with *C. puteana*. These results exceed the incipient decay levels (*ML* < 5%) recorded in the current study—16–18% after 56 days and 21% after 84 days. Negative *ML* values were initially observed for both wood species exposed to Basidiomycetes. This phenomenon can be attributed to the presence of ingrown mycelium, which, at this stage, results in minimal or no metabolization of the wood substance (Meyer and Brischke 2015) or to nutrient diffusion from the culture medium into the wood. Among all fungi tested, soft-rot fungi caused the least degradation. Final *ML* values reached 9% for beech (99 days; R^2 = 0.71657) and 4%

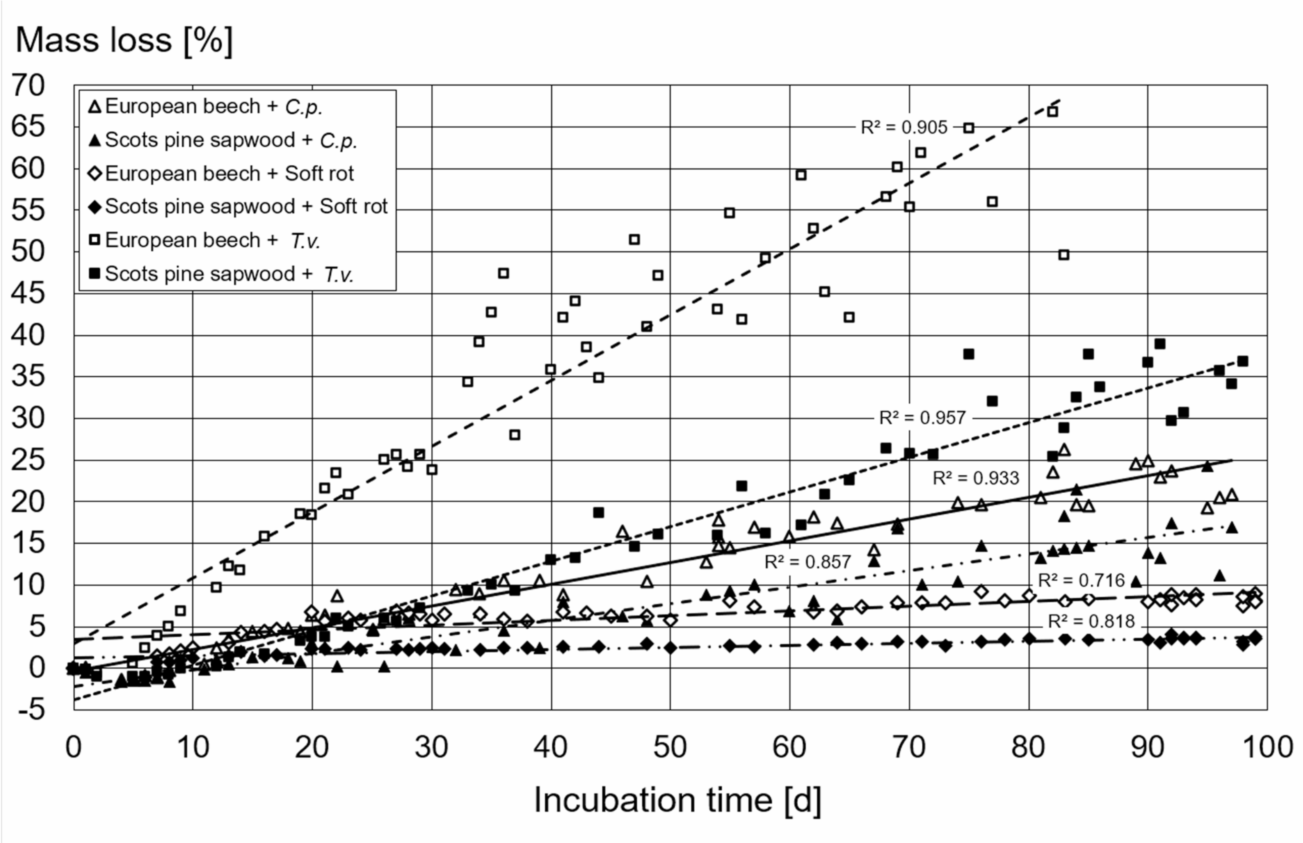

Fig. 2 Mass loss [%] of Scots pine (*Pinus sylvestris*) sw and European beech (*Fagus sylvatica*) over incubation time [days], caused by *Coniophora puteana* (*C.p.*), soft-rot fungi, or *Trametes versicolor* (*T.v.*). Each data point represents the mean of 20 specimens with dimensions of 10 mm (axial) × 5 mm × 20 mm

for Scots pine sw (99 days; $R^2 = 0.818$). For beech, incipient *ML* increased from 1% to 7% between the 7th and 20th day of incubation. This trend was similar to the 12–13% *ML* observed after 42 days in soil-bed tests conducted by Machek et al. (2001). Soft-rot fungi typically colonize wood in very moist environments, often on or below the soil surface, and can degrade both coniferous and broadleaved species (Reinprecht 2016). Machek et al. (2001) further demonstrated that non-durable hardwoods were more rapidly degraded than softwoods in soil-bed tests. Several studies support these findings, consistently reporting higher *ML* in beech compared to Scots pine sw (Morrell and Zabel 1985) and a generally lower susceptibility of softwoods to soft-rot decay under laboratory and field conditions (Militz 1996). The greater *ML* observed in beech may be due to its lower lignin content and higher proportion of ray cells, which are more susceptible to enzymatic degradation (Morrell and Zabel 1985).

4.2 Structural integrity

4.2.1 Resistance to impact milling (*RIM*)

Resistance to Impact Milling (*RIM*) indicated the structural integrity and brittleness of wood. This study first determined RIM values for non-inoculated reference specimens (*ML* = 0%). As expected, European beech exhibited a higher *RIM* value (89.1%) compared to Scots pine sw (84.4%). These findings are consistent with those by Emmerich et al. (2019), who found *RIM* values of 88.0% for European beech and 85.1% for Scots pine sw. Following fungal incubation, *RIM* values decreased markedly with increasing mass loss (*ML*), particularly in specimens exposed to brown- and white-rot fungi. In contrast, a smaller reduction in *RIM* was observed in specimens affected by soft-rot fungi, reflecting the comparatively lower degree of decay (Fig. 3). Despite similar *ML* values in both wood species after incubation with *C. puteana*, the impact on *RIM* varied substantially. The lowest *RIM* values corresponded with the highest *ML*: 50.7% in European beech and 69.8% in Scots pine sw. The absolute *RIM* reduction was thus more than twice as great in

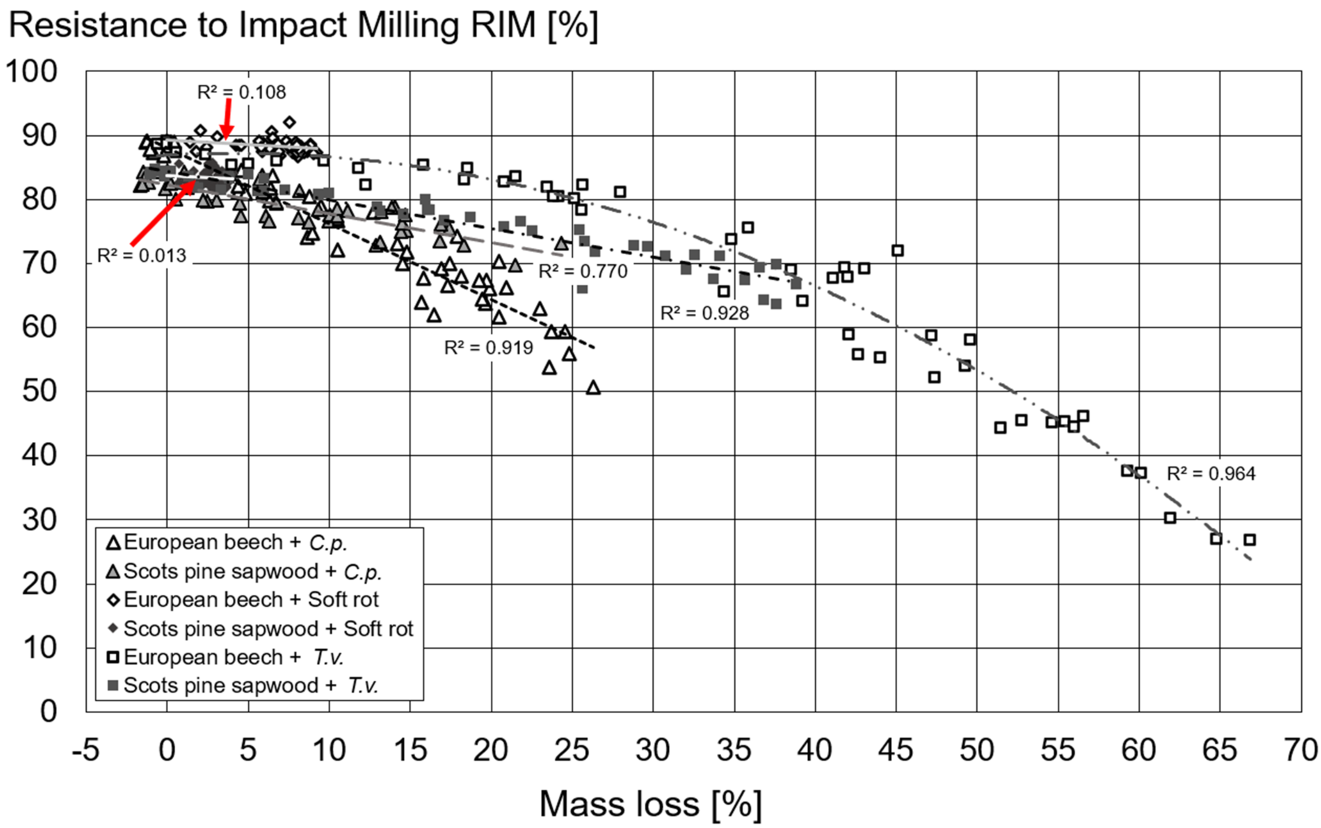

Fig. 3 Resistance to impact milling RIM [%] of Scots pine (*Pinus sylvestris*) sw and European beech (*Fagus sylvatica*) vs. mass loss [%], caused by *Coniophora puteana* (*C.p.*), soft-rot fungi, or *Trametes versicolor* (*T.v.*). Each data point for mass loss represents the mean of 20 specimens with dimensions of 10 mm (axial) × 5 mm × 20 mm

beech (43.1%) compared to Scots pine sw (17.3%). Brischke et al. (2006) reported even lower *RIM* values (22.0–29.0%) for Scots pine sw specimens (10 × 20 × 20 mm³) at approximately 24.0% *ML*, further emphasizing the sensitivity of *RIM* to fungal decay. In the current study, incipient decay (*ML* < 5%) resulted in modest *RIM* reductions of 6.9% in Scots pine sw and 8.1% in beech. The high sensitivity of the HEMI test to subtle structural changes was also described by Brischke et al. (2008). A strong linear correlation between *RIM* and *ML* was observed, particularly in beech (R^2 = 0.919), with a slightly lower but still significant correlation in Scots pine sw (R^2 = 0.770), both incubated with *C. puteana*. The widest range of *ML* was recorded in specimens incubated with *T. versicolor*, leading to the highest overall *RIM* reductions. However, reductions in *RIM* at early stages of decay (*ML* < 5%), were more pronounced following brown-rot attack: 3.6% for beech and 0.5% for Scots pine sw compared to white-rot decay. At peak *ML* for *T. versicolor* (approximately 37.6% for Scots pine sw), *RIM* values for both wood species converged around 65.0%. *RIM* values in beech declined exponentially with increasing *ML*, with more scattered data compared to the more uniform trend in Scots pine sw. The lowest *RIM* values observed were 26.8% in beech at 66.8% *ML* and 63.6% in Scots pine sw at 37,6% *ML*. The relationship between *RIM* and *ML* showed strong exponential correlations: R^2 = 0.934 for European beech and R^2 = 0.964 for Scots pine sw.

The mechanisms of fungal degradation have a pronounced influence on wood's structural properties, as clearly detectable through the HEMI test. The test proved particularly effective for detecting early brown-rot decay, consistent with findings by Brischke et al. (2006). As fungal decay progresses and *ML* increases, significant reductions in mechanical strength properties occur (Wilcox 1978; Curling et al. 2002, Brischke et al. 2006; Reinprecht 2016). The distinct patterns of *RIM* decrease across different rot types underscore the HEMI test's value in assessing fungal-induced wood degradation. Brown-rot fungi caused greater *RIM* reductions at lower *ML* in beech than white-rot fungi, a pattern likely attributable to the preferential degradation of cellulose by brown-rot fungi. This results in a more pronounced reduction of mechanical strength than the lignin-targeted degradation typically associated with white-rot fungi. These observations are in line with previous studies by Brischke et al. (2006; 2008).

4.2.2 Degree of integrity (*I*)

The Degree of Integrity (*I*) of both wood species was found to be strongly influenced by the extent of *ML* due to fungal decay (Fig. 4). The most pronounced decrease in *I* values was observed in specimens exposed to *T. versicolor*, which induced the highest *ML* values for both beech and Scots pine sw. For beech, *I* dropped to as low as 4.5% at the maximum *ML* of 66.8%. Even in the early stages of decay (*ML* < 5%), a noticeable reduction in integrity — approximately 10%— was observed. The correlation between *I* and *ML* for beech was evident, with a coefficient of determination $R^2 = 0.915$, indicating a consistent and progressive degradation of structural integrity with increasing *ML*. Scots pine sw followed a similar trend with *T. versicolor*, although the data showed more notable variability. The lowest *I* value (~20%) corresponded with the highest *ML* (~63.6%). Despite the scattering of individual data points, a strong correlation was still evident ($R^2 = 0.858$). The incipient decay phase was less clearly defined for Scots pine sw, with several specimens exhibiting negative or very low *ML* but relatively high *I* values. This phenomenon can likely be attributed to ingrown mycelium that binds the wood structure without significantly reducing mass or to the fungus utilizing non-structural elements, resulting in an artificially elevated integrity. Under exposure to the brown-rot fungus *C. puteana*, *I* values were significantly higher in beech, ranging from 40% to 60%, with a minimum value (~26%) occurring at the highest *ML* (26%). However, the correlation between *I* and *ML* was weak ($R^2 = 0.421$), suggesting additional influencing factors beyond simple mass loss. The reference *I* value for beech specimens (sterilized, oven-dried, and not incubated) in this study was approximately 59.5%, which aligns with, yet slightly exceeds, the findings of Emmerich et al. (2019) (55.9%) and Brischke (2016) (52.4%). *I* values for Scots pine sw exposed to *C. puteana* ranged from 26% to 45%, with the lowest value (27.6%) recorded at 18% *ML*. The data were highly scattered, indicating substantial natural variability in response to fungal decay. Accordingly, only a poor correlation between *I* and *ML* was identified ($R^2 = 0.271$). The reference *I* value of 41% observed in this study notably differed from Brischke (2016), who reported 28.8%, and was slightly lower than value of 47.7% reported by Emmerich et al. (2019), for specimens of identical dimensions. In contrast, soft-rot fungi induced minimal *ML* and had a negligible impact on structural integrity. European beech specimens maintained high *I* values (50–67%) within an *ML* range of 0–10%, while Scots pine sw displayed lower

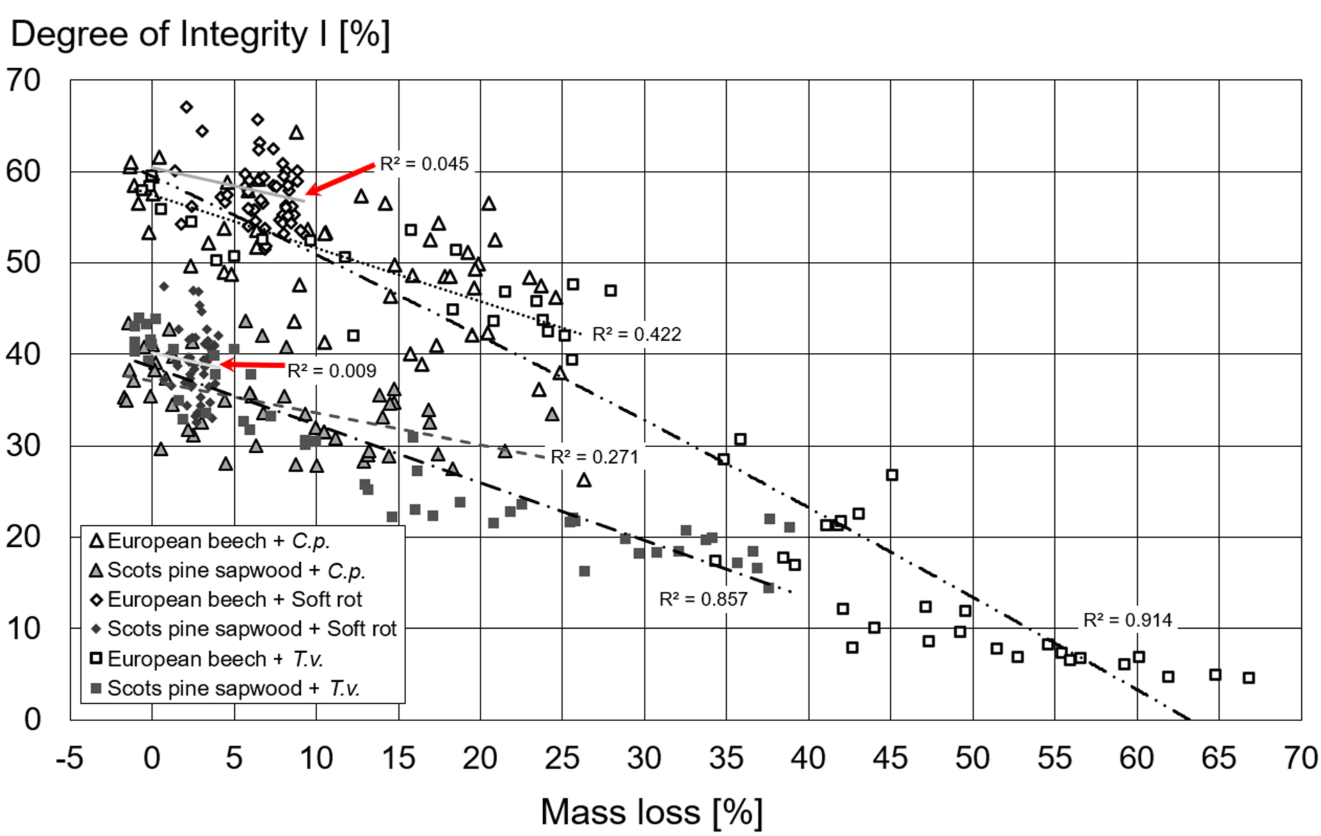

Fig. 4 Degree of integrity *I* [%] of Scots pine (*Pinus sylvestris*) sw and European beech (*Fagus sylvatica*) vs. mass loss [%], caused by *Coniophora puteana* (*C.p.*), soft-rot fungi, or *Trametes versicolor* (*T.v.*). Each data point represents the mean of 20 specimens with dimensions of 10 mm (axial) × 5 mm × 20 mm

integrity (32–48%) across an *ML* range of 0–4%. Due to the limited range of *ML*, the correlation was poor between *I* and *ML* for both species ($R^2 = 0.045$ for beech; $R^2 = 0.009$ for Scots pine sw). Broader *ML* ranges would be necessary to assess the effect of soft rot on integrity more definitively.

4.2.3 Fine fraction (*F*)

The fine fraction (*F*), defined as the percentage ratio of wood particles smaller than 1 mm to the total fragment mass after HEMI testing, provides insight into the structural degradation of wood due to fungal decay (Fig. 5). Reference values for untreated, sterilized specimens were 1.0% for European beech and 1.2% for Scots pine sw in this study. These results align reasonably well with values reported in previous studies for specimens of similar dimensions: Brischke (2016) found *F* values of 1.6% (beech) and 5.0% (Scots pine sw) and Emmerich et al. (2019) reported 1.4% for beech and 2.5% for Scots pine sw. Notably, considerable variability within species was observed across studies, reflecting the influence of natural heterogeneity in wood structure, including factors such as moisture content, density, and earlywood–latewood characteristics. The most pronounced increase in *F* values occurred in specimens exposed to *T. versicolor*, particularly in European beech. The fine fraction reached 65.8% at a maximum *ML* of 66.8%, following a clear exponential growth pattern with increasing *ML*. This relationship exhibited a strong correlation ($R^2 = 0.958$), suggesting that fine particle generation was closely tied to the degree of decay in this context. A similar trend was observed in Scots pine sw, with *F* values reaching up to 20% at a comparable *ML* (~37%), and a R^2 of 0.829, indicating a strong but less consistent relationship. Specimens incubated with *C. puteana* showed markedly different behaviors between the two wood species. For beech, *F* values reached up to 41% at a maximum *ML* of 26%, again demonstrating a strong correlation ($R^2 = 0.955$).

In contrast, Scots pine sw exhibited considerably lower *F* values, with a peak of 16.8% at 21.5% *ML*. The fine fraction for beech at approximately 24% *ML* was 36.6%, while it was 13.6% for Scots pine sw, indicating a substantially higher fragmentation tendency in beech under comparable decay conditions. This highlights the species-specific degradation mechanisms and suggests a more aggressive fragmentation process in beech exposed to the brown-rot. The overall correlation for Scots pine sw in this group remained strong ($R^2 = 0.808$), though it was weaker than that for beech. Soft-rot fungi caused minimal degradation in both species. The

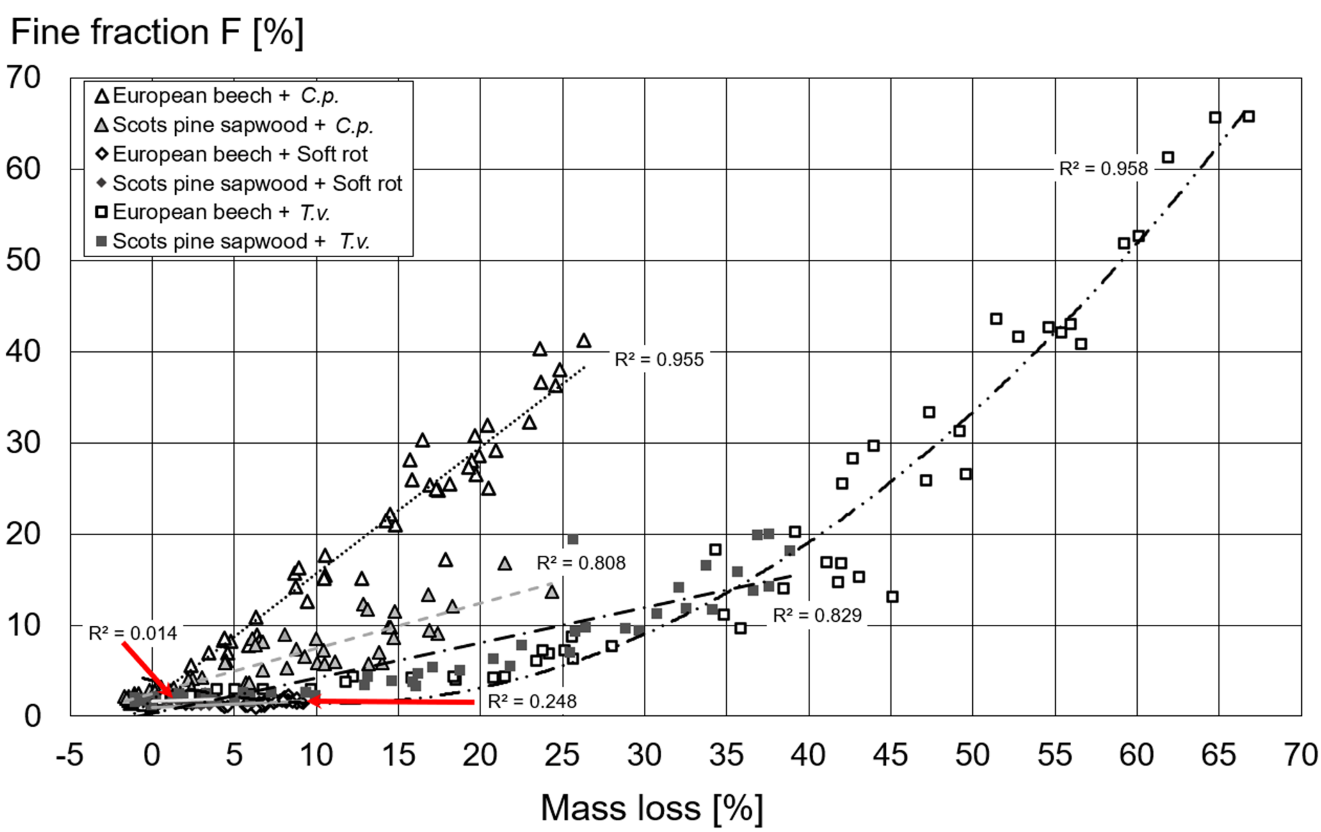

Fig. 5 Fine fraction *F* [%] of Scots pine (*Pinus sylvestris*) sw and European beech (*Fagus sylvatica*) vs. mass loss [%], caused by *Coniophora puteana* (*C.p.*), soft-rot fungi, or *Trametes versicolor* (*T.v.*). Each data point represents the mean of 20 specimens with dimensions of 10 mm (axial) × 5 mm × 20 mm

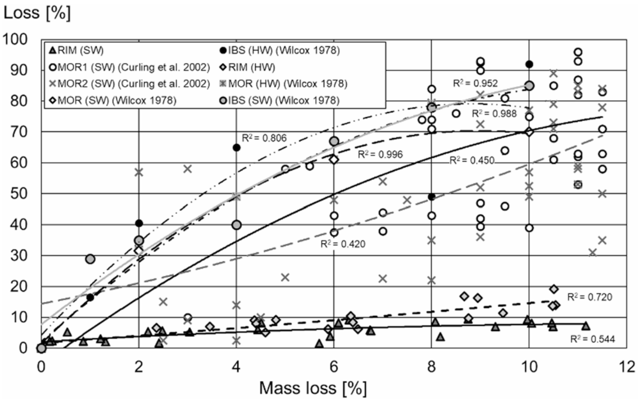

Fig. 6 Relationship between loss of various mechanical properties (*IBS* – impact bending strength; *MOR* – modulus of rupture; *RIM* – resistance to impact milling) and mass loss of wood due to early decay by brown-rot fungi in case of softwoods (SW) and hardwoods (HW). Results were taken from Wilcox (1978) (*IBS*, *MOR*) and Curling et al. (2002b) (*MOR*1 - *Gloeophyllum trabeum*; *MOR*2 - *Postia placenta*)

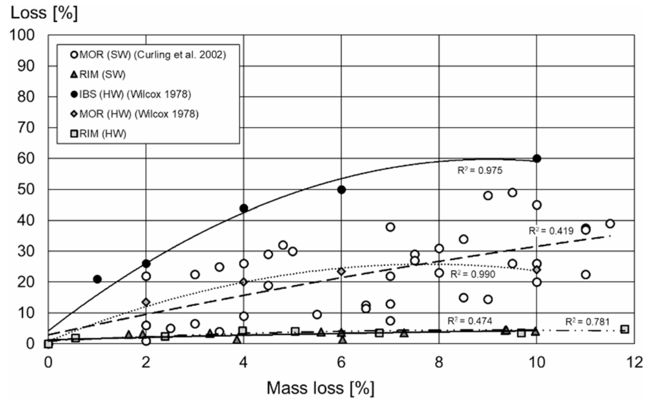

Fig. 7 Relationship between loss of various mechanical properties (*IBS* – impact bending strength; *MOR* – modulus of rupture; *RIM* – resistance to impact milling) and mass loss of wood due to early decay by white-rot fungi in case of softwoods (SW) and hardwoods (HW). Results were taken from Wilcox (1978) (*IBS*, *MOR* (HW) and Curling et al. (2002b) (*MOR* (SW)

maximum *F* value recorded for Scots pine sw was 2.6%, slightly higher than for European beech (2.4%). However, the corresponding *ML* values were low, not exceeding 4% for Scots pine sw and 9.2% for beech. Consequently, the correlation between *F* and *ML* was weak: $R^2 = 0.014$ for Scots pine sw and $R^2 = 0.249$ for beech. This suggests that within such limited *ML* ranges, fine fraction measurements are poor indicators of early-stage soft-rot decay. To better characterize the relationship between decay intensity and fragmentation for this fungal type, broader *ML* distributions are required. Such distributions could potentially be obtained by employing even smaller wood samples, which tend to yield higher *ML*.

4.3 Impact of incipient decay on different mechanical properties

The ability to detect early-stage fungal decay in wood depends on the sensitivity of the method employed, as strength loss often precedes measurable *ML* (Wilcox 1978; Zabel and Morrell 2020). Resistance to impact milling (*RIM*) was compared to strength properties reported in the literature, including modulus of rupture (*MOR*) and impact bending strength (*IBS*), for different combinations of decay type and wood species. Reductions in *MOR* and *IBS* in softwoods affected by brown-rot fungi were considerably higher than the reductions in *RIM* at comparable *ML* levels (Fig. 6). At just 2% *ML*, *IBS* decreased by approximately 35% and *MOR* by 32%, while *RIM* declined by only about 5%. *MOR* and *IBS* were reduced by 70% and 85%, respectively at 10% *ML* (Wilcox 1978), whereas *RIM* loss was limited to approximately 10%. Strong correlations between strength loss and *ML* were evident for *IBS* ($R^2 = 0.952$) and *MOR* ($R^2 = 0.996$). *RIM* also showed a moderate correlation with *ML* ($R^2 = 0.544$), similar to *MOR* values reported by Curling et al. (2002a): *MOR*1 ($R^2 = 0.450$) and *MOR*2 ($R^2 = 0.420$). The gap between mechanical strength loss and RIM reduction was also evident in hardwoods subjected to brown-rot fungi. *IBS* showed the greatest sensitivity, with a 40% reduction at only 2% *ML* and a 32% drop in *MOR*. *RIM* declined by around 6% at 2.4% *ML* and up to 20% at 10.5% ML, the highest *RIM* reduction observed across all wood-fungus combinations. The pronounced decrease in mechanical properties aligns with the mode of action of brown-rot fungi, which preferentially degrade cellulose and hemicelluloses. Since wood derives its strength primarily from highly oriented cellulose fibres and associated hemicelluloses, such degradation leads to significant structural loss (Zabel and Morrell 2020). Correlations between strength or integrity loss and *ML* were again strong: *MOR* ($R^2 = 0.988$), *IBS* ($R^2 = 0.806$), and *RIM* ($R^2 = 0.720$).

In contrast, *T. versicolor* attack led to comparatively lower mechanical properties and RIM reductions, consistent with its preferential, spatially confined degradation of lignin. For instance, *RIM* in Scots pine sw specimens was reduced by only 5% at 10% *ML*, whereas *MOR* declined by about 45%. Both properties were moderately correlated with *ML* (*RIM*: $R^2 = 0.474$; *MOR*: $R^2 = 0.419$). *IBS*, however, decreased more pronounced—by over 20% at just 1% *ML*, while *MOR* showed a 13% reduction at 2% *ML* (Wilcox 1978). These strength losses were much greater than the corresponding *RIM* reductions at early decay stages (Fig. 7). Very strong correlations were observed for *IBS* and *MOR* ($R^2 = 0.975$ and $R^2 = 0.990$, respectively), while *RIM* also showed a substantial correlation ($R^2 = 0.781$).

Overall, the results demonstrated strong relationships between *ML* and the loss of mechanical properties as well as structural integrity. The early detection of brown-rot decay in Scots pine sw specimens at *ML* values below 5%, as previously reported by Brischke et al. (2006), was confirmed in this study. The most pronounced early-stage *RIM* reduction (up to 20%) was observed in European beech exposed to *C. puteana*. In contrast, white-rot decay caused by *T. versicolor* resulted in *RIM* losses of no more than 4% at around 10% *ML*. However, *RIM* loss increased with advancing decay and higher *ML*.

The findings confirm that fungal decay by both brown- and white-rot fungi can be effectively detected using the HEMI method, particularly in early stages for brown rot. *RIM* values exhibited less variability compared to mechanical strength properties, suggesting higher measurement stability. In contrast, no meaningful correlation between *ML* and *RIM* was observed in specimens decayed by soft-rot fungi, indicating the limited effectiveness of HEMI in detecting this type of decay within the studied *ML* range.

5 Conclusion

Distinct differences in the degradation patterns between brown, white, and soft rot were clearly reflected in the *RIM* results, underlining the test's ability to differentiate between decay mechanisms. The HEMI test was highly sensitive in detecting early-stage (incipient) brown rot decay with measurable reductions in *RIM* observed at *ML* levels below 5%. White-rot fungi also caused detectable decreases in *RIM* at low *ML* values, though to a lesser extent. In contrast, soft-rot decay did not markedly alter structural integrity within the tested range, due to its relatively minor effect on *ML* and wood structure under laboratory conditions. When compared to traditional strength properties such as modulus of rupture (*MOR*) and impact bending strength (*IBS*) from previous studies, *RIM* values were lower in magnitude but demonstrated reduced variability and more consistent trends. This supports the applicability of the HEMI test as a reliable and sensitive method for identifying early decay stages. Moreover, unlike many conventional strength properties, *RIM* values are generally almost unaffected by wood density, as shown in previous studies, which contributes to greater uniformity and comparability among specimens. Future research should expand the focus on soft-rot fungi by improving biological testing protocols to enhance the clarity of their effects on wood integrity.

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Data availability Data is provided within the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

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