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Water-Related Properties and Biological Durability of Wood-Based Composites

Svojstva kompozita na bazi drva u doticaju s vodom i njihova biološka trajnost

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ABSTRACT • *There is insufficient data regarding the biodegradation of wood-based composites (WBC) by wood decay fungi. This study aimed to evaluate the biological durability and water-related properties of different WBC types. Although WBC are primarily designed for dry environments, in building applications, they may face increased moisture risks due to water leakage, condensation, or humid air. The panels, including oak-pine shield parquet (OPP), oriented strand board (OSB), birch plywood (BP), particle board (PB), laminated particle board (LPB), moisture-resistant particle board (MRPB), medium density fibreboard (MDF), laminated medium density fibreboard (LMDF) and moisture resistant medium density fibreboard (MRMDF), were subjected to attack by brown rot fungus <u>Coniphora puteana</u>. After 16 weeks of exposure, the most resistant WBC against biodegradation were BP, moisture-resistant MDF, and laminated MDF, as they exhibited a mass loss lower than 5 %. Conversely, all other WBC types showed high susceptibility to biodegradation, with a mass loss exceeding 35 %. LMDF (8 – 51 %) and MRMDF had the lowest water absorption (WA) within 168 h (2 – 46 %), while non-treated MDF exhibited the highest WA among all composite types with 190 % water uptake. With regards to thickness swelling, all WBC types, except for LPB and MDF, demonstrated values below 20 %. The influence of adhesives (phenol-formaldehyde or melamine urea-formaldehyde) used in WBC did not show a clear impact on water-related properties or biological durability.*

KEYWORDS: *biodegradation; fungi; thickness swelling; water absorption; wood-based composites*

SAŽETAK • *Ne postoji dovoljno podataka o biorazgradnji kompozita na bazi drva (WBC) gljivama truležnicama. Cilj ovog istraživanja bio je procijeniti biološku trajnost i svojstva različitih vrsta kompozita na bazi drva u doticaju s vodom. Iako su kompoziti na bazi drva ponajprije dizajnirani za suhe okolišne uvjete, u zgradama se mogu naći izloženi povećanom riziku od vlage zbog curenja vode, kondenzacije ili povećane vlage u zraku. Napadu gljiva smeđe truleži <u>Coniphora puteana</u> izloženi su površinski obrađeni višeslojni parket od hrastovine i borovine (OPP), ploča iverica s usmjerenim makroiverjem (OSB), brezova furnirska ploča (BP), ploča iverica (PB), ploča iverica obložena laminatom (LPB), vodootporna ploča iverica (MRPB), ploča vlaknatica srednje gustoće (MDF), ploča vlaknatica srednje gustoće obložena laminatom (LMDF) i vodootporna ploča vlaknatica srednje gustoće (MRMDF). Nakon 16 tjedana izlaganja u ovom istraživanju najotpornijim kompozitima na bazi drva na biorazgradnju pokazali su se brezova funirska ploča, vodootporni MDF i MDF obložen laminatom jer su imali gubitak mase manji od 5 %. Suprotno tome, svi ostali tipovi kompozita na bazi drva pokazali su visoku sklonost biorazgradnji, uz gubitak mase veći od 35 %. Najnižu apsorpciju vode (WA) unutar 168 sati imali su LMDF (8 – 51 %) i*

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MRMDF (2 – 46 %), dok je neobrađeni MDF pokazao najveću apsorpciju među svim vrstama kompozita, uz 190 %-tno upijanje vode. Kad je riječ o debljinskom bubrenju, sve su vrste kompozita na bazi drva, osim ploče iverice obložene laminatom i MDF-a, pokazale vrijednosti niže od 20 %. Za ljepila (fenol-formaldehidno ili melamin urea-formaldehidno) upotrijebljena u kompozitima na bazi drva nije potvrđen jasan utjecaj na svojstva u doticaju s vodom ili njihov utjecaj na biološku trajnost kompozita.

KLJUČNE RIJEČI: *biorazgradnja; gljive; debljinsko bubrenje; apsorpcija vode; kompoziti na bazi drva*

1 INTRODUCTION
1. UVOD

Wood-based composites (WBC) are widely used in furniture production and building construction for both interior and exterior applications. Scientific studies still address the issue of moving WBCs towards improved performance and higher sustainability (Zanuttini and Negro, 2021). The wood composite products are made of thin veneers, strands, flakes, particles, and fibres glued with an adhesive resin. Accordingly, the wood within the composites often has the same physical and biological properties as the original log. These wood properties include hygroscopicity, tendency to swell as moisture content (MC) increases, and susceptibility to biological attack at the same moisture level.

The type of adhesive and manufacturing process are among the most important factors contributing to differences in wood moisture relationships between wood composites and solid wood. The more water-resistant the bonded resin system becomes and the more deeply that resin system penetrates the wood cell wall, the more durable the wood composite becomes (Winandy and Morrell, 2017). Phenol-formaldehyde (PF) resins are typically used in the manufacture of construction plywood and oriented strand board, where exposure to weather during construction is a concern. Other moisture exposure situations, such as temporary weather exposure, occasional plumbing leaks, or wet foot traffic, may also necessitate the use of PF resins. Urea-formaldehyde (UF) resins are typically used in the manufacture of products used in interior applications, primarily particleboard and medium-density fibreboard (MDF). Melamine-formaldehyde (MF) resins are used primarily for decorative laminates and paper coating. Melamine urea-formaldehyde (MUF) resins are often used when greater water resistance is required than that obtained with UF resin (Stark *et al*., 2010).

Many WBC are generally intended for interior uses in a dry environment. However, in buildings, they are potentially subjected to elevated moisture risks due to water leaks, condensation, or damp air. When water intrusion occurs, a critical factor that affects water penetration is the water absorption rate of the wood-based materials (TenWolde and Rose, 1993). As a result, high moisture levels in building materials reach conditions where biological attack is possible, and this can result in substantial repair costs. Biodegradation has a big influence on the life cycle of various materials. Rot fungi are among the biggest groups of organisms that degrade wood materials (Schmidt, 2006). The biodegradation surveys in wooden constructions have mainly been focused on the type of decayed wood (soft- or hardwood), fungal species, and location of fungal attack (roof, floor, ceiling, etc.) (Alfredsen *et al*., 2005; Irbe *et al.,* 2012), and environmental conditions (Viitanen *et al.,* 2010). There is a lack of data on the biodegradation of WBC by wood decay fungi. The literature survey showed that laboratory studies on fungal biodegradation of WBC are mainly limited to the testing of a few panel types (Curling and Murphy, 1999; Kartal and Green III, 2003) or focused specifically on wood-plastic composites (Feng *et al.,* 2020; Yeh *et al.,* 2021; Buschalsky *et al.,* 2022) or deterioration of WBC by mould fungi (Yang, 2008). In the present study, the different types of WBC, including laminated and moisture-resistant panels, were investigated in relation to moisture and decay resistance properties. The brown rot fungus *Coniphora puteana* was selected for experiments as a widespread and economically important wood decay fungus in wooden constructions.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood-based composites
2.1. Kompoziti na bazi drva

Commercial oak-pine shield parquet (OPP) (thickness 14.1 mm), oriented strand board (OSB) (thickness 20.7 mm), birch plywood (BP) (thickness 14.7 mm), particle board (PB) (thickness 15.8 mm), laminated particle board (LPB) (thickness 16.1 mm), moisture resistant particle board (MRPB) (thickness 16.1 mm), medium density fibreboard (MDF) (thickness 16.2 mm), laminated medium density fibreboard (LMDF) (thickness 18.2 mm), and moisture resistant medium density fibreboard (MRMDF) (thickness 16.1 mm) were purchased from the retail market. The panels were conditioned at a temperature of 20 °C and 65 % relative humidity (RH) to a constant weight. The density of materials was determined for specimens 5cm × 5cm in size using the conditioned volume and conditioned mass.

2.2 Water absorption and thickness swelling
2.2. Apsorpcija vode i debljinsko bubrenje

The water absorption (WA) and thickness swelling (TS) of different WBC panels were measured according to ASTM D1037-12 (2020), with modifications using 5 cm × 5 cm specimens (6 replicates in each group). The specimens were immersed in distilled water and the weight was measured after 2 h, 4 h, 6 h, 8 h, 24 h, 48 h, 72 h, 96 h, and 168 h. Water absorption was calculated using the following equation:

$$WA\ (\%) = ((m_1 - m_0)/\ m_0))\ \times 100 \qquad (1)$$

Where m_0 is the mass of the specimen before immersion and m_1 is the mass of the specimen after immersion.

Thickness swelling was measured after 24 h, 48 h, 72 h, 96 h, and 168 h and calculated as follows:

$$TS\ (\%) = ((t_1 - t_0)/\ t_0))\ \times 100, \qquad (2)$$

Where t_0 is the thickness of the specimen before immersion and t_1 is the thickness after immersion.

2.3 Fungal resistance
2.3. Otpornost na gljive

The fungal resistance of WBC specimens was determined according to the modified European Prestandard ENV 12038:2002. Six parallel specimens with dimensions of 50 cm × 25 cm × 15 cm were cut from the pre-conditioned panels and exposed to the brown rot fungus *C. puteana* (Schumacher ex Fries) Karsten (BAM Ebw. 15) on a medium containing 5 % malt extract concentrate and 3 % Fluka agar (Sigma-Aldrich) in Kolle flasks. Scots pine wood was used as a control. Sterilized specimens were aseptically placed on a 3-mm glass supports and incubated at 22±2 °C and 70 % RH for 16 weeks. Aftero cultivation, the specimens were removed from the culture vessels, brushed free of mycelium, and oven dried at (103 ± 2) °C. The loss in dry mass (%) of the specimens was used as the criterion for determining the extent of the fungal attack. If the mean mass loss is greater than 3 %, the decay susceptibility index (*DSI*) is calculated as follows:

$$DSI = T/\ S \times 100 \qquad (3)$$

Where *T* is the mass loss (%) of an individual test specimen, *S* is the mean mass loss (%) of the appropriate set of control specimens.

DSI values of 100 indicate the same decay resistance as that of the timber used for the control. Materials with lower *DSI* values are more resistant to fungal attack.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The density of composites ranged from 526 kg/m^3 for OPP composite to 771 kg/m^3 for MDF (Figure 1). The highest density of over 700 kg/ m^3 was determined for BP, MDF, LMDF, and MRMDF materials.

Figure 2 shows the water absorption results of all tested specimens during the 2 to 168 h immersion. The lowest absorption was observed for BP, LMDF, and MRMDF reaching ~50 % at the end of the experiment. The lowest absorption correlated with the higher density of these composites (except for MDF) (Figure 1). OPP, OSB, PB, and MRPB specimens demonstrated similar absorption behaviour during the test reaching 28-47 % after 24 h, and 70-80 % after 168 h.

MDF had the highest absorption after 168 h reaching ~190 %, although after 24 h, OPP, BP, PB,

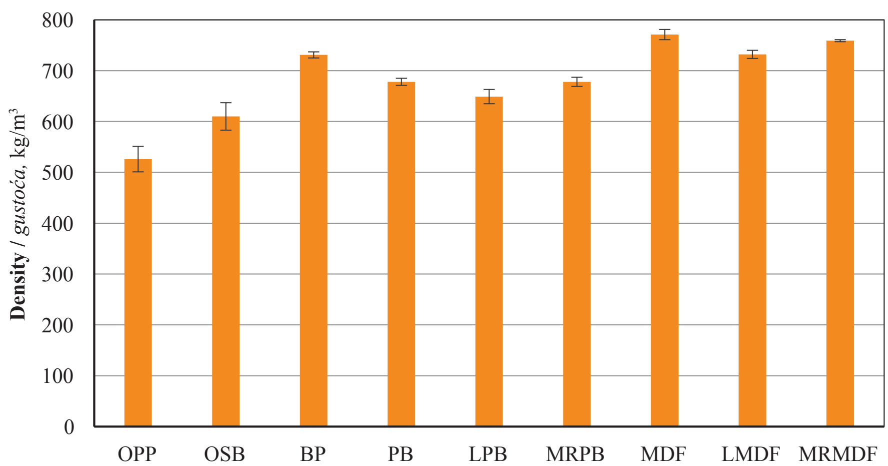

Figure 1 Density of tested specimens - oak-pine shield parquet (OPP), oriented strand board (OSB), birch plywood (BP), particle board (PB), laminated particle board (LPB), moisture-resistant particle board (MRPB), medium density fibreboard (MDF), laminated medium density fibreboard (LMDF), moisture resistant medium density fibreboard (MRMDF)
Slika 1. Gustoća ispitivanih uzoraka: površinski obrađenoga višeslojnog parketa od hrastovine i borovine (OPP), ploče iverice s usmjerenim makroiverjem (OSB), brezove furnirske ploče (BP), ploče iverice (PB), ploče iverice obložene laminatom (LPB), vodootporne ploče iverice (MRPB), ploče vlaknatice srednje gustoće (MDF), ploče vlaknatice srednje gustoće obložene laminatom (LMDF) i vodootporne ploče vlaknatice srednje gustoće (MRMDF)

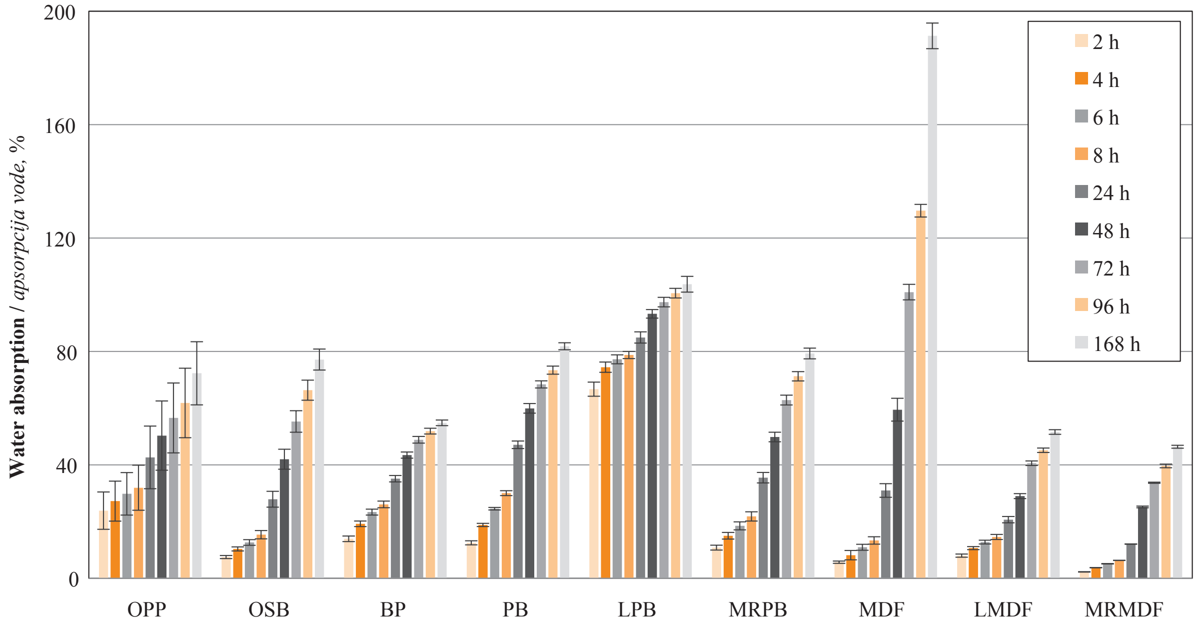

Figure 2 Water absorption of tested specimens after 2 h to 168 h - oak-pine shield parquet (OPP), oriented strand board (OSB), birch plywood (BP), particle board (PB), laminated particle board (LPB), moisture resistant particle board (MRPB), medium density fibreboard (MDF), laminated medium density fibreboard (LMDF), moisture resistant medium density fibreboard (MRMDF)

Slika 2. Apsorpcija vode ispitanih uzoraka nakon 2 do 168 h: površinski obrađenoga višeslojnog parketa od hrastovine i borovine (OPP), ploče iverice s usmjerenim makroiverjem (OSB), brezove furnirske ploče (BP), ploče iverice (PB), ploče iverice obložene laminatom (LPB), vodootporne ploče iverice (MRPB), ploče vlaknatice srednje gustoće (MDF), ploče vlaknatice srednje gustoće obložene laminatom (LMDF) i vodootporne ploče vlaknatica srednje gustoće (MRMDF)

LPB, and MRPB specimens had higher absorption compared to MDF. In general, MDF lamination and moisture resistance treatment decreased the water uptake, resulting in significantly lower absorption of LMDF (8-51 %) and the lowest absorption for MRMDF (2-46 %) specimens.

The laminated surface of PB did not protect the composite from elevated water uptake. LPB had significantly higher absorption during all immersion periods (67-103 %) than PB (13-82 %), while moisture-resistant PB had slightly lower absorption (11-79 %) compared to PB. LPB had the highest absorption after 24 h (~80 %) compared to other composites. In similar research, the physical-mechanical properties of PB manufactured with Eucalyptus wood, bamboo, and rice husk particles were assessed. Water absorption after 24 h of wood particle board was ~43 %, while for other combinations it was 67-72 % (de Melo *et al.,* 2014).

The findings provide proof that the commercial treatment aimed at reducing water absorption was effective for moisture-resistant PB and MDF compared to untreated or laminated composites. An alternative method to enhance the water-repellent properties of WBC is through modification techniques such as acetylation or thermal modification. Research conducted by Pipíška *et al.* (2020) demonstrated that OSB strand boards made of acetylated strands and thermally modified strands exhibited a substantial improvement in water resistance.

Figure 3 illustrates the thickness swelling of all WBC specimens over the period of 24 to 168 hours. Wood products incorporating larger-size wood particles like BP and OPP demonstrated consistently low and minimal swelling ranging from 6.5 % to 8.6 % throughout the entire 168h testing duration. In contrast to most particle-based panels, plywood undergoes negligible irreversible thickness swelling when subjected to moisture (Stark *et al.,* 2010). Additionally, OSB panels displayed relatively low swelling levels ranging from 7 % to 15 % during the entire testing period. Previous studies have reported that untreated BP experienced swelling between 6 % and 12 % during immersion periods of 2 to 72 hours (Bekhta *et al.,* 2020), while for untreated OSB the swelling was 20 % and 25 % after 24 h and 168 h, respectively (Pipíška *et al.,* 2020). There was no clear relation between the material density and swelling. For example, OPP and BP with similarly low swelling had different densities, while MDF with the highest density demonstrated the highest thickness swelling.

Notably, PB exhibited lower thickness swelling (13-18 %) after all testing periods, in contrast to laminated PB (22-26 %). Moisture-resistant PB demonstrated similar swelling levels to untreated PB, suggesting that lamination and moisture-resistant treatment did not effectively protect PB from long-term water exposure. In a study by de Melo *et al.* (2014), PB manufactured with Eucalyptus wood, bamboo, and rice

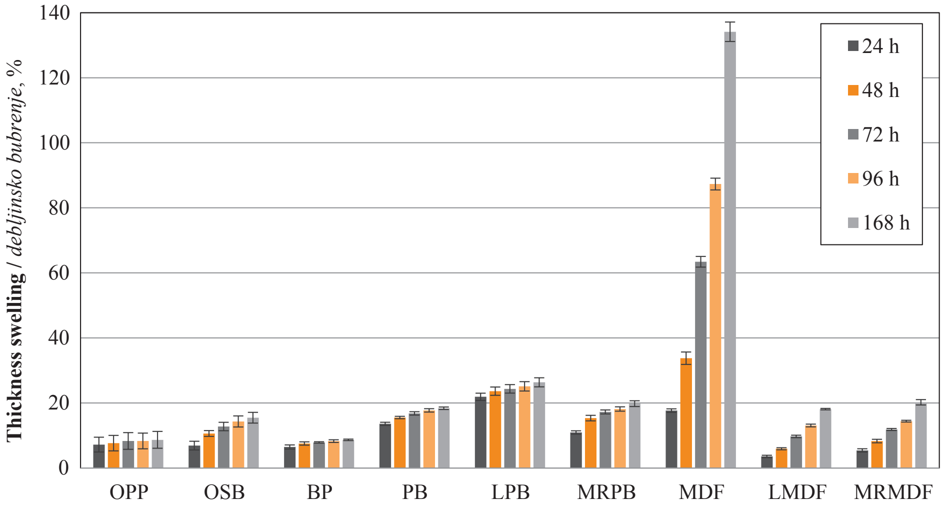

Figure 3 Thickness swelling after 24 h to 168 h immersion in water of tested specimens - oak-pine shield parquet (OPP), oriented strand board (OSB), birch plywood (BP), particle board (PB), laminated particle board (LPB), moisture resistant particle board (MRPB), medium density fibreboard (MDF), laminated medium density fibreboard (LMDF), moisture resistant medium density fibreboard (MRMDF)

Slika 3. Debljinsko bubrenje ispitivanih uzoraka nakon 24 do 168 h potapanja u vodi: površinski obrađenoga višeslojnog parketa od hrastovine i borovine (OPP), ploče iverice s usmjerenim makroiverjem (OSB), brezove furnirske ploče (BP), ploče iverice (PB), ploče iverice obložene laminatom (LPB), vodootporne ploče iverice (MRPB), ploče vlaknatice srednje gustoće (MDF), ploče vlaknatice srednje gustoće obložene laminatom (LMDF) i vodootporne ploče vlaknatice srednje gustoće (MRMDF)

husk exhibited thickness swelling of 31 %, 30 %, and 49 % after 24 h, respectively.

MDF showed the highest swelling after 48 hours, reaching 34 %, and remarkably increased to 134 % after 168h. Laminated MDF and moisture-resistant MDF displayed similar swelling patterns during the experiment, reaching 4-5 % after 24 hours and 18-20 % after 168 h. For MDF panels manufactured using bamboo, swelling reached 11-21 % after 24 hours (Marinho *et al.,* 2013). PB bonded with MUF resin and MDF panels bonded with UF resin demonstrated higher thickness swelling compared to panels containing PF resin (Figure 3), as moisture exposure leads to the breakdown of bond-forming reactions (Stark *et al.,* 2010).

Various board types displayed different susceptibility to the fungal decay after 16 weeks of exposure

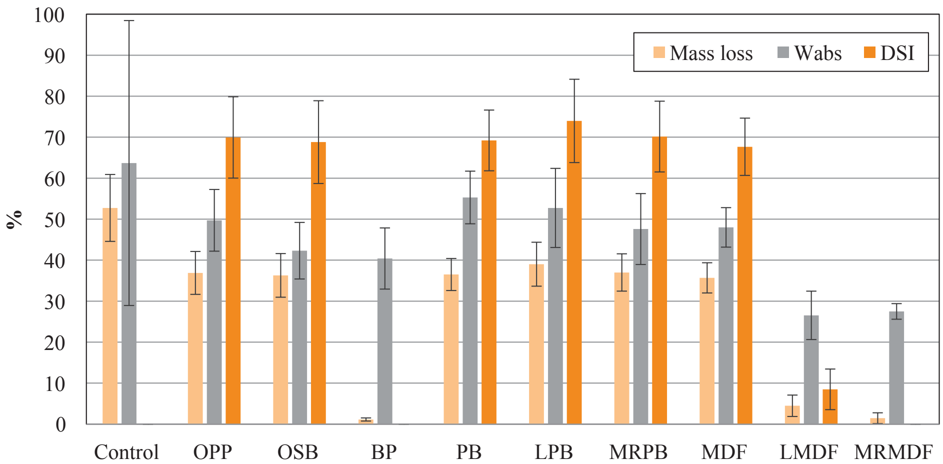

Figure 4 Mass loss (%), moisture content (W_{abs} %), and decay susceptibility index (*DSI*) of tested specimens (n = 6) after 16 weeks of degradation by brown rot fungus *C. puteana.* Abbreviations: oak-pine shield parquet (OPP), oriented strand board (OSB), birch plywood (BP), particle board (PB), laminated particle board (LPB), moisture resistant particle board (MRPB), medium density fibreboard (MDF), laminated medium density fibreboard (LMDF), moisture resistant medium density fibreboard (MRMDF)

Slika 4. Gubitak mase (%), sadržaj vode (W_{abs} %) i indeks osjetljivosti na truljenje (*DSI*) ispitivanih uzoraka (*n* = 6) nakon 16 tjedana razgradnje gljivom smeđe truleži *C. puteana*. Kratice: OPP – površinski obrađeni višeslojni parket od hrastovine i borovine, OSB – ploča iverica s usmjerenim makroiverjem, BP – brezova furnirska ploča, PB – ploča iverica, LPB – ploča iverica obložena laminatom, MRPB – vodootporna ploča iverica, MDF – ploča vlaknatica srednje gustoće, LMDF – ploča vlaknatica srednje gustoće obložena laminatom i MRMDF – vodootporna ploča vlaknatica srednje gustoće

(Figure 4). The average mass loss of the WBC specimens varied between 1.1 % for BP and 39.0 % for LPB, with pinewood control exhibiting significantly higher mass loss at 52.7 %. Among the WBC types, BP, moisture-resistant MDF, and laminated MDF reached the highest resistance to biodegradation, with mass losses below 5 %. Conversely, all other WBC types demonstrated a high susceptibility to biodegradation, with mass losses exceeding 35 %.

A mass loss above 20 % in the virulence control specimens provided confirmation of the viability of the fungal strain (ENV 12038:2002). The moisture content of both the test specimens and controls after the test exceeded 25 %, ensuring favourable conditions for fungal growth (Figure 4). The majority of tested WBC cannot be designated as fully resistant (except for BP and MRMDF) to attack by *C. puteana* since the mass loss of specimens was greater than 3 %. In this case, the DSI was calculated, with the mass loss of each test specimen being expressed as a percentage of the mean loss in mass of the control specimens. The DSI results demonstrated that laminated MDF performed the lowest value. Consequently, this material was more resistant (*DSI* 8.5) to fungal attack than other composites (*DSI*~70).

Several factors may contribute to a higher resistance to fungal attack, including physical properties, adhesive type, and wood particles. In terms of physical properties, certain composite types with a higher density above 700 kg/m³ (Figure 1) aligned with lower mass losses observed in BP, MRMDF, and LMDF panels, with the exception of MDF. However, the high mass loss observed in MDF can be attributed more to the absence of additional treatments such as moisture resistance in MRMDF or lamination in LMDF, rather than density alone.

The influence of adhesives on decay resistance yielded contradictory results. Various factors, including the fluid properties of the resin, wood anatomical characteristics and permeability, and processing conditions, contribute to resin penetration (Kamke and Lee, 2007), making it complex to isolate the specific impact of the adhesive. BP and OSB panels bonded with PF resins displayed distinct biodegradability, with BP experiencing a minor mass loss (1.1 %) and OSB panels showing high mass loss (over 30 %). This characteristic can be attributed more to the larger size of wood particles (veneers) in BP rather than the adhesive specific influence. According to Stark *et al.* (2010), plywood properties depend on the quality of veneer plies, their arrangement, the adhesive used, and the level of control of bonding conditions during production. Previous studies have also observed low mass loss in BP after decay (Irbe *et al.,* 2017). This property has been associated with the potential fungicidal effect of the PF adhesive due to the presence of phenols and formaldehyde. When water-soluble phenolic compounds were leached out, the plywood became susceptible to fungal attack (Irbe *et al*., 2017). OSB, manufactured from thin wood strands with controlled size, placement, and orientation, aims to enhance performance like structural plywood (Stark *et al.,* 2010). However, the wood strands in OSB remained vulnerable to fungal attack, indicating the need for further improvement in its resistance to decay (Figure 4).

PB panels, including laminated and moisture-resistant PB, bonded with MUF resin, were susceptible to fungal decay, resulting in mass losses exceeding 30 %. The production process of PB involves mechanically reducing the wood raw material into small particles, applying the adhesive to the particles, and consolidating them under heat and pressure to form a panel product (Stark *et al*., 2010). The presence of small wood particles and an adequate MC exceeding 47 % contributed to the efficient biodegradation of PB. Additional treatments such as lamination and moisture-resistant additives did not provide protective effects against fungal attack. In the case of lamination (LPB), the lack of protection against the fungus can be attributed to unsealed specimen edges. The moisture resistance property of MRPB is more likely associated with relative humidity, rather than material wetting. However, in practical applications, occasional wetting in constructions can lead to increased water absorption and thickness swelling, making the material more susceptible to penetration by fungal hyphae and subsequent degradation (Figure 4).

Except for moisture-resistant MDF and laminated MDF, MDF panels bonded with MUF resin demonstrated susceptibility to fungal degradation. The reduced biodegradation observed in these panels can be attributed to their hydrophobic properties with a lower MC (27 %). There are several distinguishing factors between fibreboard and particleboard, with the physical configuration of the wood element being the most notable difference. Fibreboard leverages the inherent strength of wood to a greater extent compared to particleboard, as wood is fibrous by nature (Stark *et al*., 2010).

There is ongoing exploration of various approaches to improve the biological durability of WBC. Ustaömer *et al.* (2010) noted that the decay resistance of MDF was enhanced by increasing the melamine content in the MUF resin and by using higher chemical concentrations. Treatment with vapor-boron was found to improve WBC resistance to fungal decay (Tsunoda, 2001), while the effectiveness of vacuum-impregnation of WBC with alkaline copper quat (ACQ) depended on the specific type of WBC and wood rot fungi (Tascioglu and Tsunoda, 2010). Pressure to reduce the use of wood preservatives is growing, prompting exploration of nonchemical methods that may be suitable for certain applications (Winandy and Morrell, 2017). For instance, acetylation of wood prior to composite manufacturing can be used to enhance moisture resistance. Another proposed method is thermal modification, which is believed to decrease the availability of carbohydrate compounds, thereby reducing the risk of fungal attack. Additionally, an alternative approach to enhancing the biological durability of composite materials could involve using naturally durable wood species or environmentally friendly biocides.

4 CONCLUSIONS
4. ZAKLJUČAK

Laminated and moisture-resistant MDF exhibited limited water absorption compared to other tested composite materials, reaching an absorption range of 46 – 52 % which was attributed to lamination, moisture resistance treatment, and higher density. The lowest thickness swelling observed in OPP and BP materials can be related to their larger wood particle size, and not to density. The impact of adhesive on water-related properties was not clearly evident from the observations. In terms of decay resistance, all tested WBC samples showed higher resistance compared to the control specimens. BP, as well as laminated, and moisture-resistant MDF panels, demonstrated the highest resistance, with mass losses below 5 %. The reduced fungal resistance observed in other WBC types may be related to factors such as smaller wood particle size, higher moisture susceptibility, or the absence of moisture treatment for the wood particles.

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