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Bio-based Methods with Potentials for Application in Wooden Furniture Industry

Biološke metode s potencijalom za primjenu u proizvodnji namještaja od drva

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ABSTRACT • *Furniture market is shifting towards green and innovative products. The use of bio-based methods in wooden furniture industry presents a big potential for the development of materials with new characteristics, of unique furniture items, and can reduce the environmental impact. Bio-based methods can be used for wood protection and decoration, fibre board production, and development of new wooden materials, such as wood hybrids and functionalised wood. The bio-based methods, investigated for their potentials in wood industry, include the use of living organisms, natural products, and biomimicry. Despite ongoing developments there are still major drawbacks associated with many of these technologies: unreliability and inadequate efficiency of the methods, inadequate mechanical properties or dimensional stability of the final products, and high costs. Thus, further developments are needed. In this review, we present the existing and arising bio-based methods with potential in wooden furniture production. Furthermore, we shortly present their marketing potential.*

Key words: *biotechnology; natural products; wood; furniture; wood protection; wood colouring; natural adhesives; wood functionalisation; biomimicry*

SAŽETAK • *Tržište namještaja sve se više pomiče prema zelenim i inovativnim proizvodima. Primjena bioloških metoda u proizvodnji namještaja od drva znači velik potencijal za razvoj materijala novih svojstava te za proizvodnju jedinstvenih predmeta namještaja. Osim toga, uvođenje bioloških metoda u industriju namještaja može pridonijeti i smanjenju štetnog utjecaja na okoliš. Biološke se metode mogu primijeniti u zaštiti i dekoraciji drva, u proizvodnji ploča vlaknatica i u razvoju novih drvnih materijala kao što su drvni hibridi i funkcionalizirano drvo. Spomenute metode, čiji se potencijal primjene u proizvodnji namještaja istražuje, uključuju biotehnologiju, uporabu prirodnih proizvoda i biomimikriju. Unatoč stalnom razvoju, još postoje znatni nedostatci povezani s primjenom tih tehnologija. To su složenost ili nepouzdanost metoda, neadekvatna mehanička svojstva ili dimenzijska stabilnost konačnih proizvoda te visoki proizvodni troškovi. Stoga je potrebno i dalje razvijati te metode radi njihove primjene u proizvodnji namještaja. U ovom su radu predstavljene razvijene biološke metode i one koje su u fazi razvoja a imaju potencijala za primjenu u proizvodnji namještaja od drva. Usto je ukratko opisan i njihov marketinški potencijal.*

Ključne riječi: *biotehnologija; prirodni proizvodi; drvo; namještaj; zaštita drva; bojenje drva; prirodna ljepila; funkcionalizacija drva; biomimikrija*

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1 INTRODUCTION
1. UVOD

Furniture production represents a big market (International Wooden Furniture Markets: A review, 2004; Wang *et al*., 2016), which requires design of original products to move up the value chain. This, among others, includes upgrades of the manufacturing processes and of the final product (International..., 2004). Such original products can be designed with the use of innovative bio-based technologies.

Wood biotechnology and the use of natural products in wooden furniture industry have long history and are still being developed. They have potential for development of materials with new characteristics, unique furniture items, and can help to reduce the environmental impact (Burgert *et al*., 2015; Mai *et al*., 2004; Robinson *et al*., 2012). Applications based on organisms and their products with potential in wood industry can be classified into three categories: 1) biotechnological use of live organisms or their enzymes for production of new substance or for catalytic purposes (Mai *et al*., 2004; Smith, 2009), 2) use of extracts or other non-catalytic products of organisms (Yang, 2009), and 3) biomimicry (Chen *et al*., 2017; Umorina, 2017).

There are quite a few reviews describing specialised topics of wood biotechnology or the use of natural products in the wood industry. For example, wood protection and fibre board production has been previously described in Mai *et al*. (2004) and surface functionalisation in Petrič *et al*. (2013). Furthermore, advanced breeding methods for creation of new tree and wood varieties are gaining importance (Bhalerao *et al*., 2003). However, the latter is out of the scope of this review as we focus on the processing of wood for production of furniture. Moreover, we failed to find a general overview of methods based on live organisms or their products used in wood processing. Thus, we review developed and arising methods based on live organisms or their products with potential in wooden furniture industry. Our main focus is on the methods that have not yet been widely applied in the industry. We also briefly discuss the marketing potential of these technologies.

2 ADHESIVES AND WOODEN BOARDS
2. LJEPILA I DRVNE PLOČE

Normally, production of board materials requires the use of high pressure and temperatures as well as toxic chemicals. This is associated with higher costs and adverse environmental effects (Liu *et al*., 2010; Mai *et al*., 2004). Thus, more environmentally-friendly techniques are being developed, as described by Ferdosian *et al*. (2017). This includes both natural adhesives, such as lignin and plant proteins (Ferdosian *et al*., 2017), and the use of oxidative enzymes or live organisms to increase adhesive properties of wood and catalyse covalent bond formation between adhesives (Mai *et al*., 2004). Enzymatic systems can be single-component, utilising only oxidative enzymes such as peroxidases or laccases, which are most commonly used enzyme, or two-component with addition of lignin and similar phenolic substances as adhesives. (Mai *et al*., 2004; Widsten and Kandelbauer, 2008).

Enzymes can be used in pre-treatment of wooden fibres or to aid in the gluing processes. This can reduce the heat and glue content needed to produce medium-density fibre boards. The use of enzymes may also contribute to the mechanical properties of the boards (Fackler *et al*., 2008; Mai *et al*., 2004). Pre-treatment of fibre particles with laccases increases the self-bonding properties of the fibres surface (Gabrič and Pohleven, 2014). Furthermore, adhesive surface properties can be improved by enzymatic functionalisation. Laccase-catalysed covalent binding of urea to fibres was shown to increase the adhesion. However, this effects was smaller than the effects of board density and glue content (Fackler *et al*., 2008). Laccase was also tested at the pilot level for catalysis of bonds between lignin molecules already present in the fibre particles. The process is claimed to have a potential, but it is limited by poor dimensional stability of the product and the need for the use of higher temperatures in the processing of boards (Felby *et al*., 2002). Cost effective production of laccases is also being studied. Laccase producing fungi can be grown on medium where main nutrients are waste materials (Zhou *et al*., 2014).

The use of lignin as an adhesive has been thoroughly investigated. Lignin can be used to partially substitute phenolic components in synthetic adhesives. Products created with such an adhesive have only slightly reduced strength retention and only slightly higher water uptake (Jin *et al*., 1990). Lignin can be produced either with wood degradation by brown rot fungi, which is a time consuming process with difficult extraction steps and requires further enzymatic processing of lignin, or from the industrial waste, which contains lignin with reduced adhesive properties (Gabrič and Pohleven, 2014; Jin *et al*., 1990; Mai *et al*., 2004). An alternative to lignin adhesives is the use of proteins. A combination of soy proteins and $CaCO_3$ resulted in a glue with good adhesive properties and water resistance (Liu *et al*., 2010).

3 WOOD PROTECTION
3. ZAŠTITA DRVA

Wood must be protected against biological and abiotic factors in all stages of furniture production (Yang, 2009). Selection of preservatives depends on the intended use of the wooden material, e.g. indoor or outdoor. Some outdoor protectants can be harmful to human health, leading to respiratory problems and allergies or even serious medical complications. They can also have negative effects on environment, especially at the time of the disposal (Pánek *et al*., 2014). Examples of traditional preservatives with negative effects on the health are those containing compounds of arsenic, zinc, copper, and creosotic oil. Due to their adverse effects they are often prohibited from the use in furniture industry (Pánek *et al*., 2014; Schubert *et al*., 2012). Therefore, new wood protection technologies are being developed. Biological protectants can have more targeted mode of action against wood pathogens and are biodegradable. However, they are also more sensitive to degradation and hence require special care (Mai *et al*., 2004). Another option for protection against pathogens is modification of wood properties, leading to more hydrophobic nature and reduced water content of wood (Burgert *et al*., 2015; Humar and Lesar, 2013).

3.1 Protection with microorganisms
3.1. Zaštita mikroorganizmima

Pathogenic organisms cause wood degradation and loss of mechanical properties, unwanted colouring, and production of harmful toxins (Yang, 2009). Due to high humidity in some living spaces, it is necessary to protect wood against pathogenic microorganisms. This can be done with the inoculation of wood with protective non-pathogenic organisms (Bruce & King, 1991; Mai *et al*., 2004), as further described by Mai *et al*. (2004) and Susi *et al*. (2011). Bio-controlling organisms compete with the pathogens or produce compounds that prevent the growth of pathogens (Mai *et al*., 2004; Susi *et al*., 2011). However, protection with microorganisms is not long-lasting, retaining effectiveness only for a few years (Bruce & King, 1991; Mai *et al*., 2004). It also has varying results against different fungi and in different environments (Mai *et al*., 2004). Microbial extracts may improve the reliability of protection under varying conditions (Yang, 2009). However, bio-control fungi only provide preventive protection against the invasive fungi. Thus, it is important to apply the protective organism already during the production of furniture (Bruce & King, 1991; Mai *et al*., 2004). On the other hand, application of bacterial and fungal spores on wood already infected by insects has some potential (Mai *et al*., 2004). Bio-finishes based on black mould and oil are already used in practice (van Nieuwenhuijzen *et al*., 2016). On the other hand, some bio-controlling organisms will require further research before becoming commercially applicable. These include *Streptomyces* isolates (Jung *et al*., 2018) and *Bacillus subtilis* that can be combined with the application of essential oils (Sajitha *et al*., 2018; Wang *et al*., 2012).

Fungi can also be used for increasing the permeability of the outdoors wood to commercial preservatives. However, the technology is still not regarded as economically feasible (Schwarze & Schubert, 2017; Thaler *et al*., 2012).

3.2 Protection with natural products
3.2. Zaštita prirodnim proizvodima

Natural protectants have a long tradition. Many protectants like resins, extractives, essential oils, and lignin are still being further tested (Fernández-Costas *et al*., 2017) and some have also been patented (Yang, 2009). Examples include capsaicin containing extract from chilli, extracts from durable wood species containing tannins, flavonoids, and terpenoids, and essential oils containing phenols (Pánek *et al*., 2014). The application of different extracts for the protection of wood is more thoroughly described in Yang (2009).

The use of natural protectants has various benefits. They can be applied as a protection against organisms from different kingdoms, can be nontoxic to humans, and are produced from renewable sources – organisms, ranging from plants to fungi and bacteria (Pánek *et al*., 2014; Yang, 2009). Treatment with natural products can change the surface properties of wood and thus reduce the leaching of other protectants (Fernández-Costas *et al*., 2017). Multifunctional protectants that also serve as dyes have been investigated (Colak, 2016; Ozen *et al*., 2014). Furthermore, protectants can be extracted from waste materials. An example is bark, which has protective potential due to high content of tannins, resins, and waxes (Yang, 2009). Similarly, lignin, a waste product from paper industry, has potential as protectant due to its phenolic content (Fernández-Costas *et al*., 2017). Some plant extracts with antifungal properties, such as mimosa and quebracho extracts, are already commercially available (Tascioglu *et al*., 2013).

However, the use of natural protectants still poses a problem. Their activity can be inconsistent and some of them are subjected to microbial or UV degradation, being suitable only for interior use (Pánek *et al*., 2014). Furthermore, they can be subjected to leaching or are insoluble in water, thus requiring the use of organic solvents (Yang, 2009).

3.3 Enzymatic ligation of protectants
3.3. Enzimsko povezivanje zaštitnih sredstava

Preservatives are often subjected to leaching from wood. This can be prevented by chemical ligation or grafting of preservatives into the wood. Enzymes can catalyse the creation of covalent bonds between wood and preservative (Kudanga *et al*., 2008; Petrič, 2013; Schubert *et al*., 2012). In comparison to chemical and physical methods of functionalisation, the use of enzymes is more environmentally friendly due to the reduced use of energy and chemicals (Kudanga *et al*., 2008). Additionally, the use of enzymes removes the need for expensive catalysts (Slagman *et al*., 2018). However, poor penetration of the enzymes into the wood poses a problem for the use of enzymatic grafting (Slagman *et al*., 2018).

Oxidases, including laccases, are used for grafting. Laccases, in contrast to other oxidases, require only oxygen and not hydrogen peroxide for oxidation. Furthermore, the addition of mediators enables oxidation of substances that otherwise do not fit in the active site of laccases (Slagman *et al*., 2018). Grafting often involves the use of phenolic compounds, although other substrates have been tested as well (Slagman *et al*., 2018). One of such examples is the use of iodine, which is cheap and is not associated with microbial resistance. Oxidation of iodide (I^-), which has no antimicrobial activity, to antimicrobial three iodide (I_3^-) with laccases and mediators leads to binding of three iodide to aromatic groups of lignin. This provides protection against bacteria, yeast and higher fungi. The use of laccases prevented leaching of the protectant and led to similar effectiveness as a commercial preservative. Furthermore, the lignin degradation by laccases was reported to be small (Schubert *et al*., 2012). Additional improvements can be achieved by the use of anchoring molecules that are covalently bound to the wood and serve as anchors for protectant binding (Kudanga *et al*., 2008).

3.4 Surface treatments for increased hydrophobicity
3.4. Površinska obrada radi povećanja hidrofobnosti

Wood absorbs water both from vapour and liquid state (Glass and Zelinka, 2010). This can lead to swelling and cracking of wood and enables colonisation by pathogens (Burgert *et al*., 2015; Mai *et al*., 2004). Cell wall moisture content and hence biological degradation of indoor wood is dependent on the environmental humidity, temperature and ventilation (Mai *et al*., 2004; Žlahtič and Humar, 2016). Wood with moisture content below 12 % is usually not affected by biological degradation, moisture level of 12-18 % enables infestation by insect, above 18 % enables mould growth, 28-33 % enables growth of higher fungi, and if moisture increases even further, the wood can be affected by bacterial degradation (Mai *et al*., 2004). Fungal colonisation depends on average moisture over time. Thus applied protectants must prevent both water absorption and allow drying of wood after the exposure to water (Humar and Lesar, 2013).

Many different approaches for reducing the water content of wood have been tested. Lumen of the cells in the wood can be filled up or the surface characteristics of the wood and cell walls may be changed, for example with alkylation of hydrophilic functional groups of lignin, cellulose and hemicellulose (Burgert *et al*., 2015). Water repellents, such as waxes and oils, including linseed and tung oils, are especially useful as they provide protection against water absorption and at the same time do not seal the wood surface, enabling wood drying (Humar & Lesar, 2013). Combinations of both oils and waxes were also shown to be beneficial (Žlahtič and Humar, 2016). Effectiveness of repellents depends on the successful impregnation of wood. This is affected by wood permeability and characteristics of the repellent. Performance of repellents thus varies across wood species (Humar and Lesar, 2013). Traditional agents used for decreased water absorption, such as waxes, resins and oils, are subjected to leaching from wood. Thus, it was proposed that laccases should be used for binding of hydrophobic molecules, such as lauryl gallate, on the surface of wood and subsequent creation of a resistant hydrophobic layer (Fernández-Fernández *et al*., 2015).

Another option is bio-mimicry of super-hydrophobic surfaces that repel water and also have self-cleaning properties. Super hydrophobic surfaces can be created by surface wrinkling, electrospinning, template-based extrusion, photolithography and soft lithography (Chen *et al*., 2017). General information about these methods is available elsewhere (Bhardwaj & Kundu, 2010; Meng *et al*., 2016; Ouyang *et al*., 2015; Qin *et al*., 2010; Raoufi *et al*., 2015). For example, a super-hydrophobic surface pattern imitation of *Colocasia esculenta* leaf was produced on the wood with soft lithography (Chen *et al*., 2017).

4 DECORATION
4. DEKORACIJA

Visual characteristics of wood are highly valued by consumers (Knauf, 2015; Manuel *et al*., 2015). Besides, bio-based decoration methods can be more environmentally friendly and their application can create unique decorative patterns.

4.1 Natural dyes
4.1. Prirodne boje

Consumers are becoming interested in natural dyes as production of synthetic dyes is often environmentally unfriendly and their use can be potentially harmful to health (Colak, 2016; Prabhu & Bhute, 2012; Yeniocak *et al*., 2015). Different natural dyes are still being tested, such as extracts from pomegranate, red beetroot, and fungi (Colak, 2016; Vega Gutierrez *et al*., 2016; Yeniocak *et al*., 2015).

However, there are also downsides of using natural dyes. The final colour can depend on wood composition and may be affected by UV (Yeniocak *et al*., 2015). Some dyes do not penetrate into the wood and thus colour only the surface (Vega Gutierrez *et al*., 2016). Furthermore, natural dyes can have poor affinity for binding to the wooden surfaces. Their resistance to discoloration can be improved by the use of mordants, which form complexes with dyes and thus increase their binding to the surface. Metal-based mordants (e.g. iron, aluminium) and vinegar are among commonly tested mordants for colouring of the wood and other natural products. (Colak, 2016; Goktas *et al*., 2008; Prabhu & Bhute, 2012; Vega Gutierrez *et al*., 2016; Yeniocak *et al*., 2017). However, mordants can lead to colour changes of the dye. Furthermore, some of the mordants, including the metal-based ones, have toxic properties (Prabhu & Bhute, 2012). Therefore, further research is needed to produce resistant natural dyes.

4.2 Spalting
4.2. *Spalting*

Colouring of wood can also be achieved by the use of live organisms, which produce unique patterns and can excrete protective antimicrobial substances. Process of wood colouration based on dye secretion by organisms inhabiting the wood is called spalting. As many consumers desire unique wooden products, spalted wood is highly valued, regardless of the wood species used (Robinson *et al*., 2012). One of the main concerns is the loss of mechanical properties after spalting. Thus, the use of dense hardwood has been advised (Robinson *et al*., 2007; Robinson *et al*., 2012). However, spalted wood does not have importantly reduced mechanical or acoustic properties. Moreover, spalting increases wood permeability, affecting gluing and surface finishing of the products (Robinson *et al*., 2013b). Increased permeability can be beneficial, leading to better impregnation (Schubert *et al*., 2011).

Spalting can result in various patterns and shades, depending on the used microorganism. Zone lines are usually produced by white rot fungi, while ascomycetes produce wood colouring (Robinson *et al*., 2011a). Spalting can be a consequence of excreted dyes with low molecular mass or inoculation of wood with fungi that have pigmented cell walls, leading to zone lines and blue-grey colouring, also known as blue stain (Robinson *et al*., 2012). Zone lines are easy to produce and can be created by the use of various fungi (Robinson *et al*., 2011b). Zone lines are often produced as the result of competition, for example between *Trametes versicolor* and *Bjerkandera adusta* or *Inonotus hispidus* and *Xylaria polymorpha*. *Xylaria polymorpha* can produce zone lines even when individually inoculated and without application of stressful conditions (Robinson, 2012; Robinson *et al*., 2012). Blue stain of sapwood is produced by fungi from *Ophiostoma* genera that are in nature transmitted by bark beetles. However, blue stain wood is less popular among consumers (Robinson *et al*., 2013b). Pink stain is produced by naphthoquinone of *Arthrographis cuboidea* and xylindein of *Scytalidium cuboideum*, also on conifers and bamboo. However, *Scytalidium cuboideum* produces zone lines instead of pink pigmentation when grown together with other fungi. Bright blue-green pigmentation arises due to xylindein produced by *Chlorociboria* genus on poplar wood. Yellow stain is produced by quinones of *Scytalidium ganodermophthorum* (Mai *et al*., 2004; Robinson, 2012; Robinson *et al*., 2013a; Robinson *et al*., 2013b; Vega Gutierrez *et al*., 2016). Furthermore, wood can be inoculated with a mixture of fungi or inoculated more than once with different fungi (Robinson *et al*., 2013b). For example, increased visibility of spalting can be achieved by initial bleaching of wood with white rot fungi, sterilisation and subsequent inoculation with the desired spalting fungi. However, sterilisation can only be used for small wood pieces, as increased volume leads to overly prolonged sterilisation times (Robinson *et al*., 2012). Nevertheless, this method can still be used for production of "furniture jewellery".

Spalting can be adopted at the industrial level (Robinson *et al*., 2011a). It was tested by Robinson *et al*. (2013a), who discovered that specific combinations of *Scytalidium cuboideum, Xylaria polymorpha* and *Trametes versicolor* produce the best zone lines. In order to achieve spalting fungi must be able to penetrate into the wood and grow inside it (Robinson *et al*., 2012; Vega Gutierrez *et al*., 2016). At the industrial level it is important to choose the right inoculation method, depending on the fungi (Robinson *et al*., 2013a). Additionally, prior sterilisation can increase the pigmentation (Robinson *et al*., 2011b). Growth of the fungi is then stopped before the loss of mechanical properties of wood (Robinson *et al*., 2011a). Fungal growth and spalting depend on may parameters (Robinson *et al*., 2011a), including wood species, which must be chosen based on the desired pigmentation. For example, sugar maple can be spalted by a broad range of fungi, while some wood species can be spalted with only certain fungi or none at all (Robinson *et al*., 2011a). Antifungal substances in wood can importantly reduce fungal growth, while some stressors may increase the spalting. Sugar content also affects the spalting (Robinson *et al*., 2011a). However, the success of spalting varies greatly and thus reliable combinations of wood and fungi should be chosen (Robinson, 2012).

5 NEW WOODEN MATERIALS
5. NOVI DRVNI MATERIJALI

Wood has low density, good mechanical properties, and is relatively inexpensive and sustainable. Thus, new approaches for widening the range of applications of wood are being investigated (Burgert *et al*., 2015; Gan *et al*., 2017; Li *et al*., 2018). However, the heterogeneity of wood decreases the reliability of its mechanical properties and reduces the control over the process of wood functionalisation (Frey *et al*., 2018). Functional wood based materials were described in more detail by Burgert *et al*. (2015).

5.1 Wood densification
5.1. Ugušćivanje drva

Density is one of the main factors affecting mechanical properties of wood. Wood densification can increase homogeneity and mechanical properties, while retaining the ordered structure of wood. (Frey *et al*., 2018). It increases hardness and surface abrasion resistance and can lead to colour changes (Cruz *et al*., 2018; Sozbir and Bektas, 2017). Densification can be used to improve mechanical properties of wood of low-density species. Therefore, hardwood species can be replaced by low-density species in applications such as table tops and floors (Sozbir and Bektas, 2017). Process of wood surface densification has been already industrialised (Sandberg *et al*., 2017). On the other hand, lightweight wooden materials reduce economic and ecological burden of furniture transport (Iejavs and Spulle, 2016) and have potential for multifunctional furniture.

Wood densification process is comprised of wood softening by moistening and heat treatment, followed by compression leading to collapse of cell walls, and is finished by locking the wood in compressed state by drying and cooling. Fixation of the compressed state can be further improved by impregnation with adhesives (Sandberg *et al*., 2017; Sozbir & Bektas, 2017). The process is usually applied only to the surface of the wood, leading to greater usage efficiency of the material, easier production and better mechanical properties for certain applications (Sandberg *et al*., 2017). Uneven compression enables production of wood with gradual variation in density and stiffness (Frey *et al*., 2018). Furthermore, chemical composition of wood importantly affects the mechanical properties of densified wood, as was shows on *Pinus radiata* (Cruz *et al*., 2018). Delignification can be used to ease the curving or twisting of wood (Frey *et al*., 2018).

5.2 Wood functionalisation and hybrid materials
5.2. Funkcionalizacija drva i hibridni materijali

Wood can be functionalised to induce changes in its property profile. For example, incorporation of mineral particles into the wood can increase strength, fracture resistance, hardness, and stiffness (Burgert *et al*., 2015). Furthermore, changes in magnetic, conductor and optical properties could be used to extend the range of applications of wood into electrotechnical industry (Burgert *et al*., 2015; Gan *et al*., 2017; Li *et al*., 2018). Transparent wood has already been produced; however, its optical properties are still greatly dependent on thickness and any subsequent compression of the material. It has potential for the use in buildings due to its low density and light transmittance as well as reduced heath conductivity and frailness in comparison to glass (Li *et al*., 2018). Furthermore, transparent wood can be functionalised with luminescent properties (Gan *et al*., 2017; Li *et al*., 2018).

Transparent wood can be manufactured by delignification or removal of chromophores followed by impregnation with polymer with refractive index matching the wood. The polymer fills pores in the wood that would otherwise lead to scattering of the light (Gan *et al*., 2017; Li *et al*., 2018). However, delignification is time consuming and can pose a burden for the environment (Li *et al*., 2018). Furthermore, functionalisation of bulk wood is challenging. This could potentially be improved by separation of wood into fibres, which would be functionalised and then re-aligned into the wooden structure (Frey *et al*., 2018). For example, Gradwell *et al*. (2004) used soluble pullulan as a model for lignin. Pullulan adsorbed to the cellulose surface leads to self-assembly (Gradwell *et al*., 2004).

Wood can also be used to produce hybrids with synthetic or inorganic materials. The main benefit of wood incorporation is its ordered structure (Burgert *et al*., 2015; Croitoru *et al*., 2018). For example, wood can serve as a framework for production of synthetic materials in which it is otherwise challenging to produce an ordered structure. This has potential for optical implications (Burgert *et al*., 2015). Furthermore, it was proposed that wood may be useful for substituting synthetic polymers (Li *et al*., 2018). Wooden fibres incorporated into plastics are already being used in the industry. However, protectants used in such materials often pose health risks (Croitoru *et al*., 2018). Thus, ionic liquids, substances composed entirely from ions with melting point below 100 °C (Lei *et al*., 2017), were proposed as a substitute (Croitoru *et al*., 2018).

6 MARKETING POTENTIAL
6. MARKETINŠKI POTENCIJAL

Innovations in the wood industry promise better visual and mechanical properties as well as reduced burden for the environment. This has potential for marketing, as consumers already associate wood with wellbeing, aesthetics and environmental friendliness (Manuel *et al*., 2015). Uniqueness is highly valued among consumers, especially when purchasing items with hedonistic rather than strictly functional role (Reich *et al*., 2017). Thus, "furniture jewellery" applications may have a good potential. Furthermore, the lifespan of furniture design is shortening (Scholz and Decker, 2007) and thus novel wood processing technologies may bring about innovations desired by consumers.

Environmental friendliness is important decision factor for many consumers, as shown by a Brazilian study, in which consumers were prepared to pay more for environmentally friendly furniture (de Medeiros *et al*., 2016). Environmental friendliness can be achieved by the reduced use of energy and resources, recycling and waste reduction, and by following the principles of sustainable development (Huang *et al*., 2012). However, main attributes in the choice of furniture are still elsewhere, including: comfort, design, (de Medeiros *et al*., 2016; Holopainen *et al*., 2014), brand, price (Caia *et al*., 2017), and durability (Holopainen *et al*., 2014).

Marketing for new technologies can be challenging. The degree of newness in a product must be balanced, as consumers can distrust the usability of the product or are disheartened by their own uncertainty about the proper maintenance of the item (Cojocaru *et al*., 2013). Additionally, it has been shown in a Chinese study that eco-labels are often distrusted and that many consumers are unable to distinguish between ordinary and green furniture (Caia *et al.*, 2017). Thus, not only the development of new technologies, but also research in their marketing must be conducted.

7 CONCLUSION
7. ZAKLJUČAK

The use of biotechnology, natural products or nature-inspired methods has great potential in furniture industry. These methods can lead to production of eco-friendly wood with changed physical properties and unique visual characteristics. Here presented methods may thus inspire the development of new wooden furniture products.

In general, most investigated methods include the use of enzymes, live organisms, and natural products. Additionally, production of functionalised wood and hybrid materials is also gaining importance. Nevertheless, many applications are still not developed at the industrial level. Common drawbacks include complexity or unreliability of the methods, inadequate mechanical properties or dimensional stability of the final products, and high costs. Thus, further research on both laboratory and pilot scale is required.

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