WOOD RESEARCH doi.org/10.37763/wr.1336-4561/65.2.205220
65 (2): 2020
205-220

SIZE REDUCTION DOWNCYCLING OF WASTE WOOD. REVIEW

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(Received September 2019)

ABSTRACT

The article includes research related to utilization of waste wood which is primarily size reduced due to its voluminity for next processing for lower value added products for about last twenty years. Procedures and results obtained by different authors were considered in one study. In this review a wood waste downcycling was consider as a process of transformation of large size wood products over their lifetime to the new products, where a size reduction is one of the first operations needed to achieve to. Incineration of each way was excluded from the present review, but second-generation biofuels are considered as potential products for the future. Two points of research selection according to origin and according to products made of waste wood was applied in this review. Comparison shown that the most industrially applicable implementation of treated particles obtained from waste wood is intended to the composite materials production as particleboards, fibreboards, cement-bonded and wood-plastics.

KEYWORDS: Downcycling, upcycling, wood, waste recycle, size reduction, wood particles.

INTRODUCTION

Wood waste potential depends on many factors, its next processing is mainly depended on the high voluminity and possible content of harmful substances. The estimation of the waste wood statistics in the EU is provided basically on a) wood waste from municipal waste b) construction and demolition wood, and c) waste wood from industry (by products). The most valuable and detailed data on waste management in Europe come from Eurostat. The data show orientations in terms of valorization or elimination of wood waste. However, these data don't consider certain bad practices like household heating or open burning. In 2018 European Commission published the

Guidance on cascading use of biomass with selected good practice examples on woody biomass. The Circular Economy Action Plan adopted in 2015 aims to turn Europe's economy into a more sustainable economy, promoting sustainable economic growth and generating new jobs. The actions in the plan seek to close the life-cycle loop of products and materials by keeping their value in the economy if possible, minimizing the generation of waste and maximizing recycling and reuse. These benefits both the environment and the economy.

Although the idea of wood waste recycling has only begun to become more serious in recent decades, researchers have been dealing with the issue of wood recycling in the past. But practical application in industry has been progressively and over time, considering more economic (Zeng et al. 2018) as environmental benefits (Michanickl 1996). The European wood-based panel industry relies primarily on the softwood timber supply, so waste wood and recovered wood assortments are becoming more important (Janiszewska et al. 2015, Meinlschmidt 2016). Recovered waste wood particles can be used for production of eco-friendly wood composite materials bonded by bio-based adhesives (Antov et al. 2020).

Recycling of wood waste is difficult due to a content of harmful chemicals contained both in glue used during a manufacture process (Risholm-Sundman and Vestin 2005) and in additives which originally served to protect it from moisture content, wood decaying fungi, to increase fire resistance and so on (Erbreich 2004). Different authors have used different techniques to determine the content of chemicals contained in waste wood, as for example, laser-induced breakdown spectroscopy (Uhl et al. 2001). Moskal and Haln (2002) suggested the online detector system using laser-induced breakdown spectroscopy for the analysis of copper chromated arsenate (CCA) treated wood products from the waste stream at a construction and demolition debris recycling center. Accuracy of handheld XRF analyzers on wood that has been treated with a preservative containing arsenic was determined by Block et al. (2007). Concentrations of wood preservatives in the wood chips produced in wood-waste processing facilities around 2000 in Japan was investigated by Kurata et al. (2005). Concentration levels depended on the sources of the wood wastes.

Methods of recycling the wood particles from waste wood-based materials were suggested previously by Michanickl and Boehme (1996). Several authors had been devoted to issue of a further processing of large-scale wood-based materials (Riddiough and Kearley 2001, Riddiough 2002). There are many opportunities for composites made from recycled wood-based waste resources. Research in these areas could result in a new product range in combination with other materials that are cost effective, designed to meet demands of end-use, and environmentally friendly (Boehme 2003, Wolff and Siempelkamp 2000, Rowell et al. 1993).

Review studies of wood waste carried out

After 2000, several studies were conducted that dealt with wood in the form of waste or use of wood residues. Several review studies that directly or partially (Jeffrey 2011) deal with waste wood have been published. Tam V. and Tam C. (2006) published a study related to the technology on the construction waste recycling and their viability. Timber recycling technology has been also considered, as well as other materials suitable for recycling (asphalt, brick, concrete, ferrous metal, glass, masonry, non-ferrous metal, paper and cardboard and plastic). Kartal and Imamura (2003) published a review on chemical and biological remediations of CCA-treated (chromium, copper, and arsenic) waste wood. Chemical extraction using inorganic and organic acids and bioremediation using bacteria and fungi were summarized. Several alternative methods for the disposal of CCA treated wood waste have been published also by Helsen and Van den Bulck (2005). Alternative disposal methods include recycling and recovery, chemical extraction, bioremediation, electrodialytic remediation and thermal destruction. Dias et al. (2007) determined waste wood as one of precursors of activated carbon (AC), which is a preferred adsorbent for the removal of micropollutants from the aqueous phase. AC can be prepared from conventional waste from wood industry to remove organic pollutants, dyes, volatile organic compounds, and heavy metals. Required high surface areas can be obtained using either physical or chemical activation.

The main reason to build this review study was to describe attitudes of different researchers to a waste wood processing in points of selection according to its origin and according to products made of it, sorting the industrially applicable implementations in large scale as well.

Source of wood waste

Many studies solve a problem of accumulation of waste in the place of its origin. Usually large amounts of this waste end up in dumps every day with the highest environmental impacts (Di Maria et al. 2018). Authors distinguish municipal wood waste from land fields (Stahl et al. 2002), wood waste from construction site (Wang et al. 2016, 2017), demolition waste (Asari et al. 2004, Huang et al. 2002, Rautkoski et al. 2016), and wood industrial waste (Ahmed et al. 1998), also closely specified by type, f. e. hardwood residue (Shulga et al. 2014), untraditional softwood residue (Ozaki et al. 2005, Al Maadeed et al. 2014), or used railway sleepers (Ashori et al. 2012). Some atypical solutions are mentioned as well, as pruning residuals in olive groves and vineyards (Recchia et al. 2009). The bark is not a typical wood waste but since it is produced in parallel as byproduct from sawmills many authors are concerned with this issue, not preferring its direct energy use (Andres et al. 2010, Ghitescu et al. 2015, Medveď et al. 2019, Mirski et al. 2020). Generally, bark has often had three main uses: an animal bedding, an energy recovery and a mulching (in gardening and landscaping). These are generally low values uses.

A great source of wood waste are agglomerated materials as particle boards (PB) mainly from old furniture (Ihnát et al. 2017, 2018, Balberčák et al. 2017, 2018, Wan et al. 2014), oriented strand boards (OSB) (Schoo et al. 2003, Wan et al. 2014, Ihnát et al. 2017, 2018, Zeng et al. 2018), and middle density fiberboards (MDF) (Wan et al. 2014, Ihnát et al. 2018, Petar and Savov 2019).

Size reduction and wood waste downcycling

Regarding to the wood waste processing in the terms of sequence: reduce-reuse-recycle (Falk 1997), a cascading utilization of resources is encouraged (Höglmeier et al. 2014). Basically, wood recycling is almost always associated with the disintegration (size reduction) of bulk wood waste into small particles (chips, fiber, etc.,) which are reused to produce composite materials (Ihnát et al. 2015). The particles obtained have mostly reduced mechanical and other properties (Buyuksari et al. 2010) and therefore added just in certain proportions (Chen et al.2006). The process whereby a product is recycled to obtain a new product with a lower added value (technical or utility) is called downcycling and is a frequent phenomenon in the processing of waste wood. Upcycling of this waste material group is unique (Meinlschmidt and Mauruschat 2015, Russ et al. 2013) and almost impossible to apply in a mass production.

Methods of the size reduced particles treatment

Attention was focused on methods of removing chemical loads from waste wood. Kabir et al. (2006) found out that most of the CCA components could be extracted by 10% H_2O_2 at 50°C in 6 hours with an average extraction efficiency of 95% for Cr, 94% for Cu and 98% for As. The extract containing Cr^{III}, Cu^{II} and As^{V} could be oxidized in several stages by aqueous 2.5%

w/w H_2O_2 in less than 2 h. Shupe et al. (2006) used steam treatment to remove residual creosote content of sawdust obtained from weathered, out-of-service poles. Steaming was successful in reducing the creosote content to a level of 1.31%. Hse et al. (2013) provided a recovery of metals from CCA treated southern pine wood particles by the extraction in a microwave reactor with the binary combinations of an acetic acid and phosphoric acid. The highest recovery rate of metals achieved with a mixture of 2.75% phosphoric acid and 0.5% AA at 130°C in 10 min in the microwave oven.

Special attention has been paid to recycling of panelboards. In generally, three different principles can be applied for disintegration of panelboards: mechanical, thermo-hydrolytic and chemical, or combinations thereof (Kharazipour and Kües 2007). These processes were mostly described before 2000 and improved or novelized later. Fleischer and Marutzky (2000) were addressed to degradation of glued UF joints in waste particleboards. Lykidis and Grigoriou (2008) provided four different hydrothermal treatments applied in order to recover wood particles from waste particleboards and use them in the production of new (recycled) ones. It was found that other recycling cycles caused the deterioration in the quality of the recycled boards as regards their mechanical properties. Lykidis and Grygoriou (2011) concluded that the optimum hydrothermal recovery parameters were 45% water retention, 150°C temperature, and 10 min duration. Roffael and Hüster (2012)provided thermohydrolytic treatment of chips from waste UF-bonded particleboards using the flask method at 103°C for the reaction period of 24 h due to degradation of the UF-resin. Wan et al. 2014 subjected medium density fiberboard (MDF), particleboard (PB), and oriented strandboard (OSB) panels to steam explosion treatment. Downgraded panels were treated with thermal chemical impregnation using 0.5% butanetetracarboxylic acid (BTCA) to disintegrate UF bonds and were processed with mechanical hammermilling. The hammermilling of recycled PB was less likely to break particles down into sizes less than 1 mm^2. Moezzipour et al. (2017) investigated the changes in the chemical properties of wood fibers after hydrothermal recycling of MDF wastes as an important aspect of recycling process which may be efficient on quality of recycled MDF boards. Hydrothermal recycling was done at different temperature (105, 125 and 150°C) in which subsequently defibrillation step was performed.

Recycling of heavily contaminated wood

Recycling of CCA, or creosote-protected products forms a separate category of recycling due to classification as hazardous waste (Humar et al. 2011). Also, common disposal of wood treated with the chromated copper borate (CCB) due to toxic elements (Cu, Cr, and B) is not considered as environmentally sound solutions (Humar et al. 2004). Mengeloglu and Gardner (2000) evaluated flakeboards produced from recycled CCA treated and untreated southern pine (*Pinus* spp.) using two adhesives (polymeric methylene diphenyl diisocyanate and liquid phenol-formaldehyde) and two common flaking techniques (ring and disc flakes). Clausen et al. (2001) remediated CCA-treated southern yellow pine chips utilizing acid extraction alone and using acid extraction followed by bioleaching with the metal-tolerant bacterium *Bacillus* licheniformis. Chips were used to make particleboard with 10 percent urea-formaldehyde resin. Reduction of the strength properties was observed. Kartal and Clausen (2001) evaluated the effect of remediation processes with oxalic acid (OA) extraction and *Bacillus licheniformis* fermentation, on leaching of copper, chromium, and arsenic from particleboards made from remediated wood particles. The particleboard containing OA-extracted and bioremediated particles showed generally high leaching losses of remaining elements. Exposure of particleboards to decay fungi in soil block tests indicated that boards containing CCA-treated particles were most resistant to fungal degradation. Zhou and Kamdem (2002) investigated effect of Portland cement/ particles from CCA treated red pine ratio on properties of result products and this was determined as a ratio of 3. Catallo and Shupe (2003) described the treatment of 15 years old creosote-treated pine utility pole wood in an anoxic supercritical water. The creosote-derived hydrocarbon residues in the chipped wood were nearly completely recovered, and the wood itself was transformed into a mixture of hydrocarbons including substituted benzenes, phenolics, and light PAHs. Kamdem et al. 2004 studied the feasibility of using recycled plastic and wood particles from CCA-treated wood removed from service. CCA pressure-treated red pine lumber removed from service after 21 years utilization was milled to the wood flour and blended with virgin or recycled high-density polyethylene at 50:50 wood flour-to-plastic weight ratio. Effects of different ratios of recycled CCA-treated wood and untreated virgin wood on flakeboard properties were compared by Li et al. (2004). Clausen et al. (2006) fabricated particleboard and flakeboard panels from remediated CCA-treated southern yellow pine. Treated wood, flaked or comminuted into particles, was remediated using oxalic acid extraction, followed by bioleaching with the metal-tolerant bacterium *Bacillus licheniformis* in trial experiment. Remediation resulted in removal of 80% Cu, 71% Cr, and 89% As for the particulate material and 83%Cu, 86%Cr, and 95% As for the flaked material.

New downcycled wood waste products

New value added (technical or economical) of new products made of wood particles treated from waste wood is a measure of a sufficiency of its downcycling. Second generation biofuels made from waste wood (Okuda et al. 2008, Shi et al. 2009) are considered for future industrial production with a high potential. Secondary downcycling was provided, the possibility to utilize fiber sludge, waste fibers from pulp mills for combined production of liquid biofuel was investigated by Cavka et al. (2011). Laboratory production of ethanol from sawdust was provided by Chen et al. (2017), also by Afzal et al. (2018). In 2016 the first industrial-scale production of its kind in the world has been launched in Finland. Different pretreatment methods had been studied as a dilute acid pre-treatment on wood dust (Akhabue et al. 2019) or steam explosion on wood particles from waste boards (Pažitný 2019). Iakovlev et al. (2020) used two grades of recycled wood to fractionate on a pilot scale) the monomeric sugars, lignin and lignosulfonates using SO2-Ethanol-Water (AVAP®) technology, including pretreatment, separation of cellulosic and hemicellulosic streams, and saccharification.

Different example of waste wood downcycling was shown by Bekhta et al. (2019), who examined lignocellulosic waste fibers obtained from fiberboard wet process, recycled paper process, and cellulose process as adhesive additives on some physical and mechanical properties and formaldehyde emission of adhesives and plywood panels. Reduction of formaldehyde emissions by up to 27.8, 24.9, and 19.4%, respectively compared with control panels was achieved. The shear strength of plywood panels with all investigated sludges met the requirements of the EN 314-2 standard.

Janiszewska et al. (2016) liquefied mixed hardwood-softwood powder and bark and tested as binders for particleboards made of recycled wood. The liquefaction reaction was carried out with a mixture of solvents from polyhydroxyl alcohols and p-toluenesulfonic acid as a catalyst. Then the liquefied waste from woods were characterized production as a partial substitute for synthetic urea-formaldehyde resin. It was demonstrated that the substitution of UF resin up to 20% did not have a significant effect on the mechanical properties.

Li et al. 2020 produced polyhydroxyalkanoate (PHA) via mixed a microbial consortia as an green alternative to replace the traditional petroleum-based polymers. Authors synthesized PHA using a volatile fatty acids (VFAs) obtained from the co-fermentation of pretreated wood waste and sewage as carbon source. High PHA yield of 0.71 g COD PHA/g COD VFAs and PHA content of 50.3 g PHA/100 g VSS were obtained at VFAs ratio (even:odd) of 88:12 after seven cycles cultivation.

Also, biochar may be stated in this review in a different position as wooden pellets and briquettes directly intended for combustion. As biochar understood as high-value, climate-friendly soil improvement material made from woody biomass. When used in soil, biochar reduces the need to use energy-intensive soil fertilizers, since it provides excellent nutrients for plants in the right form and can also substitute peat as a growth and water-retaining medium. Biochar is a product made via pyrolysis or torrefaction, means a process where waste wood is exposed to high temperature and oxygen deficiency (Yargicoglu et al. 2015).

Wood waste may be a bit an interesting source of raw material for pulp and paper industry as well. But environmental aspects would have to outnumber the economic ones. Kraft pulp from industrial wood waste was evaluated and compared with softwood and hardwood pulp by Ahmed et al. (1998). Pulp bleachability was also evaluated. Compared to loblolly pine pulp, industrial wood waste pulp needed less cooking time to achieve the same kappa number and achieved a higher pulp yield for a similar kappa number. Balberčák et al. (2017) described a method of the evaluation and preparation of fluting liners produced from semichemical pulp made of waste wood particleboards and oriented strand boards (OSB). Combination with old corrugated cardboards (OCC) used to improve their strength properties. The semichemical pulp was obtained by a mildly alkaline boiling process. Properties as thickness, bulk density, Gurley, tensile strength, tensile index, breaking length, burst index, CMT30 and SCT were monitored on lab sheets 127 g·m^{-2} and 170 g·m^{-2}. Values of pH and residual NaOH and Na_2CO_3 were determined in batch leachate. In the next study (Balberčák et al. 2018) authors described an alkaline cooking process from a sorted fraction of the 4-8 mm chips obtained from same waste sources. Pulp industry uses recycling in broad range. Virgin southern pine fibers and recycled old corrugated cardboard (OCC) were used to produce fiberboards. The virgin fiber was generated using a Kraft process (Hwang et al. 2005). Bending properties and dimensional stability were linearly dependent on virgin fiber ratios. Authors note that all panels with recycled fiber content greater than 40% failed to meet any commercial requirement.

Irle et al. (2019) aimed to generate high-value products from recovered wood to achieve even higher rates of wood recycling. Authors described the extraction of nano-crystalline cellulose from waste MDF and produced laminated beams from recovered wood.

But even though a cases mentioned above the downcycling of wood waste is most economically advantageous for the production of composite materials. For this reason, we will describe in detail the research carried out in the areas of production: particlesboards, fiberboards, wood –plastic and cement-bonded composites:

Particleboards (PB)

Wang et al. (2007) manufactured a low formaldehyde emission particleboard from recycled wood waste chips using polymeric 4,4´ methylene-diphenyl isocyanate (PMDI) and phenol-formaldehyde (PF) resins for use in indoor environments. The results showed that the formaldehyde emission released decreased linearly with increasing PMDI/PF particle ratio linearly. It was found that the increasing of PMDI/PF particle ratio positive influences on bending strength, internal bonding strength and screw holding. Ihnát et al. (2017) described a method of the particles preparation from waste particleboards (chipboards) and oriented strand boards (OSB). Method of the waste boards destruction, depending on the glue base urea-formaldehyde (UF) or melamine-urea formaldehyde (MUF), further processing and final particle characterization were determined.

Merrild and Christensen 2009 showed that the greenhouse gas emissions (GHG) related to upstream activities (5 - 41 kg CO_2 equivalents to one tonne of wood waste) are negligible compared to the downstream processing (560 - 120 kg). Savings in GHG emissions downstream are mainly related to savings in energy consumption for drying of fresh wood for particleboard production. Merrild and Christensen (2009) issued a potentially large downstream GHG emissions savings, which can be achieved by recycling of waste wood (1.9 - 1.3 tonnes). However, the GHG account highly depends on the choices made in the modelling of the downstream system. Kim and Song (2014) quantified the environmental impacts per tonne of wood wastes. The results showed that the particleboard from wood wastes produces 428 kg CO_2 eq compared to particleboard from fresh woods.

Fiberboards (MDF)

Recycled fibre material might be further used in paper making or in fibreboard production (Dix et al. 2001a,b), although it is dark and not as sufficient as other pulps. Mantanis et al. (2004) described a process based on refiner techniques and allows the use of mixtures of fresh wood and waste panel chips as a raw material for dry-process fiberboard production. Testing results revealed that under conventional gluing and pressing conditions, the process effectively recycles the waste boards at a wood substitution level of at least 25%. Ju and Roh (2017) used recycling wood fiber from waste MDF for the manufacturing of interior decorative accessories. Coloristic analyze was provided on fibers dyed by using different reactive dyes. The recycling fiber looked a little darker than the virgin fiber, also the recycling fiber showed a littlehigher values of color yields. Ihnát et al. (2018) described a process for the preparation of fibre from waste wood particleboards, oriented strand chipboard and medium density fibreboard (MDF). The obtained wood particles were characterized by the fractional composition of chips and subsequently mechanically defibred with subsequent characterization of fiber obtained for its reuse in the manufacture of MDF. A quantity of formaldehyde released into the water when cooking waste MDF and PB was set up depending on the cooking time. Lubis et al. 2018 studied the effect of recycled fiber content on the recycling properties of MDF. Statistical analysis indicates that the minimum of 10% recycle fibers can be used without diminishing the properties of recycled MDF. Fiber length of the recycled fibers obtain from recycled MDF is about 12% shorter than that of the virgin fibers and the percentage of shorter fibers is higher (≤0.68 mm) for the former than the latter (Zeng et al. 2018).

Wood –plastic composites

To reduce the energy input for residue milling for obtaining a lignocellulosic filler as well as to activate its surface for the further modification, the optimal parameters of low temperature acid hydrolysis of the hardwood residue under mild conditions were used (Shulga et al. 2014). Recycling wood and plastic waste into wood-plastic composites (WPCs) was discussed by Wang et al. (2017b). Flexural strength, thickness swelling, water absorption and thermal insulation were observed. Melamine resin was adopted for impregnating anti-microbial agents on the surface. Poly-diallyl-dimethyl-ammonium chloride (PolyDADMAC) and silver were used as well. All the agents showed excellent bactericidal rate against to the *Escherichia coli*. In terms of weight loss and strength reduction due to fungal decay (*Coriolus versicolo*r), polydiallyldimethylammonium chloride, silver and cetyltrimethylammonium bromide (CTAB) provided the highest resistance. PolyDADMAC and copper provided the most protection against an algal growth (*Chlorella vulgaris*). Lyutyy et al. (2017) determined the release of formaldehyde, phenol, and ammonia from flat pressed WPC obtained from recycled polyethylene and wood particles by chamber method in a laboratory scale. It was found that formaldehyde, phenol and ammonia emission of flat pressed WPC are much lower than steady-state emission.

Cement-bonded particleboards

Some authors prefer cement composite materials that are a significant solution to the problem lignocellulosic wastes, generated worldwide, from various sources such as agriculture, construction, wood and furniture industries leading to environmental concerns. However, in this effort there are various restraints like compatibility of these wastes with cement, their toxicity, and limited composite strength (Karade 2010). Bao et al. (2001) used charcoal obtained from wood-based waste materials to determine the properties of charcoal-cement composite boards. Thirteen types of mixture ratios of charcoal to cement were used to produce 10mm-thick composite boards. The flexural strength of the board showed the maximum at the charcoal/cement mix ratio of 0.05, and then decreased as the mix ratio increased. The possibility of recycling waste medium density fiberboard (MDF) into wood–cement composites was evaluated by Qi et al. (2006). New fibers and recycled steam exploded MDF fibers had poor compatibility with cement so a rapid hardening process with carbon dioxide injection was adopted. After 3–5 min of carbon dioxide injection, the composites reached 22–27% of total carbonation and developed 50–70% of their final (28-day) strength. Wang et al. (2016) developed a practicable technology for recycling construction waste wood into formaldehyde-free cement-bonded particleboards. A high strength, light weight, and thermal/noise insulation are value-added features of new products at density of the particleboards to 1.54 $g \cdot cm^{-3}$ and the volume of capillary pores was effectively reduced from 0.16 mL g^{-1} to 0.02 mL g^{-1}. The high fracture energy at 6.57 N mm^{-1} and flexural strength of 12.9 MPa were achieved as well. The particleboards also manifested outstanding structure-borne noise reduction (at 32-100 Hz) and low thermal conductivity (0.29 W m^{-1} K^{-1}). X-ray diffraction, thermogravimetry, and mercury intrusion porosimetry were used for analyses. It was found that the use of 2% $CaCl_2$ improve the wood-cement compatibility at wood-to-cement ratio of 3:7 by weight. Wang et al. (2017a) proposed a novel use of alumina and red mud to improve water resistance of magnesia-phosphate cement (MPC) particleboards. Addition of alumina or red mud (Mg/Al or Mg/Fe at optimal molar ratio of 10:1) facilitated formation of amorphous Mg/Al or Mg/Al/Fe phosphate gel, with enhanced compressive strength. Alumina improved short-term water resistance, whereas red mud provided a better long-term water resistance. Red mud-MPC binder enhanced strength retention (by 22.8%) and reduced water absorption (by 26.4%) of particleboards after 72 h water immersion. The X-ray diffraction analyses and scanning electron microscopy were used for analyze.

CONCLUSIONS

Wood waste is becoming a substitute for raw wood on an increasingly wide scale, not only in Europe. Until recently, economic reasons outnumbered environmental ones. Downcycling of waste wood, after its size reduction, has a major application in re-incorporation into wood based composite materials. However, the results of the studies show that recycled wood particles have lower mechanical properties than primarily obtained from fresh wood, or some other restrictions exist and therefore the principle of addition to a certain limit must be maintained. New progressive materials and other ways of using of waste wood, mainly chemically treated, need to be developed in the future.

ACKNOWLEDGMENTS

This research was supported by the Slovak Research and Development Agency under the contract No. APVV-17-0330.

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