

WOOD-BASED BUILDING MATERIALS WITH A THERMAL ENERGY STORAGE FUNCTION

Meysam Nazari, Mohamed Jebrane, Nasko Terziev

Swedish University of Agricultural Sciences, Department of Forest Biomaterials and Technology, Sweden, Uppsala

ABSTRACT

Encapsulating of phase change materials (PCM) in ceilings, floors and walls improved energy storage in buildings. The results show 10% saving of thermal energy by using bio-based, building materials with added functionality.

The environmental impact of fossil-based materials on the construction industry and significant energy consumption in housing have driven the production of bio-based, renewable and sustainable materials for building applications. This is achieved by incorporating bio-based PCM into wood materials for thermal energy storage in residential buildings.

Phase change materials absorb and release heat when changing from a solid to a liquid state. Organic PCM in form of fatty acids or esters produced from renewable resources, e.g., vegetable oils are suitable for the purpose. PCM can be impregnated in solid wood, wood fibers or sawdust and in the developed wood-based composite materials.

The bio-composites store and release heat energy in the human comfort temperature range of 18–21°C. A step in the technology is the development of a bio-composite consisting of sawdust impregnated with ethyl palmitate (EP) as PCM and linseed oil as bio-based binder. The composite consists of 25% ester and has 50 J/g latent heat while being thermally stable up to 200°C.

The new building materials are exposed in models for long-term monitoring and data collection for material behaviour and LCA. The thermal energy saving after 1 year of exposure was 10% and the model house had a better climate performance with 5.4% lower impact during its lifetime in comparison to the model house without PCM.

Key words: bio-based phase change materials, bio-based composites, building materials, impregnation, wood materials, thermal energy storage.

INTRODUCTION

Thermal energy for residential heating is one of the largest energy-demanding sectors and recent studies report that 40% of the energy generated in the EU is consumed in buildings. Thermal storage technologies have the potential to offer a flexible and reliable way to store heat using renewable, bio-based phase change materials (bioPCM) encapsulated in lignocellulosic fibers.

The present study is a conceptual research project that combines lignocellulosic cells and bioPCM (e.g., fatty acids) in a composite material that can store thermal energy in "green" buildings. The new material *a*) reacts in a "smart" way to the temperature changes in the environment; *b*) possesses certain physical-mechanical properties that make it useful and *c*) has a long service life.

Development of smart biomaterials with "tailored properties" is a highly desirable goal within the concept of more and better use of natural "green" ecological products. As a natural biomaterial, wood is already "smart" due to its inherent wood-moisture interactions that cause reversible changes to the material's physical and mechanical properties, e.g. shrinkage-swelling,

changes in stiffness and strength, thermal and electrical conductivity. Wood is also a carbon sink and any approach that can extend its life, optimize its use and reduce carbon emissions is beneficial for the environment.

The study employs both native and isolated biomaterials to address energy savings and improved material properties for capture-release applications that are in demand in the green economy sector. The overall aim is to develop and study functional incorporation (or impregnation) of biomolecules in lignocellulosic fibers, e.g. solid wood, wood shavings and fibers to increase heat storage and heat conduction while maintaining strength, reducing moisture absorption and improving biological resistance and sound insulation properties of the original material.

MATERIAL AND METHODS

IMPREGNATION OF PCM IN SOLID WOOD AND FIBERS AND LEACHING

Solid wood, wood fibers and wood shavings were impregnated with bioPCM (fatty acids or esters) under various pressure, vacuum, temperature and duration.

THERMAL CHARACTERIZATION OF THE MATERIALS

Differential scanning calorimetry (DSC), the T-History method, and thermogravimetric characterization methods were used for thermal analyzes of bioPCM. While DSC method can only be used to analyze small (a few μg) and uniform samples of PCM, using the T-history method makes it possible to investigate the melting temperature, degree of supercooling, heat of fusion, specific heat, and thermal conductivity for large samples and several bioPCMs simultaneously.

The thermal conductivity of the wood/bioPCM composite was measured according to the standard method ISO 9869-1 (2014) (Thermal insulation – Building elements – In-situ measurement of thermal resistance and thermal transmittance. Part 1: Heat flow meter method.), known as the heat flux meter method. Thermogravimetric analysis (TGA) evaluated thermal stability of bioPCM. The new materials are subjected to thermal aging under controlled climate conditions (700 cycles in climate chambers) and studied by DSC and Fournier transform infrared spectroscopy (FTIR).

MICROSCOPY

Light microscopy was used to assess the material's morphology and location of bioPCM in the wood cells. Osmium tetroxide (OsO_4) was used as a specific/chemical marker known to react strongly with ethylene bonds of unsaturated triglycerides which were reduced to osmium black (OsO_2).

LEACHING AND PHYSICAL PROPERTIES

Moisture uptake tests of composites with and without PCM were performed in a climate chamber according to the Nordtest Project protocol (Rode, C., Peuhkuri, R., Time, B., Svennberg, K., Ojanen, T. And Mukhopadhyaya, P., 2007). Moisture buffer value (MBV), which is the amount of moisture a material can store and release during duty cycling in an environment

with variation in relative humidity was measured (Sawadogo, M., Benmahiddine, F., Hamami, A.E.A., Belarbi, R., Godin, A. And Duquesne, M., 2022). The test was performed at a constant temperature of 23°C in a climate chamber. The samples were preconditioned at 50% relative humidity (RH) for 24 h, weighed and placed back into the climate chamber at 75% RH for 24 h. After the samples were weighed, the RH was increased to 95% and then decreased to 33% while the mass of the samples was measured at an interval of 24 h.

DURABILITY

Termites, insects and moulds were considered as the most likely hazard for the treated wood. Subterranean termites, *Reticulitermes lucifugus* was used, in accordance with the standard EN 117 (2012) (Wood preservatives. Determination of toxic values against *Reticulitermes* species (European termites). Laboratory method). In the test, based on an artificial mini-colony, 250 termites were released in contact with the bioPCM-impregnated samples for 8 weeks.

The resistance of control and bioPCM-treated samples to the wood borer *Hylotrupes bajulus* was tested in accordance with EN 47 (2016) (Wood preservatives. Determination of the toxic values against larvae of *Hylotrupes bajulus* (Linnaeus). Laboratory method). Susceptibility of the bioPCM-impregnated samples to mould growth and discoloration was tested according to AWWA standard E24-06 (2015) (Standard method of evaluation the resistance of wood product surfaces to mold growth). The mold growth on the sample surfaces was classified by visual examination according to a scale from 0 (no visible growth) to 5 (very abundant growth, 100% coverage).

FIRE SAFETY

Cone calorimeter tests were performed according to the procedures specified in the standard ISO 5660-1 (2015) (Reaction-to-Fire Tests – Heat release, smoke production and mass loss rate – Part 1: Heat release rate (Cone Calorimeter Method) and smoke production rate (Dynamic Measurement)) using a cone calorimeter with fire test technology. Prior to testing, the composites were conditioned to equilibrium at 50% RH and 23°C. The samples were irradiated with a heat flux of 50 kW/m². During the test, flame ignition time, heat release rate (HRR) and total heat release (THR), smoke production rate (SPR) and mass loss were measured.

PROTOTYPE TESTS UNDER DIFFERENT CLIMATIC CONDITIONS

The building materials were exposed in models for long-term monitoring and data collection for material behavior and life cycle assessment (LCA). Wooden floors and fully bio-based chipboards, both with bio-PCM in the intermediate structure and in the wood particles were tested in small prototypes (models of 1 m³ volume) in three locations in Europe – Uppsala (Sweden), Kuchl (Austria) and Florence (Italy).

ENVIRONMENTAL ANALYSES

The environmental impact of a product system was analysed by evaluating its input and output throughout its life cycle according to standard ISO 14040 (2006) (Environmental management – Life cycle assessment – Principles and framework) and ISO 14044 (2006) (Environmental management – Life cycle assessment – Requirements and guidelines). The

phases of the method are definition of goals and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation.

RESULTS AND DISCUSSION

New multicomponent mixtures of fatty acids for thermal energy storage were developed. The blends are based on fatty acids from coconut oil (CoFA), oleic acid (OA) and linoleic acid (LA). The fatty acids were mixed into various compositions to produce stable PCM (Pasupathy, A., Velraj, R., Seeniraj, R., V. 2008; 11. Tyagi, V., V., Kaushik, S., K., Tyagi, S., K., Akiyama, T., 2011; Bland, A., Khzouz, M., Statheros, T., Gkanas, E., I., 2017; Souayfane, F., Fardoun, F., Biwole, P., H., 2016; Kuznik, F., David, D., Johannes, K., Roux, J., J., 2011). The phase transition of the developed PCMs is in the range of living comfort temperature of 18–25°C, with no incongruent melting, less than 0.6°C supercooling and specific heat and enthalpy in the range of 1–5 J/g K and 40–100 J/g. The results showed that the bioPCMs are chemically and thermally stable after 700 melting/freezing cycles. The thermal conductivity of the mixtures averaged 0.2 W/m K in the liquid phase and 0.35 W/m K in the solid phase. Among the developed combinations, the mixture of LA/CoFA (20:80) was selected as the best PCM for low-temperature thermal energy storage.

Another approach was a selection of already available bioPCM. Ethyl palmitate (EP) was found to have suitable properties. The enthalpy of EP was almost twice as high compared to LA/CoFA (20:80) or 104 and 78 J/g melting and solidification enthalpy, while 200 and 160 J/g enthalpy were calculated for EP. The results showed that both materials (LA/CoFA and EP) have a suitable working temperature range and reasonable latent heat. In terms of thermal performance, EP is better with higher enthalpy and congruent phase transition.

IMPREGNATION OF PCM IN SOLID WOOD AND WOOD PARTICLES

BioPCMs were impregnated in untreated and heat-modified solid wood through a vacuum pressure process in a pilot-scale impregnation plant. The autoclave temperature was set at 60°C to ensure melting of the PCM. Before impregnation, the samples were conditioned in a climate room with 70% relative humidity and 23°C for 2 weeks. Two impregnation schemes were used to achieve medium (55%) and high (90%) weight percent gain (WPG). The high WPG was obtained by immersing the samples in the PCM and applying a vacuum of 350 mbar for 10 min followed by 6 bar air pressure for 1 h. The medium WPG was obtained when a pre-pressure of 0.75 bar for 60 min was applied instead of the initial vacuum.

Prior to the impregnation with EP, pine sawdust with a particle size of approx. 2 mm at 80°C for 24 h. The autoclave temperature was set to 60°C to ensure melting of the EP, and the sawdust particles were immersed in the ester and a vacuum of 350 mbar was applied for 10 min followed by 6 bar pressure for 1 h. Pine and beech wood was impregnated with a) linoleic acid and coconut oil fatty acids (LA/CoFA (20:80) and b) ethyl palmitate esters (EP). Wood particles were only impregnated with EP. Light microscopy demonstrated the distribution of PCM in the wood structure. Rays in both pine and beech wood served as pathways for impregnation of bioPCM to partially fill the tracheids (pine) and vessels (beech).

Thermal characterization showed that the impregnated wood had significant thermal mass, ability to store excess energy in terms of latent heat and keep the temperature constant for a long time. The stored latent heat in the impregnated samples was 30–44 J/g and twice as much for the

EP ester. The results showed that the impregnated pine and beech wood with approx. 40% WPG of PCM had an increase in conductivity by 8 to 11%. A problem discovered after the impregnation was 8-9% leaching of bioPCM from the wood.

In order to reduce/eliminate leaching of PCM and prepare a product (solid wood for the inner layer parquet), heat-modified pine, beech and spruce sapwood was impregnated and analyzed. The leaching test showed that the leaching decreased to 3–5% for all wood species.

DURABILITY, MOISTURE UPTAKE AND FIRE RESISTANCE

Biodegradation of solid wood impregnated with bioPCM was tested against termites (*Reticulitermes lucifugus*), the wood borer *Hylotrupes bajulus* and molds. The impregnated samples were significantly less susceptible to termite attack than the controls, i.e. the PCM tested were resistant to *R. lucifugus*. The wood borer *H. bajulus* could not survive in the test. The mould test revealed that the wood impregnated with LA/CoFA and EP was identically susceptible to mould discoloration compared to the non-impregnated control samples. The study proved that solid wood used for encapsulation of PCM for building purposes can serve identically or slightly better than similar wooden building elements in terms of attack by the above microorganisms and insects.

An example is the moisture adsorption when the RH increases from 50 to 95% shows that the moisture ratio in the materials with PCM increased by 3–4% while the material without PCM increased by 5.5-6%. The presence of PCM in the solid wood and composite material ensures better dimensional stability than the samples without PCM. The materials containing PCM showed poorer fire safety than the traditional building materials. Solid wood and wood composites were classified in group D (flammable) while those containing PCM were in the lower class E (extra flammable).

APPLICATION OF THE NEW MATERIALS

A technology for encapsulation of bioPCM in solid wood and fibers in the pilot facility at SLU, Uppsala was developed and tested. Ethyl palmitate (EP) was impregnated in *a*) solid wood lamellas for parquet and *b*) fibers for bio-composite (Fig. 1). The fibers were bound in a bio-composite using epoxidized linseed oil in a low-temperature (appr. 40°C) polymerization reaction. The new materials are fully characterized (thermal, structural, physical characterisation and durability).

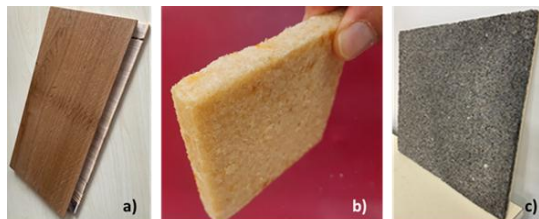


Figure 1: Solid wood and composite materials with integrated PCM (ethyl palmitate ester) prepared at laboratory scale; a) parquet; b) wood composite (9×9 cm) with spruce pulp fibers; c) bio-composite (60×60 cm) with wood particles and recycled paper fibers.

To minimize the leaching of PCM and increase the adhesion between the wood particles and the polymer matrix, a portion of non-impregnated mechanical pulp fibers (or recycled paper

fibers) was added to the impregnated wood particles before mixing with the polymer matrix. The amount of impregnated wood particles in the composite was 50% (25% wood particles and 25% EP), while the non-impregnated fibers represent 12.5% of the total weight of the composite. Epoxidized linseed oil (ELO) (37.5%) was used as a binder in the composite. ELO was prepolymerized by adding a strong Lewis acid at room temperature and then mechanically mixed with impregnated and non-impregnated particles and fibers. After mechanical mixing of the binder and fibers, the mixture was transferred to a teflon mold and cold-pressed at room temperature at 12.3 kg/cm² pressure for 30 min. After pressing, the mold was placed in a climate room at 40°C for 12 h for polymerization. Fig. 2 graphically shows the production process of wood particles/fibers reinforced composites. It should be mentioned that for the control samples (composites without PCM) identical processing was used with non-impregnated materials.

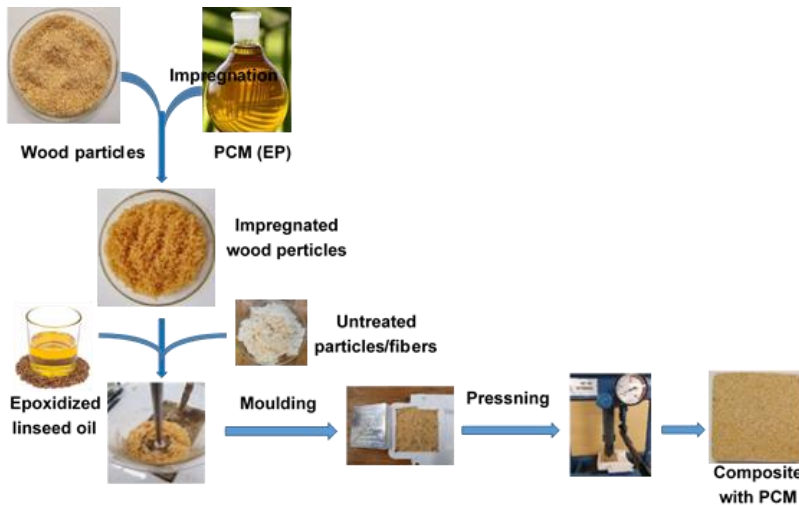


Figure 2: Processing of wood composite material with bioPCM for thermal energy saving.

Energy-smart wooden floor was developed by incorporating bioPCM into the middle layer of the product. In addition, fully bio-based wallboards were produced by incorporating bioPCM into wood particles as by-products of the wood processing industry and bonded by a bio-epoxy made from linseed oil and using recycled paper as filler. The produced wooden floors and wallboards were installed in small models in 3 countries (Uppsala (Sweden), Kuchl (Austria) and Florence (Italy), Fig. 3), while control models with common building materials, e.g., medium density fiberboard (MDF) and regular wood floor served as controls (Fig. 4).



Figure 3: Models exposed in Uppsala, Sweden och Kuchl, Austria.

The purpose of the model experiments in European climates is to reveal the effect of using the new materials for saving of thermal energy compared to models without PCM. Therefore, the indoor temperature was set at 20°C inside both models to measure how much electricity is used to keep the temperature constant at 20°C while the outdoor temperature changes. The experiments started in April 2023 and are ongoing.



Figure 4: Inside the models in Uppsala, Sweden. Control model with medium density fiberboard (MDF) as wall material and ordinary floor (left), and the model reinforced with new wallboards and floor with PCM (right).

Fig. 5 shows the results for Uppsala, Sweden from August 2023 to June 2024, which confirms the more stable indoor temperature in the model with the new material and 10% saving of heating energy during the year. The electricity consumption is represented by the brown and gray thick lines in Fig. 5.

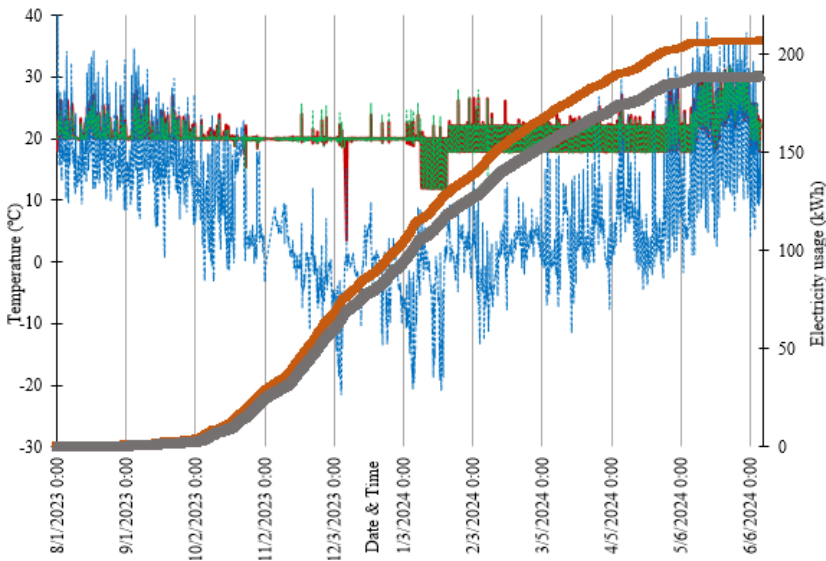


Figure 5: Results of the model experiment in Uppsala, Sweden; indoor temperatures, outdoor temperature, real time and accumulated (total) electricity use.

The environmental impact comparison between the models with and without PCM built in Uppsala showed that materials with PCM have initial negative effect in the beginning of the production chain. Assuming a 50-year lifespan, a building model with PCM has better environmental performance in terms of climate impact. PCM in solid wood and wood composite materials saves energy, which compensates its initial higher climate impact than traditional building materials (wood and wood fibers) (Bejo, L., 2017; Heinonen, J., Säynäjoki, A., Junnonen, J., M., Pöyry, A., Junnila, S., 2015). After 50 years, when the model's lifespan is over, a waste management and additional benefits are expected. In total, the materials with PCM are the alternative with 5.4% lower climate impact during the life of the building.

CONCLUSIONS

Summarizing the results of the study, the following conclusions can be drawn:

1. A positive effect of 10% saving of thermal energy by using almost 100% bio-based and innovative building materials is possible. The most important finding of the study is that it is completely possible from a technological point of view to process PCM and wood materials with existing technical means into innovative building products. The thermal energy savings can be further increased by choosing the PCM and the amount that is impregnated in the wood material.

2. The studied combination of fatty acids and the fatty acid ester are suitable for construction applications. The two PCMs (CoFA/LA and EP) are: 1) non-corrosive; 2) have enthalpy of 90-100 and 170-200 J/g; 3) has melting/freezing temperature within 18-25°C; 4) non-toxic; 5) thermally and chemically stable.

3. PCM can be encapsulated in solid wood and wood fibers by impregnation. The optimal weight gain of PCM is 50-60% in solid wood and 100% in fibers to avoid leaching. The process is carried out according to an already existing technology and equipment, i.e. ensures easy implementation in practice. The properties of the encapsulated PCM are as above apart from the enthalpy (the latent heat) which is twice as low compared to the PCM itself due to PCM is mixed with the wood fibers to 50:50. Solid wood and fiber composites with PCM consist of almost 100% biomaterial.

4. The biggest disadvantage of the new materials is fire safety. It needs to be improved significantly. Leaching of PCM from the wood fiber composite material is eliminated but is still a problem when PCM is impregnated into solid wood.

5. The LCA showed that the processing and use of the new materials with PCM has better climate performance with 5.4% lower environmental impact than the reference materials without PCM.

ACKNOWLEDGEMENTS

The study was carried out within the framework of Smart Energy Systems Research and Innovation Program (ERA-Net E2B2) in the project „Bio-Based Phase Change Materials Integrated into Lignocellulose Matrix for Energy Store in Buildings (BIO-NRG-STORE)”.

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UNIVERSITY OF FORESTRY

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INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

1/2025

INNO vol. XIV Sofia

ISSN 1314-6149
e-ISSN 2367-6663

Indexed with and included in CABI

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

Science Journal
Vol. 14/ p. 1–104
Sofia 1/2025

ISSN 1314-6149
e-ISSN 2367-6663

Edition of
FACULTY OF FOREST INDUSTRY – UNIVERSITY OF FORESTRY – SOFIA

The Scientific Journal is indexed with and included in CABI.

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Cover Design: Desislava Angelova

Printed by: INTEL ENTRANCE

Publisher address: UNIVERSITY OF FORESTRY – FACULTY OF FOREST INDUSTRY
Kliment Ohridski Bul., 10, Sofia, 1797, BULGARIA

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TWELFTH INTERNATIONAL SCIENTIFIC AND TECHNICAL
CONFERENCE**

**INNOVATIONS IN FOREST INDUSTRY AND
ENGINEERING DESIGN INNO 2024**

**7 – 9 October, Hotel Imperial Plovdiv, a member of Radisson Individuals,
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Twelfth International Scientific and Technical Conference
**INNOVATIONS IN FOREST INDUSTRY AND
ENGINEERING DESIGN INNO 2024**,
is supported by the National Science Fund, Bulgaria,
with co-financing agreement № КП-06-МНФ/40 от 13.08.2024

CONTENTS

HOW TO FIND RESONANCE WOOD?	7
Nikolay Bardarov, Nikolai Minkovski	
ANALYSIS OF DIAMETER TAPER IN FIR (<i>ABIES ALBA</i> Mill.) AND SPRUCE (<i>PICEA ABIES</i> L.) SAWLOGS FROM 1ST AND 2ND QUALITY CLASS	13
Ana Marija Stamenkoska	
OPTIMAL PRETREATMENT CONDITIONS OF INDUSTRIAL HEMP RESIDUES TO GLUCOSE	20
Vencislav Blyahovski, Stoyko Petrin, Ivo Valchev, Vesislava Toteva	
SATURATED WATER STEAM CONSUMPTION STANDARD FOR THE PROCESS OF STEAMING BEECH WOOD WHILE ELIMINATING DIFFERENCES IN THE COLOR OF SAPWOOD AND FALSE HEARTWOOD.....	26
Ladislav Dzurenda	
MACHINES FOR PRIMARY LOG CUTTING: PART II – COMPARATIVE ASSESSMENTS AND ANALYSIS	36
Valentin Atanasov	
WOOD-BASED BUILDING MATERIALS WITH A THERMAL ENERGY STORAGE FUNCTION	44
Meysam Nazari, Mohamed Jebrane, Nasko Terziev	
EFFECT OF STAINING ON THE ROUGHNESS OF BEECH FURNITURE SURFACES ..	53
Krasimira Atanasova, Dimitar Angelski	
INCORPORATING SOCIAL DESIGN FOR DISABILITY-INCLUSIVE SOCIAL ENTREPRENEURSHIP: A CATALYST FOR SOCIETAL TRANSFORMATION	63
Maria Kitchoukova, Emil Kitchoukov	
PRODUCTION AND TRADE OF WOODEN PRODUCTS IN BULGARIA FOR THE PERIOD 2007–2021 – QUANTITATIVE ANALYSIS AND FACTORS OF INFLUENCE ..	72
Nikolay Neykov, Radostina Popova-Terziyska	
MODELING INNOVATIVE PRODUCTS THROUGH DESIGN THINKING	80
Gergana Ivanova Koleva, Diana Ivanova Georgieva	
CHALLENGES IN THE CIRCULAR ECONOMY OF BULGARIA	93
Todor Stoyanov, Nikolay Neykov, Emil Kitchoukov93	
SCIENTIFIC JOURNAL „INNOVATIONS IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN“	102