1862
RIGA TECHNICAL
UNIVERSITY

Ilze Vamža

BIOECONOMY INNOVATIONS IN CONIFER VALUE CHAIN

Doctoral Thesis

RTU Press
Riga 2023

RIGA TECHNICAL UNIVERSITY
Faculty of Electrical and Environmental Engineering

Institute of Energy Systems and Environment

Ilze Vamža
Doctoral student in the doctoral programme "Environmental Engineering"

BIOECONOMY INNOVATIONS IN CONIFER VALUE CHAIN

Doctoral Thesis

Scientific Supervisors
Professor Dr. habil. sc. ing.
DAGNIJA BLUMBERGA

Docent Dr. chem.
KĀRLIS VALTERS

Riga 2023

ANOTĀCIJA

Darbs ir strukturēts kā publikāciju kopa, kurā aplūkota skujkoku vērtību ķēde un tās iespējamie uzlabojumi. Aptuveni pusi Latvijas teritorijas klāj meži, kuros dominē priežu stādījumi. No Latvijas valsts mežu apsaimniekotajām platībām 45 % ir priežu stādījumi un 22 % - egļu stādījumi. Šie ir ievērojami resursi ar lielu potenciālu videi un Latvijas tautsaimniecībai. Jau 20. gadsimta sākumā no Rīgas ostām tika eksportēts ievērojams koksnes apjoms, diemžēl lielākoties mastika un zāģmateriāli, kas tika nosūtīti uz Centrāleiropas valstīm, kur tie radīja lielāku pievienoto vērtību. Tomēr mūsdienās, sākoties cīņai pret klimata pārmaiņām un Eiropas Zaļajam kursam, nepieciešamība ilgtspējīgi izmantot bioresursus ir kļuvusi vēl aktuālāka: 1) cenšoties atsaistīt ekonomikas izaugsmi no resursu patēriņa un 2) lai samazinātu CO_2 emisijas, kas saistītas gan ar fosilās, gan biodegvielas sadedzināšanu. Šajā darbā izmantotā teorētiskā analīze sniedz līdzsvarotu skatījumu uz bioekonomikas attīstību ietekmējošajiem faktoriem gan valsts, gan uzņēmumu līmenī. Aplūkojot resursu efektivitāti skujkoku koksnes vērtību ķēdē, promocijas darbā sniegta padziļināta analīze par vairākiem inovatīviem produktiem un tehnoloģijām, kas veicinātu resursu efektivitāti gan valsts, gan uzņēmumu līmenī. Darbā ir iekļauts arī eksperimentālais pētījums par skaiduplātņu izgatavošanu no skujkoku mežizstrādes atlikumiem un bioloģiskas izcelsmes saistvielas, pilnībā izslēdzot fosilās izcelsmes saistvielas. Darbs aprobēts ar septiņām zinātniskām publikācijām, vienu zinātniskās publikācijas manuskriptu un vienu vizuālo prezentāciju starptautiskā zinātniskā konferencē.

ANOTATION

The work is structured as a set of publications looking at the conifer value chain and how it can be improved. Approximately half of Latvia is covered by forests dominated by pine forests. Of the area managed by Latvia's state forests, 45% is pine plantations and 22% is spruce plantations. These are significant resources with great potential for the environment and the Latvian economy. Already at the beginning of the 20th century, a considerable amount of timber was exported from Riga's ports, unfortunately mostly mastic and sawn timber, which was shipped to Central European countries where it generated more added value. However, today, with the fight against climate change and the European Green Deal, the need to use bioresources sustainably has become even more pressing: 1) to decouple economic growth from resource consumption and 2) to reduce CO_2 emissions associated with both fossil and biofuel combustion. The theoretical analysis used in this work provides a balanced view of the factors influencing the development of the bioeconomy at both national and company level. Looking at resource efficiency in the softwood value chain, the thesis provides an in-depth analysis of several innovative products and technologies that would contribute to resource efficiency at both national and company level. The thesis also includes a pilot study on the production of chipboard from softwood logging residues and bio-based binders, completely excluding fossil-based binders.

The work has been validated by seven scientific publications, one manuscript of a scientific publication, and one visual presentation at an international scientific conference.

PATEICĪBAS

Paldies maniem promocijas darba vadītājiem Dr.chem Kārlim Valteram un Dr.habil.sc.ing. Dagnijai Blumbergai! Pateicos Dr.chem Kārlim Valteram, kas pacietīgi atbalstīja publikāciju rakstīšanā un iemācīja paskatīties uz savu darbu ar lasītāju acīm. Izsaku pateicību Dr.habil.sc.ing. Dagnijai Blumbergai, kas motivēja iet uz priekšu, vienlaikus skatoties zem kājām. Vadītāju veltītais laiks nereti palīdzēja sakārtot domas un pašu darbu – publikāciju vai promocijas darbu. Paldies arī manu publikāciju līdzautoriem! Īpašs paldies Jānim Andrim Krūmiņam, Fabian Diaz un Armandam Grāvelsiņam ar kuriem diskusijās pavadītais laiks palīdzēja atrisināt kādu tehnisku jautājumu. Paldies akadēmiskās vides kolēģiem, kas ikdienā iedvesmoja ar savu paraugu un domu lidojumiem!

Paldies manam dzīvesbiedram Mārtiņam un brālim Harijam, kuri lielo pārmaiņu laikā atslogoja manus uzdevumus ārpus akadēmiskās vides!

TABLE OF CONTENTS

INTRODUCTION

The author investigates the relevance and implications of existing practices, product development, and carbon mitigation strategies within the wood value chain. The study aligns with the principles of biobased industries, the bioeconomy, value-added opportunities, and the global goal of achieving carbon neutrality by 2050. By adopting a comprehensive approach, this research aims to provide insights into the potential of conifer value-chain. Work explores the interconnections between different aspects within the wood value chain, investigates environmental impacts of recycling of cross-laminated timber, thermal insulation packaging from forest residues, bio-based adhesives for engineered wood products, carbon storage in wood based products, carbon dynamics in various carbon pools, and the development of 100% bio-based particle boards from forest logging residues.

THE RELEVANCE OF THE TOPIC

The primary objective of this study is to contribute to the advancement of biobased industries by exploring the factors and technologies impacting the transition to more resource effective and carbon neutral economy. Work elucidates sustainable practices and innovative product development in the wood value chain. By replacing fossil-based resources with renewable biological resources, the research supports the transition toward a more sustainable and environmentally friendly economy. Additionally, the study aligns with the concept of the bioeconomy, emphasizing the sustainable utilization of biological resources. By focusing on value-added opportunities, this research investigates the enhancement of wood-based products through the development of bio-based adhesives, thermal insulation material, and 100% bio-based particle boards. These endeavours aim to increase the value, competitiveness, and economic viability of the Forest sector while concurrently reducing the atmospheric carbon.

Moreover, this research addresses the urgent need to achieve carbon neutrality by 2050 and using mathematical modelling explores potential policies for using the Forest sector as a carbon buffer. It explores carbon dynamics among carbon pools and evaluates the potential of carbon storage in wood particle boards. By developing a mathematical model, this study provides a better understanding of carbon sequestration potential within the wood value chain. The obtained insights can be utilized by policymakers in the forest sector to develop efficient policies that align with global carbon neutrality goals and facilitate the transition to a sustainable bioeconomy.

Ultimately, this research contributes to the body of knowledge surrounding sustainable practices, product development, and carbon mitigation strategies in the wood value chain. Its findings and recommendations provide a basis for practical solutions that drive the transition towards a low-carbon and sustainable future, benefiting both the Forest sector and the society.

THE AIM OF THE INVESTIGATION

To reach the primary objective of this study – to contribute to the advancement of biobased industries, the factors and technologies impacting the transition to more resource effective, and carbon neutral economy were explored. Sustainable practices, product development, and carbon mitigation opportunities within the wood value chain were investigated, aiming to enhance resource efficiency, promote environmentally friendly solutions, and contribute to the overall sustainability of the industry. Following tasks were set to reach the overarching goal:

1. Determine the factors impacting the bioeconomy focusing on resource efficiency.
2. Develop a bioresource utilization index to evaluate the value added to the wood biomass.
3. Propose cascade and circularity approaches to enhance wood-value chain resource efficiency and carbon storage in the economy.
4. Conduct LCA for innovative products developed in line with this work.
5. Conduct a literature review on bio-based adhesives from various wood residues.
6. Conduct an experimental study for a product that would increase the added value of the raw material beyond its current use.

THE NOVELTY OF THE RESEARCH

This research combines multiple evaluation methods and aspects of sustainability: value-added, carbon footprint, and carbon storage dynamics. The novelty of the research lies in the exploration of sustainable practices, product development, and atmospheric carbon mitigation within the wood value chain. While there may already be existing research papers and patents on specific topics within this domain, the novelty of this research lies in the comprehensive approach. This research aims to provide a comprehensive examination of multiple aspects within the wood value chain, ranging from recycling cross-laminated timber to carbon dynamics in various carbon pools. This holistic perspective adds value by considering the interconnections and potential synergies between different areas, leading to a more integrated understanding of sustainability and reduction of the carbon footprint of wood-based industry. This thesis seeks to address sustainability challenges and promote environmentally friendly solutions in the wood value chain by examining various topics such as bio-based adhesives, thermal insulation packaging, and 100% bio-based particle boards, this work can potentially propose integrated solutions that combine different innovations and technologies for more sustainable wood-based products and practices. In addition, the research on carbon dynamics can serve as a basis for specific policy development, empowering Forest sector policymakers with a tool for efficient policy development. A mathematical model on carbon dynamics among carbon pools can contribute to a better understanding of carbon sequestration potential and the environmental impact of wood-based products.

This research elucidates seven main factors that impact the bioeconomy and further focuses on Forest sector exploring the seven factors in lines with the wood value chain. Therefore, the novelty of this research also stems from its practical implications and real-world applications.

Examined viability and sustainability of recycling cross-laminated timber, developed thermal insulation packaging, or creating 100% bio-based particle boards provides insights and potential solutions that have tangible impacts on the wood industry, resource efficiency, and carbon mitigation efforts.

HYPOTHESIS

Wood value chain despite its bio-based raw material can be utilised not only for energy production, but also for a long-term carbon storage. By integrating sustainable practices, product development, and carbon mitigation strategies within the wood value chain, it is possible to enhance resource efficiency, reduce the carbon footprint of wood-based industry, and promote environmentally friendly solutions while maintaining economic viability.

PRACTICAL RELEVANCE

According to Latvia National Research and Innovation strategy for smart specialization – RIS3 national economy needs to transform towards resource efficiency and social innovations in main economy areas – including forestry as one of the biggest areas. According to National Research Ecosystem report 2014.-2018., only a small fraction of research has been devoted to innovations in wood biomass use. Therefore, the practical relevance of this research lies in multiple aspects: (1) patent of 100% bio-based chipboard from forest residues; (2) system dynamics model for carbon flows in Forest economy; (3) multiple propositions for improvements in resource efficiency of Forest economy.

STRUCTURE OF THE RESEARCH

Dissertation is based on seven scientific publications with overreaching goal to evaluate and explore opportunities to increase the resource efficiency and value of conifers in Latvia's Forest economy. Multiple methods have been used in this work covering the topic in multiple levels – National, Market, Enterprise, and product (as depicted in Fig.1.)

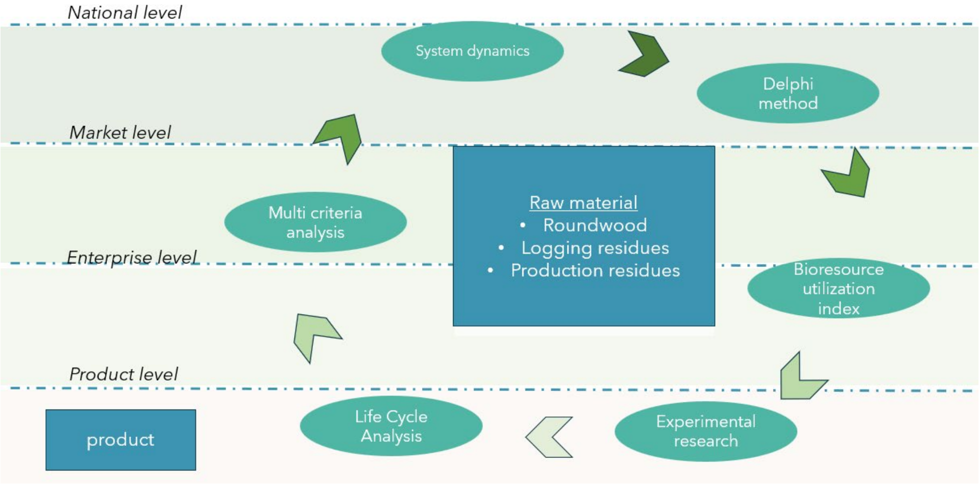


Figure 1. Visual research structure

Identifying the phenomenon or problem to be analysed: The first step was to clearly define the phenomenon or problem that will be the focus of this work – Latvia's Forest economy and the use of Scots pine.

Data for analysis was gathered in according to levels described above and corresponding methodology used to reach the required milestones for further work. Main methodologies used in this work are: Life Cycle Assessment, Multicriteria analysis, System dynamics modelling, Delphi method, Experimental research on chipboard material, and newly created Bioresource utilization index approved in scientific publication.

SCIENTIFIC APPROBATION

Publications

1. A Review of Bio-Based Adhesives from Primary and Secondary Biomass for Wood Composite Applications
   Vamza, I., Krigers, G., Valters, K.
   Environmental and Climate Technologies, 2022, 26(1), pp. 1350–1360
2. CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios
   Viksne, G., Vamža, I., Terjanika, V., ...Pubule, J., Blumberga, D.
   Environmental and Climate Technologies, 2022, 26(1), pp. 1158–1168
3. Bioresource utilization index – A way to quantify and compare resource efficiency in production
   Vamza, I., Kubule, A., Zihare, L., Valters, K., Blumberga, D.
   Journal of Cleaner Production, 2021, 320, 128791
4. Bioeconomy triple factor nexus through indicator analysis
   Zihare, L., Kubule, A., Vamza, I., Muizniece, I., Blumberga, D.
   New Biotechnology, 2021, 61, pp. 57–68
5. Complete Circularity in Cross-Laminated Timber Production
   Vamza, I., Valters, K., Luksta, I., Resnais, P., Blumberga, D.
   Environmental and Climate Technologies, 2021, 25(1), pp. 1101–1113
6. Criteria for choosing thermal packaging for temperature sensitive goods transportation
   Vamza, I., Valters, K., Dzalbs, A., Kudurs, E., Blumberga, D.
   Environmental and Climate Technologies, 2021, 25(1), pp. 382–391

7. Life Cycle Assessment of Reprocessed Cross Laminated Timber in Latvia
Vamza, I., Diaz, F., Resnais, P., Radziņa, A., Blumberga, D.
Environmental and Climate Technologies, 2021, 25(1), pp. 58–70

8. Forest residues towards climate neutral products
Krumins J. A., Vamza I., Dzalbs A., Blumberga, D.
Buildings (iesniegts manuskripts)

Reports at Scientific Conferences

1. System dynamics thinking to optimize carbon storage in the wood-based economy
Vamza I., Gravelsins A., Kasakovska A., Blumberga D., Prodanuks T.
European Biomass Conference EUBCE2023

Other scientific publications

1. Single Cell Oil Production from Waste Biomass: Review of Applicable Industrial By-Products
Spalvins, K., Vamza, I., Blumberga, D.
Environmental and Climate Technologies, 2019, 23(2), pp. 325–337

2. Multi-Criteria Analysis of Lignocellulose Substrate Pre-Treatment
Vamza, I., Valters, K., Blumberga, D.
Environmental and Climate Technologies, 2021, 24(3), pp. 483–492

3. Analysis of Bioeconomy Affecting Factors-Climate Change and Production
Indzere, Z., Kubule, A., Zihare, L., Vamza, I., Blumberga, D.
Environmental and Climate Technologies, 2021, 25(1), pp. 1293–1304

1 LITERATURE REVIEW

Enhancing Sustainability in Engineered Wood Materials

Replacing conventional building materials with wood alternatives can have a great reduction of atmospheric carbon [1]. As building with wood has experienced renaissance led by cross-laminated timber and glued laminated timber [2], it is time to take the next step and improve the sustainability of engineered wood materials as almost all conventional engineered wood materials are produced using some kind of fossil binders [3]. Chipboards or particleboards (PB) are one of the main wood products in international trade. Although the current process of wood particle board production has been modernized for a long time, in essence production of boards still involves the use of fossil additives [4] and toxic binders or their components [5], as well as the use of quality wood [3]. Production efficiency has been improved and solutions have been sought to reduce the impact on the environment during the entire product life cycle [6]. Chipboards have multiple variations and according to market research reports, these materials are mostly used for construction and furniture [7]. Chipboard is one of the main wood products in international trade. Its global demand and production have seen an upward trend in recent years. Chipboard is an engineered wood product produced from high-quality wood chips by bonding them together with synthetic resin or other suitable adhesive at a certain temperature and pressure. Particle board consists of three layers: two surface layers and one base layer between the surface layers. The surface layers consist of fine particles, while the base layer is made of larger and coarser particles. Fine particles usually do not add to material integrity but is very important for the final material lamination process as smooth surface is crucial for efficient coverage. Materials for the lamination significantly impacts the final material functionality as it can increase scratch resistance and water repellency [8].

Although low-quality wood is being integrated into chipboards, it is not the preference of industry but rather necessity due to intense deforestation and need for the biomass [3]. Referring to the United Nations (UN) Food and Agriculture Organization (FAO) report, the global production of roundwood in 2020 (including fuelwood and industrial roundwood) was estimated at 3,966 million m^3 (fuelwood - 1,945 million m^3 and industrial roundwood – 2,021 million m^3). Compared to the year 2000, the global timber production intensity has increased by about 24%. Timber market models and estimates developed so far show that if the world's population reaches 10 billion, the demand for wood will be greater than the global supply of this raw material, which could lead to an increase in wood prices and uncontrolled cutting of protected forest areas for illegal timber trade. The importance of forests and the need to protect their resources is only one of the reasons to move towards environmental sustainability as one of the main parameters of the timber industry when choosing raw materials for industrial production needs. In order to maintain a stable and steady production of roundwood and timber and to protect wood resources, necessary steps should be taken to increase the productivity by using the raw material more efficiently or explore completely new and alternative raw materials to replace high-quality wood [9]. Additionally, wood use in higher value added product production has gained traction, e.g., fibres for textile [10].

Foreseeing the future needs for resources in general, there has been multiple research and innovations oriented towards alternative biomass and adhesives for the engineered wood market [11]. Pędzik (2021) and colleagues have reported the potential of chipboard production using residues from forest management, tackling the need for sustainable raw material. Although the team concluded, that the produced boards are applicable to P2 functionality (suitable for dry environment), the adhesive used in this research is urea-formaldehyde based [9]. Mirski and colleagues recently have explored the pine bark as an additive for chipboards using the urea-formaldehyde and melamine-urea-formaldehyde resins [12]. Both of these adhesives are fossil-based. Formaldehyde compounds are most often used in adhesives. One of the most important areas of its production is urea-formaldehyde resin, but formaldehyde is classified as a compound that can cause cancer (class 3 carcinogen), poisonous, corrosive and allergenic [13], [14], [15, p. 5], [16], [17]. The wood particles are first mixed with glue and then formed from them into an inlay, which is then hot-pressed to form a panel product [9], [12].

Although some types of panels are relatively new to the market, others were developed and successfully implemented more than a hundred years ago. However, even for those types of boards and panels that have long existed in the timber industry, the optimization of the manufacturing parameters is still not complete. Technological developments and new market and regulatory requirements, in combination with the raw material situation, drive continuous improvements in wood panels and their manufacturing processes [18].

Traditionally, plywood and oriented strand board (OSB) mechanical properties have been characterized by strength and rigidity. They are resistant to various types of deformation and impact damage. For most applications, stiffness and strength is one of the biggest advantages of wood panels. Ultimate stiffness is measured as resistance to deformation under uniform and concentrated loads and forces that would deform the plate from its inherent shape in the plane of the panel. Stiffness often makes it possible to use wood structural panels without additional reinforcements with other materials. Load-bearing wood panels are perfectly suited for applications of bulky dimensions and loads, which are commonly used in construction Industry [13], [19]. Chipboards on the other hand are more suited for indoor applications like furniture and some instances decorative panelling. As previously described, these types of boards are mainly used for their smooth surface allowing for variations in finishes by laminating them [8]. Therefore, the integrity of the board itself can be lower compared to OSB or plywood, making the chipboards the most realistic product for green improvements.

Significant innovations have been made to ensure that wood panels do not have a negative impact on human health or the environment. Formaldehyde emissions from the manufacturing process of various panels have been significantly reduced in recent decades, and further reduction remains the focus of effort and investment for panel manufacturers, adhesive suppliers, and researchers. In addition, a relatively recent problem observed in the manufacturing process is the detection and reduction of other volatile organic compound (VOC) emissions. Several developed studies on the analysis of the life cycle of wood chipboards (life cycle assessment), replacing synthetic resins with biological binders, such as soy protein, lignin, tannin, etc., show a reduction in the impact on the environment [6], [16]–[18], [20].

One of the main driving forces for the continuous development of wood panels and, accordingly, their production processes, is the continuous change in the availability of raw materials and permits for use. The basic composition of the biomass used to make the boards usually depends on what raw material is available regionally. Therefore, the composition of the biomass and the final product may vary between plants in different regions. In addition, there are not only regional differences in raw materials, but also their changes over time, caused by several factors, for example, the management plans of forest areas are regularly changed. In addition, the demand for wood, which until now was mainly used in the production of boards, has increased significantly in several regions in other sectors, especially in the energy sector. As a result of these changes, wood panel manufacturers are beginning to pay more attention to optimizing their production processes and switching to alternative biomass types, including recycled and other lower quality wood. However, the variability of the quality and composition of wood raw material creates significant difficulties in ensuring quality uniformity. Studies analyzing the effect of the chemical composition of wood on the strength of wood chipboards show that different board strength can be obtained with changes in the content of wood particle cellulose, lignin, hemicellulose, tannin, as well as extractive substances and at different particle pH, particle porosity and permeability, as well as for changes in the anatomical and chemical properties of other wood particles [18], [21].

The cost of the raw materials used, namely adhesive and wood chips, make up the largest part of the cost of finished chipboard. Total material costs account for 40-60% of total production costs. Research to date indicates that adhesive costs account for 30-50% of the total material cost of chipboard production, with the remaining 50-70% of the material cost being wood chips, chips or logs. Therefore, glue and wood chips are assumed to account for 15-30% and 30-40% of the total production cost, respectively. Other cost components such as energy, labour and chipboard processing costs account for approximately 15-20%, 5-20% and 25-30%, respectively. According to various authors of scientific literature, material costs account for approximately 66% of total production costs. Undeniably, the cost of materials, which includes the cost of adhesive and wood chips, most often accounts for more than half of the total cost of production. Consequently, replacing wood chips with alternative raw materials other than high-quality wood could lead to significant cost savings [13].

Additives such as citric acid and 1,2,3,4-butanetetracarboxylic acids may be added to increase the performance (strength and resistance to moisture) of natural binders and to facilitate their use [22]. The use of organic acids in adhesives or their production is a common approach. For example, citric acid as a crosslinker and a hydrolytic agent can be used as a plasticizer in starch matrices due to its structural properties. Another organic substance which can be used as an alternative to formaldehyde resins are tannins because they have many phenolic rings in their structure. Citric acid promotes the reaction of tannin and sucrose at lower temperatures, thus potentially reducing energy consumption. An alternative to citric acid can be ricinoleic acid, which can be obtained from renewable sources – castor oil [23]. Ricinoleic acid is a C18 fatty acid that is also used in the production of lubricants, its properties are made so different by the dual nature of fatty acids – their acid functional group makes them polar, while the long tail of the molecule has non-polar properties [24]. Tannins, in addition to greater mechanical strength, also help protect the material from water. To make the adhesive easier to work with, it is desirable to obtain a relatively flowing consistency to avoid unnecessary consumption and ensure the homogeneity of the material [25], [26]. A more fluid adhesive that flows into the gaps in the surface of the substrate increases the contact surface between the surfaces of the substrate, thus also increasing the tensile strength and modulus of elasticity. Proportions vary, but experiments show that acid concentration in solution should be around 25% in order to achieve the desired viscosity [22], [26].

Alternatively, it is possible to follow the path of the synthetic additive by adding vinyl acetate to the starch. In this case, the long starch molecules are crosslinked with smaller vinyl acetate molecules that could be linked to the hydroxyl group of glucose by ester bonds. This process is called grafting as the smaller monomers are added on the sides of starch polymer [27]. Such addition of synthetic excipients can increase not only the mechanical strength, but also the water repellence. Vinyl acetate prohibits water penetration, but starch on the other hand forms hydrogen bonds – it attracts water and swells very easily, which in turn reduces the mechanical strength of the material [27]. Samyn describes some biomimetic and gene engineering solutions for green adhesives, but at this point these approaches are at low technology readiness levels [28].

Starch structure – its branching intensity, also differ from plant to plant. Hence different results can be achieved from corn [29], cassava [30] and other starch sources [31], [32].

Chitin is a similar natural polymer to starch and cellulose. It forms the cell membranes of fungi as well as the exoskeletons of invertebrates. The chitin monomer is glucose, which, like cellulose, is linked by β-1,4-glycoside bonds, the difference being that the hydroxyl group at carbon 4 in the glucose monomer is replaced by an acetyl amine group. Chitin, unlike cellulose, also contains nitrogen. By treating chitin with alkali, it can be hydrolysed to smaller oligosaccharides. Chitosan is obtained in this way, but it must be deacylated by treatment with an organic acid, such as acetic acid, to make it sticky. The obtained glue can be used not only for gluing timber, but also for wound treatment, helping to stop bleeding. There are evidence that chitosan can be used as coagulant in wastewater treatment plants [33]. Chitosan is electrostatically attracted to negatively charged surfaces, which is possible because the deacylation of chitin leaves a free $-NH3^+$ group [34], [35]. The polarity of chitosan means that this adhesive also binds water well, so the properties of the wood deteriorate in the presence of water.

The positive aspect of chitosan is its production potential from the production residues of other products, so it can become a by-product, such as in production of shelled shrimp [34].

Another promising adhesive derived from natural raw materials is polyol adhesive. It can be obtained by transesterification of vegetable oil with glycosylated starch [36]. Higher hydroxyl content in polyol improve the bond strength, hence making these polyols more suitable for wood-based panel production [29] but are not compostable at the end of their life cycle [37]. Polyols are transesterified fatty acids, when they are joined by ester bonds, there are few microorganisms or enzymes in nature that could break them down. Polyurethane, on the other hand, is obtained by reacting isocyanate with fatty acids, the biggest negative aspect of which is toxic cyanide [38] when it is formed during combustion, so flame retardants are always added to polyurethanes, which makes it more difficult to process at the end of its life [39]. Due to cyanide safety issues, nonisocyanide polyurethanes (NIPUs) are developed by using tannins as isocyanide replacement [38].

With the push and support from policy makers to green chemistry, safer adhesives have been developed but at this point there are only few available on the market [40], [41] but at this time they do not reach the >95% bio-based components requirements. Most of the adhesives' summarized in Table 3.1. working principle is based on condensation reactions as in urea-formaldehyde. Research in bio-based adhesives field could be divided into multiple groups – specific compounds (latex, vanillin), compound groups (e.g., lignin, hemicellulose, suberin), and non-specific substances with adhering properties (e.g., bark powder). Although all might result in good adhering properties, the specific compound development would be favourable in industry as can ensure the most persistent product quality for the user.

Carbon in wood based panels

Forestry practices produce large amounts of waste and residues from the harvestable yield. This can present significant management problems, as the logging residues release carbon dioxide without adding value to the economy. Meanwhile, sustainable energy sources and raw material feedstock are required with increasing global population and rising demand for construction products and materials. Forestry waste and logging residues are under-utilized resources for energy and material production. To date, there has been little activity to utilise these resources in a "low carbon" way. It is estimated that for every cubic meter of logged wood material removed, a cubic meter of wastes and residues (e.g., stumps, branches, greenery) is left in the forest. Currently, of all wood-derived biomass produced globally, 20 % can be accounted as primary production loss left in the woods to decay, which could instead be used as a feedstock for a variety of products, including the production of fuels, polymers and building materials and products [42].

Wood, like products made from it, has a significant advantage over other building materials – they are an essential source of CO_2 sequestration. It has been observed that there exists a direct correlation between the amount of CO_2 sequestered and the amount of wood-derived biomass harvested to produce high-added value products – with increasing amounts of wood harvested or rising efficiency of timber used, the amount of carbon sequestration is also increased [43]. The overall decarbonisation solutions can be achieved if sustainable carbon cycles, including using Carbon Capture and Utilisation technologies, are implemented (figure 1.1.) [44]–[46].

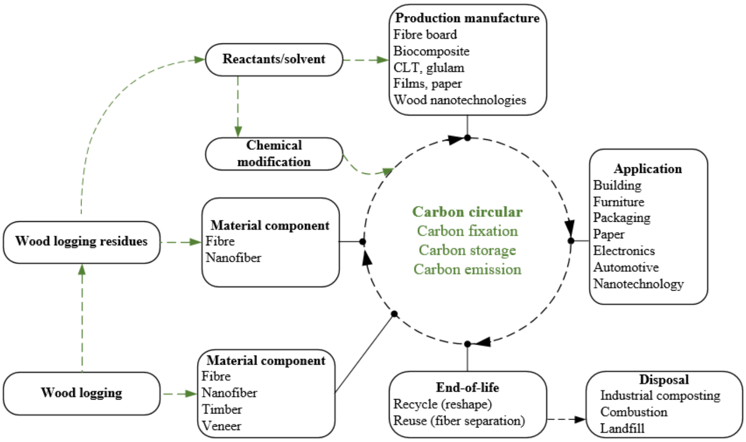


Fig 1.1. The sustainable carbon cycle of wood logging residues [42].

In the wood-based product sector, significant potential for CO_2 sequestration can be attributed to the production of wood-based panels and engineered wood products [47], [48]. In a 2017 study about carbon storage in wood products, the carbon sequestration potential of three different wood-based panels was reviewed – OSB, chipboard and medium density fibreboard (MDF). According to the IPCC methodology, all three of these products are included in the national inventory reports as harvested wood products that store carbon, thus serving as a CO_2 buffer to withhold it from reaching the atmosphere. It was calculated that a cubic meter of PB and OSB sequester 720 kg of CO_2 each and that a cubic meter of MDF sequesters 820 kg of CO_2, considering the number of emissions from material production[49].

However, despite this advantage, producing such panels is quite an energy-intensive process. The Best Available Techniques (BAT) Reference Document to produce Wood-based Panels states that the average amount of thermal energy required to produce one cubic meter of the material is 0.955 MWh for PB, 0.4 MWh for OSB and 1.65 MWh for MDF panels. The average amount of electrical energy required to produce one cubic meter of the material is 0.155 MWh for PB, 0.115 MWh for OSB and 0.505 MWh for MDF panels [49]. In turn, producing such thermal insulation materials as Ecowool and mineral wool requires 0.00416 MWh and 0.200 MWh of electricity per cubic meter of product. Although rigidboards are popular insulation material, they are mostly produced from expanded polystyrene or polyurethane foam - both are produced from fossil resources eliminating the opportunity to store CO_2 in such products. Nevertheless, rigid and flexiboards from wood fibres are becoming more popular. There is a wide range of insulation materials available on the market, varying in composition and thermophysical properties.

Manufacturing insulation materials could become one of the future opportunities of the forestry industry of Latvia, if the logging residues would be utilized for this purpose. Forestry companies mainly sell the logging residues for energy production. As companies in the forestry sector move to increase the efficiency and productivity of their production, the utilisation of wastes and residues previously considered low value is becoming an increasingly attractive option. Using these by-products to manufacture thermal insulation is one of the potential solutions for increasing their value [50], [51].

Mitigation of CO_2 emissions has become a top question in the last decades. Therefore, understanding processes within rural CO_2 economy sectors, factors, interconnections and effects on the environment and nature quality and guidelines for future activities are crucial. Valorisation of CO_2, including direct capture and utilization, transformed CO_2 utilization or pre-processed CO_2 utilization, can positively affect the reduction of CO_2 emission and the development of rural areas [44]–[46], [52] The changes in wood waste treatment practices and production of the rigid board from wood logging residues can have a positive effect on mitigating CO_2 emissions, providing its storage in the products. This work aims to analyse the environmental impact of this insulating material. Using an underestimated resource to produce thermal insulation material can be viable from economic and technological perspective. The practice could be favourable from product demand, and raw material supply perspective by adding value to wood value-chain.

Wood in construction

In lines with the Europe's Green Deal and overall ambition to reduce the carbon footprint of human activities, building and construction industries are a good direction to look. According to life cycle assessment on environmental impact of a dwelling in EU, individual family houses have the biggest negative annual impact per person per m^2. Significant negative impact is from building construction – mainly due to the metal that has been used for concrete reinforcement, used metal has 40% effect on Human toxicity [53]. According to European Commission, building construction and use consumes half of all the extracted materials and produced energy [54]. Hence any improvements in construction and building industries could bring significant positive change regarding environmental impact of human activities.

As abovementioned, concrete and steel have the most negative impact. In order to reduce the global warming potential (GWP) of building construction and exploitation, alternatives to reinforced concrete are being explored. For comparison – GWP of concrete with ~ 40 MPa strength is from 120 to 60 kg CO_2/m^3 for some greener concrete variations [55], in contrast cross-laminated timber with the same strength has only 40 kg CO_2/m^3 GWP [56]. Wood based products were popular in the mid-20th century but increasing fire safety concerns and demand for high-rise buildings motivated the use of steel reinforced concrete. Up to 2014 cement industry experienced steady growth globally reaching 4 Gt of annual production, since then the annual production volumes have not changed [57]. Search for more sustainable options have led to engineered wood products (EWP), these materials are made from various types of primary and secondary timber. Wood biomass has become desirable again, this time it is due to its added benefit of carbon storage. Naturally timber has great load bearing capabilities, EWP exploit these properties and offer structural materials with much lower environmental impact than concrete. Wood-based panel market is growing globally, by the estimates the size of it in 2019 was 124.416 billion euros [58] and it continues to grow. Geographically the biggest market share is held by Asia Pacific region, it accounts for around 54%. Europe holds around 24% of the wood-based panel market. Wood-based market can be divided in terms of application or product category. Some of the most popular products are medium density fibreboards, chipboards, plywood, softboard and hardboard. Product popularity varies in different regions, for example – oriented strand boards (OSB) are the most popular products in United States. In Europe the most popular ones are chipboards and medium density boards (MDF) holding around 75% of Europe's market. Cross laminated timber is another product that can serve as an alternative in construction, this product is developed in Central Europe and at this point its market share has not even reached half a billion. Nevertheless, material like cross-laminated timber (CLT) is a good example of EWP [59]. CLT panels are produced from planks adhered together layer by layer. To ensure higher mechanical strength, layers are oriented on top of each other to 90° in relation to bottom layer. Mechanical properties of the final panels are dependent on used adhesive, thickness of the separate layers and type of wood. Lower grade planks can be used, but in order to achieve uniformity of the material, knots are usually cut out of the planks before gluing them together [60]. Overall EWP category is becoming more popular in the construction industry [61]. Another benefit of CLT and other EWP is their low density, this is important factor for building mid- and high-rise buildings as the structures of lower levels need to hold up all the weight above them. Higher strength to weight ratio is more desirable [62].

Hemström *et al.* 2011 research concluded that stakeholder attitudes towards wood in construction are changing. In Sweden restrictions on mid-rise wood constructions have been lifted since 1994 [63], in Latvia only since 2015 it is allowed to build up to six story buildings from wood, but only if evacuation routes are fire proofed and equipped with sprinklers [64]. Nevertheless, 15 years after lifting restrictions architects in Sweden still considered concrete as the most reliable material in comparison to steel and wood, even if wood ranked highest in environment, design and project categories. Project category included costs, construction time, work environment and transport [63].

Despite the stakeholder attitude towards building with wood, EWP like medium-density fiberboard, CLT and laminated veneer lumber (LVL) have proven that their physical properties are similar to widely used materials with higher negative impacts on environment. For example – wood fiber insulation materials thermal conductivity matches the one of rockwool, with the added benefit of increased heat capacity. Due to LVL considerable compressive strength this material can replace steel beams however CLT has considerable compressive and flexural strength, hence it can be used in weight bearing wooden constructions [61]. According to OECD [65] globally life quality is increasing, as mentioned by FAO [66] this is one of the factors demand for wood-based panels are expected to rise even more. Hence biobased panels that could provide consumers with the same functional qualities could be well accepted not only by environmentally conscious consumers, but developers who will need to find a way to meet the growing customer demand.

In the mid-rise wood building segment popular choice has become CLT, there are multiple examples of eight-storey projects [62], [63]. Pre-made panels is one of the reasons construction with CLT is significantly faster as noted by Hemström *et al.* [63]. Specific shapes can be cut prior material transportation to construction site. This approach allows to cut down the onsite operation time and reduces the transported mass and fuel consumption in return. Nevertheless, all the cuttings are sent to waste stream as their dimensions are useless for application in construction. These cuttings account for around 15% of produced CLT [67]. Usual treatment of CLT waste is incineration as added chemical inhibit biodegradation making it unsuitable for landfills [62]. Life cycle assessment have been often used to compare environmental impact during construction, exploitation and end of life stages of reinforced concrete structures versus CLT structures [68]. At this point many papers have been published on this topic evaluating various geographical cases [56], [62], [68], [69]. Nevertheless, the amount of cuttings and their impact have not yet been studied. To increase the resource efficiency when building with wood, this work explores environmental impacts of CLT cutting reprocessing into functional full size CLT panels in comparison with business-as-usual scenario of CLT waste disposal. Technology for CLT reprocessing is developed in lines with industrial research and all the mass flows are based on the results of it.

The potential of thermal insulation material from logging residues for packaging

Temperature sensitive products have been challenging commodities as transportation of them requires more energy and resources. In many cases temperature monitoring is required to guarantee the quality of the product. Commodities like meats [70] can spoil if temperature rises, vaccines require even stricter temperature regimes as they can lose efficiency when exposed to higher or lower temperatures than recommended [71]. In both cases temperature fluctuations out of the required range requires recall of the product. This can be very expensive and sometimes life threatening [72] in case of vaccines and first aid kits.

Temperature sensitive product logistics require cold chain – continuous low temperature regime from storage after production to transport and final storage before getting to the end consumer. Usually, logistics managers are responsible that cold chain is not broken in any link, ensuring the required temperature regime. Additionally, there are costs, CO_2 footprint and other factors that need to be considered when cold chain logistics is being developed. There are multiple aspects logistics management need to consider – required temperature regime, available infrastructure, time frame and available financial resources [73]. In every case risk assessment needs to be conducted and precautions weighed. Multiple tools can help to ensure efficient product transportation - The Global Positioning System [74] along with temperature logging [72] can provide real-time information on location and temperature of the product. Temperature logging can provide information, but in no way, it is a tool that can impact the situation, only help to elucidate the weak points in cold chain. Temperature fluctuations of the transported goods can be prevented by using dry ice or cold packs [72] and thermal insulation packaging [75].

All the above-mentioned equipment and tools impacts the carbon footprint of the whole cold chain. The most popular thermal insulation material used in temperature sensitive product transportation is polystyrene [76] – styrene is synthesized from ethylene and benzene and then polymerized [77]. Ethylene and benzene are chemicals acquired in petroleum refining process [78] making polystyrene a non-renewable polymer. In addition, its carbon footprint is considerable making up 64.98 kg of CO_{2eq} per m^3 expanded polystyrene with heat conductivity of 0.031 W/m·K [79]. Polystyrene has a negative impact on environment not only in production process, but at the end of its use as well. Song *et al.* experiment results show that polystyrene can lose its mass for as much as 5% after a month of exposure to Sun and outdoor weather, nevertheless polystyrene's mineralization can take hundreds or even thousands of years. This polymer breaks down when exposed to UV light, natural exposure from the Sun is sufficient for polystyrene to break down in microplastics and even nanoplastics [80]. In this form it is dispersed in natural bodies of water where it is ingested by marine life and ends up in food network leading to humans [81].

To address the environmental issues regarding cold chain and logistics overall, green logistics approach has been implemented. Green logistics deals with reduction of the negative aspects of goods transportation – like noise, air pollution, greenhouse gas emissions, accidents resulting in wastage and so on [82]. In many companies the necessity for temperature sensitive product transportation is so rare that it is outsourced, leaving the decision making regarding packaging, vehicle and the rest of logistics in the hands of another company [83]. According to Lammgard and Andersson (2014), around 70% of companies claim that the environmental aspect is important when outsourcing the transportation service for their goods [84].

World Health Organization (WHO) have recognized the impact of global vaccine cold chains on environment. Inefficient fuel use, poor quality insulation of buildings, fossil fuel use and many more factors contribute to the negative environmental impact [85]. Packaging has been recognized as another important contributor to the negative impact on environment, hence WHO is in search of more sustainable packaging regarding vaccine logistics, including thermal packaging used for temperature sensitive product shipment [86].

Already 10 years ago corn based packaging was highlighted by WHO as a sustainable choice in vaccine transportation [86]. Today there are companies like “Greencellfoam” [87] that offer biodegradable solutions made from corn, this material is often provided by logistics companies under generic name – starch-based packing peanuts. Technology behind starch-based packing peanuts is similar to polystyrene extrusion. Usually, some kind of blowing agent (air or supercritical CO_2) is used to enable air bubble production in the extruded material [88], [89]. Although this material is completely compostable with lower negative impact at the end of its life in comparison to conventional plastic foams, it is denser [88], hence more expensive to use in air cargo shipping. In addition, the hydrophilic properties of starch-based foams make them prone to size reduction in humid environments and even dissolving if the material comes in contact with water. To counteract the hydrophilic nature, there are attempts to merge starch with small amounts of plastics, as this reduces the carbon footprint in comparison to conventional plastic foams while increasing the product water resistance [90].

Another commercially available thermal insulation material for packaging use is mycelium based. “Ecovative” were the pioneers leading this material to the market in 2007. Agricultural and wood waste can be used to produce mycelium-based insulation material [91]. As seen in nature, fungus weaves through the substrate and interlocks the substrate particles in a rigid structure. This can happen due to fungus morphology – its cells are making filamentous structures called hyphae – these strand like structures allow for fungus to connect with each other and create a network [92]. Substrate locking with hyphae can result in stiff material with better strength than polystyrene. In addition to mycelium-based materials produced from agricultural and wood waste being biodegradable, production technology consumes considerably less energy than polystyrene production - 652 MJ and 4667 MJ, respectively [91]. Downside of mycelium insulation materials is its production time as it is limited to the slow growth of mycelium [93].

Another thermal insulation material produced from waste is feather insulation found on the market under the brand name of “Pluumo” [94]. In European Union alone annually around 3 million tonnes of feather waste are created from poultry farms. Feathers contain natural fibers that can be used in non-woven form to achieve low thermal conductivity of 0.030 W/m·K providing better thermal insulation than polystyrene foam. Feather insulation has the same weakness as other already discussed thermal insulation materials – water. Fiber structure makes it easy for water to seep into the material with capillary forces [95]. Hence waterbirds constantly preen their feathers with a waxy secretion to make them water resistant [96]. Plucked and processed feathers lose their coating making them prone to water absorption. The weak spot of thermal packaging from feather mat is the base of the box where all the weight of transported goods is pushing down – reduced thickness of feather mat greatly impacts the quality of packaging by increasing the thermal conductivity [95]. A similar material prone to the same problem is made out of sheep wool – on the market under the name “Woolcool” [97]. Although the macroscopic structure of wool is different from feathers, it is made of the same protein fibers called keratin, making the material hydrophilic. Like bird uropygial gland, sheep have glands on the skin that produce waxy substance called lanolin, impregnating the wool to make it water repellent. Sheep wool has good thermal insulation properties of 0.033 W/m·K [98].

Riga Technical University’s research team has developed a thermal insulation material from logging residues without any synthetic additives. Material shows similar thermophysical properties as abovementioned insulation materials, but contrary to packing peanuts, Pluumo, and Woolcool it is more rigid and does not lose its properties when product is compressing at it.

As shown above, there are multiple new and innovative thermal packaging solutions on the market, but none have been as successful as polystyrene boxes. There are many criteria that logistics management needs to consider while choosing the right packaging. Some of the more environmentally sustainable packaging solutions provide more efficient thermal insulation than other but all fall short in some respects, hence it is necessary to elucidate the most important criteria evaluated from the industry’s perspective that is dealing with temperature sensitive product transportation. In this research pairwise comparison was used to determine the most important factors regarding thermal packaging from the perspective of logistics managers in Latvia’s biotechnology, pharmacology, and fine chemical enterprises.

Resource efficiency

Energy efficiency has been a major challenge ever since the Industrial Revolution began. Today improvements in technology are related to resource efficiency improvements and increased quality, along with innovations in completely new product creation [61]. Preference for specific technology is impacted by production volume and raw materials used, as well as regional legislation [99]. Policy has a strong role in technology development as strategic incentives to research and development lead to their improved production efficiency of technologies. Their adoption in new and existing production plants could lead to growing demand for biomass feedstock [100]. Due to existing legislation it is expected that the demand for biomass feedstock for production will indeed grow in local, EU, and even at the global level [101] reducing the negative impact of production on climate [102]. However, biomass cannot substitute for fossil resources to the same amount needed to satisfy demand for products and energy, so that European requirements are now focusing on more effective biomass usage and biowaste management. Burning of fossil fuel releases the carbon sequestered millions of years ago back into the atmosphere, hence increasing the amount in the active carbon cycle [103]. To slow down climate change, fossil resources would need to be completely replaced by bioresources [104] and alternative energy sources, such as hydrogen. This would require an immense commitment on the part of industry, as demand dictates supply. Demand not only dictates the amount of available bioresources, but also stimulates the development of new greener technologies [105]. Bioresources vary in composition even more than fossil resources, requiring more variable technologies and demanding a more flexible approach from industry [101]. In addition, various biomass leads to different products with varying value per ton of raw material [100]. Therefore, production of biomass with higher added value is so important, and technology development of new and underused biomass to raise its value. Recognizing the crucial role of research and development (R&D) in innovative technology development [100], the EU allocates considerable resources to promoting R&D biotechnologies [101].

Resource efficiency and bioeconomy are becoming more ubiquitous terms in global scale. Bioeconomy is viewed as a frame for sustainable bioresource consumption by adding value to society. The same goes for raw materials used within bioeconomy. Although, European Union directive 2008/98/EC [106] defines that by-product of production is not classified as waste, in reality often by-products of production are treated as waste in enterprises and sent to waste streams.

In this research we are evaluating various factors impacting by-product utilization or redirection to waste streams. All factors are interlinked in "bioresource nexus" and specific indicators can be used to describe these linkages [107]. We propose a simple calculations' method to determine by-product utilization efficiency describing "Waste – bioresource" linkage. In conventional economics demand creates supply, in terms of bioeconomy demand for bioresource is often limited to technological capabilities and knowledge base of stakeholders. One resource can be used to produce products with various added value levels [108] and cascading is viewed as most sustainable way of bioresource utilization. Cascading refers to bioresource utilization for higher added value product production where created leftovers are redirected to production of another, usually lower value, product [109].

While technological approaches in food manufacturing have offered new markets and opportunities, they must also respond to changing environmental concerns [33]. Conservation of resources, recycling and reuse of materials, utilization of by-products and bioconversion of waste materials in addition to reduction of environmental loadings are contributing to environment sustainability [110]. Biowaste is quite a broad term including wastewaters, agricultural residues as well as residues from slaughterhouses [111]. Each of these types of waste burdens environment in different ways. Wastewaters might bring toxic pollutants within it causing stress to aquatic ecosystem and reducing biodiversity [112], in addition elevated biological oxygen demand (BOD) can cause dead zones [113]. Other organic matter, like manure and agricultural residues, but mainly food waste are causing methane production due to anaerobic digestion taking place in landfills [114]. According to Bandara *et al.* 2007 research, 90% of generated waste in households are organic, moreover households with higher income level are producing more organic waste linking biowaste production with socio-economic factors [115]. Despite this link it is almost impossible to assess the waste to bioresources flow on national scale due to limitations of available data. Biowaste's burden on environment has led to development of various technologies to relieve the stress. Most noticeable being wastewater treatment, reducing BOD in natural bodies of water [116] and landfill gas collection facilities [117]. In many cases, reducing burden on environment has led to profit generation. As example in Latvia, SIA "Getliņi Eko" – the biggest municipal solid management company has developed a profitable side business by collecting landfill gas. The use of heat energy and electricity generated from landfill gas combustion allowed them to successfully grow tomatoes[118], in this case energy intensive culture [119] is produced entirely using organic waste. Nexus impacting this decision is further investigated in this study using other enterprises. The abovementioned example is an apt representation of bioeconomy, showing that biowaste can serve as raw material for acquiring other products [111]. According to EU "bioeconomy […] encompasses the production of renewable biological resources and the conversion of these resources and **waste streams into value added products**, such as food, feed, bio-based products and bioenergy" [120]. On the contrary, OECD in their definition concentrates on the benefits bioeconomy is providing to society: "bioeconomy to be the aggregate set of economic operations in a society that use the latent value incumbent in biological products and processes to capture new growth and welfare benefits for citizens and nations" [121]. Though expressed differently, one can argue that biowaste is the very embodiment of "latent value" as often biowaste is sent to polygon despite the possibilities for using it to acquire higher added value products, like reducing sugars[122]–[124] that can further be used for ethanol or even enzyme production [123]. Perhaps the most obvious usage of biowaste is biogas production [125], this can be done straight in polygon of municipal waste [117] or in biogas plants [126]. So, despite absence of term "waste" in OECD definition, it is still considered a crucial bioresource and its value depends on the selected management approach.

In fact, OECD project to design a bioeconomy policy agenda for government is strongly concentrated on biotechnologies like gene engineering not once mentioning waste [121]. EU approach is more grounded and oriented on managing resources to their full potential – using every last bit of raw material for the same or various product generation. The OECD approach is oriented on using bioresources to their highest potential – creating products with highest possible added value. When it comes to the actual situation, there are plenty of companies producing biowaste but fewer companies are applying actual biotechnologies in context of gene editing or working with modified organisms. There are almost half a million manufacturing enterprises in EU using bio-based raw materials, and accordingly producing biowaste [127]. The actual amount of produced biowaste is unknown.

In the scope of this study using bottom-up approach we are looking into the enterprise level of biomass utilization – enterprises using biomass to produce specific products. We are analyzing the nexus involving biomass, biowaste and bioproducts, as well as additional detected factors in this nexus. In addition, we are proposing an indicator for evaluation of by-product utilization in enterprise.

Factors for waste to bioresource flow

As mentioned above, biowaste and bioresources can be one decision away from each other. So far industrial energy efficiency is studied as main position to cut down CO_2 emissions and reduce industry's caused effect on climate change, "Our World in Data" reports that electricity and heat production sector is the biggest CO_2 emitter [128]. As our understanding of natural carbon cycle and storage becomes broader, there are more policies aimed at preventing destruction of carbon rich biotopes [129], [130] as well as stimulating circular economy. In 2015 European Union adopted whole Circular economy package including specific deliverables [131]. Nevertheless, there are ongoing discussions on how to evaluate and measure various factors impacting industrial energy efficiency [132], [133], but factors for bioeconomy have not been discussed enough. Industrial clusters have been drivers for development of various competences, there are clusters related to bioeconomy with respective key performance indicators [134], 78% of these indicators are economical in nature.

Technology and waste

In the context of bioeconomy, technology as a term covers a vast field – from mechanical technologies to biotechnologies like gene engineering. As bioeconomy is based on bioresources – increasing amount of bio resource productivity means larger capital circulation in this field. In earlier stages of industrial development, increase of bioresource amount in economy was achieved by simply expanding land used for bioresource cultivation. With growing threats of climate change and decreasing area of wildlife habitats [135], it has become clear that expansion is not an option anymore and other ways for acquiring greater amount of biomass needs to be found. Today it can be done by using biotechnologies like gene engineering. Hence, there has been a great boost to bioeconomy from field of life sciences. Possibilities for boosting lipid production in plants [136] and microorganisms [137] have been studied widely for further applications to biodiesel production, in addition, manipulations to achieve better lignin biomass for 2nd generation biodiesel production have been done [138]. EU is recognising the importance of technologies in life science. According to Deloitte research, EU has the biggest cited publication amount in field of biotechnology in comparison to United States and major Asian countries [139]. In addition, considerable amount of financial resources are dedicated to EU Food, Agriculture, Fisheries and Biotechnology programme Activity 2.3: "Life sciences, biotechnology and biochemistry for sustainable non-food products and processes" [140].

When it comes to manufacturing companies, technologies usually are a crucial part of production. Applying effective technologies in the production process can reduce the amount of generated waste or simply increase the production yield. As food production companies are dealing with considerable amount of organic matter, this could be a field with potential for bioeconomy development.

Nevertheless, there are multiple factors impacting bioeconomy principle adoption. In this research we are elucidating factors impacting this segment of circular bioeconomy development as well as proposing indicator to characterise utilisation of bioresource's potential. As a case study we are analysing two producers using the same type of biological raw material but creating different products. Varying waste types allowed us to calculate various scenarios for by-product utilisation. Although EU have clearly defined difference dividing waste from by-product, after interviewing managers in three enterprises, we concluded that terms by-product and waste are used interchangeably. Figure 1.2. represents scheme adopted from Eurostat

Manual on waste statistics, with our modification to show dissolved border between by-products and waste.

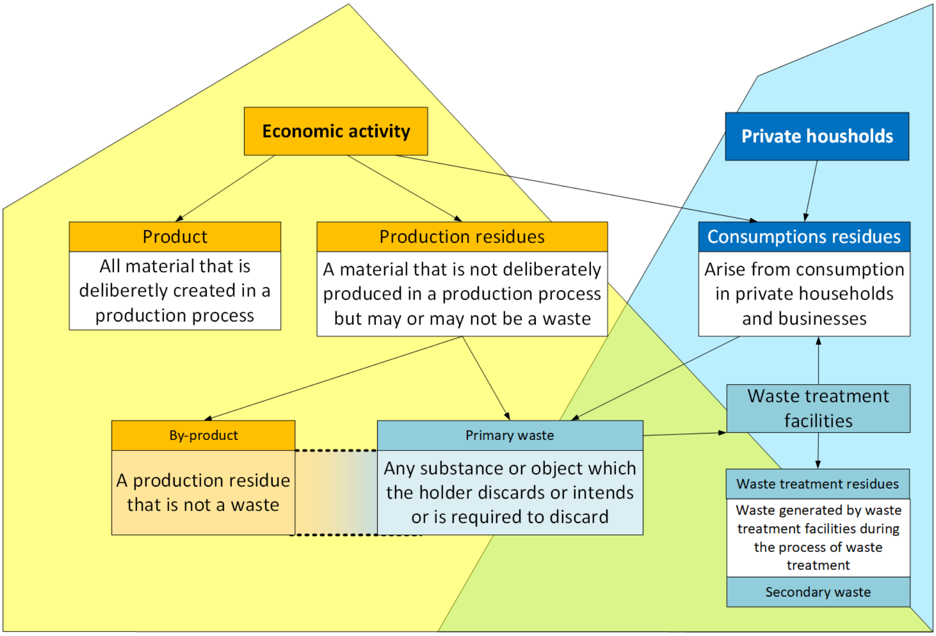


Fig.1.2. Waste generation scheme [141].

To evaluate reasons behind decision making leading to various choices, multiple interviews were conducted with production managers as well as representatives from companies dealing with produced waste. In real-life situations by-products and primary waste is not so clearly divided, as companies often discard by-products as waste, in some cases by-products are used but not to their full potential.

Bioresource value

In bioeconomy resource value can be estimated from bio-based value pyramid representing five ways for biomass use: (1) Pharmaceuticals & Fine chemicals (PFCs); (2) Food & Feed; (3) Bioplastics & Polymers; (4) Bulk chemicals and (5) Energy, Heat & Fuels in descending order of value [108]. Although biogas fits in fifth category as a source of energy, we argue that fourth category would be better fitted for biogas. As burning process oxidises organic compounds into inorganic carbon dioxide (a well-known greenhouse gas) leaving only ash, after biogas production leftover digestate can be used to improve nutrient content in soil [142]. This classification could be backed up by Stegmann et al., representing energy recovery and composting as part of circular economy, partially feeding back resources into sustainable biomass sourcing [108].

Top of the bio-based value pyramid is occupied by PFCs as usually these products have higher economic value, as well as by-products can be further used in various applications. One example of bioresource use in PFCs is potatoes – product that typically is used for food and feed can be processed into PFCs like ascorbic acid and phenolic compounds [143], [144]. More importantly, these PFCs can be extracted from potato peels in this way increasing added value of by-product from food industry.

2 METHODS

In this work Bioeconomy is analysed in multiple levels – from the product level to National level, using corresponding methodologies. Results of this work will be depicted in the same order as corresponding methods.

Experiments for chipboard production

To promote the transition from fossil based resources in material production, laboratory experiments for chipboard preparation from conifer logging residues and bio-based binders were conducted. Binders were chosen on the basis of literature review. Experimental work to produce bio-based chipboards from logging residues were done according to described methodology. Logging biomass was delivered in 50L to 100L polyethylene bags as wood chips from forest felling where branches were chipped with needles intact. Although the content of wood chips varied depending on the location and environment in which the wood chipping was carried out, as well as on the proportions of wood biomass, after visual assessment it was concluded that the wood chips mainly contained the heartwood and sapwood, bark, needles, fresh and decayed biomass particles, and mineral particles. To determine the mineral contents, chemical analysis of different supplied biomasses was carried out, placing a small part of selected biomass in a 500 ml polyethylene bag and taking it to the Waste products and fuel research and testing laboratory of Ltd "Virsma" for analysis. Along with mineral content, the volatile substances in biomass were determined according to the LVS EN ISO 18123:2016 standard.

Based on the literature review on chipboard production, multiple parameters were chosen to be tested for chipboard production from conifer logging residues. As multiple wood-based panel types are widely produced and improved, there is a vast body of literature describing the production process of such materials, therefore the parameters in this work were chosen accordingly [18].

Experimental stand was custom made and included hydraulic press with hand pump (Hansa Flex - 10 t); Analog pressure gauge (Hansa Flex - 600 bar, ± 50 bar); Digital manometer (Hansa Flex - 1000 bar, ± 1 bar); Cylindrical heating elements (alternating currents); Temperature sensors; Heating metal blocks/surfaces. Experimental stand depicted in Figure 2.1.

Fig.2.1. Hydraulic hot press

Additionally, the stand included plate drying stand; metal frames: metal frame without perforations for holding biomass, and metal frame with perforations for biomass retention and steam discharge; metal lining for steam removal; Teflon fabric.

Biomass moisture content determination

Chips delivered from forest contained varying but significant amounts of moisture. The different amount of moisture in the wood chips was observed under different weather conditions during chipping and delivery of logging residues. Biomass as received from logging sites can be seen in Figure 2.2.

Fig.2.2. Biomass as received from logging site.

Therefore, first the wood chips were removed from polyethylene bags and placed indoors for drying to an air-dry moisture content of approximately 8% to 10%. The average time for biomass drying was one calendar week, but it depended on the initial moisture content. The moisture content of the wood chips before and after drying was determined with a Greisinger GMH 3830 probe by inserting it into the wood chips and reading the moisture content value from the device interface.

Milling

To obtain the required biomass particle size or size range, the dried wood chips were ground using a hammer mill. The initial grinding of the chips was carried out with a two-horizontally rotating axis chipper to grind it into smaller particles, which, if necessary, could be sieved immediately to separate larger particle sizes or placed in a "Vibrotehnik PM-120" hammer mill to obtain even smaller particles.

Size separation

Two methods were used to obtain the desired particle size. After the chips were crushed in the custom-made horizontal axis chipper, the chips were placed in a "Vibrotehnik PM-120" laboratory size hammer mill with an in-tegrated metal screen. (2) Sieving of the crushed particles was performed using a Retsch AS-400 sieve shaker and metal sieves with different mesh opening sizes. The separation approach allowed to assess the bark and other fine particle im-pact on board durability. Particles fractions of < 2.8 mm, 2.8-8 mm, and 8.0-10.0 were used to determine the fine logging residue particle impact on board mechanical properties.

Mixing

Depending on the type of adhesive used in the plate pressing experiment group, it was either added to the biomass in the form of a ready-made powder, or the powder was first dissolved in water to obtain the adhesive in a viscous form according to the established production protocol, and then added to the biomass. In both variants, the binder was added to the logging residue particles no longer than 48 h prior biomass pressing to prevent mould formation, moisture change, and other aspects that would potentially cause unwanted additional effects on the investigated parameters.

Board preparation

The production of boards was carried out using previously prepared logging residue biomass with the required particle size (mm), moisture mass fraction (%). The board formation process was carried out in the following stages:

Digital pressure gauge was turned on and reset. In case of using analogue pressure gauge, no power-up or reset was done.

The required temperature was set using the heating element control controller.

When the temperature shown by the temperature sensors indicated that the set temperature (± 5 °C) has been reached, a metal frame was placed on the lower heating surface and the Teflon cloth inserted into it. After that, the prepared biomass was formed into the frame by hand and a metal screen for steam discharge, and a Teflon fabric was laid on top.

Pressing was performed by squeezing the hand pump until the required pressure was displayed on the manometer (±10 bar for the digital manometer and ±50 bar for the analog manometer).

The countdown was started, and the pressure controlled with the hand pump during pressing.

After the desired time, the pressure was released evenly by carefully turning the pressure release valve on the hand pump.

Finally, the produced board was removed from the press and placed in the drying rack overnight.

Referring to the information provided in the scientific literature, the size, geometry or shape of the wood particles and the relative position of the particles significantly affect the mechanical strength of particle board [18]. In this group of experiments, the effect of particle size of logging residues on the strength of the manufactured boards was tested. To determine the impact of logging residue particles on strength, the particle size was divided into three parts: < 2.8 mm, 2.8-8 mm, and 8.0-10.0. The hot pressing pressure was chosen to be 600 bar at a temperature of 140 °C and 160 °C.

Board testing

Density

The European standard EN 323:1996 has been developed for determining the density of wooden boards. With reference to EN 323:1996, the density of timber boards was determined as the ratio of the mass of each test specimen board to its volume. Both plate parameters were determined at the same moisture content of the sample. A caliper with an accuracy of ± 1 mm was used to determine the dimensions of the plates. On the other hand, for mass determination - laboratory scales with an accuracy of ± 0.01 g were used. The width and thickness of each logging residue plate and sheet was determined at three points - at the extreme longitudinal edges of the plates and sheets, and at the midpoint and at its edges according to the European Standardisation Organisations' (1993) EN 323:1993 standard "Wood-based panels - Determination of modulus of elasticity in bending and of bending, applicable at the European level".

Mechanical properties

For determining the bending strength and modulus of rupture (MoR) of wooden boards, the standard EN 310:1993 was used. This standard defines a method for testing the modulus of elasticity (MoE) and flexural strength of horizontally placed boards in the bending of timber boards with a nominal thickness of ≥ 3 mm. The modulus of elasticity and flexural strength, also called modulus of rupture (MoR) are determined by applying a load to the centre of the test specimen supported at two external points. The modulus of elasticity is calculated using the slope of the linear region of the load-deflection curve. The calculated value is the apparent modulus rather than the true modulus because the test method includes both shear and bending. The bending strength of each sample is calculated by determining the strength of the maximum bending load F_{max} of the full cross-section of the sample until the mechanical collapse of the sample.

To determine the strength of plates according to the EN 310:1993 standard, following steps were taken: (1) Sawing lines of the sheets were marked on the prepared boards according to the dimensions determined in the methodology so that the midpoint of the marked sheets was as close as possible to the midpoint of the board; (2) Sheets from the prepared board were cut out using a stationary circular saw; (3) Placement of the distance of the outer support points of the stand for determining the resistance according to the approach determined in the standard methodology; (4) The plates were placed symmetrically on the support points of the strength test stand; (5) The load tube on the plate was placed at its longitudinal midpoint, perpendicular to the longitudinal direction of the sheet; (6) Predetermined load to the sheet was applied in a certain time interval (kg/min) depending on the deformation of the sheet at the initially applied load (Fig.2.3.)

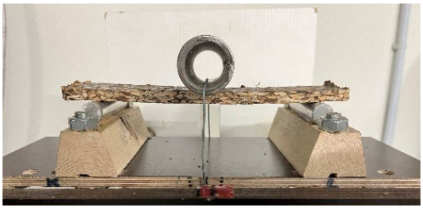


Fig.2.3. 3-point testing stand for determination of maximum bending load.

Data analysis

In this study, two-factor analysis of variance (ANOVA) with replications was employed to investigate the effects of two independent variables on the observed outcomes. Particle size, temperature, and pressure were manipulated as independent variables to evaluate both their individual impacts and potential interactions. An Analysis of Variance (ANOVA) was performed on the dataset, which comprised a total of 102 data points. These data points were obtained from 17 unique factor combinations, each of which was repeated six times to ensure statistical robustness. Each of the six repetitions involved the creation of two distinct samples. To ensure data accuracy and reliability, each of these two samples was further divided into three equal parts. Subsequently, each of these six sub-samples underwent a destructive measuring method to acquire individual data points. This rigorous approach allowed for a comprehensive and replicable dataset. Measurements were made according to the previously described methodology. Data preparation involved structuring the collected data into columns for each combination of factor levels, with rows representing replications. This data organization facilitated an effective assessment of the independent variables' effects. To conduct the two-factor ANOVA Microsoft Excel's "Data Analysis" tool was used.

ANOVA allowed for three simultaneous hypotheses testing: H_1: there is no significant difference in 1st variable results, H_2: there is no significant difference in 2nd variable results, and H_3: there are no significant interactions between both factors.

As the Post Hoc test T-test was chosen for the pairwise comparison of disproven null hypothesis. Each composition and parameters were replicated at least three times and produced boards sawn in three equal parts for MoR testing, and density calculations, resulting in at least six repetitions. Calculated standard deviations are depicted in graphs, confidence value of P-value of 5% was used in the analysis.

Multi criteria decision making

Many multi-criteria decision-making (MCDM) methods have been developed to provide decision makers with tools based on mathematical logic. All MCDM methods have some subjectivity aspect to them and many MCDM methods provide different results as shown by Zlaugotne *et al.* [145]. Siksnelyte *et al.* recognized Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method as the one having the most benefits in comparison to PROMETHEE, PROMETHEE II, VIKOR, WASPAS, WASPAS-G and Fuzzy Sets. Analytical hierarchy process (AHP) had the second-best benefit count [146]. In addition, Lee et al. 2012 have used AHP specifically for technology transfer adoption in companies, hence showing the compatibility of AHP to organizational decision making [147]. In this work TOPSIS was chosen in combination with AHP. As the combination of these two methods is helpful for evaluating how close to the ideal solution are all the alternatives, as TOPSIS method not only elucidates the best alternative but gives the closeness to the ideal solution coefficient [148]. Hence, by using TOPSIS more detailed picture of "How ideal all the alternatives are?" can be acquired. To acquire weights for TOPSIS, AHP was used. AHP is one of the most widely used multi-criteria analysis methods because it allows to easily compare criteria with each other [142]. In this work, the Saaty's scale was used to compare the criteria, in which nine degrees of importance were verbally denoted, indicating the importance of one criterion over another. The scale of nine ratings starts with 1 which stands for equal importance, and ends with 9 which stands for extreme importance [149].

Initial criteria for all the MCDM conducted in this work were identified in open interviews with representatives of companies working in the pharmaceutical and fine chemicals and logistics field. By allowing the representatives to answer open questions like "How is thermal packaging chosen?", criteria and their indicators were elucidated. In many cases it became clear that industry is not using quantitative indicators for each criterion. For example, criterion "sustainable" was often described as non-fossil raw material without any numerical value assigned to the corresponding criterion. Further, literature and product data sheets were analyzed to validate the criteria. The analyzed product data sheets were containing information based on performance, for example, hours held in temperature below +8 °C [94], [97], [150], indicators like thermal conductivity and density were found in scientific literature on corresponding materials [88], [91], [95]. Therefore, some criteria e.g., forementioned "sustainability" was assigned with values based on qualitative measures. The highest rating of 3 was assigned to materials from secondary or tertiary raw materials without any fossil-based additives. Rating 2 was assigned to materials with more than 30% of bio-based raw material (based on the initial interviews this number was chosen), and 1 was assigned to materials made from fossil-based raw materials.

Analytical hierarchy process

To determine the importance of chosen criteria, pairwise comparison was conducted. As it is impossible for humans to grasp the reciprocal relationships of 12 criteria at the same time, the method for pair analysis was chosen. Using this approach experts were asked to compare only two criteria at a time, each expert did the total of 66 comparisons for thermal packaging. Comparison was done verbally as suggested by Saaty *et al.* 2010 [149] by determining, is one criteria equally important as the other, less important or more important. After verbal comparison, numerical values were assigned to each compared pair using scale of 9. In the chosen scale 9 was signifying very high importance, 6 - strong to very strong importance, 3 - moderate importance and 1 - equal importance [151] and marked in the digital survey form.

Overall, 10 questionnaires were disseminated among the identified pharmaceutical and fine chemical industry enterprises in Latvia, including big companies like Grindex and Olainfarm. It was expected that the approached companies were heavily impacted by the global pandemic, only five responded and three were eligible to questions as companies made their own decisions regarding temperature sensitive product logistics. Two companies outsourced this service hence were unsuitable for multi criteria analysis and criteria comparison, nevertheless their reported practice will be discussed in the Results part of this study. The chosen companies assigned the questionnaire to logistics team experts within the company. All the criteria included in the digital survey for the comparison are compiled in Table 2.2.

TABLE 2.2. THERMAL PACKAGING CRITERIA USED FOR PAIRWISE COMPARISON

Criteria	Description
Odor	Material has no considerable scent
Resistance to humidity	Material does not dissolve or get damaged to the point it loses its thermal resistance
Vapor resistance, [m]	S_d value of thermal insulation material. Represents the resistance to water vapor taking up certain air layer thickness [m]. Mostly relevant for shipments with dry ice
Branding opportunities	Material can be printed on
Sustainability	Raw material of thermal packaging is renewable
Ability to hold temperature, [hours]	Packaging can hold specific temperature for more than 24 hours. Criterion represents in situ measurements of temperature in relevant environment and packed test goods – representing goods that would be transported
Thermal conductivity, [W/m·K]	In lines with this study 0.04 W/m·K was considered the threshold for thermal conductivity to be considered low. Thermal conductivity characterizes the material by its ability to conduct heat energy. Heat energy is always transferred down the gradient.
Reusability	Material can be re-used multiple times
Available in multiple sizes	Multiple dimension options are available

Price, [euros per 39l box]	Per packaging solution
Durability	Material can be used without supportive tertiary packaging (e.g., cardboard box)
Density, [kg/m^3]	Weight to volume ratio of packaging solution

Mathematically all the chosen criteria are plotted on a matrix and by solving the matrix, eigenvalues were found. These values, also called eigenvectors, represent the importance of each criteria – higher value means higher importance in the final decision. Indicative eigenvalues were calculated in Microsoft Excel [152] and used for further analysis. Consistency threshold of 0.2 was used, as done before [153] when multiple stakeholders were surveyed.

To evaluate the importance of each criterion, experts with experience on CLT production were asked to rate reciprocal relations of criteria. For evaluation, experts were acquainted with Saaty's scale and criteria plotted in Excel to generate questionnaires for experts to fill. Questionnaires were sent out via e-mail.

The acquired ranking was used in AHP in order to calculate the normalized eigenvectors representing the importance of each criterion [149]. Criteria and their ranking were plotted in Excel in a comparison matrix as shown by Delvere et al. [154]. Consistency ratio <0.2 was determined, and the calculated weights were used for further steps.

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

To compare alternatives in question, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used. TOPSIS allows to compare multiple options by multiple criteria. First stage of TOPSIS was gathering data set of indicators for each thermal packaging material. Data were acquired from product data sheets [94], [97], [150] and patent claims. In the second step normalization of indicators was performed. Values were weighed based on responses from experts. In the next step normalized values were weighed, directions of vectors and their proximity to desirable and avoidable results were calculated. The final step was to calculate the proximity to the ideal solution represented by a value of 1 [155].

TOPSIS methodology was chosen because it requires only few indicators, while providing comparable data to draw conclusions. For further multi-criteria analysis only criteria with comparable numerical values were chosen, reducing the number of criteria from 12 to 5. Chosen criteria were density, thermal conductivity, environmental sustainability, ability to hold temperature, and price. Criteria like odour, availability in multiple dimensions were determined as on-off type of criteria – if material would have considerable odour, it would not be used, the same with availability in multiple dimensions – most of the companies needed the thermal packaging to be available in at least 3 different sizes. In case when thermal packaging producer is not offering these multiple sizes, this product would not be considered. Resistance to humidity and vapor resistance are both important for certain kind of transportation – transportation where there is a high humidity risk e.g. transportation with ice, and transportation using dry ice accordingly. Reusability and durability were excluded as expert principles for determining material's accordance for reuse was differing. Durability as material's ability to be used without supporting cardboard box was excluded from further analysis as this option was rarely used by experts in their represented companies.

The basic assumption of TOPSIS methodology is that the most preferred solution is one with the shortest distance to the desirable result and greatest distance from the result to be avoided. Multiple innovative packaging materials along with conventional polystyrene were compared regarding five criteria.

The same method – using AHP and TOPSIS combination was used in this work twice – for abovementioned thermal insulation packaging and cross laminated timber production residue utilization.

TOPSIS decision-making method was based on previously calculated weights for AHP, and data collected from the literature. Four alternatives for CLT residue utilization were considered:

- MDF;
- Mycelium insulation;
- Solid fuel;
- PB.

Products were analyzed from green economy perspective, hence criteria that would represent it was chosen. Overall, five criteria:

1. Production costs;
2. Energy consumption;
3. CO_2 emissions;
4. Product market price;
5. Final product to wood residues ratio were chosen.

Values for analyzed criteria were gathered from scientific literature, market data [42] and life cycle inventories [148][43], [44] on the chosen products.

Production costs included energy, raw material, and labour costs to produce one metric ton of the product. Energy consumption and CO_2 emissions during production process of one metric ton of product was calculated from energy consumption and source (grid or cogeneration). "New product to raw material" criterion represented the extra material needed for the production of new product (one of alternatives). Ratio of new product to raw material also represented how much of the raw material originally used for product production could be replaced with wood resides. Product market price represents value what the consumer pays to acquire the material from market.

Data were gathered from life cycle inventories and other works. In case of life cycle inventories of PB and MDF data were reflected using functional unit or one square meter, hence values were converted to tonne using material density.

For comparison, the considered alternatives and their criteria were arranged in a decision-making matrix and the matrix data were normalized.

$$\begin{array}{c}A_1\\A_2\\A_3\\A_4\end{array}\begin{bmatrix}v_{11} & v_{12} & v_{13} & v_{14}\\ v_{21} & v_{22} & v_{23} & v_{24}\\ v_{31} & v_{32} & v_{33} & v_{34}\\ v_{41} & v_{42} & v_{43} & v_{44}\end{bmatrix}, \tag{1}$$

where

A_n	Explored alternatives.
v_n	criteria, normalized matrix.

The obtained normalized values were multiplied by the weights obtained by AHP and the distance of each criterion to the ideal solution was determined.

To evaluate robustness of the TOPSIS results, sensitivity analysis was conducted. To compare sensitivity of the assigned weights (ω), TOPSIS method described by Li *et al.* was used [156]. Changes in the importance of product market price was calculated by introducing unity variation β_{pm} that represents the changes in product market price weight. After changes the product market price weight (ω'pm), all the other criteria weights (ω) were recalculated according to:

$$\begin{cases}\omega_1' = \dfrac{\omega_1}{1+(\gamma_{pm}-1)\cdot\omega_{pm}}\\ \omega_{pm}' = \dfrac{\omega_{pm}\cdot\gamma_{pm}}{1+(\gamma_{pm}-1)\cdot\omega_{pm}}\\ \omega_n' = \dfrac{\omega_n}{1+(\gamma_{pm}-1)\cdot\omega_{pm}}\end{cases}, \tag{2}$$

where

ω'_{pm}	Product market price criteria weight after changes
ω'_n	Other criteria weights after changes in ω_{pm}
γ_{pm}	Initial variation, calculated according to:

$$\gamma_{pm} = \frac{\beta_{pm} - \beta_{pm}\cdot\omega_{pm}}{1-\beta_{pm}\cdot\omega_{pm}}, \tag{3}$$

where

β_{pm}	Unity variation, calculated according to:

$$\beta_{pm} = \frac{\omega_{pm}'}{\omega_{pm}}, \tag{4}$$

Life Cycle Assessment Methodology

The life cycle assessment (LCA) methodology is the most common tool used to quantify and compare in a quantitative manner the impacts from different products or processes such as the one under study. Every product (good or service) has a life cycle, from its design, then the resource extraction, transporting, production or manufacturing, commercialization, consumption or use, and final disposition. The LCA core is to collect and group the resource consumption, emissions to the environment and environmental exchanges in all activities, that are needed to produce a determined good, and translate them into comprehensive environmental impact categories [53], [157].

This allow to think beyond climate change, which is usually the main parameter judged when assessing environmental issues. The main advantage of LCA is the ability to analyse impacts from a global perspective, avoiding "burden-shifting" [55] by allowing the assessment in many and diverse impact categories, regularly summarized in climate change, stratospheric ozone depletion, tropospheric ozone creation (smog), eutrophication, acidification, toxicological stress on human health and ecosystems, resource depletion, water use, land use, noise, and others [56].

The most used methodology for performing LCA is the LCA ISO standard 14040 and 14044 where the principles and framework for LCA are described and the requirements and guidelines to perform the assessment presented. It is in ISO 14044, where the key four steps are defined: goal and scope, life cycle inventory, life cycle impact assessment, and life cycle interpretation [57]. Such steps will be covered in detail in the next section.

Goal and Scope Definition

The scope requires a clear description of the function and functional unit, system boundaries, methodology, and data requirements to sufficiently address the stated goal. This study was done as a comparative one where the waste treatment in the conventional scenario is assumed to be the same as reported in [158], meaning it is assumed the CLT cuttings are used for energy recovery, more specifically in district heating and electricity production. However, transport of cuttings is not considered neither in this nor in the new proposed scenario, where cuttings are re-processed *in-situ* to generate new CLT pieces. Thus, the scope of this study is to evaluate only the activities related to the use given to cuttings in both scenarios despite the geographical location with respect to the waste treatment facility.

This is an attributional model where output data from [158] is normalized to the current scenarios considering the specific activities, material and energy flows required to conduct the re-process of cuttings for a specific residential construction project in Latvia. Then, the results of this study are only applicable to this scenario as foreground data was obtained directly from construction companies and the amount of cuttings subject to waste or re-process may vary from one project to another, as well as foreground data related to materials and energy.

For the baseline scenario, the intended waste treatment is energy recovery, and the values for electricity, and heat generated are taken directly from Wood Based Panel Market Report [159] as well as the related impact from this End-of-Life (EoL) stage. Then, the impact results are normalized to the amount of waste expected from the construction project under evaluation, and these values are understood as the environmental impact results in the different mid-point categories resulting from the Environmental Product Declaration (EDP) methodology. For the proposed scenario, the same amount of cuttings resulting from the construction site, instead of being sent to the waste treatment plant, are re-processed to create useful new CLT units, that could be even sold to other projects or used internally within the same building site. However, despite the re-processing activity, there are cuttings still left for waste, and it is assumed those leftovers are disposed in the same way as in the baseline scenario.

The EDP method has been recently updated (2018) including water scarcity footprint category based on Boulary *et al.* 2016 developed method [160]. In the time from 2013 to 2018, EDP version under which the Environmental Product Declaration was obtained for this CLT material did not include such category, this one has been left out of this study to keep comparison consistency. The LCA performed in this project was completed using *Simapro 9.0* software integrated with *Ecoinvent 3.6* database.

Functional Unit

The functional unit (FU) is a measure of the performance of the functional outputs of the product system and its main objective is to give a reference to which the inputs and outputs are related. Such a reference is needed to guarantee the equivalence of LCA results. The definition of a functional unit must then include both the quantitative and the key qualitative aspects to prevent subjectivity when subsequently defining an equivalence. In this case, the functional unit is one cubic meter (1 m^3) of CLT material used in the construction site.

System Boundaries

Considering the Environmental Product Declaration system boundaries for the material under study and the system boundaries considered there, the scheme presented in Fig. 4 has been developed for this LCA.

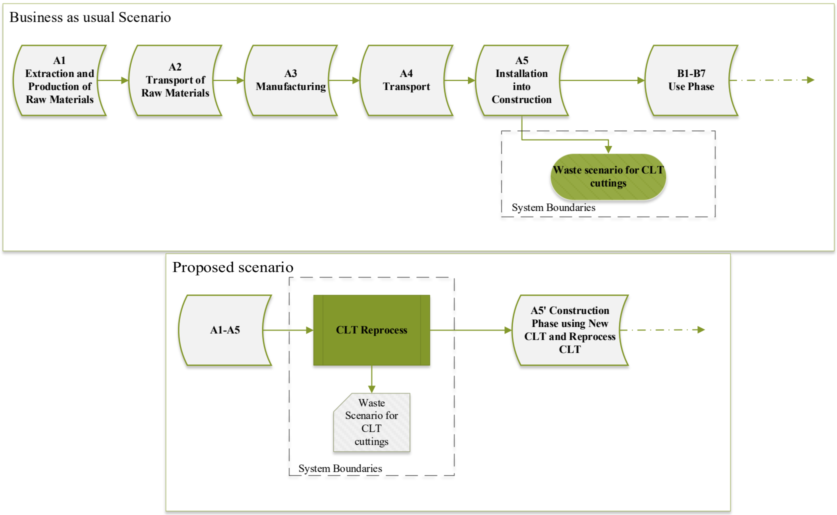


Fig. 2.4. System boundaries for the business as usual and proposed scenarios. Business as usual scenario describes incineration of CLT cuttings, Proposed scenario describes larger CLT cutting reprocessing into new full size panels.

The system boundaries in the baseline scenario only covers the waste treatment of cuttings generated in the construction site without bearing in mind transport to waste treatment plant since the distance is considered an uncertainty due to variability of possible geographical locations of building sites. Phases A1–B7 are displayed in the figure 2.4. to provide the context of the system, nevertheless only phases inside the dashed box are the ones within the study's system boundaries. Extra phases are only informative to show the overall life cycle of CLT.

For the proposed scenario, the re-process activity is carried out in-situ, without any need for transport to another location. The remaining cuttings not fitted to be re-processed are disposed using the same treatment technology considered for the baseline scenario, and again, the transport to the waste treatment facility is not considered due to distance uncertainty.

Limitations and Assumptions

Among the limitations that apply for the two scenarios under comparison, the exclusion of transport activities is the main one due to the uncertainty on both: the geographical location of the waste treatment facility and the construction site as it varies depending on the project. However, it is important to notice, that transporting wastes does come with an environmental burden from the vehicle itself and the fuel combustion, moreover, the higher the amount of waste to be transported, the higher the environmental impact will be; hence it is likely that by reducing the amount of waste subject to transported, an additional environmental benefit might be perceived despite not been accounted for in this study.

Another assumption to bear in mind is the fact of the re-process being carried out in the same location as the construction of the residential houses is taking place. This is important since it might be possible, under different case studies, that cuttings leftover after construction need to be sent to another location for re-processing and then dispatched back to the same location or sold to another construction project in a different one. For this cases study, since the re-processing activities are conducted in the same place, no additional environmental toll from transport is created.

Life Cycle Inventory

For the baseline scenario, the results from the energy recovery at the end of life (EoL) stage in [58] were taken directly for 1 m^3 and normalized to the amount of waste generated in the particular construction site. According to the foreground data collected, per each cubic meter of CLT used, 0.128 m^3 ends up as waste cuttings. The benefits resulting from the energy recovery of 1 m^3 are estimated in 612 MJ of electricity and 4208 MJ of thermal energy for district heating. Their associated environmental impact is shown in Table 2.3 for a cubic meter of material disposed. Nevertheless, the values within the model are normalized to the actual amount of cuttings sent to waste in each scenario. For this scenario, cuttings are used for energy regeneration, thereby avoiding consumption of energy from the grid. This leads to positive environmental impacts represented as negative values in all Impact categories. Miniscule impact is associated only with Depletion potential of the stratospheric ozone layer.

Table 2.3. Impact Assessment for 1 m^3 of CLT Disposed

Impact category	Unit	Total per m^3
Acidification Potential	kg SO_2 eq	–0.1786
Eutrophication Potential	kg PO_4 eq	–0.04186
Global Warming Potential	kg CO_2 eq	–32.510
Formation potential of tropospheric photochemical oxidants	kg C_2H_4 eq	–0.01664
Abiotic depletion potential for non-fossil resources	kg Sb eq	–0.000112
Abiotic depletion potential for fossil resources	MJ	–0.04217
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	0.000004012

For the proposed scenario where re-process activities allow to recover part of the cuttings by making new CLT units, the inventory collection goes toward gathering impacts from 3 stages:

1. Production of brand new CLT units;
2. Materials and energy required for the re-process activity itself;
3. The waste treatment of the unrecoverable cuttings.

Since by creating new CLT units from cuttings, brand new CLT units are potentially replaced in a construction site, the impact of such new re-processed CLT units are considered as an avoided product, hence the environmental impact results from phases A1–A3 (Fig. 1) are normalized and mathematically treated consequently with this approach. Impacts of stages A1–A3 for 1 m^3 are shown in Table 2.4.

Table 2.4. Impact Assessment of Producing 1 m^3 of CLT (A1–A3 Stages).

Impact category	Unit	Total
Acidification Potential	kg SO_2 eq	0.6272
Eutrophication Potential	kg PO_4 eq	0.1116
Global Warming Potential	kg CO_2 eq	–0.05673
Formation potential of tropospheric photochemical oxidants	kg C_2H_4 eq	0.1144
Abiotic depletion potential for non-fossil resources	kg Sb eq	0.0002468
Abiotic depletion potential for fossil resources	MJ	1497
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	0.0000125

The inventory of material and energy required for re-processing 0.128 m^3 of leftover cuttings (value per FU), are normalized to the following: 0.0904 kg of adhesive (polyurethane adhesive) and 0.466 kWh of electricity taken from the national grid. According to the foreground data obtained, 69.72 % of the cuttings re-processed are successfully converted into new CLT modules while the remaining 30.28 % are not suitable for re-process and must be left as waste material for treatment. The impact related to such treatment is taken from Table 2.3. and normalized to the corresponding value in this scenario.

Assumptions for LCA: Scenario of Individual House Project

To illustrate the amount of available CLT for reprocessing, individual house project (Fig. 2.5.) was chosen. Load bearing structure is entirely created from CLT. Doors and windows are cut out creating a considerable amount of cutting waste.

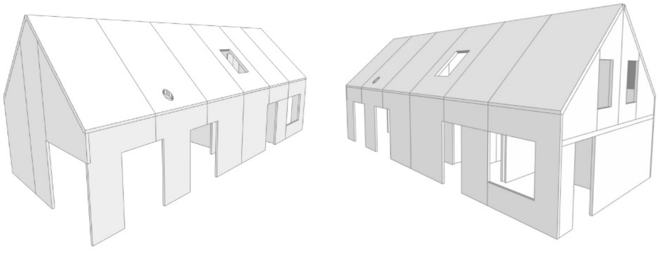


Fig. 2.5. 3D representation of individual house CLT weight bearing construction.

Not all the cuttings were suitable for new master panel production. Important criterion for cutting reuse was their flat surface area. Complicated geometrical shapes were sorted out, leaving the ones with reusable surface area above 1 m^2 with dimensions along X axis (example shown in Fig. 2.6.) not less than 800 mm.

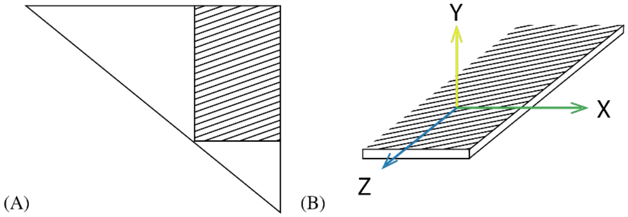


Fig. 2.6. (A) Reusable area of cutting represented with striped pattern. Width of the reusable area is 810 mm and length 1056 mm; (B) schematic representation.

In the chosen scenario for each house eight of the irregular cuttings were suitable for reprocessing into new master panels. To ensure efficient reprocessing, firstly the cuttings were calibrated to adjust the width (X axis) so they could be adhered together and pressed perpendicular to Z axis, cut to desired master panel length of 3 m and after that gluing and pressing could be continued perpendicular the X axis (Fig. 2.6.(B)). In this manner around 70 % of the cuttings can be reprocessed into new 3x6 m CLT panels. All the CLT cuttings from chosen individual house project and their dimensions are represented in Table 2.5. As can be seen in the Table 2.5., there are three types of CLT panels used – 80 mm, 120 mm and 150 mm. By evaluating scenario of cutting re-processing from 10 individual houses, we are generating scenario where cuttings can be re-processed straight away, otherwise panels with 120 mm and 150 mm thickness will need to be stored to accumulate adequate quantity for reprocessing.

Table 2.5. CLT Cutting Origins and Dimensions.

Origin	Thickness	Cutting dimensions		Dimensions after squaring	
	mm	Width, mm	Length, mm	Width, mm	Length, mm
Door	80	1525	2400	1525	2200
Door	80	1525	2400	1525	2200
Door	80	1525	2400	1525	2200
Door	80	1525	2400	1525	2200
Door	80	1237	2420	1025	2220
Door	80	1025	2400	1025	2200
Window	80	825	1425	810	1025
Window	80	825	1425	810	1025
Door	80	817	2400	810	2200
Door	80	825	2400	810	2200
Door	80	810	2220	810	2020
Door	80	810	2220	810	2020
Geometrical cutting	80	irregular	irregular	810	1526
Geometrical cutting	80	irregular	irregular	810	1478
Geometrical cutting	80	irregular	irregular	810	1056

Geometrical cutting	80	irregular	irregular	810	1016
Geometrical cutting	80	irregular	irregular	810	921
Geometrical cutting	80	irregular	irregular	810	1396
Geometrical cutting	80	irregular	irregular	810	866
Geometrical cutting	80	irregular	irregular	810	848
Window	80	1625	1625	1625	1225
Window	120	840	1520	840	1120
Floor slab	150	2420	3380	2420	2980

To continue with LCA, calculations based on acquired data were conducted. As a result, 18 (29.7 m^3) pieces of re-processed master panels (3x6 m) were produced and additional 6.23 m^3 incomplete panels with 3 m by length that could be further used for new master panel production.

To propose meaningful points of innovation that would stimulate the development of bioeconomy, theory-based analysis was used. Often this approach is used in social sciences, White (2009) described it for project evaluation and result improvements. Theory-based analysis for impact evaluation consists of six consecutive steps: (1) Mapping out the causal chain (programme theory) (2) Understanding the context (3) Anticipating heterogeneity (4) Rigorous evaluation of impact using a credible counterfactual (5) Rigorous factual analysis (6) Using mixed methods [161]. Methods used specifically for theory-based analysis to understand the most valuable conifer value chain impacts on bioeconomy are described further.

Delphi method

Despite the clear definition of raw material, it is still unknown how to stimulate the development of bioeconomy, as the intertwining factors impacting it have not clearly been identified. Nevertheless, the field has been developing in multiple sub-areas e.g. agriculture, and forestry. In addition, these sub-areas in many cases are conflicting amongst each other – food vs. fiber vs. energy *[162]*. In order to understand the context and map out the causal loops (chain), work by Muizniece et al. was used as a basis for 24 factor *[102]* evaluation and mapping using Delphi methodology. The Delphi method was used to gather expert opinions on the 24 factors relevant to the development of bioeconomy. The Delphi method is a structured process for collecting and distilling expert opinions on a specific topic or problem. In this study, the Delphi method involved two times on two expert groups – (1) academic, and (2) industry experts. Work with industry experts was specifically focused on mapping the causal chain of bioresource utilization (bioresource nexus). For the academic experts iterative rounds of anonymous questionnaires were sent out. Participants were asked to provide their opinions on interactions between multiple factors (e.g., Bioresources, Technology, Pollution, and the rest from Muizniece et al. work *[102]*) or questions related to bioeconomy in general. The expert panel for the Delphi method was selected based on their scientific work on the Bioeconomy field. The expert panel consisted of 13 experts from leading Latvia’s universities in Bioeconomy fields representing a range of perspectives – biotechnologies, industrial symbiosis, policy, energy etc. The surveys or questionnaires used in the Delphi method were developed based on a review of the relevant literature and input from the research team.

Thematic analysis was conducted of the Delphi expert questionnaires. The goal of thematic analysis was to identify patterns and organize the factors in coherent causal loops accordingly. Thematic analysis was conducted in an iterative manner, common patterns within the expert responses were elucidated, refined as new data were collected. The results of the Delphi method were then used to inform the selection of a relevant theoretical framework for theory-based analysis, and nexus building of factors impacting bioeconomy development.

The use of the Delphi method in this study has several strengths, including gaining Latvia specific insights and indicators based on statistics and literature. However, it is important to note that the Delphi method also has limitations, especially expert biases. To address these limitations, experts with diverse academic backgrounds were chosen.

The second expert group for the Delphi method was focused on industry experts. As it is less reliable that experts from industry would clearly understand the factors in question unanimously equally, questionnaire approach was replaced by interview method described further.

Interviews

To evaluate the causal chain around bioresources, as well as explore the possibility of other factors impacting the proposed indicators and links in the academic expert surveying, qualitative interviews with managers from involved enterprises were conducted. The interview format was semi-structured, as this type of interview lets the interviewer to ask open questions and gives the possibility to go deeper into various aspects of the revealed facts [163]. Semi-structured interviews have been already used in bioeconomy research [164], [165]. During the interviews, the overall attitude and motivation regarding bioresource, by-product and waste utilization was determined. Efficiency of by-product utilization was determined by collecting data from enterprises, including real consumption of raw materials as well as the produced bio-waste and by-products. Technical directors of three enterprises using the same bioresource as raw material were interviewed. Due to sensitive information interviewees were providing, interviews were not recorded, instead the interviewer produced comprehensive notes on the acquired information.

Algorithmic logic for Nexus building

Bioresource nexus was created by analysing the information acquired in the interviews and validated with literature analysis and by-product data from the enterprises in question. Qualitative and quantitative data were collected from interviews. The overall algorithm for building of bioresource nexus is shown in Figure 2.7. Following the algorithm, two interviews were conducted, then as the second interview elucidated new factors, a third interview was conducted. The created algorithm demands to continue interviews until there are no new factors. In this specific case study, three interviews were sufficient, and results published. Additional interviews afterwards have confirmed no new factors. Steps two and three represent the minimum interviews necessary to gain an overall idea of the factors impacting the specific subject. As during second interview some new factors were identified, third interview was conducted to see if more factors would be identified. If there are no new factors the algorithm continues. The research was divided in smaller modules for a structured approach. While picking enterprises for this research, various production companies using the same type of biomass as a raw material were considered. An important factor in choosing the enterprises was their willingness to participate.

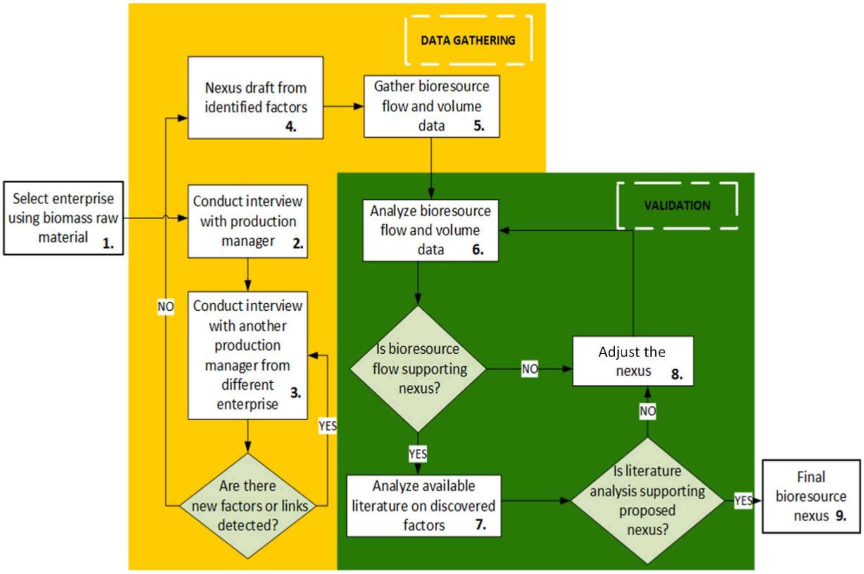


Fig.2.7. Algorithm for bioresource nexus building.

The methodology depicted in Figure 2 can be applied for evaluation and building of various nexus using a bottom-up approach. In this study the bottom-up approach allows to analyse factors for organic by-product flow back into bioeconomy through bioresource. Nexus provides information on factors impacting the system, but additional by-product data analysis provided information on effectiveness of this by-product – bioresource flow.

Bioresource utilization index

Bioeconomy development impacting factor causal chain was supplemented with more detailed bioresource utilization causal chain. In lines, with the theory-based analysis heterogeneity of impact must be expected. Meaning – all actions on the same objects in causal loops will not lead to equal results. In order to measure the impacts on bioeconomy for internally made decisions regarding bioresource flow in enterprise, bioresource utilization index was developed.

The calculations were made using biomass dry weight. If there were no available data on the actual dry weight of the by-product, estimations were made by using values found in literature.

The main categories analysed were production residues, damaged raw material, raw material that does not meet production standards, products that do not meet the market standards, other production leftovers, dissolved, and undissolved carbohydrates. As company managers disagreed to more detailed information disclosure, the raw material, product, or production technology could not be described in this work.

Bioresource flow in an enterprise was evaluated by comparison with waste management hierarchy [166] and bio-based value pyramid [108] shown in Figure 2.8. with the chosen coefficients from 0 representing no value and 1 representing the highest possible added-value to bio-based material. The bio-based value is assigned to the raw material or the by-product when it is used for the corresponding application in the bio-based pyramid.

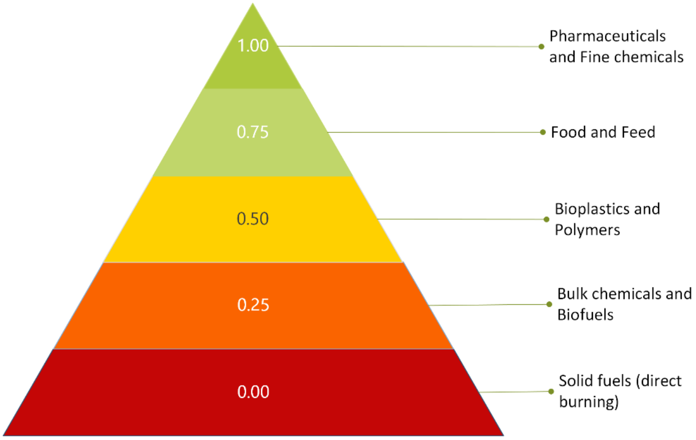


Fig.2.8. Bio-based value pyramid. Five bioresource utilization options by categories and assigned coefficients corresponding to each group of bioresources [108] BBV – bio-based value and the corresponding coefficient, 1 representing the greatest value and 0 representing no value from the point of bioeconomy.

Each level in the bio-based value pyramid (Fig.2.8.) was given a corresponding coefficient representing the value for bioresource utilization – coefficient of 1 was attributed to PFCs, coefficient of 0.75 to Food and Feed, 0.5 to Bioplastics and Polymers, 0.25 to Bulk chemicals and Biogas, but Energy, Heat and Fuels were assigned the value of 0. The bioresource utilization index provides insight into production efficiency regardless of the product type, hence no value is assigned to the product. The calculations were conducted with various generated by-product utilization options and attributing corresponding coefficients from the previously described bio-based value pyramid.

$$B_{u_{ind.}} = (P + BP_1 \times c1 + BP_2 \times c2 + BP_3 \times c3 + BP_4 \times c4 + BP_5 \times c5)/RM \quad (5)$$

$B_{u_{ind.}}$ – Bioresource utilization index;

P – product [kg of dry weight];

BP_n – by-product [kg of dry weight];

c_n – coefficient assigned to bio-based value pyramid;
RM – used raw material [kg of dry weight].

Carbon accounting in wood-based products

To produce fibreboard insulation panels, wood fibres of strong and uniform quality must be obtained. Although MDF and other fibreboard producers traditionally use roundwood as a raw feedstock, novel methods of cleaning and sorting waste wood or production residues from other woodworking industries have enabled alternative sources of wood materials on dedicated production lines [99]. A 2013 study about the chase characteristics of wood chips produced from logging residues concluded that wood chips produced from logging residues have a moisture content of 50 % and are suitable for use in small and medium size boilers [167]. It is assumed that the wood chips obtained from logging residue feedstock will be of sufficient quality to produce fibreboard panels.

The material balance of the new fibreboard insulation panel is shown in Table 2.6. Material density was assumed maximum for rigid board production from the BAT Reference Document for Wood-based Panels [99]. Material balance was chosen based on fibreboard and insulation board data from the Forest Product Conversion Factors document [168], assuming an increased bark and decreased wood content. The weight content of bark, binders and fillers, moisture, and wood in one cubic meter of the finished insulation panel were calculated based on the chosen material density and material balance.

For the new fibreboard insulation material manufacturing process, the standard dry manufacturing process was chosen from the BAT Reference Document for the Production of Wood-based Panels [99].

Table 2.6. Fibreboard insulation material balance

	Content, kg/m^3	Balance, %	Source
Density	220	100	[99]
Bark	6.6	3	[168]
Binders and fillers	11	5	
Moisture	13.2	6	
Wood	189.2	86	

It is assumed that the new plant would produce 300 000 m^3 of fibreboard insulation material annually, based on average plant capacities in the industry [99]. To calculate the specific amounts of heat and electric energy needed to produce one cubic meter of the material, existing insulation material manufacturing plant data was used. Assuming that an existing plant has an electrical capacity of 5 MW and a heat capacity of 10 MW [169] and operates for 8000 hours annually, the manufacturing plant would require 0.13 MWh of electricity and 0.26 MWh of thermal energy to produce one cubic meter of fibreboard insulation material. Energy consumption for the most energy-intensive manufacturing processes is shown in Table 2.7. The drying of the wood fibres consumes the most energy, mainly in the form of thermal energy, as the fibres need to be dried from a moisture content nearing 100 % to 5 % (moisture calculated as difference between original weight and oven dry weight divided by oven dry weight)[18]. The dryers also need to be ventilated, using mechanical ventilators that consume electricity. The second most energy-intensive process is refining the fibres, which requires powerful motors that consume the most electricity. Thermal energy is also needed for refining to supply hot steam for cooking and washing wood chips. The pressing of the fibreboard mat requires thermal energy in the form of steam and electricity for the press rollers; however, for the production of rigid board insulation, the energy consumption is minimised, as the temperature required is relatively low. Lastly, all other processes requiring electricity are grouped, such as chipping, sawing and profiling [99].

Table 2.7. Energy consumption for production calculated from [99], and [169]

Manufacturing process	Electricity, MWh/m^3	Thermal energy, MWh/m^3
Drying	0.03	0.16
Refining	0.08	0.08
Pressing	0.01	0.02
Chipping, sawing, profiling	0.01	-
Total	0.13	0.26

To calculate the possible amount of CO_2 stored in the material, eight different standards for biogenic carbon accounting in products were reviewed. Many of the reviewed standards were based on various standards for Life Cycle Analysis (LCA). Still, in this case, only standards relevant to forest-based building materials and biogenic carbon were used. The standards used can be grouped into those that deal only with building materials (ISO-21930, EN-15804, CEN/TR-16970, EN-16485) and those which cover all products (PAS-2050, ISO/TS-14067, PEF). The standards can also be distinguished by geographical coverage, as some are international standards (ISO-21930, PAS-2050, ISO/TS-14067), and others are specific to Europe (EN-15804, CEN/TR-16970, EN-16485, PEF) and have stronger links to government regulation [170], [171]. As there currently exists no scientific consensus on which standard and method are the most appropriate for use, an average value derived from all standards was proposed.

The initial calculation for CO_2 stored in the material calculated as follows:

$$msqCO_2 = m_{dry}(timber) \times C_f \times \frac{m_{CO_2}}{m_C}\,, \tag{6}$$

where

msq_{CO_2}	mass of CO_2 sequestered, $kgCO_2$;
$m_{dry}(timber)$	dry weight of timber in the finished product, kg;
C_f	percentage of carbon in dry matter (for timber = 0.5);
m_{CO_2}	molecular mass of CO_2 = 44 g/mol;
m_c	molecular mass of carbon = 12 g/mol.

By substituting the masses of carbon and CO_2, Eq. (6) becomes:

$$msqCO_2 = m_{dry}(timber) \times 0.5 \times \frac{44}{12}, \tag{7}$$

where $msqCO_2$ is the mass of CO_2 sequestered in the finished product and $m_{dry}(timber)$ is the dry weight of timber in the finished product.

Only the CO_2 sequestered from the wood and bark content for the new product is calculated. The carbon content for bark is assumed to be the same as wood (50 %).

To maximise the CO_2 storage potential of the new fibreboard insulation material, the energy production sources for the manufacturing process need to be reviewed and analysed, as energy production is the single most significant source of emissions and can potentially offset the avoided CO_2 stored in the product material. Indeed, producing heat and power from the most environmentally friendly renewable sources would be the best way to minimise emissions from manufacturing. However, this may not always be the most technologically and economically viable option. Thus, energy production for product manufacturing needs to be assessed from an environmental point of view while considering the technological and economic aspects. Three energy production scenarios were evaluated based on the proposed manufacturing plant capacity of 5 MW electrical capacity and 10 MW heat capacity [170], current trends in the sector and possible future technologies. Technological, economic and environmental data for the three proposed scenarios are shown in Table 2.8. The capacities of the energy production plants were chosen according to the required minimum heat capacity of the manufacturing plant of 10 MW, as all the process heat needs to be produced on-site to meet heat and steam requirements. The electrical power of the energy production plant can be lower than the electrical demand of the manufacturing plant, as electricity can also be supplied from the grid. The first proposed scenario is to produce heat and power with a biomass combined heat and power (CHP) plant, which would use wood chips as fuel. The chosen CHP technology is a wood chip boiler combined with a steam turbine. The second proposed scenario is a natural gas CHP plant with a gas turbine technology well suited for industrial processes. The third proposed scenario is a wood biomass combustion plant (CP) producing only thermal energy, using wood chips as fuel, combined with Solar Photo-voltaic (PV) panels for electricity production.

To evaluate environmental impacts, five different emission values were considered for each scenario: NO_X (nitrogen oxides), CO (carbon monoxide), VOC (volatile organic compounds), PM (particulate matter) and CO_2 (carbon dioxide).

Table 2.8. Technological, economic and environmental parameters of proposed energy production scenarios

Parameter	Wood biomass CHP	Natural gas CHP	Wood biomass CP + PV panels	Sources
Electrical capacity, MWe	5	7.5	4	[172] [173] [174]
Thermal capacity, MWth	12	10.7	12	[172], [173]
Electrical efficiency, %	25	29.2	-	[173], [175]
Thermal efficiency, %	60	41.4	85	[173], [175]
Total efficiency, %	85	70.6	85	[173], [175]
Capital costs, EUR/kW[a]	3310	1510	965[b]	[176]
O&M costs, $\%_{CAPEX}$	2	2.5	2[b]	[176]
Fuel cost, EUR/MWh	25	81.2	25	[177], [178]
NO_X emissions, g/MWh[c]	29	27	9.1	[173], [179]
CO emissions, g/MWh[c]	8	31.5	2.5	[173], [179]
VOC emissions, g/MWh[c]	0	27	0	[173], [179]
PM emissions, g/MWh[c]	44	0	13.6	[173], [179]
CO_2 emissions, kg/MWh[d]	0	202	0	[180]

[a] Based on the electrical capacity for CHP and thermal capacity for CP

[b] Does not include the cost of PV panels

[c] Applies to electricity produced for CHP and thermal energy for CP

[d] Applies to both electrical and thermal energy produced

The capital costs of the standalone biomass combustion plant are assumed to be 30 % lower than the costs of the same thermal capacity CHP plant. Still, they are recalculated according to the thermal capacity of the combustion plant. Similarly, emission levels for the standalone biomass combustion plant are assumed to be the same as for the biomass CHP plant. Still, they are recalculated for a total thermal efficiency of 85 % instead of 60 % and apply only to the thermal energy produced.

The capital costs and O&M costs for the Solar PV panels are chosen according to the peak capacity of Solar PV panel installation. A Solar PV panel installation with an electrical capacity of 4 MWe is assumed to have a peak capacity of 5.4 MWp. The capital costs for an installation of this size are 510 EUR/kWp, and O&M costs 6.5 EUR/kWp [174].

A multicriteria analysis using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was conducted. The criteria chosen for the analysis are shown in Table 2.9. The values of the criteria were calculated using data from Table 2.8. and applied to the manufacturing plant's selected electrical and thermal energy demand parameters, with the annual plant production capacity of 300 000 m^3 of fibreboard insulation material. The criteria values were calculated relative to one cubic meter of the finished product.

To perform the multicriteria analysis, the criteria weights need to be determined. The criteria weights were determined using the Analytical Hierarchy Process (AHP) method.

Table 2.9. Chosen criteria for the multicriteria analysis

Technological criteria	Economic criteria	Environmental criteria
Fuel energy content, GJ/m^3	Capital costs, EUR/m^3	NO_X emissions, g/m^3
	Fuel costs, EUR/m^3	CO emissions, g/m^3
	O&M costs, EUR/m^3	VOC emissions, g/m^3
	Bought/sold electricity, EUR/m^3	PM emissions, g/m^3
		CO_2 emissions, kg/m^3

With the obtained criteria weights, the results of the multicriteria analysis were calculated. The result is shown as a relative closeness coefficient to the ideal solution. The results can have a value ranging from 0 to 1, with the ideal solution being a value of 1. The closer the coefficient of a proposed alternative is to the maximum value of 1, the closer it is to the ideal solution.

System Dynamics Modelling

Important benefit of Bioeconomy is to be considered neutral or even negative carbon emissions. While considering the development of bioeconomy, this needs to be part of the evaluation. Therefore, when considering the Bioeconomy development in Forestry, the factors need to be evaluated over long period of time. System Dynamics modelling uses stocks and flows as a basis to describe the state and events of various systems. In this work system dynamics modeling was used to illustrate the carbon flow in wood-based value chain.

System dynamics uses integral calculus to determine the volume of stocks, in this work the main stock is determined as carbon (C). This does not show the direct impact on global warming as carbon has multiple forms e.g., CO, CO_2, CH_4 that each impact global warming differently. System dynamics approach demands the definition of dynamic hypothesis, in this case the dynamic hypothesis was defined as follows: Complete utilization of logging and production residues in conifer value chain can lead to delay of carbon release into atmosphere.

System Dynamics Model building

The dynamic hypothesis is a theory about what structure exists that runs the system. A dynamics hypothesis can be stated verbally, as a causal loop diagram, or as a stock and flow diagram.

In the case of this research, causal loop of carbon flow in nature was defined. Further the dynamic hypothesis was supplemented with Bern's model of carbon sequestration involving human activity (Fig.2.9.).

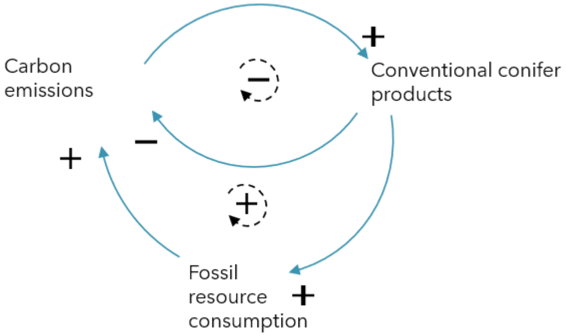


Fig.2.9. Causal loops of carbon in the conifer value chain.

Defined dynamic hypothesis is based on the common assumption that wood products are carbon neutral as they balance the carbon in atmosphere by sequestering it during the tree growth phase. Nevertheless, the hypothesis states that there is an unintended effect of fossil resource consumption increase during the whole wood value chain. When more products are produced, more fossil resources are consumed – fossil-based adhesives, additives, fuel, and fossil energy used during the production process.

The model was built according to the identified causal loops and expanded based on the market, and scientific literature analysis. Stocks represented carbon, thereby multiple calculations in the model are made to convert CO_2 emissions, product densities, biomass densities etc. to tonnes of carbon. Density of the wood was assumed to be 420 kg/m^3 based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use [181].

Only National market was considered, therefore imports and exports were not taken into account although including trade with external markets would show additional valuable dynamics.

Atmospheric carbon was defined as 0 at the starting point of the simulation in order to assess the impact of explored scenarios. Atmospheric carbon stock and corresponding carbon flows are depicted in Figure 2.10.

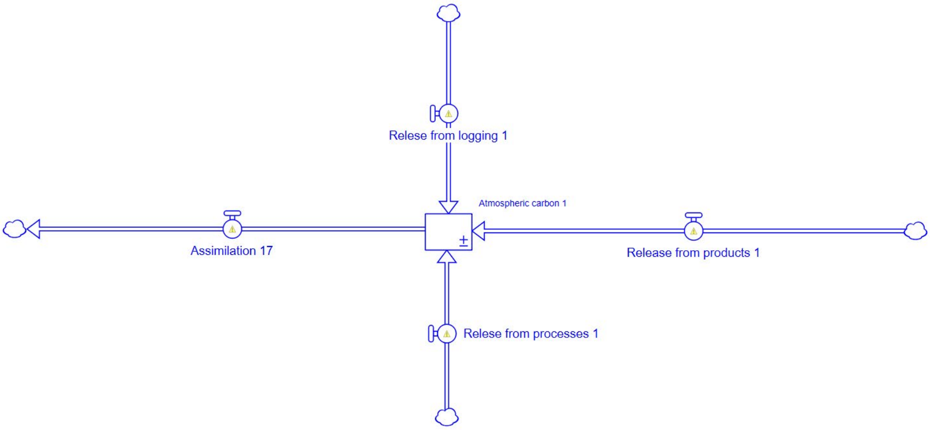


Fig.2.10. Atmospheric carbon stock and corresponding carbon flows: one outflow and three inflows.

Model was divided into three sectors – Forest, Product production, and Atmosphere. Forest sector was divided into tree stocks assigning a biomass stock for each age decade starting from 0 to 10 and ending with 151-160 years and lastly, trees older than 160 years. This was due to multiple reasons, firstly due to carbon assimilation dynamics *[182]* and secondly to match the available statistical data*[183]* to use biomass as means of model validation. For the purpose of illustrating the system dynamics approach for carbon accounting and planning, only data regarding Scots pine forests managed by National State forests were used.

Model was supplemented with data from multiple sources – Central Statistical Bureau of Latvia[184], United Nations Statistics Division of the Food and Agriculture Organization, and empirical data from peer reviewed literature [168], [182], [183], [185], [186].

3 RESULTS AND DISCUSSION

Chipboard from conifer logging residues and bio-based binders

Thorough literature review elucidated multiple promising bio-based adhesives, multiple of whom could be acquired from various biological production residues. Adhesives and their biological sources are compiled in Table 3.1.

Table 3.1. Biobased adhesives and their uses from scientific literature

Biological source	Compound	Polymer formation reaction	Primary raw material*	Uses	References
Penicillium oxalicum	Anhydrous citric acid	Polycondensation	Yes	Wood composites	[187], [188]
Shrimp and other crustaceans	Chitosan (Carbohydrate)	Polycondensation	No	Medicine, wood composites	[189],[190][46]
Vibrio parahaemolyticus	Exopolysaccharides	Polyaddition	No	Research, low technology readiness	[191]
Flowering plants	Latex (Isopropene)	Polymerization	Yes	Wood composites	[192]–[195]
Wood	Lignin (Aromatic polymer)	Polycondensation	No	Wood composites, foams	[196], [197]
Oleaginous plants	Polyols	Polyaddition	Yes	Wood composite, foam	[36],[198], [199]
			No	Wood composites	[198],[200]
Wheat	Protein	Polycondensation	Yes	Paper	[201],[202]
Fish	Protein	Polycondensation	No	Wood composites	[203]
Rapeseed cake	Protein, carbohydrates, and other residues after oil press	Polycondensation	No	Wood composites	[204]
Potatoes	Starch (Carbohydrate)	Polycondensation	Yes	Packaging	[205]–[207]
Tree bark	Tannin (Polyphenol)	Polycondensation	No	Wood composites	[208], [209]
Tree bark, cork	Suberin	Polycondensation	No	Wood composites	[197], [210], [211]
Potato tubers		Polycondensation	No	Research, low technology readiness	[187]
Flowering plants	Tannin (Polyphenol)	Polyaddition	Yes	Wood composites	[23],[38]
Wood	Hemicellulose (Carbohydrate)	Polycondensation	No	Wood composites	[197], [212]

Biological source	**Compound**	**Polymer formation reaction**	**Primary raw material***	**Uses**	**References**
	Vanillin (Phenol)	Polycondensation	No	High temperature environment	[213]
Vanilla planifola	Vanillin (Phenol)	Polycondensation	Yes	High temperature environment	[213],[214]
Bovine milk	Casein (protein)	Polymerization	Yes	Composites	[215]
Saccharomyces cerevisiae	Casein (protein)	Polymerization	Yes	Composites	[216]

* Biological source marked as “No” is classified as secondary or tertiary raw material.

Based on the literature review, most of the bio-based adhesives are plant-based, and more than half of the plant based raw materials are secondary bioresources (Fig.3.1.).

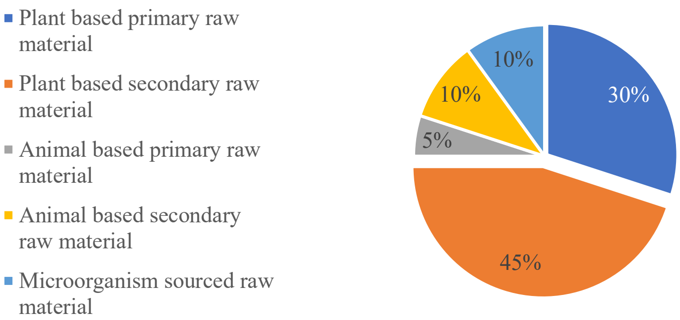


Fig.3.1. Biological source of bio-based adhesives

Chipboard from conifer logging residues

Analyzing the strength results of the boards whose wood particles were obtained using the two-horizontally rotating axis chipper, no strong relationship between the particle size and the obtained strength result was observed.

Pressure and temperature range was chosen from literature and initial tests narrowed down the temperature and pressure to working range producing valid boards after qualitative assessment. Boards produced by applying extreme variable values were burnt, crumbled or produced cavities. Some examples are depicted in Figure 3.2.

Fig. 3.2. Boards produced under extreme independent variable values.

For the further tests 140°C and 160°C temperatures, 390, 590, 600, and 660 bar pressure were chosen, additionally, the impact of particle size was evaluated using multiple range particle size up to 10.0 mm separated as described in methodology section.

ANOVA results showed that there were no significant impacts of temperature range to material durability, but particle size and the way particles were acquired showed significant impact on results.

Initial durability results for three particle size boards are depicted in Figure 3.3. The highest strength was obtained for plates with a particle size of <2.8 mm, and the highest inconsistency was detected under high pressure board preparation for medium particle size boards. Boards prepared from the 8.0-10.0 size fraction was generally less durable than the rest, but as seen from the statistical analysis the difference between MoR of 2.8-8.0 and 8.0-10.0 particle size boards in 660 bar pressure was not significant (P=0.27).

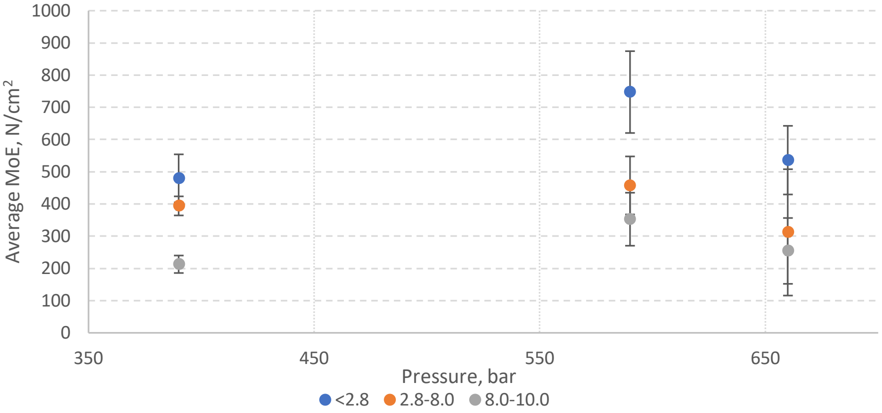


Fig.3.3. Modulus of elasticity depending on pressure for and particle size : <2.8 mm particle size boards; 2.8-8.0 mm particle size boards; 10.0 mm particle size boards. MoE – Modulus of Elasticity

T-test showed that there was no significant impact of the chosen pressure extremes (390 bar and 660 bar) to board durability (p=0.43) for the <2.8 mm particle boards, the boards produced by applying 590 bar pressure showed significantly higher durability compared to 390 bar (P=0.002) and 660 bar (P=0.01) pressures.

For the further tests 600 bar setting was chosen. According to biomass tests conducted in external laboratory, some supplied biomass had a high sand content in the ash (ashing at 550 °C) showing up to 26% and around 2% sand content in the raw biomass. Therefore, further tests were done by using the hammer mill approach by milling the previously chipped and sifted >1mm fractions. Larger particles were combined to prepare boards in the range of 2.8 mm to 10 mm particle size as initial tests did not show significant difference between these two fractions in the chosen pressure range. Boards were prepared using 140 °C and 160 °C temperature regimes to assess temperature and particle size impacts on board mechanical properties. Initial tests for temperatures were done prior to this study, elucidating the 140 °C and 160 °C temperature range as the most suitable for further testing, as lower range temperatures produced boards that were not truly bonded and higher temperatures produced burnt boards. Results from 140 °C and 160 °C temperature tests are depicted in Figure 3.4.

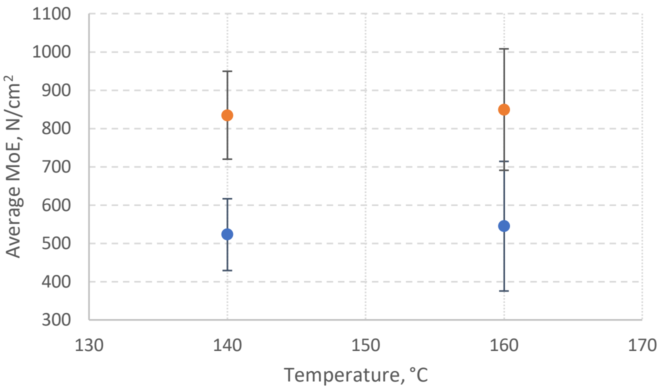


Fig.3.4. Modulus of elasticity of <2.8 mm particle size boards (blue), and for 2.8-10.0 particle size boards (orange) depending on hot press temperature

The results from combining 2.8-8.0 and 8.0-10.0 fractions showed a great increase in board durability, showing better results than prior. Nevertheless, smaller fraction boards showed decrease in durability, this might be explained by bark removal from the biomass. By separating sand from the biomass, other smaller particles got removed from the raw material – including finer bark and needle particles. To explain such change, temperatures were further tested by combining the hammer milled biomass with chipped and sieved particles. Results depicted in Figure 3.5. show that although the larger particle size boards show roughly the same results as the standard deviations overlie in the same areas on the graph, smaller particle size boards show increased results, with one outlier even reaching the minimum MoR threshold determined by European standard for wood chip materials EN 312-2:1997. Additionally, the calculated standard deviations are quite large, this might be caused due to particle separation methodology used in this work.

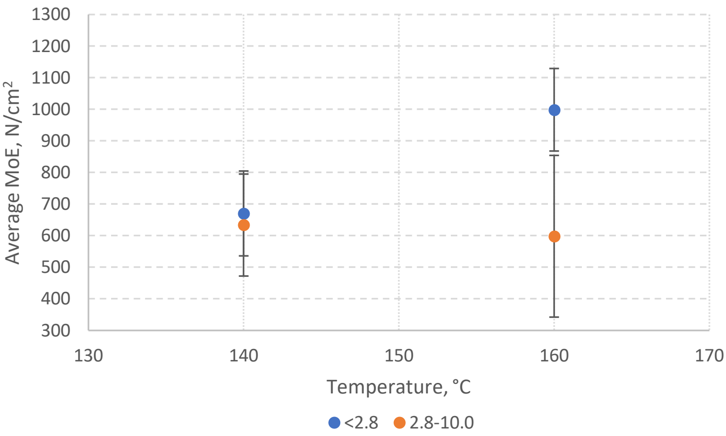


Figure 3.5. Modulus of elasticity of <2.8 mm particle size boards (blue), and for 2.8-10.0 particle size boards (orange) depending on hot press temperature for combined particles.

Smaller particles pressed together makes the final product more dense loosing the desirability of such woodchip boards. Nevertheless, there was no corelation of overall density increase and increased durability when boards from all particle sizes were compared. Density and mechanical durability of prepared samples are depicted in Table 3.2.

Table 3.2. Overview of the durability and density of produced chipboard from logging residues samples.

Pressure, bar	Temperature, °C	Particle size, mm	MoE, N/cm^2	Density, kg/m^3
HC[1]				
390	140	<2.8	480 ±74	775 0
590	140	<2.8	747 ±127	872 ±52
660	140	<2.8	536 ±107	894 ±51
390	140	2.8-8.0	394 ±30	759 ±34
590	140	2.8-8.0	458 ±90	882 ±46
660	140	2.8-8.0	312 ±196	774 ±71
390	140	8.0-10.0	213 ±27	660 ±38
590	140	8.0-10.0	353 ±82	796 ±28
660	140	8.0-10.0	254 ±102	784 ±87
HM[2]				
600	140	<2.8	523 ±94	824 ±53
600	140	2.8-10.0	835 ±115	913 ±14
600	160	<2.8	545 ±169	885 ±40
600	160	2.8-10.0	849 ±159	913 ±58
Sifted combined				
600	140	<2.8	670 ±134	795 ±81
600	140	2.8-10.0	634 ±161	759 ±62
600	160	<2.8	999 ±131	892 ±26
600	160	2.8-10.0	598 ±256	843 ±58

Particle size achieved by HC-horizontal 2-axis chipping and sifting, HM – Hammermilling with screen on particle outlet.

While various research groups have explored the utilization of logging residues and pine bark in chipboard production, the prospect of entirely eliminating fossil-based adhesives has remained a focus of investigation [9], [12]. With today's climate objectives it is crucial to completely rethink construction and housing approaches by completely excluding fossil carbon from the market [1]. Therefore scientific community and industry need to find working alternatives. This research provided insights on logging residue usefulness for chipboard production and provides a few valuable takeaways confirming previous work on logging residue potential application in chipboard production even without fossil-based adhesives. Although laboratory research has been done using particle size separation using sieves, it might be useful to consider gravimetric separation by cyclones as this would result in more even particle dimensions [18] and therefore lead to more consistent results. It was shown that the smallest conifer logging residue particle size might have a positive impact on 100% bio-based chipboard durability and methods for mineral separation from the bark material could be explored, perhaps by using flotation. There already is research on creating adhesives from bark extractables along other bio-based adhesives [11], and this research confirms the potential of chipboard transition away from fossil resources and towards completely bio-based materials.
Bio-based carbohydrate adhesive was used in this research as previous tests without any adhesive, materials showed low durability and other unwanted effects like bulging and burning of the material. Chosen adhesive showed promising results, but search for more efficient adhesive is still open. Previously done literature review on adhesives elucidates multiple bio-based options, even potential adhesives from other industry residues. Successful research in this direction could potentially result in chipboards from mostly residue based raw materials – biomass and adhesive.

Improved circularity in cross laminated timber production

Evaluation of cross laminated timber cutting reprocessing

The proposed case scenario where cuttings from CLT are re-processed was modelled in *SimaPro* according to the defined FU and the results are presented first in a comparative way with the business-as-usual scenario, and then it is disaggregated by unit process. The impact assessment is presented at midpoint level (kg of substance equivalent) as recommended by the EDP method and ISO standards in Table 4. Results in business-as-usual scenario correspond to the energy recovery phase for 0.128 m^3 of CLT; on the other hand, the results in the proposed scenario correspond to the sum of the three considerations aforementioned: impact from the re-process activity, avoided impact from putting in the market new CLT modules, and the impact related to the energy recovery of remaining cuttings not re-processed.

Table 3.3. Characterization results comparison between Business as usual and Proposed scenario using panel cutting reprocessing.

Impact category	Unit	Business as usual	Proposed scenario
Acidification Potential	kg SO_2 eq	–0.023	–0.059
Eutrophication Potential	kg PO_4 eq	–0.005	–0.011
Global Warming Potential	kg CO_2 eq	–4.155	–0.524
Formation potential of tropospheric photochemical oxidants	kg C_2H_4 eqv	–0.002	–0.008
Abiotic depletion potential for non-fossil resources	kg Sb eq	–1.43E–05	–2.35E–05
Abiotic depletion potential for fossil resources	MJ	–0.005	–122.457
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	5.13E–07	–9v.20E–07

In the business-as-usual scenario, most of the impact categories show a benefit to the environment since it is understood, that the electricity and thermal energy generated from the incineration of CLT material would replace conventional electricity production in Latvia, according to the market for electricity mix in the *Ecoinvent 3.6* database. In the proposed scenario, even higher benefits to the environment are obtained, due to the energy recovery for 30.28 % of the leftover cuttings and the delivered avoided impact from new CLT modules.

Percentual changes of moving from a business-as-usual scenario towards the proposed one are easily seen in Fig. 3.3.

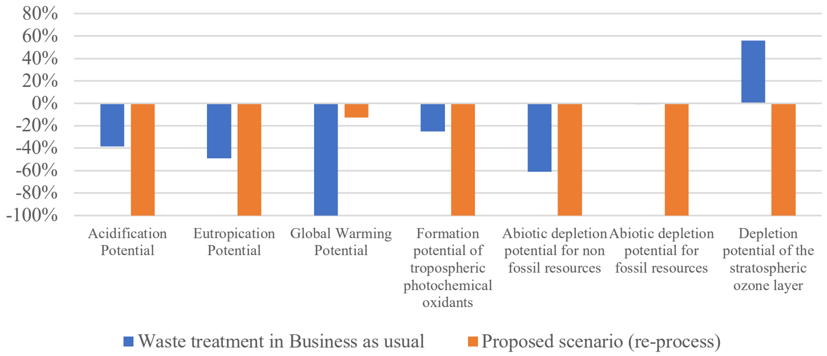


Fig. 3.3. Characterization results showing comparison between Business as usual (blue) and Proposed scenario (orange). Negative values indicate reduced impact of the specific category.

In general, the nowadays EoL stage or waste treatment of CLT delivers benefits to the environment in almost all the impact categories assessed within the EDP method, but for the ozone layer depletion one. Nevertheless, the proposed new set of activities that give birth to new CLT panels reducing the amount of waste to be incinerated, aids to increase the already delivered benefits in all areas except for the global warming potential, this as result of the lower electricity production that would have eventually substitute the production from conventional sources in the specific Latvian market. It is worth to notice that the GWP benefits under the business-as-usual scenario is due to the fact of substituting energy production from the local market by the energy recovery from a one hundred percent renewable source such as wood. In all other areas benefits from the new approach surpasses the original ones.

Regarding the proposed re-processing of CLT cuttings scenario, the adverse effects to the environment are coming from the re-process activity, since the waste scenario is the same as for the business as usual, thus resulting in an environmental benefit, and the new produced CLT modules are considered as an avoided product. Under the evaluation of the proposed scenario, it was found the main driver in most of the evaluated impact categories is the use of polyurethane adhesive (Fig. 3.4.), except in the ozone layer depletion one.

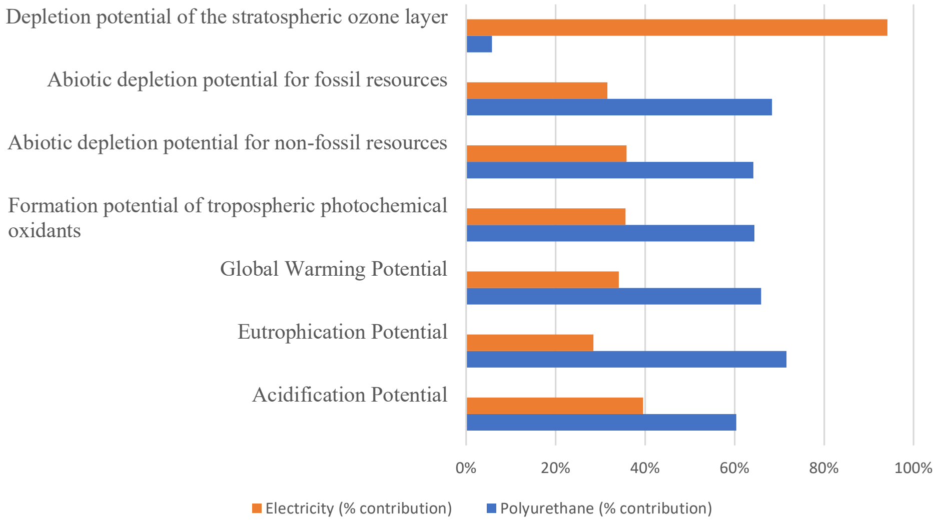


Fig. 3.4. Environmental impact contribution per re-processing inputs show comparative environmental impacts of electricity and polyurethane on CLT production

Multi criteria decision making

Based on the conducted AHP weights for criteria of wood residue, recycling was calculated and used in TOPSIS analysis to elucidate the best alternative from companies working with CLT perspective.

According to expert evaluation, production costs are the most important when considering potential applications of wood residue. Production costs are followed by product market price, and wood residue to new product ratio. Results of AHP are shown in Fig. 3.5.

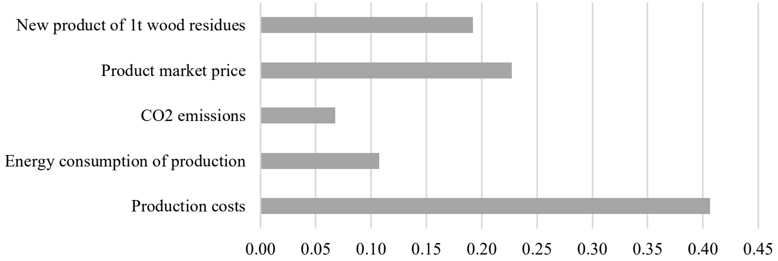


Fig. 3.5. Weights show the significance of each of the five criteria by allocating each criterion a corresponding part of the total criteria weight sum.

Calculated weights were used further used for TOPSIS analysis. Data matrix of alternatives and their corresponding criteria are depicted in Table 3.4. along with calculated weights.

Table 3.4. Data Matrix with Considered Alternatives for Cross Laminated Timber Cutting Use Cases (A_n) and Corresponding Data of Weighed Criteria (x_n)

	(x_1) Production costs	(x_2) Energy consumption	(x_3) CO_2 emissions	(x_4) Product market price	(x_5) New product to wood waste ratio	
Criteria weights (ω)[1]	0.41	0.11	0.07	0.23	0.19	
Units	€/tonne	MWh/t	Kg CO_2/t	€/tonne	t	Reference
(A_1) Medium density fibreboard	250	1.6	1088	586	0.9	[148], [217]
(A_2) Mycelium insulation material	68	0.28	47	140	0.9	[148] [218]
(A_3) Solid fuel	113	0.02	38	204	1	[148]
(A_4) Particle boards	147	0.77	150	350	0.9	[148]

Note [1] Weights calculated with analytical hierarchy process approach.

TOPSIS approach elucidated the mycelium thermal insulation material as the most promising wood residue utilization option and MDF production as the least preferable option (Fig. 3.6.). Mycelium thermal insulation gained closeness coefficient (CC) of 0.65 to the ideal solution. According to expert evaluation and literature data, solid fuels gained CC of 0.59 showing that solid fuel production is still closer to ideal than non-ideal solution. Nevertheless, when raw material cascades are considered, burning the by-product is considered as the least preferable option, especially if the by-product could still be recycled for other purposes [219].

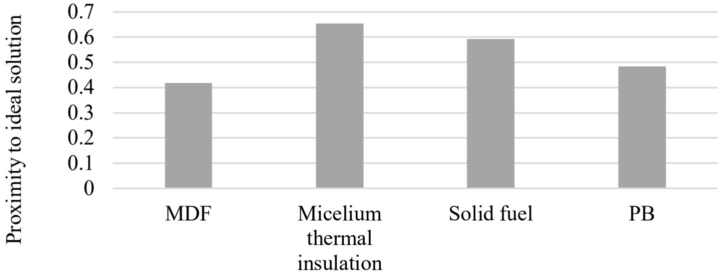


Fig. 3.6. Multi-criteria analysis results, showing options considered and their proximity to the most preferable alternative represented on y-axis. (PB – chipboardoard; MDF – medium density fiberboard).

Sensitivity analysis of criteria weight showed the similarity of two preferable options – mycelium thermal insulation and solid fuel. By changing the weight of product market price according to unity variation β_{pm}, mycelium thermal insulation material and solid fuel alternatives experienced the same trend. When the weight of product market price doubles, these two alternatives lose their positive proximity to the ideal solution. MDF experience mirrored trend to mycelium thermal insulation and solid fuel alternatives, but PB is the least impacted by the changes in product market price (Fig.3.7.)

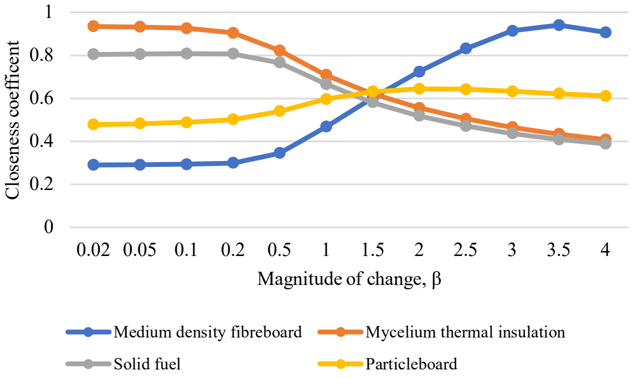


Fig. 3.7. TOPSIS results sensitivity analysis. Sensitivity analysis is conducted by changing weight of product market price and re-calculating the rest of assigned weights. X-axis depicts magnitude (β) of change of product market weight and y-axis depict the closeness coefficient of all alternatives to the ideal solution.

Additional sensitivity analysis on product market price change was conducted to evaluate how the most ideal alternative – mycelium thermal insulation material's closeness coefficient to the ideal solution and how the closeness coefficient of other alternatives would be impacted. A step of 10 % change was chosen and results are depicted in Fig. 3.8. Despite of the product market price reduction of 50 %, mycelium thermal insulation was still the most preferable alternative, gaining greater distance from the second best alternative – solid fuel.

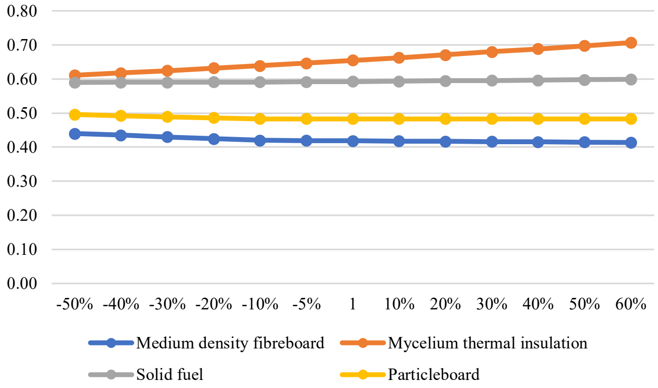


Fig. 3.8. Sensitivity analysis on mycelium thermal insulation's market price change on the closeness coefficient to the ideal solution change.

As production costs were the only criterion where mycelium thermal insulation material took the lead from the start, sensitivity analysis was conducted to find out how big should be the changes in mycelium thermal insulation production for the material to lose its most preferred rank. Sensitivity analysis on mycelium thermal insulation production cost (Fig. 3.9.) show that 60 % increase on production costs would make mycelium alternative less desirable as solid fuel production.

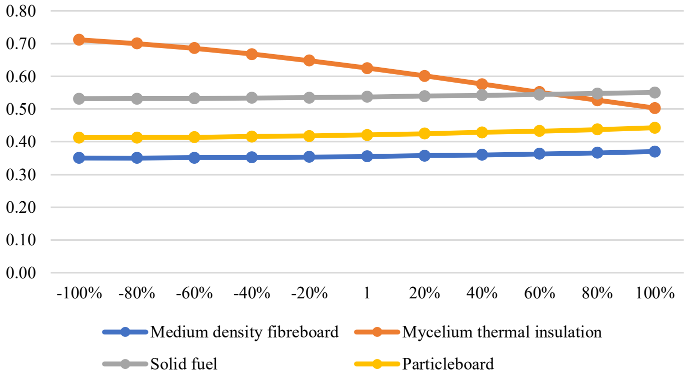


Fig. 3.9. Sensitivity analysis on mycelium thermal insulation's production cost changes.

Evaluation of natural thermal packaging market fit

Innovations must be driven by market demand to gain traction. In the context of inventing entirely new materials, a comprehensive evaluation is necessary. Employing pairwise comparisons of all 12 criteria provides an overall perspective on the relative importance of each criterion in relation to the others. The results of weighing are shown in Figure 3.10.

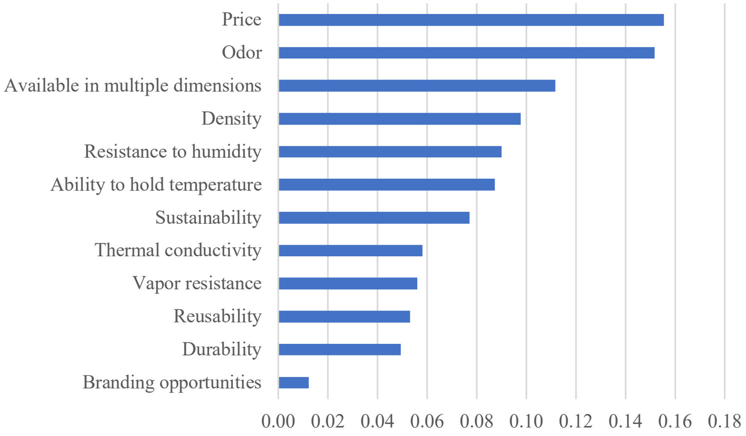


Fig. 3.10. Weights show the significance of each of the 12 criteria by allocating each criterion a corresponding part of the total criteria weight sum. Weight sum always equal to 1.

Interestingly, enterprises with specialty in fine chemicals and companies using thermal packaging for internal use, like sample transfer among branches, expressed the importance of reusable packaging. In these cases, companies are preferring thermal packaging that can withstand at least 10 application times. On the contrary – pharmaceutical companies claimed that packaging was used only one time, as its visual appearance after one use is no longer suitable for medication.

To compare the thermal packaging options available on the market, only five criteria were chosen for further analysis. Criteria like neutral smell was excluded as none of the materials available on the market reported has some scent and this would be only an on-off criteria. Availability of dimensions was not analysed as experts from different companies were interested in various sizes, making this criterion specific to each case.

Water resistance was considered as being an important criterion, but it covers a lot of aspects: (1) water absorption; (2) water release after absorption; (3) weather material stays intact after being exposed to water. The third aspect is very important, at the same time it should be considered for each specific case. For example, corn-starch foam could be the most preferred option for shipping electronics, as it can absorb mechanical shock and protect the goods, but as it dissolves in water it cannot be used in shipments with higher humidity, e.g., iced products, as humidity would destroy the packaging. At the same time water resistance is not important in the case of electronics as usually the cargo is protected from it and in case it is compromised by water the shipment is recalled.

Additionally, criteria for durability were excluded along with vapor resistance, repeated use, and graphical identity. Vapor resistance was excluded as it is most important for shipments with dry ice and companies are avoiding this shipping option due to the hazardous nature of dry ice. Each company considered various re-use times as optimal – experts from testing laboratories and other companies who use the packaging only internally admitted that they reuse the packaging at least ten times and it can look quite scuffed but most important is its functionality. On the contrary, pharmaceutical companies used the packaging only one time as its visual appearance was compromised after the use. Graphical identity was the least important criterion and similarly as scent – it is an on-off criterion, so it was left out of further analysis. Criteria chosen for further analysis were weighed and results are depicted in Figure 3.11.

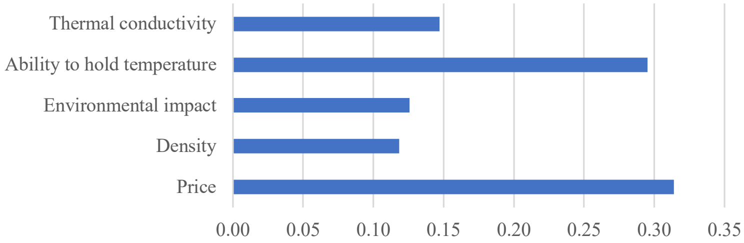


Fig. 3.11. Chosen quantitative criteria and their weights showing the importance of each criterion in the final decision making for thermal packaging materials.

A shown above, after narrowing down to five criteria, price, and ability to hold temperature took a considerable lead as being the two most important criteria, they together accounted for more than a half of the impact on the final decision.

Most preferable material

To evaluate the most preferable "green" thermal packaging available on the market, four products were compared to polystyrene packaging. Using previously determined weights, following thermal insulation materials were compared: non-woven feathers, non-woven wool, starch foam, mycelium, and polystyrene (Fig.3.12.).

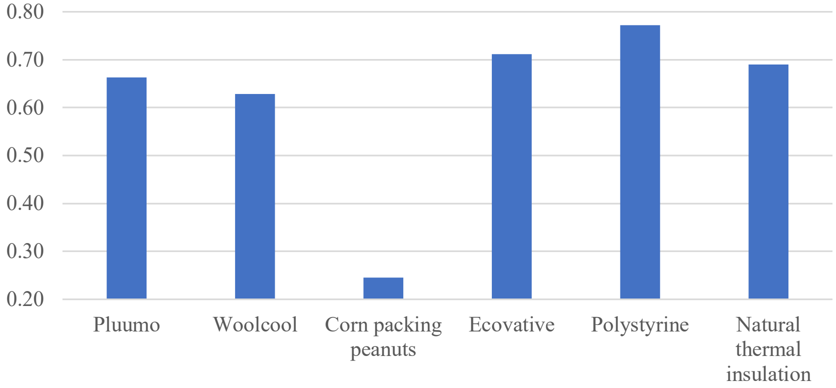


Fig. 3.12. Technique for Order of Preference by Similarity to Ideal Solution ranking of thermal packaging materials. Y axis represents the proximity to ideal solution 1.

Among thermal packaging options the closest proximity to ideal solution (represented by 1 on Y axis in Figure 3) by applying TOPSIS method was assigned to non-woven wool followed by feathers and polystyrene, the lowest rank was assigned to starch foam and mycelium was second-to-last in the ranking.

CO_2 storage in wood-based panels

The amount of stored biogenic CO_2 in the new fibreboard insulation material for the eight different accounting standards is shown in Table 3.5. The stored amount has been calculated for one cubic meter of the new fibreboard insulation material.

Table 3.5. Stored biogenic CO_2 in rigid board insulation material depending on accounting standard.

Technical standard	Stored CO2, kg/m3	Source
EN-15804 (2012)	359	[18]
ISO/DIS-21930 (2015)	251	[29]
EN-15804 (2012) +A1:2013	359	[18]
CEN/TR-16970 (2016)	359	[18]
EN-16485 (2014)	359	[18]
ISO/TS-14067 (2013)	90	[30]
PEF v2.2 (2016)	90	[30]
PAS-2050 (2011)	291	[31]

For standards EN-15804 (2012), EN-15804 (2012) +A1:2013, CEN/TR-16970 (2016) and EN-16485 (2014) the calculated amount of stored CO_2 is the same, as they are all based on the same standard of EN-15804 (2012) and assume that the amount is calculated with the formula shown in Eq. (7), with no further elaboration. ISO/TS-14067 (2013) and PEF v2.2

(2016) standards are based on the previous ISO-14040/44 standard for LCA, and do not differ in calculating the stored CO_2.

Standards based on the EN-15804 standard offer the highest amount of CO_2 stored in one cubic meter of the product – 359 $kgCO_2/m^3$, while the lowest amount of CO_2 stored can be attributed to standards based on the previous ISO-14040/44 LCA standard – 90 $kgCO_2/m^3$. Considering all standards, an average value of 270 $kgCO_2/m^3$ stored can be assumed as the result if no single carbon accounting method is chosen.

The calculated criteria values and weights for the multicriteria analysis of three different energy production scenarios are shown in Table 3.6.

Table 3.6. Criteria values and weights

	Wood biomass CHP	Natural Gas CHP	Wood biomass CP + PV panels	Criteria weight
Fuel energy content, GJ/m^3	1.56	2.26	1.10	0.079
Capital costs, EUR/m^3	12.68	38.01	8.45	0.210
Fuel costs, EUR/m^3	55.17	37.75	47.80	0.288
O&M costs, EUR/m^3	1.10	0.94	0.89	0.152
Bought/sold electricity, EUR/m^3	3.84	-9.45	19.77	0.110
NO_X emissions, g/m^3	3.14	4.95	2.36	0.028
CO emissions, g/m^3	0.86	5.78	0.64	0.016
VOC emissions, g/m^3	0	4.95	0	0.020
PM emissions, g/m^3	4.7	0	3.5	0.040
CO_2 emissions, kg/m^3	0	90	0	0.057

The results of the multicriteria analysis of three different energy production scenarios are shown in Fig.3.13.

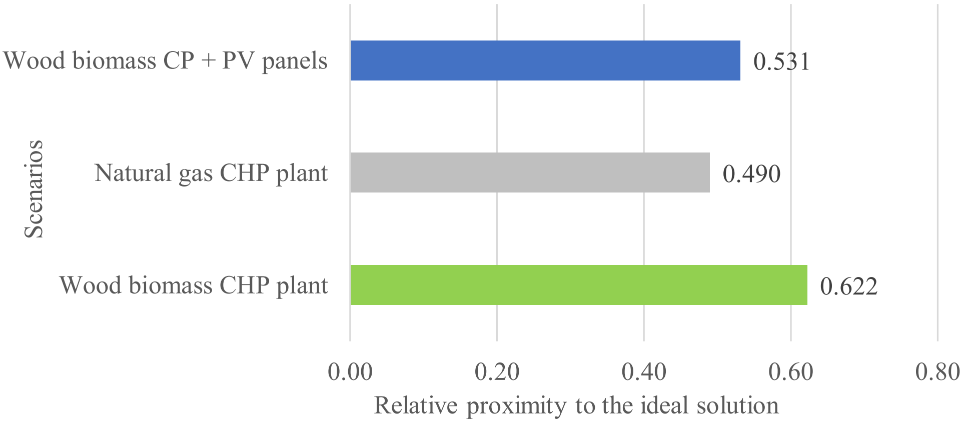


Fig. 3.13. Multicriteria analysis results evaluating energy production scenarios for rigid board production process

The results of the multicriteria analysis show that the best scenario for energy production for the manufacturing plant is the wood biomass CHP plant (0.622). In second place are the wood biomass combustion plant and Solar PV panel scenario (0.531), barely beating out the natural gas CHP plant scenario (0.490). While currently, the multicriteria analysis shows that the fossil resource use scenario of natural gas is relatively close in valuation compared to the renewable resource use scenarios of wood biomass, it is evident that the evaluation of the natural gas CHP plant scenario could decrease in the future, as the world moves to use more renewable resources. Nevertheless, the natural gas CHP plant scenario still needs to be reviewed and considered, so it can be clearly shown that there are better renewable resource alternatives, which are the wood biomass CHP and combustion plants. Although the main focus of this study was to compare carbon accounting methods, this additional step illustrates the importance of energy source when carbon storage is considered. In case efficient logging residue sorting technology is developed, the bark and other non-fibre residues could serve as an energy source.

Carbon in Forest economy

Carbon dynamics in Forest economy was estimated using system dynamics modelling. Model's Forest sector was validated using data from National Forest bioresource monitoring. Forest biomass validation depicted in figure 3.14.

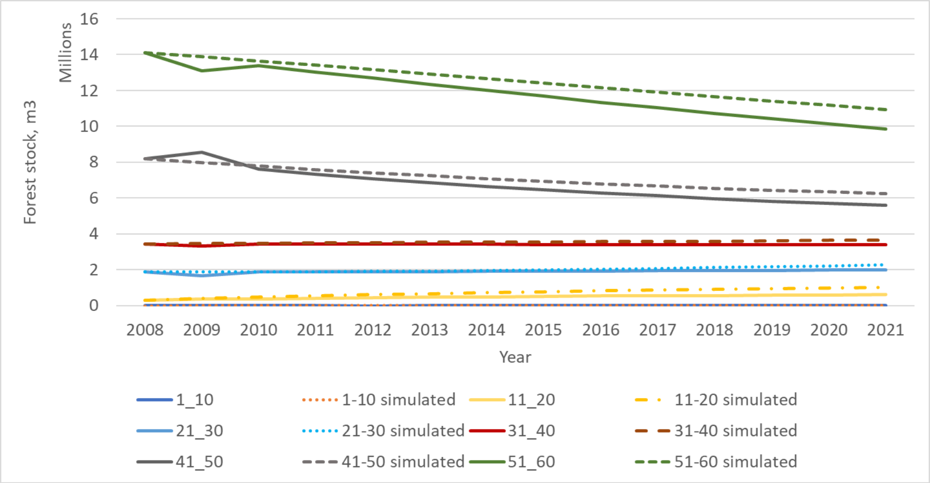


Figure 3.14. Model validation using 1- to 60- year-old Scots pine forest stands in Latvia State Forests owned lands.

Forest biomass data was available in the time frame from 2008 to 2021, therefore, to assess the carbon flow in the future, model was run up to 2160. As forest management lies out of this research scope, relative harvesting values were used – static rates in % for each forest age group. Although this is not the most beneficial way to harvest timber, it provided some stability. Statistics data showed that some age groups had a decreasing trend and using a stable harvest rate allowed for them to recover. Scots pine biomass forecast in territories managed by Latvian State Forests are shown in Figure 3.15.

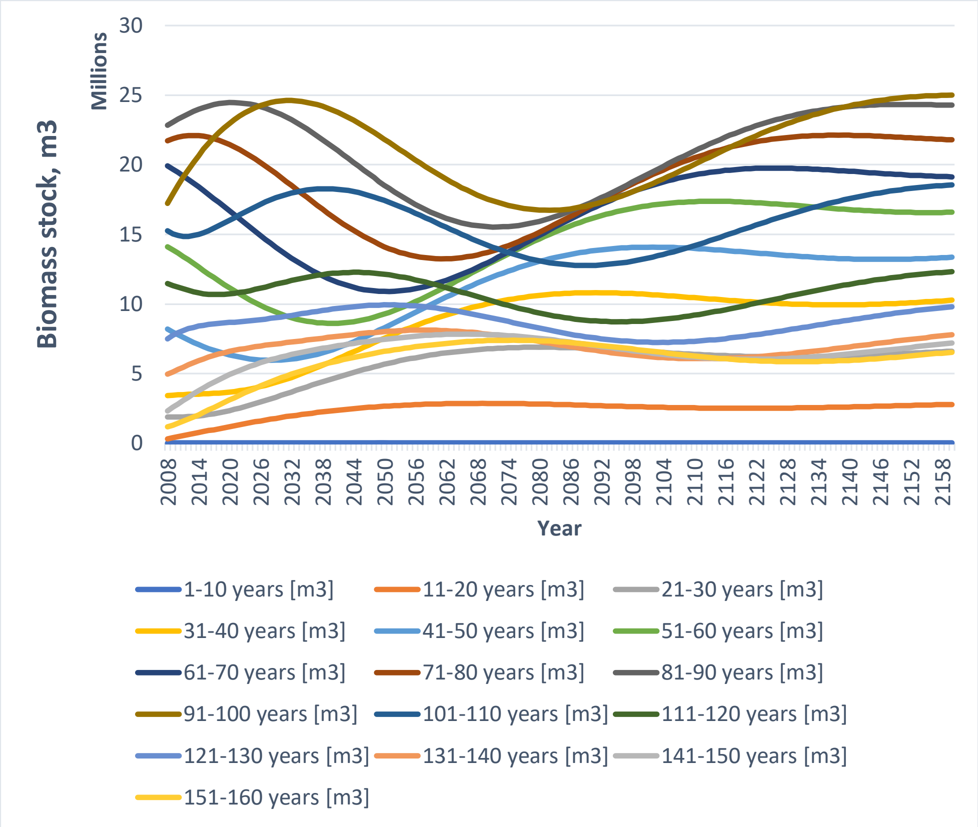


Fig. 3.15. Model of Scots pine biomass stock in Latvia State Forests

Chosen scenarios for product sector include CLT, and thermal insulation material for packaging and building insulation. Results depict (Fig.3.16.) carbon stock in Atmosphere over 152-year period.

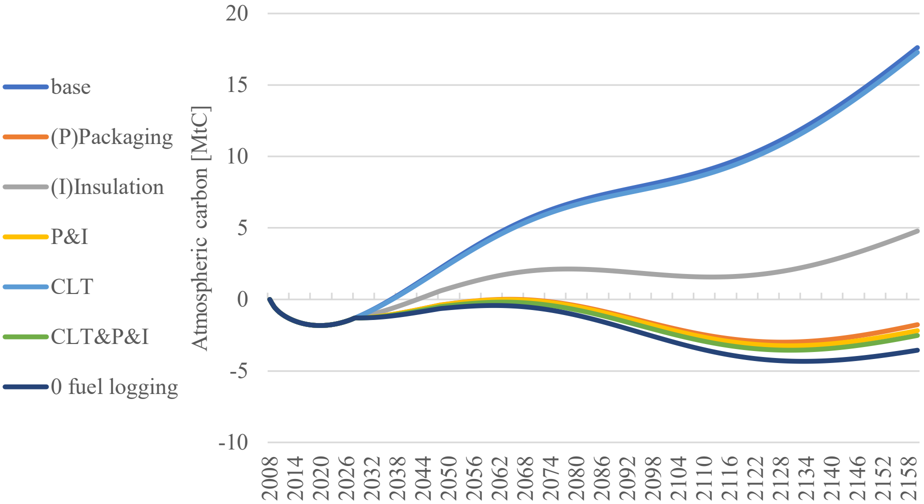


Fig.3.16. Carbon stock in atmosphere depending on chosen scenarios: base – base scenario, (P)Packaging – partial logging residue utilization for thermal packaging, (I)Insulation - partial logging residue utilization for building thermal insulation, P&I - partial logging residue utilization for thermal packaging and building thermal insulation, CLT – CLT cutting reprocessing in new panels, CLT&P&I – combined CLT, P, and I scenarios, 0 fuel logging – no fuel is accounted for logging.

Bioeconomy impacting factors and indicators

Top-down approach

After expert evaluations and application of the Delphi method, seven primary bioeconomy-affecting factors and their linkages were identified (Fig. 3.17.). The linkages discussed were based on scientific literature and are described as direct or indirect based on how they affect narrowed down factors.

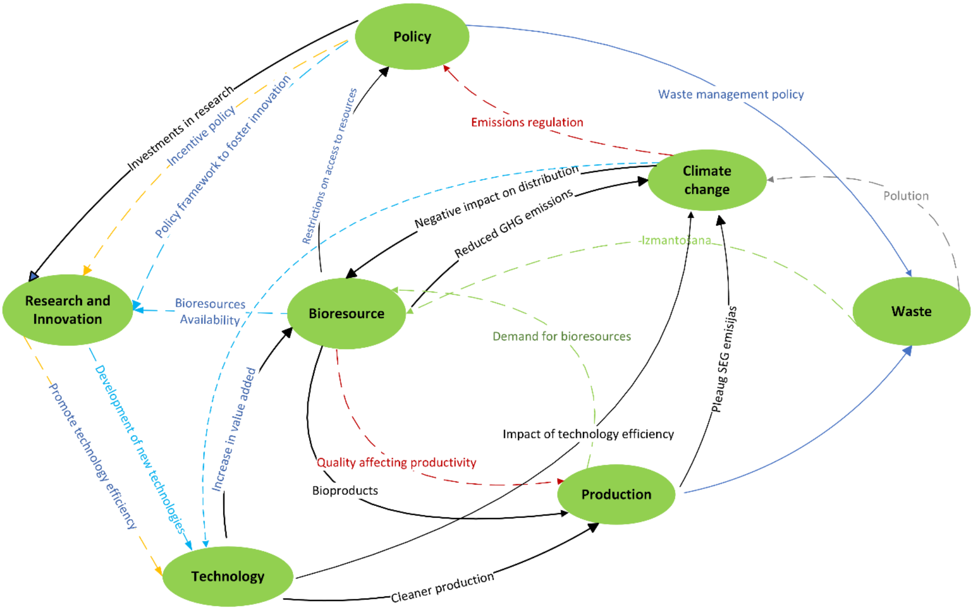


Fig.3.17. Graphical representation of seven bioeconomy influencing factors and their interlinkages related to Forest value chain [220]

The main nexus identified from graphical representation linkages (Fig. 3.17.) are: (1) Policy – Research and Innovations - Technology; (2) Production – Waste – Climate change; (3) Production – Waste – Bioresources; (4) Policy – Production – Bioresources; (5) Technology – Production – Climate change; (6) Climate change – Policy – Production; (7) Policy-Technology - Production – Bioresources; (8) Climate change – Bioresources – Production. Factors like Consumption and Economic growth did not make it to the final cut of 7 factors from the top-down approach. As expected according to theory based analysis, when causal chains are detected, heterogeneity should be expected. It was predictable that analysis from one dimension will not show the full causal chain, therefore top-down approach was added and experts from industry chosen for another focus group on whom Delphi methodology was used to refine the causal chain. A few new factors were detected using the bottom-up approach. Factors like Behaviour was elucidated only when bottom-up approach was used. Previously the Financial resources factor was left out using the top-down approach but resurfaced as important when assessing enterprise level factors.

Bottom-up approach

It is important to notice that a large proportion of biomass defined as waste is in fact by-products according to the EU definition, but in some cases, production managers are referring to by-products as waste. The by-product group might be referred to as waste only due to lack of technology – by-products might spoil due to inappropriate storage or they can be hard to retrieve, like sugars from waste after blanching. Nevertheless, behaviour and knowledge strongly impact the by-product-to-waste flow. When enterprise's management does not want to deal with finding new applications or buyers of the by-products, the biomass is simply directed to waste stream. In addition, companies worry about disclaiming their practices publicly, this can slow down the progress and opportunities for innovation as there is no exchange of information amongst enterprises sticking to closed innovation.

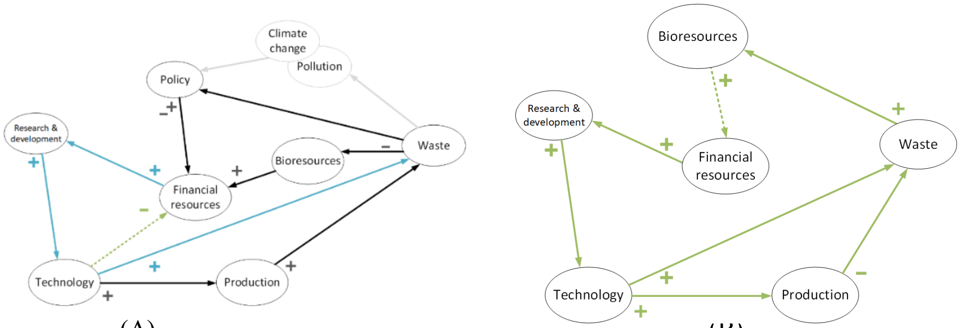
According to Demirbas (2011), waste reduction is the most preferred waste management option [166], according to elucidated nexus, waste can negatively impact company's financial resources and positively impact available bioresource amount. In case of blanched, peeled, and ready to use vegetable production, more efficient peeling technologies might be implemented to reduce the total amount of peels generated. In many cases by-products properly treated would not become waste, hence proper utilization of them would reduce the relative waste amount in proportion to the product.

After analysing links and respective products, conclusion was reached that indicators for these links might be economic or technologic in nature. An indicator can characterize the economic value of byproducts, energy efficiency of technology or efficiency of the production itself.

It is a frequent practice to motivate companies for research and development by providing incentives specifically for technologies reducing carbon emissions [221], alternatively fines are used as a tool to prevent companies from pollution.

In every enterprise there are already existing technologies affecting the overall production process. After interviews we concluded that the existing technologies are impacting the production efficiency, which is in turn affecting the amount of generated waste. As waste increases the risk of pollution [124] and climate change due to methane production in landfills [117], [222], these climate threats are leading to policy change from local authorities. Enforced policy might provide incentives for developing cleaner production, alternatively taxes might be enforced on the disposed waste [223]. As these policies cause pressure on an enterprise's financial resources, enterprises are forced to invest in R&D and find a technological solution that would result in positive gains – investment in the new technologies is smaller than potential taxes or fines related to the policies. Two new technologies might be considered – one that reduces waste during production and another that allows to extract bioresources from waste. Both approaches can lead to reduction of waste. In terms of waste management – reduction is the most preferred option [166], but using waste to produce PFCs can be considered as a good option as well. As mentioned above – diverging by-product flows to production of another product group from the top of the bio-based value pyramid can lead to value cascading, hence prolong resource circulation in bioeconomy.

In the discussed examples (Fig.3.18.) of path B, the loop finishes with a positive feedback on financial resources. In this specific case study, two instances when R&D lead to path A and three leading to path B were detected. One instance from path A led to path B in a previously described manner.



(A) (B)

Fig.3.18. Flows between various bioeconomy factors detected in the interviews. Path (A) on the left side is continuing and leading to path (B) on the right side of the illustration. Arrows illustrate the direction one factor is impacting the others. Dashed line represents a crucial place in enterprise for the change. Whether Technology impacts Financial resources in a positive or negative way and weather enough bioresources are retrieved from waste in order to be beneficial for Financial resources is shown with (+) – increases next factor (-) – decreases it.

The overall enterprise nexus was developed including additional factors. After analysing information acquired in the interviews, we concluded that knowledge and behaviour are crucial factors in this nexus. Although, companies are not always aware of this, knowledge and behaviour in a company can lead to implementation of a new, more environmentally friendly, technology [224]. It is clear how financial resources in a company play a large role in environmental innovations [221], but behaviour and company culture is often left out of the picture.

As can be viewed in Figure 3.19., local policies, production as well as knowledge and decision makers in a company are impacting the link between waste and bioresources. The gray area in Fig. 5 represents factors that are out of enterprise scope, although climate change and pollution might have an impact on enterprise functionality – there could be a pressure to relocate the production site due to lack of resources [225], [226]. These two factors have a long-term impact, hence policies imposing fiscal measures have a more noticeable and rapid impact. For bioeconomy evaluation a central core consisting of bioresources-production-waste leading back to bioresources was detected. In this case waste represents lost or disposed resources, by-products used efficiently lead back to bioresource and are used in the production of another product.

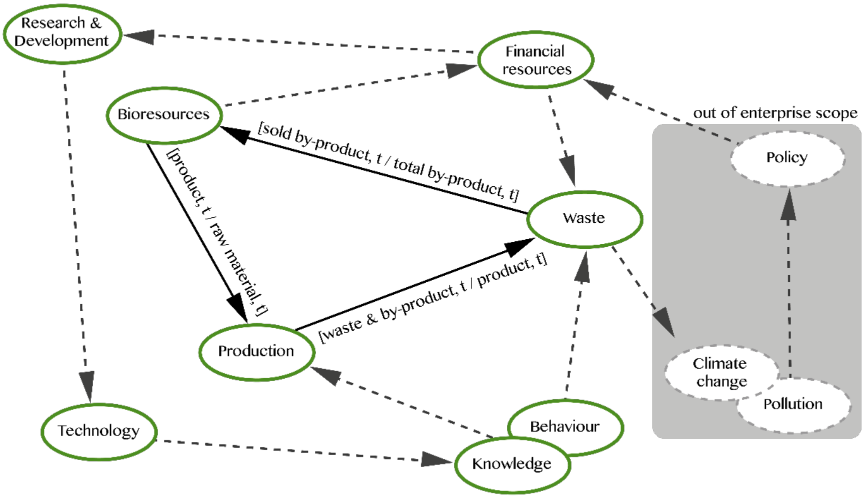


Fig.3.19. The proposed nexus of bioresources flow in an enterprise showing all the relevant factors. Green – primary factors, grey dashed – secondary factors; arrows represent direction of what factors impact each other. Central arrows represent the bioresource-production-waste-bioresource factor cluster used for the proposed bioresource utilization index calculations. Assessment of the impact from changes in Production-Waste-Bioresources. Although enterprises are responsible for the emissions they produce, it is National and Regional level scope that drives new policies (depicted as the grey area)

To evaluate company's added value to circular bioeconomy, a bioresource utilization index was calculated using the approach described in Methods section. For this analysis two enterprises from the three interviewed before were chosen. An overall bioresource utilization state in an enterprise is estimated – a bioresource utilization index closer to 1 shows bioresource utilization. The constructed scenarios with corresponding biomass utilization indexes are represented in Table 3.7.

Two studied cases and four alternative scenarios for each case. RM – raw material, BBV 1 to 0 represents bio-based value pyramid levels starting from the top. Percentages in the table represent the amounts of dry biomass sent to a specific product, waste, or by-product stream. Scenarios represent by-product use for pharmaceuticals and fine chemicals BBV1, food and feed BBV0.75, bioplastics and polymers BBV0.5, bulk chemicals and biogas BBV0.25, energy and heat BBV0. Waste is dry mass of wasted organic by-products and waste as rotten raw material. BU_{ind} – the calculated bioresource utilization index. Actual situations in respective two enterprises: II_{base} – the base scenario for the first enterprise, IX_{base} - the base scenario for the second enterprise.

Table 3.7. Alternative scenario representation by biomass allocation.

Scenario		RM	BBV1	BBV0.75	BBV0.5	BBV0.25	BBV0	Waste	Product
Enterprise No. 1	I	100%	0%	0%	0%	0%	0%	34%	66%
	II$_{case}$	100%	0%	0%	0%	34%	0%	0%	66%
	III	100%	0%	5%	0%	12%	0%	17%	66%
	IV	100%	0%	0%	0%	12%	7%	16%	66%
	V	100%	9%	6%	7%	12%	0%	0%	66%
Enterprise No. 2	VI	100%	0%	0%	0%	0%	8%	32%	59%
	VII	100%	0%	0%	0%	0%	0%	41%	59%
	VIII	100%	0%	0%	0%	37%	0%	3%	59%
	IX$_{case}$	100%	0%	5%	0%	32%	0%	3%	59%
	X	100%	9%	32%	0%	0%	0%	0%	59%

By-product flows by dry weight. RM – raw material; BBV – bio-based value represents the added value to biomass. Added value is represented with corresponding coefficient 1-high value, 0.75- Moderately high value, 0.5-medium value, 0.25-low value and 0-no value. Table represents the allocation of biomass by dry weight in constructed scenarios (I, III to VIII and X) and detected scenarios (II$_{case}$ and IX$_{case}$) for Enterprise No. 1 and Enterprise No. 2.

Each company is represented by five scenarios, I to V and VI to X for each company, respectively, with base scenarios II for the first and IX for the second. For each enterprise in the worst-case scenario II and VII it is assumed that damaged raw material and all generated by-products, products that do not meet market standards, and other production leftovers are sent to waste and sugars along with starches that are not retrieved from water or used in any other way. By calculating the worst-case scenario, it is possible to evaluate the general efficiency of production process, as the index shows how much product can be acquired from a certain amount of raw material. There might be two explanations if the index is exceptionally low; in this case – first, the raw material contains a small concentration of the product or second, the technology is inefficient and there could potentially be a place for improvement. Base scenario for both production companies included storage of raw material, in this step material could be lost as it might get damaged due to incorrect storage conditions or simply prolonged storage. The enterprise represented in cases VI to X does not store the raw material as long as the first enterprise. The damaged raw material is stored as waste and sent to a biogas production plant along with other raw material that has been sorted out due to being unfit for production needs.

Scenarios I to V included peeling where up to 5% of raw material is excluded from further production. As scenario II (actual situation) shows – at this point peelings are stored as waste and transferred to biogas production plant. In scenarios II to V and VIII to IX still at least 12% of the raw material or by-product is sent to biogas production, this is the amount that is damaged during storage or sorted out for not meeting the safety standards for being used as food. In scenarios III, V, IX and X a significant amount of created by-products is used as food and feed. Usually, the sorting process is meant for sorting out damaged raw materials or products that are not meeting the market standards. However, in many cases the raw material or product is in good condition, it is simply misshapen, or size does not match the production line requirements, hence it could still be used as food or feed. In scenarios III and V peels are used for animal feed, in addition, in scenario V a small portion of the raw material was used as a food product, because the amount of raw material was too small for production line. Although it is quite easy to redirect such by-products as peels and misshapen vegetables to livestock feed, it might be more feasible to sell these by-products to food producers. The Yurosek case proves that even misshapen vegetables can be used to produce higher added value foods - in 1986 Yurosek as an entrepreneur decided to try out producing "baby-carrots" from overgrown and misshapen carrots by cutting and physically shaping them into bite-size shapes [227], hence increasing the economic value of this bioresource from animal feed to food. The smaller size of the raw material was in higher demand from restaurants. Scenarios IV and VI both show that a portion of by-products is being used to create solid fuels. as energy recovery is considered downcycling of a material [69], this is the least preferable utilization option of a material. This idea is supported by the proposed bioresource utilization index, as scenarios IV and VI generate one of the lowest bioresource utilization index, lower being only scenarios where all generated side streams are redirected to waste. A portion of the analysed material is leached into water by blanching in the form of simple sugars or as starch during washing and cutting or grinding process. Best case scenarios V and X explore the option for these carbohydrates to be used for fine chemical production by the mixotrophic cultivation of algae [228],[229] or other microorganisms. In addition, scenario V explores the option of leached starch to be used for poly-lactic acid production as in this enterprise a considerable amount of starch was lost as suspended solids in wastewater. As mentioned before, BBW 0.25 is assigned to by-products used for biogas production. This is the most popular choice in enterprises dealing with organic by-products. The lowest bioresource index represents scenario where all by-products are wasted, in this case the index is dependent only on product/raw material ratio. As can be seen in Fig. 3.20., the highest bioresource utilization index calculated was 0.88. The highest score in bioresource utilization index is affected by best available techniques as well as the demand from PFC industry as in most cases status quo in this industry is to purchase raw materials with the highest purity. As more environmentally sustainable and safe options are becoming more popular in the PFC industry, more options for wood biomass utilization are surfacing in the market. Wood used to be on the bottom of the bio-based value pyramid, but today there are plenty of fine chemicals being extracted from it, such as terpenes [230], lignin [196] and betulin [231]. It is expected that opportunities for vegetable and fruit peels and other food production by-product utilization will grow, as more research trying to find possible uses for them is taking place [144], [232].

As mentioned before, production companies often choose to direct by-product to biogas production (in this study represented by BBW 0.25 or 4th level from the top), although this study shows that often by-products rich in reducing sugars might be used for PFCs production [143], [233], if veterinarian standards are met, by-product can be used as feed for livestock.

The overall comparison between scenarios can be seen in Figure 3.20. In food processing industry, sugars and soluble proteins are lost during blanching [234], retrieving these compounds from wastewaters requires too much energy for this process to be feasible. Organic compounds like starch can be extracted from production wastewaters [235]. In addition, after starch extraction from the raw material, juice is produced as by-product, it is a colloid substance that can be used for soil fertilization or proteins can be extracted and used as feed [143].

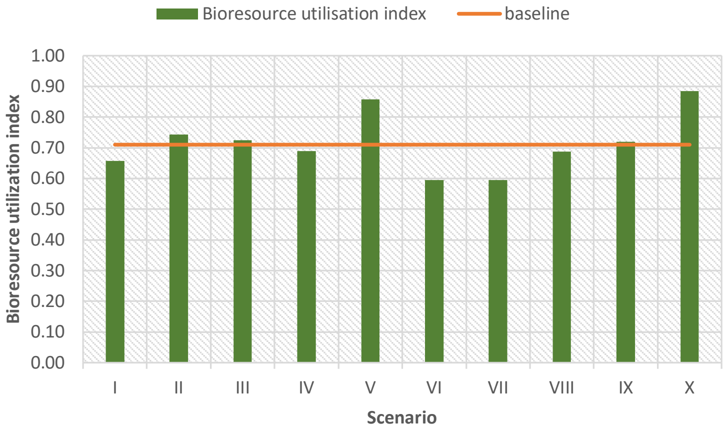


Fig.3.20. Bioresource utilization index calculated for Enterprise No. 1 and 2. actual situations represented by case II and IX and four alternative scenarios (I, III to VIII and X). Baseline is represented by median from all ten scenarios as one bioresource is used in all cases. Baseline shows that actual scenarios are very close to median (orange), showing that actual situation is somewhat in-between of worst and best possible case.

Hence in these calculations, the weight lost during blanching is considered as lost raw material. For determination of bioresource potential use in the enterprise, all biomass materials should be considered as bioresource.

4 CONCLUSIONS

Despite almost the concerns that Latvia exports low value timber, the topic is still relevant today. This thesis unearths transformative insights into the bioeconomy and conifer value chain innovations. All explored innovations are aimed towards resource efficiency and production residue stream redirection towards value added products. Research encompassed the potential of logging residues in 100% bio-based chipboards, thermal insulation packaging, and assessments of residue management strategies.

Although scientific literature covers logging residue and pine bark applications for chipboard production the possibility of completely excluding fossil-based adhesives is not sufficiently explored. With today’s climate objectives it is crucial to completely rethink construction and housing approaches by completely excluding fossil carbon from the market. Therefore, scientific community and industry need to find working alternatives. This thesis provided insights on logging residue usefulness for chipboard production and provided useful takeaways confirming previous work on logging residue potential application in chipboard production even without fossil-based adhesives. Although laboratory research has been done using particle size separation using sieves, it might be useful to consider gravimetric separation by cyclones as this would result in more even particle dimensions and therefore lead to more consistent results. It was shown that the <2.8 mm conifer logging residue particle size might have a positive impact on 100% bio-based chipboard durability. In addition, methods for mineral separation from the bark material could be explored, perhaps by using flotation. At the same time, there is already research on creating adhesives from bark extractables along other bio-based adhesives, and this research confirms the potential of chipboard transition away from fossil resources and towards completely bio-based materials.

Chosen adhesive showed promising results, but search for more efficient adhesive is still open. Literature review on adhesives elucidates multiple bio-based options, even potential adhesives from other industry residues. Successful research in this direction could potentially result in chipboards from mostly residue based raw materials – biomass and adhesive.

Results of experimental studies, market research and overall bioeconomy assessment showed that conifers as a dominant group of Latvia's forest species harbour a great potential for increasing the added value Forest economy. It is possible to improve the resource efficiency of the conventional conifer value chain by introducing innovative products and technologies for more efficient residue use, e.g., CLT cutting reprocessing. Therefore, it is possible to add value to conifer value chain without significant reorientation of primary raw material use.

Currently, the implementation of resource efficiency measures in companies depends on subjective viewpoints of decision-makers. To stimulate the utilization of residual materials from conventional conifer processing streams for higher value-added products, regulatory measures from policymakers are necessary. This conclusion arises from the theory based analysis on Bioeconomy development. As bottom-up approach showed – the enterprise resource efficiency is dependent on decision-maker's knowledge and subjective attitude towards the issue. If there is no internal knowledge of the potential for production residues, the residues will be directed towards energy, as this path is well known although adds the least value. However, despite available knowledge, there are only a few successful implementations of innovative technologies. Consequently, the conclusion is that, between the two factors, "behavioural" and "knowledge", the "behavioural" factor holds greater significance in the development of the conifer value chain.

Another aspect that would benefit from policy-maker involvement is carbon accounting. In this work multiple methods were compared. Methodologies clearly state the boundaries and underlying calculations, and consequentially show varying results. The significant number of accounting methods lead to situations where the results can only be used for specific cases, the same as Life Cycle Assessments. Tailor-made analysis can provide answers to very specific questions. Nevertheless, it is important to agree on a single accounting method that would allow the current situation of National and International Economy level to be assessed and future scenarios to be modelled. This thesis provide system dynamics as a comprehensive approach for carbon accounting and modelling. In the scope of this work System Dynamics modelling approach was used to illustrate the concept of dynamic carbon accounting. Initial modelling results showed that the popular assumption of net zero emissions from wood-based products need to be reconsidered, as model shows carbon accumulation in atmosphere from the activity in Forest economy. Therefore, sustainability of wood products needs to be evaluated in the long term and in conjunction with the possibilities of the energy sector. For carbon to be effectively stored in wood and its products, the issue of fossil fuel dependency and product longevity needs to be addressed. Bio-based products have the capacity to buffer carbon release into atmosphere even when fossil fuel is used, nevertheless it is important to balance the product lifespan with time the carbon took to assimilate into the biomass.

Despite the plans outlined in the Green Deal to decouple resource consumption from economic growth, the market anticipates an increase in demand for wood raw material volume. Therefore, additional alternatives need to be explored for the innovative products discussed in this study. Increasing the production volume of cross-laminated timber (CLT) and replacing concrete in multi-story buildings would significantly enhance the long-term carbon storage capacity in Latvia's economy.

Finally, bottom-up approach enhances the importance of waste reduction and search for new technologies that would enhance the resource efficiency leading to financial savings. This work illustrates the importance of production residue redirection towards use in products that could store the assimilated carbon for longer periods.

5 REFERENCES

[1] A. H. Buchanan and S. B. Levine, “Wood-based building materials and atmospheric carbon emissions,” *Environ. Sci. Policy*, vol. 2, no. 6, pp. 427–437, 1999, doi: 10.1016/S1462-9011(99)00038-6.

[2] O. Espinoza and U. Buehlmann, “Cross-Laminated Timber in the USA : Opportunity for Hardwoods ?,” *Curr. For. Rep.*, vol. 4, no. 1, pp. 1–12, 2018.

[3] T. Nishimura, “6 - Chipboard, oriented strand board (OSB) and structural composite lumber,” in *Wood Composites*, M. P. Ansell, Ed., Woodhead Publishing, 2015, pp. 103–121. doi: 10.1016/B978-1-78242-454-3.00006-8.

[4] R. Mújika-Garai *et al.*, “Stabilization of Paraffin Emulsions Used in the Manufacture of Chipboard Panels by Liquid Crystalline Phases,” *J. Dispers. Sci. Technol.*, vol. 28, no. 6, pp. 829–836, Jul. 2007, doi: 10.1080/01932690701341777.

[5] A. Marcon *et al.*, “Outdoor Formaldehyde and NO2 Exposures and Markers of Genotoxicity in Children Living Near Chipboard Industries,” *Environ. Health Perspect.*, vol. 122, no. 6, pp. 639–645, Jun. 2014, doi: 10.1289/ehp.1307259.

[6] A. Arias, S. González-García, S. González-Rodríguez, G. Feijoo, and M. T. Moreira, “Cradle-to-gate Life Cycle Assessment of bio-adhesives for the wood panel industry. A comparison with petrochemical alternatives,” *Sci. Total Environ.*, vol. 738, p. 140357, Oct. 2020, doi: 10.1016/j.scitotenv.2020.140357.

[7] “Particle Board Market Size, Share, Growth Analysis, By Application, End-Use - Industry Forecast 2023-2030.” Accessed: Aug. 09, 2023. [Online]. Available: https://www.skyquestt.com/report/particle-board-market

[8] G. Nemli and G. Çolakogˇlu, “The influence of lamination technique on the properties of particleboard,” *Build. Environ.*, vol. 40, pp. 83–87, Jan. 2005, doi: 10.1016/j.buildenv.2004.05.007.

[9] M. Pędzik, K. Tomczak, D. Janiszewska-Latterini, A. Tomczak, and T. Rogoziński, “Management of Forest Residues as a Raw Material for the Production of Particleboards,” *Forests*, vol. 13, no. 11, Art. no. 11, Nov. 2022, doi: 10.3390/f13111933.

[10] L. Melani and H.-J. Kim, “The surface softness and mechanical properties of wood pulp–lyocell wet-laid nonwoven fabric,” *J. Text. Inst.*, vol. 112, no. 8, pp. 1191–1198, Aug. 2021, doi: 10.1080/00405000.2020.1805962.

[11] “A Review of Bio-Based Adhesives from Primary and Secondary Biomass for Wood Composite Applications - ProQuest.” Accessed: Aug. 10, 2023. [Online]. Available: https://www.proquest.com/openview/fb15004e0a1b7adca03fa6536009000c/1?pq-origsite=gscholar&cbl=626454

[12] R. Mirski, A. Derkowski, J. Kawalerczyk, D. Dziurka, and J. Walkiewicz, “The Possibility of Using Pine Bark Particles in the Chipboard Manufacturing Process,” *Materials*, vol. 15, no. 16, Art. no. 16, Jan. 2022, doi: 10.3390/ma15165731.

[13] S. H. Lee *et al.*, “Particleboard from agricultural biomass and recycled wood waste: a review,” *J. Mater. Res. Technol.*, vol. 20, pp. 4630–4658, Sep. 2022, doi: 10.1016/j.jmrt.2022.08.166.

[14] A. Pizzi and K. Mittal, *Handbook of Adhesive Technology, Revised and Expanded*. CRC Press, 2003. doi: 10.1201/9780203912225.

[15] Q. Yuan, Z. Liu, K. Zheng, and C. Ma, “Chapter 5 - Wood,” in *Civil Engineering Materials*, Q. Yuan, Z. Liu, K. Zheng, and C. Ma, Eds., Elsevier, 2021, pp. 239–259. doi: 10.1016/B978-0-12-822865-4.00005-2.

[16] M. A. H. Mohd Azman *et al.*, “Life Cycle Assessment (LCA) of Particleboard: Investigation of the Environmental Parameters,” *Polymers*, vol. 13, no. 13, Art. no. 13, Jan. 2021, doi: 10.3390/polym13132043.

[17] M. Puettmann, E. Oneil, and J. Wilson, “Cradle to Gate Life Cycle Assessment of U.S. Particleboard Production,” 2013.

[18] H. Thoemen, M. Irle, and M. Sernek, *Wood-based panel technology*. 2010.

[19] “Strength & Stiffness - Performance Panels.” Accessed: Aug. 07, 2023. [Online]. Available: https://www.performancepanels.com/strength-stiffness

[20] J. E. McDevitt and W. J. Grigsby, “Life Cycle Assessment of Bio- and Petro-Chemical Adhesives Used in Fiberboard Production,” *J. Polym. Environ.*, vol. 22, no. 4, pp. 537–544, Dec. 2014, doi: 10.1007/s10924-014-0677-4.

[21] S. Bardak, G. Nemli, T. Bardak, S. Bardak, G. Nemli, and T. Bardak, “The quality comparison of particleboards produced from heartwood and sapwood of European larch,” *Maderas Cienc. Tecnol.*, vol. 21, no. 4, pp. 511–520, Dec. 2019, doi: 10.4067/S0718-221X2019005000407.

[22] P. Zheng, Q. Lin, F. Li, Y. Ou, and N. Chen, “Development and characterization of a defatted soy flour-based bio-adhesive crosslinked by 1,2,3,4-butanetetracarboxylic acid,”

Int. J. Adhes. Adhes., vol. 78, no. June, pp. 148–154, 2017, doi: 10.1016/j.ijadhadh.2017.06.016.

[23] D. E. Teixeira, D. D. C. Pereira, A. P. D. Nakamura, and S. S. Brum, "Adhesivity of bio-based anhydrous citric acid, tannin-citric acid and ricinoleic acid in the properties of formaldehyde-free medium density particleboard (Mdp)," *Drv. Ind.*, vol. 71, no. 3, pp. 235–242, 2020, doi: 10.5552/drvind.2020.1917.

[24] D. Zheng, X. Wang, M. Zhang, Z. Liu, and C. Ju, "Anticorrosion and lubricating properties of a fully green lubricant," *Tribol. Int.*, vol. 130, no. August 2018, pp. 324–333, 2019, doi: 10.1016/j.triboint.2018.08.014.

[25] K. Umemura and S. Kawai, "Development of Wood-Based Materials Bonded with Citric Acid*," *For. Prod. J.*, vol. 65, no. 1–2, pp. 38–42, Mar. 2015, doi: 10.13073/FPJ-D-14-00036.

[26] D. E. Teixeira, D. D. C. Pereira, A. P. D. Nakamura, and S. S. Brum, "Adhesivity of bio-based anhydrous citric acid, tannin-citric acid and ricinoleic acid in the properties of formaldehyde-free medium density particleboard (Mdp)," *Drv. Ind.*, vol. 71, no. 3, pp. 235–242, 2020, doi: 10.5552/drvind.2020.1917.

[27] R. V. Gadhave, P. A. Mahanwar, and P. T. Gadekar, "Starch stabilized polyvinyl acetate emulsion: Review," *Polym. Renew. Resour.*, vol. 9, no. 2, pp. 75–84, 2018, doi: 10.1177/204124791800900203.

[28] P. Samyn, "A platform for functionalization of cellulose, chitin/chitosan, alginate with polydopamine: A review on fundamentals and technical applications," *Int. J. Biol. Macromol.*, vol. 178, pp. 71–93, 2021, doi: 10.1016/j.ijbiomac.2021.02.091.

[29] F. Ferdosian, Z. Pan, G. Gao, and B. Zhao, "Bio-based adhesives and evaluation for wood composites application," *Polymers*, vol. 9, no. 2. MDPI AG, 2017. doi: 10.3390/polym9020070.

[30] Y. Monroy, S. Rivero, and M. A. García, "Sustainable panels design based on modified cassava starch bioadhesives and wood processing byproducts," *Ind. Crops Prod.*, vol. 137, 2019, doi: 10.1016/j.indcrop.2019.04.062.

[31] P. Nordqvist, M. Lawther, E. Malmström, and F. Khabbaz, "Adhesive properties of wheat gluten after enzymatic hydrolysis or heat treatment - A comparative study," *Ind. Crops Prod.*, vol. 38, no. 1, pp. 139–145, 2012, doi: 10.1016/j.indcrop.2012.01.021.

[32] T. Huang *et al.*, "Fish gelatin modifications: A comprehensive review," *Trends Food Sci. Technol.*, vol. 86, no. February, pp. 260–269, 2019, doi: 10.1016/j.tifs.2019.02.048.

[33] T. Y. Wu, A. W. Mohammad, J. M. Jahim, and N. Anuar, "Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes," *J. Environ. Manage.*, pp. 1467–1490, 2010, doi: 10.1016/j.jenvman.2010.02.008.

[34] D. W. Ningsi, Suhasman, and S. Saad, "Characteristic of Chitosan Adhesive from Shell Shrimp Litopenaeus vannamei and Their Application for Producing Particleboard," in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Aug. 2019. doi: 10.1088/1757-899X/593/1/012015.

[35] S. Tokura and H. Tamura, "Chitin and Chitosan," *Compr. Glycosci. Chem. Syst. Biol.*, vol. 2–4, pp. 449–475, 2007, doi: 10.1016/B978-044451967-2/00127-6.

[36] S. D. Desai, J. V. Patel, and V. K. Sinha, “Polyurethane adhesive system from biomaterial-based polyol for bonding wood,” *Int. J. Adhes. Adhes.*, vol. 23, no. 5, pp. 393–399, 2003, doi: 10.1016/S0143-7496(03)00070-8.

[37] L. Hou and E. L. W. Majumder, “Potential for and distribution of enzymatic biodegradation of polystyrene by environmental microorganisms,” *Materials*, vol. 14, no. 3, pp. 1–20, 2021, doi: 10.3390/ma14030503.

[38] M. A. Aristri *et al.*, “Bio-based polyurethane resins derived from tannin: Source, synthesis, characterisation, and application,” *Forests*, vol. 12, no. 11, pp. 1–23, 2021, doi: 10.3390/f12111516.

[39] V. Superti, T. V. Forman, and C. Houmani, “Recycling thermal insulation materials: A case study on more circular management of expanded polystyrene and stonewool in switzerland and research agenda,” *Resources*, vol. 10, no. 10, Oct. 2021, doi: 10.3390/resources10100104.

[40] United Soybean Board, “NU GREEN SOYA® PARTICLEBOARD SCORES ENVIRONMENTAL CERTIFICATIONS.” [Online]. Available: https://soynewuses.org/case-study/nu-green-soya-particleboard-scores-environmental-certifications/

[41] SOLENIS, “SOYADTM ADHESIVE TECHNOLOGY.” [Online]. Available: https://www.solenis.com/en/research-and-development/innovations/soyad-adhesive-technology

[42] C. Montanari, P. Olsén, and L. A. Berglund, “Sustainable Wood Nanotechnologies for Wood Composites Processed by In-Situ Polymerization,” *Front. Chem.*, vol. 9, no. July, pp. 1–12, 2021, doi: 10.3389/fchem.2021.682883.

[43] I. Muizniece, A. Gravelsins, I. Brauners, A. Blumberga, and D. Blumberga, “Innovative Bioproducts from Forest Biomass. Method of Analysis,” *Energy Procedia*, vol. 113, pp. 434–441, 2017, doi: 10.1016/j.egypro.2017.04.035.

[44] V. Terjanika and J. Pubule, “Barriers and Driving Factors for Sustainable Development of CO2 Valorisation,” *Sustainability*, vol. 14, no. 9, Art. no. 9, Jan. 2022, doi: 10.3390/su14095054.

[45] V. Terjanika, J. Gusca, J. Pubule, and D. Blumberga, “Analysis of CO2 Valorisation Options for Regional Development,” *Environ. Clim. Technol.*, vol. 25, no. 1, pp. 243–253, Jan. 2021, doi: 10.2478/rtuect-2021-0017.

[46] V. Terjanika, D. Blumberga, and J. Pubule, “Regional Development Scenarios and Model Boundaries for CCU in Energy Sector in Latvia,” in *2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, Nov. 2021, pp. 1–5. doi: 10.1109/RTUCON53541.2021.9711727.

[47] X. Xu, P. Xu, J. Zhu, H. Li, and Z. Xiong, “Bamboo construction materials: Carbon storage and potential to reduce associated CO2 emissions,” *Sci. Total Environ.*, vol. 814, p. 152697, Mar. 2022, doi: 10.1016/j.scitotenv.2021.152697.

[48] N. Tripathi, C. D. Hills, R. S. Singh, and C. J. Atkinson, “Biomass waste utilisation in low-carbon products: harnessing a major potential resource,” *Npj Clim. Atmospheric Sci.*, vol. 2, no. 1, 2019, doi: 10.1038/s41612-019-0093-5.

[49] V. Kazulis, I. Muizniece, L. Zihare, and D. Blumberga, "Carbon storage in wood products," *Energy Procedia*, vol. 128, pp. 558–563, 2017, doi: 10.1016/j.egypro.2017.09.009.

[50] K. Veitmans and U. Grinfelds, "WOOD FIBER INSULATION MATERIAL," vol. 2, 2016.

[51] I. Vamza, A. Kubule, L. Zihare, K. Valters, and D. Blumberga, "Bioresource utilization index – A way to quantify and compare resource efficiency in production," *J. Clean. Prod.*, vol. 320, p. 128791, Aug. 2021, doi: 10.1016/j.jclepro.2021.128791.

[52] T. Singh *et al.*, "Emerging technologies for the development of wood products towards extended carbon storage and CO2 capture," *Carbon Capture Sci. Technol.*, vol. 4, p. 100057, Sep. 2022, doi: 10.1016/j.ccst.2022.100057.

[53] M. Lavagna *et al.*, "Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock," *Build. Environ.*, vol. 145, no. September, pp. 260–275, 2018, doi: 10.1016/j.buildenv.2018.09.008.

[54] European Commission, "EUR-Lex - 52014DC0445 - EN." Accessed: Oct. 20, 2020. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52014DC0445&from=en

[55] H. S. Müller, M. Haist, and M. Vogel, "Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime," *Constr. Build. Mater.*, vol. 67, no. PART C, pp. 321–337, 2014, doi: 10.1016/j.conbuildmat.2014.01.039.

[56] Athena Sustainable Materials Institute;, "A Life Cycle Assessment of Cross-Laminated Timber Produced in Canada," no. February, p. 37, 2013.

[57] IEA, "Global cement production, 2010-2019 – Charts – Data & Statistics - IEA." Accessed: Oct. 30, 2020. [Online]. Available: https://www.iea.org/data-and-statistics/charts/global-cement-production-2010-2019

[58] Grand View Research, "Wood Based Panel Market Size, Share & Trends Analysis Report By Product (Plywood, MDF, HDF, OSB, Particleboard, Hardboard), By Application (Furniture, Construction), By Region, And Segment Forecasts, 2020 - 2027." Accessed: Feb. 09, 2021. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/wood-based-panel-market

[59] "Panels & Furniture Asia May/Jun 2020." Accessed: Oct. 28, 2020. [Online]. Available: http://www.panelsfurnitureasia.com/ebook/PFA_MayJun2020/index.html

[60] R. Cherry, A. Manalo, W. Karunasena, and G. Stringer, "Out-of-grade sawn pine: A state-of-the-art review on challenges and new opportunities in cross laminated timber (CLT)," *Constr. Build. Mater.*, vol. 211, pp. 858–868, 2019, doi: 10.1016/j.conbuildmat.2019.03.293.

[61] J. Hildebrandt, N. Hagemann, and D. Thrän, "The contribution of wood-based construction materials for leveraging a low carbon building sector in europe," *Sustain. Cities Soc.*, vol. 34, no. July, pp. 405–418, 2017, doi: 10.1016/j.scs.2017.06.013.

[62] A. Jayalath, S. Navaratnam, T. Ngo, P. Mendis, N. Hewson, and L. Aye, "Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia," *Energy Build.*, vol. 223, p. 110091, 2020, doi: 10.1016/j.enbuild.2020.110091.

[63] K. Hemström, K. Mahapatra, and L. Gustavsson, "Perceptions, attitudes and interest of Swedish architects towards the use of wood frames in multi-storey buildings," *Resour. Conserv. Recycl.*, vol. 55, no. 11, pp. 1013–1021, 2011, doi: 10.1016/j.resconrec.2011.05.012.

[64] "Noteikumi par Latvijas būvnormatīvu LBN 201-15 " Būvju ugunsdrošība "," in *Cabinet of Ministers Nr.333*, 2015, pp. 1–39. Accessed: Oct. 28, 2020. [Online]. Available: https://likumi.lv/ta/id/275006-noteikumi-par-latvijas-buvnormativu-lbn-201-15-buvju-ugunsdrosiba-

[65] OECD, "OECD (2017) , How's Life? Measuring well-being," 2017, doi: 10.1787/how.

[66] I. Barboutis and V. Kamperidou, "Properties of two different thicknesses 3-ply plywood of tree-of-heaven veneers," *22nd Int. Sci. Conf. Wood Good - EU Preaccession Chall. Sect. Proc.*, no. January 2011, pp. 9–16, 2011.

[67] C. X. Chen, F. Pierobon, and I. Ganguly, "Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) produced in Western Washington: The role of logistics and wood species mix," *Sustain. Switz.*, vol. 11, no. 5, 2019, doi: 10.3390/su11051278.

[68] L. Guardigli, F. Monari, and M. A. Bragadin, "Assessing environmental impact of green buildings through LCA methods:Acomparison between reinforced concrete and wood structures in the European context," *Procedia Eng.*, vol. 21, pp. 1199–1206, 2011, doi: 10.1016/j.proeng.2011.11.2131.

[69] R. N. Passarelli, "Environmental Benefits of Reusable Modular Mass Timber Construction for Residential use in Japan: an LCA Approach," *Modul. Offsite Constr. MOC Summit Proc.*, vol. 2017, no. MLIT 2016, pp. 157–164, 2019, doi: 10.29173/mocs89.

[70] S. Singh, K. K. Gaikwad, M. Lee, and Y. S. Lee, "Temperature sensitive smart packaging for monitoring the shelf life of fresh beef," *J. Food Eng.*, vol. 234, pp. 41–49, 2018, doi: 10.1016/j.jfoodeng.2018.04.014.

[71] C. M. Hanson, A. M. George, A. Sawadogo, and B. Schreiber, "Is freezing in the vaccine cold chain an ongoing issue? A literature review," *Vaccine*, vol. 35, no. 17, pp. 2127–2133, 2017, doi: 10.1016/j.vaccine.2016.09.070.

[72] U. Kartoglu and J. Milstien, "Tools and approaches to ensure quality of vaccines throughout the cold chain," *Expert Rev. Vaccines*, vol. 13, no. 7, pp. 843–854, 2014, doi: 10.1586/14760584.2014.923761.

[73] E. B. Mariano, J. A. Gobbo, F. de C. Camioto, and D. A. do N. Rebelatto, "CO2 emissions and logistics performance: a composite index proposal," *J. Clean. Prod.*, vol. 163, pp. 166–178, 2017, doi: 10.1016/j.jclepro.2016.05.084.

[74] C. Pan, S. Yu, and S. Li, "Research on the development mode and evaluation system of green cold chain logistics in China," *Chin. Control Conf. CCC*, pp. 7541–7546, 2017, doi: 10.23919/ChiCC.2017.8028547.

[75] K. Wang, L. Yang, and M. Kucharek, “Investigation of the effect of thermal insulation materials on packaging performance,” *Packag. Technol. Sci.*, vol. 33, no. 6, pp. 227–236, 2020, doi: 10.1002/pts.2500.

[76] B. A. Vaughan, Michael, M. S.Webster-Gardiner, T. R. Cundari, and T. B. Gunnoe, “A rhodium catalyst for single-step styrene production from benzene and ethylene,” *Proc. Int. Astron. Union*, vol. 348, no. April, pp. 421–424, 2015, doi: 10.1017/s1743921307007752.

[77] P. Dai, Z. H. Mo, R. W. Xu, S. Zhang, and Y. X. Wu, “Cross-Linked Quaternized Poly(styrene-b-(ethylene-co-butylene)-b-styrene) for Anion Exchange Membrane: Synthesis, Characterization and Properties,” *ACS Appl. Mater. Interfaces*, vol. 8, no. 31, pp. 20329–20341, 2016, doi: 10.1021/acsami.6b04590.

[78] W. Wei, Z. Lv, G. Yang, S. Cheng, Y. Li, and L. Wang, “VOCs emission rate estimate for complicated industrial area source using an inverse-dispersion calculation method: A case study on a petroleum refinery in Northern China,” *Environ. Pollut.*, vol. 218, pp. 681–688, 2016, doi: 10.1016/j.envpol.2016.07.062.

[79] E. Lewis and E. Lewis, “Environmental Product Declaration,” *Sustainaspeak*, pp. 106–107, 2018, doi: 10.4324/9781315270326-75.

[80] Y. K. Song, S. H. Hong, S. Eo, G. M. Han, and W. J. Shim, “Rapid Production of Micro-And Nanoplastics by Fragmentation of Expanded Polystyrene Exposed to Sunlight,” *Environ. Sci. Technol.*, vol. 54, no. 18, pp. 11191–11200, 2020, doi: 10.1021/acs.est.0c02288.

[81] B. Jovanović, “Ingestion of microplastics by fish and its potential consequences from a physical perspective,” *Integr. Environ. Assess. Manag.*, vol. 13, no. 3, pp. 510–515, 2017, doi: 10.1002/ieam.1913.

[82] R. Dekker, J. Bloemhof, and I. Mallidis, “Operations Research for green logistics - An overview of aspects, issues, contributions and challenges,” *Eur. J. Oper. Res.*, vol. 219, no. 3, pp. 671–679, 2012, doi: 10.1016/j.ejor.2011.11.010.

[83] S. Rogerson, “Influence of freight transport purchasing processes on logistical variables related to CO2 emissions: a case study in Sweden,” *Int. J. Logist. Res. Appl.*, vol. 20, no. 6, pp. 604–623, 2017, doi: 10.1080/13675567.2017.1308472.

[84] C. Lammgård and D. Andersson, “Environmental considerations and trade-offs in purchasing of transportation services,” *Res. Transp. Bus. Manag.*, vol. 10, pp. 45–52, 2014, doi: 10.1016/j.rtbm.2014.04.003.

[85] T. H. E. Need *et al.*, “Green supply chains : a glimpse into the future ?”.

[86] S. Newland, “Sustainability in Vaccine Packaging Draft,” no. May, 2011.

[87] Greencellfoam, “Greencellfoam.” 2021. [Online]. Available: https://greencellfoam.com/green-cell-foam

[88] I. Mariam, K. Y. Cho, and S. S. H. Rizvi, “Thermal properties of starch-based biodegradable foams produced using Supercritical Fluid Extrusion (SCFX),” *Int. J. Food Prop.*, vol. 11, no. 2, pp. 415–426, 2008, doi: 10.1080/10942910701444705.

[89] S. B. Kalambur and S. S. Rizvi, “Starch-based nanocomposites by reactive extrusion processing,” *Polym. Int.*, vol. 53, no. 10, pp. 1413–1416, 2004, doi: 10.1002/pi.1478.

[90] S. Kalambur and S. S. H. Rizvi, “An overview of starch-based plastic blends from reactive extrusion,” *J. Plast. Film Sheeting*, vol. 22, no. 1, pp. 39–58, 2006, doi: 10.1177/8756087906062729.

[91] S. Bruin, “Mycelium: a Building Block for Parkstad Limburg,” no. 2008, p. 30, 2018.

[92] S. S. Schmieder *et al.*, “Bidirectional Propagation of Signals and Nutrients in Fungal Networks via Specialized Hyphae,” *Curr. Biol.*, vol. 29, no. 2, pp. 217-228.e4, 2019, doi: 10.1016/j.cub.2018.11.058.

[93] G. P. Boswell, H. Jacobs, F. A. Davidson, G. M. Gadd, and K. Ritz, “Growth and function of fungal mycelia in heterogeneous environments,” *Bull. Math. Biol.*, vol. 65, no. 3, pp. 447–477, 2003, doi: 10.1016/S0092-8240(03)00003-X.

[94] “Home — pluumo.” Accessed: Mar. 29, 2021. [Online]. Available: https://www.pluumo.com/home

[95] E. Dieckmann, B. Nagy, K. Yiakoumetti, L. Sheldrick, and C. Cheeseman, “Thermal insulation packaging for cold-chain deliveries made from feathers,” *Food Packag. Shelf Life*, vol. 21, no. June, p. 100360, 2019, doi: 10.1016/j.fpsl.2019.100360.

[96] M. S. Braun, F. Sporer, S. Zimmermann, and M. Wink, “Birds, feather-degrading bacteria and preen glands: The antimicrobial activity of preen gland secretions from turkeys (Meleagris gallopavo) is amplified by keratinase,” *FEMS Microbiol. Ecol.*, vol. 94, no. 9, pp. 1–14, 2018, doi: 10.1093/femsec/fiy117.

[97] “Woolcool Thermal Insulated Packaging Company | Food & Pharmaceutical.” Accessed: Mar. 29, 2021. [Online]. Available: https://www.woolcool.com/

[98] T. M. Tuzcu, “Hygro-Thermal Properties of Sheep Wool Insulation,” p. 110, 2007.

[99] “BAT reference documents | Eippcb.” Accessed: Aug. 16, 2023. [Online]. Available: https://eippcb.jrc.ec.europa.eu/reference/

[100] D. Maes and S. Van Passel, “Effective bioeconomy policies for the uptake of innovative technologies under resource constraints,” *Biomass Bioenergy*, vol. 120, no. October 2018, pp. 91–106, 2019, doi: 10.1016/j.biombioe.2018.11.008.

[101] Directorate-General for Research and Innovation (European Commission), *A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment : updated bioeconomy strategy*. LU: Publications Office of the European Union, 2018. Accessed: Aug. 16, 2023. [Online]. Available: https://data.europa.eu/doi/10.2777/792130

[102] I. Muizniece, L. Zihare, and D. Blumberga, “Obtaining the factors affecting bioeconomy,” *Environ. Clim. Technol.*, vol. 23, no. 1, pp. 277–291, 2019, doi: 10.2478/rtuect-2019-0018.

[103] E. A. Wrigley, “Energy and the English industrial revolution,” *Philos. Trans. R. Soc.*, pp. 1–10, 2013, doi: 10.5860/choice.48-4603.

[104] N. Gaurav, S. Sivasankari, G. Kiran, A. Ninawe, and J. Selvin, “Utilization of bioresources for sustainable biofuels: A Review,” *Renew. Sustain. Energy Rev.*, vol. 73, pp. 205–214, Jun. 2017, doi: 10.1016/j.rser.2017.01.070.

[105] F. Engelmann, “Use of biotechnologies for the conservation of plant biodiversity,” *Vitro Cell. Dev. Biol. - Plant*, vol. 47, no. 1, pp. 5–16, Feb. 2011, doi: 10.1007/s11627-010-9327-2.

[106] European Parliament and Council, “Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives (Waste framework,” *LexUriServ Do*, pp. 3–30, 2008, doi: 2008/98/EC.; 32008L0098.

[107] D. Fang and B. Chen, “Linkage analysis for the water–energy nexus of city,” *Appl. Energy*, vol. 189, pp. 770–779, 2017, doi: 10.1016/j.apenergy.2016.04.020.

[108] P. Stegmann, M. Londo, and M. Junginger, “The Circular Bioeconomy: Its elements and role in European bioeconomy clusters,” *Resour. Conserv. Recycl. X*, vol. 6, no. July 2019, p. 100029, 2020, doi: 10.1016/j.rcrx.2019.100029.

[109] K. Höglmeier, B. Steubing, G. Weber-Blaschke, and K. Richter, “LCA-based optimization of wood utilization under special consideration of a cascading use of wood,” *J. Environ. Manage.*, vol. 152, pp. 158–170, 2015, doi: 10.1016/j.jenvman.2015.01.018.

[110] G. T. Kroyer, “Impact of food processing on the environment-an overview,” *LWT - Food Sci. Technol.*, vol. 28, no. 6, pp. 547–552, 1995, doi: 10.1016/0023-6438(95)90000-4.

[111] G. Evans, *Biowaste and Biological Treatment*. 2013.

[112] M. Kuzmanović *et al.*, “Ecotoxicological risk assessment of chemical pollution in four Iberian river basins and its relationship with the aquatic macroinvertebrate community status,” *Sci. Total Environ.*, vol. 540, pp. 324–333, Jan. 2016, doi: 10.1016/j.scitotenv.2015.06.112.

[113] P. Muñoz, A. Drizo, and W. Cully Hession, “Flow patterns of dairy wastewater constructed wetlands in a cold climate,” *Water Res.*, vol. 40, no. 17, pp. 3209–3218, 2006, doi: 10.1016/j.watres.2006.06.036.

[114] J. Clemens and C. Cuhls, “Greenhouse gas emissions from mechanical and biological waste treatment of municipal waste,” *Environ. Technol. U. K.*, vol. 24, no. 6, pp. 745–754, 2003, doi: 10.1080/09593330309385611.

[115] N. J. G. J. Bandara, J. P. A. Hettiaratchi, S. C. Wirasinghe, and S. Pilapiiya, “Relation of waste generation and composition to socio-economic factors: A case study,” *Environ. Monit. Assess.*, vol. 135, no. 1–3, pp. 31–39, 2007, doi: 10.1007/s10661-007-9705-3.

[116] A. Jlil. Saad A, “COD and BOD Reduction of Dosmetic Wastewater using Activated sludge, Sand Filters and Activated Carbon in Saudi Arabia,” *Biotechnology*. pp. 473–477, 2009.

[117] P. A. Trubaev *et al.*, “Investigation of Landfill Gas Output from Municipal Solid Waste at the Polygon,” *J. Phys. Conf. Ser.*, vol. 1066, no. 1, 2018, doi: 10.1088/1742-6596/1066/1/012015.

[118] “Getliņi skaitļos | Getlini.Lv.” Accessed: Mar. 19, 2020. [Online]. Available: https://www.getlini.lv/

[119] D. Dorais, M., Schwarz, *Tomatoes*. CAB International, 2018. Accessed: Feb. 19, 2020. [Online]. Available: https://books.google.lv/books?hl=en&lr=&id=SVdoDwAAQBAJ&oi=fnd&pg=PA1&dq

=tomatoes+energy+intensive+growing&ots=efWK9Xblt4&sig=RbyHxsGNNMTcVqN3T9yeiJIWr98&redir_esc=y#v=onepage&q=energy&f=false

[120] EUROPEAN COMMISSION, *Innovating for Sustainable Growth: A Bioeconomy for Europe*, no. February. 2012, pp. 1–47.

[121] OECD, "OECD International Futures Programme The Bioeconomy to 2030: Designing a Policy Agenda," 2006.

[122] J. Jiang, C. Gong, J. Wang, S. Tian, and Y. Zhang, "Effects of ultrasound pre-treatment on the amount of dissolved organic matter extracted from food waste," *Bioresour. Technol.*, vol. 155, pp. 266–271, 2014, doi: 10.1016/j.biortech.2013.12.064.

[123] E. Rosales, S. Rodríguez Couto, and A. Sanromán, "New uses of food waste: Application to laccase production by Trametes hirsuta," *Biotechnol. Lett.*, vol. 24, no. 9, pp. 701–704, 2002, doi: 10.1023/A:1015234100459.

[124] J. P. H. Van Wyk, "Biowaste as a resource for bioproduct development," *Environ. Earth Sci.*, vol. 19, no. 5, pp. 875–883, 2011, doi: 10.1007/978-3-540-95991-5-82.

[125] C. Zhang, H. Su, J. Baeyens, and T. Tan, "Reviewing the anaerobic digestion of food waste for biogas production," *Renew. Sustain. Energy Rev.*, vol. 38, pp. 383–392, 2014, doi: 10.1016/j.rser.2014.05.038.

[126] S. Rasi, A. Veijanen, and J. Rintala, "Trace compounds of biogas from different biogas production plants," *Energy*, vol. 32, no. 8, pp. 1375–1380, 2007, doi: 10.1016/j.energy.2006.10.018.

[127] eurostat, "Business economy - size class analysis - Statistics Explained." Accessed: Feb. 18, 2020. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Archive:Business_economy_-_size_class_analysis#Sectoral_analysis

[128] H. Ritchie and M. Roser, "CO_2 and Greenhouse Gas Emissions - Our World in Data," Our World in Data. Accessed: Feb. 11, 2020. [Online]. Available: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#co2-emissions-by-sector

[129] M. J. P. Sullivan *et al.*, "Diversity and carbon storage across the tropical forest biome," *Sci. Rep.*, vol. 7, no. July 2016, pp. 1–12, 2017, doi: 10.1038/srep39102.

[130] M. ; Janowiak *et al.*, "United States Department of Agriculture Considering Forest and Grassland Carbon in Land Management," 2017. [Online]. Available: http://www.ascr.usda.gov/complaint_filing_cust.html

[131] European Commission, "Circular Economy Strategy," no. November 2008, p. 9, 2015.

[132] E. Cagno, E. Worrell, A. Trianni, and G. Pugliese, "A novel approach for barriers to industrial energy efficiency," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 290–308, Mar. 2013, doi: 10.1016/j.rser.2012.11.007.

[133] S. Sorrell, A. Mallett, and S. Nye, "Barriers to industrial energy efficiency: a literature review," 2011. doi: 10.1016/j.rser.2015.03.002.

[134] L. Axelsson, M. Franzén, M. Ostwald, G. Berndes, G. Lakshmi, and N. H. Ravindranath, "Perspective: Jatropha cultivation in southern India: Assessing farmers'

experiences," *Biofuels Bioprod. Biorefining*, vol. 6, no. 3, pp. 246–256, 2012, doi: 10.1002/bbb.

[135] R. P. Powers and W. Jetz, "Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios," *Nat. Clim. Change*, vol. 9, no. 4, pp. 323–329, 2019, doi: 10.1038/s41558-019-0406-z.

[136] T. Vanhercke *et al.*, "Metabolic engineering of biomass for high energy density: Oilseed-like triacylglycerol yields from plant leaves," *Plant Biotechnol. J.*, vol. 12, no. 2, pp. 231–239, 2014, doi: 10.1111/pbi.12131.

[137] M. Tai and G. Stephanopoulos, "Engineering the push and pull of lipid biosynthesis in oleaginous yeast Yarrowia lipolytica for biofuel production," *Metab. Eng.*, vol. 15, no. 1, pp. 1–9, 2013, doi: 10.1016/j.ymben.2012.08.007.

[138] R. Vanholme *et al.*, "Metabolic engineering of novel lignin in biomass crops," *New Phytol.*, pp. 978–1000, 2012.

[139] Deloitte, "Researcher's Report, DG Research and Innovation," 2014. Accessed: Feb. 18, 2020. [Online]. Available: http://ec.europa.eu/euraxess/index.cfm/general/researchPolicies

[140] L. Levidow, K. Birch, and T. Papaioannou, "EU agri-innovation policy: Two contending visions of the bio-economy," *Crit. Policy Stud.*, vol. 6, no. 1, pp. 40–65, 2012, doi: 10.1080/19460171.2012.659881.

[141] eurostat, *Manual on waste statistics A handbook for data collection on waste generation and treatment*. 2013. doi: 10.2785/4198.

[142] J. Pubule, A. Blumberga, F. Romagnoli, and D. Blumberga, "Finding an optimal solution for biowaste management in the Baltic States," *J. Clean. Prod.*, vol. 88, pp. 214–223, 2015, doi: 10.1016/j.jclepro.2014.04.053.

[143] V. Priedniece, K. Spalvins, K. Ivanovs, J. Pubule, and D. Blumberga, "Bioproducts from potatoes. A review," *Environ. Clim. Technol.*, vol. 21, no. 1, pp. 18–27, 2017, doi: 10.1515/rtuect-2017-0013.

[144] P. P. Singh and M. D. A. Saldaña, "Subcritical water extraction of phenolic compounds from potato peel," *Food Res. Int.*, vol. 44, no. 8, pp. 2452–2458, 2011, doi: 10.1016/j.foodres.2011.02.006.

[145] B. Zlaugotne, L. Zihare, L. Balode, A. Kalnbalkite, A. Khabdullin, and D. Blumberga, "Multi-Criteria Decision Analysis Methods Comparison," *Environ. Clim. Technol.*, vol. 24, no. 1, pp. 454–471, Jan. 2020, doi: 10.2478/rtuect-2020-0028.

[146] I. Siksnelyte, E. K. Zavadskas, D. Streimikiene, and D. Sharma, "An overview of multi-criteria decision-making methods in dealing with sustainable energy development issues," *Energies*, vol. 11, no. 10, 2018, doi: 10.3390/en11102754.

[147] S. Lee, W. Kim, Y. M. Kim, and K. J. Oh, "Using AHP to determine intangible priority factors for technology transfer adoption," *Expert Syst. Appl.*, vol. 39, no. 7, pp. 6388–6395, 2012, doi: 10.1016/j.eswa.2011.12.030.

[148] A. M. R. Group, "Biomass Markets: Weekly biomass markets news and analysis," 2022.

[149] T. L. Saaty and M. Sodenkamp, *The Analytic Hierarchy and Analytic Network Measurement Processes: The Measurement of Intangibles Decision Making under*

Benefits, Opportunities, Costs and Risks, vol. 103. 2010. doi: 10.1007/978-3-540-92828-7.

[150] “High Performing Foam Packaging — Green Cell Foam.” Accessed: Apr. 15, 2021. [Online]. Available: https://greencellfoam.com/data

[151] T. L. Saaty, “Deriving the ahp 1-9 scale from first principles,” *Proc. – 6th ISAHP 2001*, pp. 397–402, 2001.

[152] K. D. Goepel, “Implementing the Analytic Hierarchy Process as a Standard Method for Multi-Criteria Decision Making in Corporate Enterprises – a New AHP Excel Template with Multiple Inputs,” pp. 1–10, 2013, doi: 10.13033/isahp.y2013.047.

[153] B. Adem Esmail and D. Geneletti, “Multi-criteria decision analysis for nature conservation: A review of 20 years of applications,” *Methods Ecol. Evol.*, vol. 9, no. 1, pp. 42–53, 2018, doi: 10.1111/2041-210X.12899.

[154] I. Delvere, M. Iltina, M. Shanbayev, A. Abildayeva, S. Kuzhamberdieva, and D. Blumberga, “Evaluation of polymer matrix composite waste recycling methods,” *Environ. Clim. Technol.*, vol. 23, no. 1, pp. 168–187, Jan. 2019, doi: 10.2478/rtuect-2019-0012.

[155] A. Ishizaka and N. H. Nguyen, “Calibrated fuzzy AHP for current bank account selection,” *Expert Syst. Appl.*, vol. 40, no. 9, pp. 3775–3783, 2013, doi: 10.1016/j.eswa.2012.12.089.

[156] P. Li, H. Qian, J. Wu, and J. Chen, “Sensitivity analysis of TOPSIS method in water quality assessment: I. Sensitivity to the parameter weights,” *Environ. Monit. Assess.*, vol. 185, no. 3, pp. 2453–2461, 2013, doi: 10.1007/s10661-012-2723-9.

[157] EUROPEAN COMMISSION, “COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS ON RESOURCE EFFICIENCY OPPORTUNITIES IN THE BUILDING SECTOR.” Brussels, 2014.

[158] Lars G. F. Tellnes, “ENVIRONMENTAL PRODUCT DECLARATION of Cross laminated timber panels,” Norwegian Institute of Wood Technology, 2017.

[159] Grand View Research, “Global Expanded Polystyrene Market Size Report, 2021-2028,” 2020. Accessed: Sep. 28, 2022. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/expanded-polystyrene-eps-market

[160] Anne-Marie Boulay *et al.*, “The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE)”.

[161] H. White, “Theory-based impact evaluation: principles and practice,” *J. Dev. Eff.*, vol. 1, no. 3, pp. 271–284, 2009, doi: 10.1080/19439340903114628.

[162] T. Vogelpohl and A. E. Töller, “Perspectives on the bioeconomy as an emerging policy field,” *J. Environ. Policy Plan.*, vol. 23, no. 2, pp. 143–151, 2021, doi: 10.1080/1523908X.2021.1901394.

[163] S. Jamshed, “Qualitative research method-interviewing and observation,” *J. Basic Clin. Pharm.*, vol. 5, no. 4, p. 87, 2014, doi: 10.4103/0976-0105.141942.

[164] D. D’Amato, S. Veijonaho, and A. Toppinen, “Towards sustainability? Forest-based circular bioeconomy business models in Finnish SMEs,” *For. Policy Econ.*, vol. 110, no. June 2018, p. 101848, 2020, doi: 10.1016/j.forpol.2018.12.004.

[165] D. A. Gârdan, M. Andronie, I. P. Gârdan, I. E. Andronie, M. Iatagan, and I. Hurloiu, “Bioeconomy development and using of intellectual capital for the creation of competitive advantages by Smes in the field of biotechnology,” *Amfiteatru Econ.*, vol. 20, no. 49, pp. 947–666, 2018, doi: 10.24818/EA/2018/49/647.

[166] A. Demirbas, “Waste management, waste resource facilities and waste conversion processes,” *Energy Convers. Manag.*, vol. 52, no. 2, pp. 1280–1287, 2011, doi: 10.1016/j.enconman.2010.09.025.

[167] K. Gruduls, “Characteristics of wood chips from logging residues and quality influencing factors,” vol. 2, 2013.

[168] FAO, ITTO and United Nations, “Forest Product Conversion Factors | UNECE.” UNITED NATIONS PUBLICATION. Accessed: Aug. 29, 2023. [Online]. Available: https://unece.org/forests/publications/forest-product-conversion-factors

[169] “Fiber Insulation Board Lines by Dieffenbacher GmbH.” Accessed: Aug. 29, 2023. [Online]. Available: https://www.environmental-expert.com/products/fiber-insulation-board-lines-190613

[170] L. G. F. Tellnes, C. Ganne-Chedeville, A. Dias, F. Dolezal, C. Hill, and E. Z. Escamilla, “Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: A review study for construction materials based on forest products,” *IForest*, vol. 10, no. 5, pp. 815–823, 2017, doi: 10.3832/ifor2386-010.

[171] J. Pubule, D. Blumberga, F. Romagnoli, and M. Rochas, “Analysis of the environmental impact assessment of power energy projects in Latvia,” *Manag. Environ. Qual. Int. J.*, vol. 23, no. 2, pp. 190–203, Jan. 2012, doi: 10.1108/14777831211204930.

[172] B. G. E. News, “5 MWe biomass cogeneration plant officially opened in the city of Slatina,” Balkan Green Energy News. Accessed: Aug. 29, 2023. [Online]. Available: https://balkangreenenergynews.com/5-mwe-biomass-cogeneration-plant-officially-opened-in-the-city-of-slatina/

[173] “Combined Heat and Power Technology Fact Sheet Series: Thermal Energy Storage”.

[174] Danish Energy Agency and Energinet, “Technology Data for Generation of Electricity and District Heating.” Mar. 22, 2018. Accessed: Aug. 29, 2023. [Online]. Available: https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and

[175] T. Abbas, M. Issa, and A. Ilinca, “Biomass Cogeneration Technologies: A Review,” *J. Sustain. Bioenergy Syst.*, vol. 10, no. 1, Art. no. 1, Jan. 2020, doi: 10.4236/jsbs.2020.101001.

[176] I. Tsiropoulos, D. Tarvydas, and A. Zucker, “Cost development of low carbon energy technologies: Scenario-based cost trajectories to 2050, 2017 edition,” JRC Publications Repository. Accessed: Aug. 29, 2023. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC109894

[177] "Pieaug koksnes šķeldas cena, apkure ar šķeldu ir 5 reizes lētāka nekā ar dabasgāzi." Accessed: Aug. 29, 2023. [Online]. Available: https://lr1.lsm.lv/lv/raksts/eiro-fokusa/pieaug-koksnes-skeldas-cena-apkure-ar-skeldu-ir-5-reizes-letaka-.a155970/

[178] "Brīdina par gāzes cenas pieaugumu aprīlī līdz 250-300 eiro/MWh," Dienas Bizness. Accessed: Aug. 29, 2023. [Online]. Available: https://www.db.lv/zinas/bridina-par-gazes-cenas-pieaugumu-aprili-lidz-250300-eiromwh-506624

[179] O. US EPA, "Catalog of CHP Technologies." Aug. 23, 2015. Accessed: Aug. 29, 2023. [Online]. Available: https://www.epa.gov/chp/chp-technologies

[180] "Siltumnīcefekta gāzu emisiju aprēķina metodika." Accessed: Aug. 29, 2023. [Online]. Available: https://likumi.lv/doc.php?id=296651

[181] Harald Aalde (Norway), Patrick Gonzalez (USA), Michael Gytarsky (Russian Federation), Thelma Krug (Brazil), Werner A. Kurz (Canada), Stephen Ogle (USA), John Raison (Australia), Dieter Schoene (FAO), and N.H., Ravindranath (India), Nagmeldin G. Elhassan (Sudan), Linda S. Heath (USA), Niro Higuchi (Brazil), Samuel Kainja (Malawi), Mitsuo, and Matsumoto (Japan), María José Sanz Sánchez (Spain), and Zoltan Somogyi (European Commission/Hungary), "2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use."

[182] P. Vanninen, H. Ylitalo, R. Sievänen, and A. Mäkelä, "Effects of age and site quality on the distribution of biomass in Scots pine (Pinus sylvestris L.)," *Trees*, vol. 10, no. 4, pp. 231–238, Apr. 1996, doi: 10.1007/BF02185674.

[183] LVMI "Silava," "Nacionālais meža monitorings." Accessed: Aug. 29, 2023. [Online]. Available: https://www.silava.lv/petnieciba/nacionalais-meza-monitorings

[184] "Felling areas and stock volume | Oficiālās statistikas portāls." Accessed: Aug. 29, 2023. [Online]. Available: https://stat.gov.lv/en/statistics-themes/business-sectors/forestry/8922-felling-areas-and-stock-volume

[185] V. P. Ikonen, S. Kellomäki, and H. Peltola, "Linking tree stem properties of Scots pine (Pinus sylvestris L.) to sawn timber properties through simulated sawing," *For. Ecol. Manag.*, vol. 174, no. 1–3, pp. 251–263, 2003, doi: 10.1016/S0378-1127(02)00035-X.

[186] FAO, "Global Demand for Wood Products," *State Worlds For.*, p. 96, 2009.

[187] R. Järvinen, H. Rauhala, U. Holopainen, and H. Kallio, "Differences in suberin content and composition between two varieties of potatoes (Solanum tuberosum) and effect of post-harvest storage to the composition," *LWT - Food Sci. Technol.*, vol. 44, no. 6, pp. 1355–1361, 2011, doi: 10.1016/j.lwt.2011.02.005.

[188] O. Sawant, S. Mahale, V. Ramchandran, G. Nagaraj, and A. Bankar, "Fungal Citric acid production using waste materials: A mini-review," *J. Microbiol. Biotechnol. Food Sci.*, vol. 8, no. 2, pp. 821–828, 2018, doi: 10.15414/jmbfs.2018.8.2.821-828.

[189] T. Kleekayai and W. Suntornsuk, "Production and characterization of chitosan obtained from Rhizopus oryzae grown on potato chip processing waste," *World J. Microbiol. Biotechnol.*, vol. 27, no. 5, pp. 1145–1154, 2011, doi: 10.1007/s11274-010-0561-x.

[190] J. Qu, X. Zhao, Y. Liang, T. Zhang, P. X. Ma, and B. Guo, "Antibacterial adhesive injectable hydrogels with rapid self-healing, extensibility and compressibility as wound

dressing for joints skin wound healing," *Biomaterials*, vol. 183, pp. 185–199, Nov. 2018, doi: 10.1016/j.biomaterials.2018.08.044.

[191] S. K. Satpute, I. M. Banat, P. K. Dhakephalkar, A. G. Banpurkar, and B. A. Chopade, "Biosurfactants, bioemulsifiers and exopolysaccharides from marine microorganisms," *Biotechnol. Adv.*, vol. 28, no. 4, pp. 436–450, 2010, doi: 10.1016/j.biotechadv.2010.02.006.

[192] A. A. Agrawal and K. Konno, "Latex: A model for understanding mechanisms, ecology, and evolution of plant defense against herbivory," *Annu. Rev. Ecol. Evol. Syst.*, vol. 40, pp. 311–331, 2009, doi: 10.1146/annurev.ecolsys.110308.120307.

[193] Triveni Soubam and Arun Gupta, "Eco-friendly natural rubber latex and modified starch-based adhesive for wood-based panels application- A review," *Maejo Int. J. Energy Environ. Commun.*, vol. 3, no. 1, pp. 49–53, 2021, doi: 10.54279/mijeec.v3i1.245163.

[194] J. Thuraisingam, A. Gupta, and M. Subramaniam, "Natural Rubber Latex (NRL) and rice starch as an alternative binder in wood composite industry," *Aust. J. Basic Appl. Sci.*, vol. 10, no. 17, pp. 101–106, 2016.

[195] J. Epping *et al.*, "A rubber transferase activator is necessary for natural rubber biosynthesis in dandelion," *Nat. Plants*, vol. 1, no. 5, pp. 1–9, 2015, doi: 10.1038/NPLANTS.2015.48.

[196] M. Alinejad *et al.*, "Lignin-Based Polyurethanes: Opportunities for Bio-Based Foams, Elastomers, Coatings and Adhesives," *Polymers*, vol. 11, no. 7, p. 1202, 2019, doi: 10.3390/polym11071202.

[197] F. H. Isikgor and C. R. Becer, "Lignocellulosic biomass: a sustainable platform for the production of bio-based chemicals and polymers," *Polym. Chem.*, vol. 6, no. 25, pp. 4497–4559, 2015, doi: 10.1039/c5py00263j.

[198] X. Pan, Y. Tian, J. Li, Q. Tan, and J. Ren, "Bio-based polyurethane reactive hot-melt adhesives derived from isosorbide-based polyester polyols with different carbon chain lengths," *Chem. Eng. Sci.*, vol. 264, p. 118152, 2022, doi: 10.1016/j.ces.2022.118152.

[199] L. A. Heinrich, "Future opportunities for bio-based adhesives-advantages beyond renewability," *Green Chem.*, vol. 21, no. 8, pp. 1866–1888, Apr. 2019, doi: 10.1039/c8gc03746a.

[200] S. Cui, X. Luo, and Y. Li, "Synthesis and properties of polyurethane wood adhesives derived from crude glycerol-based polyols," *Int. J. Adhes. Adhes.*, vol. 79, no. April, pp. 67–72, 2017, doi: 10.1016/j.ijadhadh.2017.04.008.

[201] Y. Fahmy, N. A. El-Wakil, A. A. El-Gendy, R. E. Abou-Zeid, and M. A. Youssef, "Plant proteins as binders in cellulosic paper composites," *Int. J. Biol. Macromol.*, vol. 47, no. 1, pp. 82–85, 2010, doi: 10.1016/j.ijbiomac.2010.03.012.

[202] M. Flambeau, A. Redl, and F. Respondek, *Proteins From Wheat: Sustainable Production and New Developments in Nutrition-Based and Functional Applications*. Elsevier Inc., 2016. doi: 10.1016/B978-0-12-802778-3.00004-4.

[203] H. N. Cheng, Z. He, C. H. Li, J. M. Bland, and P. J. Bechtel, "Preparation and evaluation of catfish protein as a wood adhesive," *Int. J. Polym. Anal. Charact.*, vol. 26, no. 1, pp. 60–67, 2021, doi: 10.1080/1023666X.2020.1844361.

[204] I. Yang, G. S. Han, S. H. Ahn, I. G. Choi, Y. H. Kim, and S. C. Oh, “Adhesive properties of medium-density fiberboards fabricated with rapeseed flour-based adhesive resins,” *J. Adhes.*, vol. 90, no. 4, pp. 279–295, 2014, doi: 10.1080/00218464.2013.793161.

[205] A. Kokel and B. Török, “Sustainable production of fine chemicals and materials using nontoxic renewable sources,” *Toxicol. Sci.*, vol. 161, no. 2, pp. 214–224, 2018, doi: 10.1093/toxsci/kfx214.

[206] I. Muizniece and D. Blumberga, “Thermal Conductivity of Heat Insulation Material Made from Coniferous Needles with Potato Starch Binder,” *Energy Procedia*, vol. 95, pp. 324–329, 2016, doi: 10.1016/j.egypro.2016.09.014.

[207] R. F. Tester, J. Karkalas, and X. Qi, “Starch structure and digestibility Enzyme-Substrate relationship,” *Worlds Poult. Sci. J.*, vol. 60, no. 2, pp. 186-195+248+250, 2004, doi: 10.1079/WPS20040014.

[208] J. Santos, N. Delgado, J. Fuentes, C. Fuentealba, J. Vega-Lara, and D. E. García, “Exterior grade plywood adhesives based on pine bark polyphenols and hexamine,” *Ind. Crops Prod.*, vol. 122, 2018, doi: 10.1016/j.indcrop.2018.05.082.

[209] S. Janceva *et al.*, “Eco-Friendly Adhesives Based on the Oligomeric Condensed Tannins-Rich Extract from Alder Bark for Particleboard and Plywood Production,” *Materials*, vol. 15, no. 11, Art. no. 11, Jan. 2022, doi: 10.3390/ma15113894.

[210] P. Korkalo *et al.*, “Clonal Variation in the Bark Chemical Properties of Hybrid Aspen: Potential for Added Value Chemicals,” *Molecules*, vol. 25, no. 19, Art. no. 19, Jan. 2020, doi: 10.3390/molecules25194403.

[211] J. Rizhikovs *et al.*, “Characterization of suberinic acids from birch outer bark as bio-based adhesive in wood composites,” *Int. J. Adhes. Adhes.*, vol. 112, p. 102989, Jan. 2022, doi: 10.1016/j.ijadhadh.2021.102989.

[212] E. Norström, L. Fogelström, P. Nordqvist, F. Khabbaz, and E. Malmström, “Xylan - A green binder for wood adhesives,” *Eur. Polym. J.*, vol. 67, pp. 483–493, May 2015, doi: 10.1016/j.eurpolymj.2015.02.021.

[213] N. K. Sini, J. Bijwe, and I. K. Varma, “Thermal behaviour of bis-benzoxazines derived from renewable feed stock ‘vanillin,’” *Polym. Degrad. Stab.*, vol. 109, pp. 270–277, 2014, doi: 10.1016/j.polymdegradstab.2014.07.015.

[214] B. R. F. da Silva *et al.*, “PROPERTIES OF CROSS-LAMINATED TIMBER BONDED WITH AN ADHESIVE BASED ON TANNINS FROM THE BARK OF Mimosa tenuiflora TREES,” *Rev. Arvore*, vol. 46, pp. 1–10, 2022, doi: 10.1590/1806-908820220000020.

[215] A. Mahieu, A. Vivet, C. Poilane, and N. Leblanc, “Performance of particleboards based on annual plant byproducts bound with bio-adhesives,” *Int. J. Adhes. Adhes.*, vol. 107, p. 102847, Jun. 2021, doi: 10.1016/j.ijadhadh.2021.102847.

[216] “Expression of bovine .beta.-casein in Saccharomyces cerevisiae and characterization of the protein produced in vivo | Journal of Agricultural and Food Chemistry.” Accessed: Aug. 21, 2023. [Online]. Available: https://pubs.acs.org/doi/pdf/10.1021/jf00094a049

[217] B. Rivela, M. T. Moreira, and G. Feijoo, “Life Cycle Inventory of Medium Density Fibreboard,” no. May, 2007, doi: 10.1065/lca2006.12.290.

[218] M. Jones, A. Mautner, S. Luenco, A. Bismarck, and S. John, “Engineered mycelium composite construction materials from fungal biorefineries: A critical review,” *Mater. Des.*, vol. 187, p. 108397, Feb. 2020, doi: 10.1016/j.matdes.2019.108397.

[219] M. Kalverkamp, A. Pehlken, and T. Wuest, “Cascade use and the management of product lifecycles,” *Sustain. Switz.*, vol. 9, no. 9, 2017, doi: 10.3390/su9091540.

[220] L. Zihare, A. Kubule, I. Vamza, I. Muizniece, and D. Blumberga, “Triple factor nexus in bioeconomy through indicator analysis,” *New Biotechnol.*, vol. 61, no. November 2020, pp. 57–68, 2020, doi: 10.1016/j.nbt.2020.11.008.

[221] E. Uyarra, P. Shapira, and A. Harding, “Low carbon innovation and enterprise growth in the UK: Challenges of a place-blind policy mix,” *Technol. Forecast. Soc. Change*, vol. 103, pp. 264–272, 2016, doi: 10.1016/j.techfore.2015.10.008.

[222] Å. Davidsson, C. Gruvberger, T. H. Christensen, T. L. Hansen, and J. la C. Jansen, “Methane yield in source-sorted organic fraction of municipal solid waste,” *Waste Manag.*, vol. 27, no. 3, pp. 406–414, 2007, doi: 10.1016/j.wasman.2006.02.013.

[223] Z. Dvulit, O. Melnyk, Y. Chyrkova, N. Petryshyn, and M. Bortnikova, “Diagnostics of the structural risk level in the sphere of waste management at Ukrainian railways,” *MATEC Web Conf.*, vol. 294, p. 02005, 2019, doi: 10.1051/matecconf/201929402005.

[224] J. Á. Del Brío and B. Junquera, “A review of the literature on environmental innovation management in SMEs: Implications for public policies,” *Technovation*, vol. 23, no. 12, pp. 939–948, 2003, doi: 10.1016/S0166-4972(02)00036-6.

[225] M. K. Linnenluecke, A. Stathakis, and A. Griffiths, “Firm relocation as adaptive response to climate change and weather extremes,” *Glob. Environ. Change*, vol. 21, no. 1, pp. 123–133, Feb. 2011, doi: 10.1016/j.gloenvcha.2010.09.010.

[226] F. Gasbarro, F. Rizzi, and M. Frey, “Adaptation Measures of Energy and Utility Companies to Cope with Water Scarcity Induced by Climate Change,” *Bus. Strategy Environ.*, vol. 25, no. 1, pp. 54–72, Jan. 2016, doi: 10.1002/bse.1857.

[227] I. Sidhu, “Profiles in Doing Both: Mike Yurosek, Father of the ‘Baby Carrot,’” Forbes. Accessed: Mar. 20, 2020. [Online]. Available: https://www.forbes.com/sites/indersidhu/2010/11/04/profiles-in-doing-both-mike-yurosek-father-of-the-baby-carrot/#4b07b50228d9

[228] D. Mitra, J. (Hans) van Leeuwen, and B. Lamsal, “Heterotrophic/mixotrophic cultivation of oleaginous Chlorella vulgaris on industrial co-products,” *Algal Res.*, vol. 1, no. 1, pp. 40–48, 2012, doi: 10.1016/j.algal.2012.03.002.

[229] T. Heredia-Arroyo, W. Wei, R. Ruan, and B. Hu, “Mixotrophic cultivation of Chlorella vulgaris and its potential application for the oil accumulation from non-sugar materials,” *Biomass Bioenergy*, vol. 35, no. 5, pp. 2245–2253, 2011, doi: 10.1016/j.biombioe.2011.02.036.

[230] C. D. Tanzi, M. A. Vian, C. Ginies, M. Elmaataoui, and F. Chemat, “Terpenes as green solvents for extraction of oil from microalgae,” *Molecules*, vol. 17, no. 7, pp. 8196–8205, 2012, doi: 10.3390/molecules17078196.

[231] C. A. Dehelean *et al.*, “Study of the betulin enriched birch bark extracts effects on human carcinoma cells and ear inflammation,” *Chem. Cent. J.*, vol. 6, no. 1, pp. 1–9, Nov. 2012, doi: 10.1186/1752-153X-6-137.

[232] S. Rafiq, R. Kaul, S. A. Sofi, N. Bashir, F. Nazir, and G. Ahmad Nayik, “Citrus peel as a source of functional ingredient: A review,” *J. Saudi Soc. Agric. Sci.*, 2018, doi: 10.1016/j.jssas.2016.07.006.

[233] B. Escaramboni, E. G. Fernández Núñez, A. F. A. Carvalho, and P. de Oliva Neto, “Ethanol biosynthesis by fast hydrolysis of cassava bagasse using fungal amylases produced in optimized conditions,” *Ind. Crops Prod.*, vol. 112, no. December 2016, pp. 368–377, 2018, doi: 10.1016/j.indcrop.2017.12.004.

[234] J. D. SELMAN, P. PRICE, and R. K. ABDUL-REZZAK, “A study of the apparent diffusion coefficients for solute losses from carrot tissue during blanching in water,” *Int. J. Food Sci. Technol.*, vol. 18, no. 4, pp. 427–440, 1983, doi: 10.1111/j.1365-2621.1983.tb00285.x.

[235] G. Da, D. Dufour, C. Marouzé, M. L. Thanh, and P. A. Maréchal, “Cassava starch processing at small scale in North Vietnam,” *Starch/Staerke*, vol. 60, no. 7, pp. 358–372, 2008, doi: 10.1002/star.200800202.

FULL PUBLICATIONS IN THE FOLLOWING ORDER:

1. A Review of Bio-Based Adhesives from Primary and Secondary Biomass for Wood Composite Applications
   Vamza, I., Krigers, G., Valters, K.
   Environmental and Climate Technologies, 2022, 26(1), pp. 1350–1360
2. Logging residues as a future for engineered wood
   Krumins J. A., Vamza I., Dzalbs A., Blumberga, D.
   Sustainability (subbmitted and rviewed manuscript)
3. Life Cycle Assessment of Reprocessed Cross Laminated Timber in Latvia
   Vamza, I., Diaz, F., Resnais, P., Radziņa, A., Blumberga, D.
   Environmental and Climate Technologies, 2021, 25(1), pp. 58–70
4. Complete Circularity in Cross-Laminated Timber Production
   Vamza, I., Valters, K., Luksta, I., Resnais, P., Blumberga, D.
   Environmental and Climate Technologies, 2021, 25(1), pp. 1101–1113
5. Criteria for choosing thermal packaging for temperature sensitive goods transportation
   Vamza, I., Valters, K., Dzalbs, A., Kudurs, E., Blumberga, D.
   Environmental and Climate Technologies, 2021, 25(1), pp. 382–391
6. Bioeconomy triple factor nexus through indicator analysis
   Zihare, L., Kubule, A., Vamza, I., Muizniece, I., Blumberga, D.
   New Biotechnology, 2021, 61, pp. 57–68
7. CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios
   Viksne, G., Vamža, I., Terjanika, V., ...Pubule, J., Blumberga, D.
   Environmental and Climate Technologies, 2022, 26(1), pp. 1158–1168
8. Bioresource utilization index – A way to quantify and compare resource efficiency in production
   Vamza, I., Kubule, A., Zihare, L., Valters, K., Blumberga, D.
   Journal of Cleaner Production, 2021, 320, 128791

Appendixes

Environmental and Climate Technologies
2022, vol. 26, no. 1, pp. 1350–1360
https://doi.org/10.2478/rtuect-2022-0102
https://content.sciendo.com

A Review of Bio-Based Adhesives from Primary and Secondary Biomass for Wood Composite Applications

Ilze VAMZA[1*], Guntars KRIGERS[2], Karlis VALTERS[3]

[1–3]*Institute of Energy Systems and Environment, Riga Technical University, Azenes street 12/1, Riga LV-1048, Latvia*

Abstract **– Today there is a great demand in the market of wood-based panels like medium density fibreboard (MDF), plywood and oriented strand board (OSB). These boards provide functionality in various industrial fields from building to furniture production. All are produced from timber and some type of binding resin, the most often used in Europe are phenol formaldehyde (FF), isocyanate (MDI) and melamine urea formaldehyde (MUF). These resins guarantee sturdiness of the material but are toxic to humans and makes recycling of the wood-based panels very difficult. There are attempts of wood-based panels industry to transition away from fossil-based adhesives. Various resins have been developed using lignin and tannin or protein. Soy based adhesive SOYAD™ has already reached the market, other soy protein-based adhesives are integrated into ultra-low formaldehyde emission particle boards like Nu green 2® and Transform™. This paper gives an overview on bio-based adhesives that are used or have the potential to be used for wood-based panel production.**

Keywords **– Bioresources; plant-based; polyaddition; polycondensation; polymerization; urea-formaldehyde; wood composites**

1. INTRODUCTION

Adhesives are required for many fields of engineering, engineered wood products are no exception. Fibres in timber have great load bearing properties, but the strength of these fibres decreases dramatically when applied in any other way than perpendicular to the longitudinal axis [1]. Engineered wood products are created to even out the load bearing properties of timber by disrupting the natural timber structure and binding the biomass back together with adhesives. Wood-based panels (WP) can be used for construction and carpentry applications. The application of WP depends on their characteristics, such as hardness, surface properties, strength and composition. An important property of WP is moisture resistance; greater resistance can be acquired by the right adhesive or coating. One of the most popular WP are: particle boards (PB), fibreboards, oriented strand boards (OSB). Density of the boards ranges from 650 kg m^3 to 1000 kg m^3 [2]. Fibreboards are classified by density – low density fibreboards (LDF) with 400–600 kg/m^3, medium density fibreboard (MDF) 600–750 kg/m^3 and high-density fibreboard (HDF) with up to 1000 kg/m^3 density [3]. For easier processing and for economic reasons, wood panels are mostly made of softwood. Fibreboards usually use synthetic adhesive such as urea-formaldehyde, melamine-formaldehyde or phenol-formaldehyde [4]. Hardening adhesives are easy to handle with woodworking tools, hence in

---

[*] Corresponding author.
E-mail address: Ilze.Vamza@rtu.lv

woodworking industry they are preferred over elastic adhesives. Downside of these popular formaldehyde adhesives is their formaldehyde emissions which are toxic to living organisms. The constant demand of wood-base panels in European Union market 2013 – 57 700 thousand m^3; 2014 – 68 800 thousand m^3; 2015 – 64 400 thousand m^3; 2016 – 65 000 thousand m^3 is forcing the development of new products [5].

To make the WP industry more sustainable and use of its products safer, greener adhesive options need to be considered. Despite the upper hand of green adhesives regarding sustainability and health benefits, greener adhesives fail to meet industry's requirements of high strength of internal bonds, dimensional stability, temperature resistance, fast curing, and good viscosity regulation [6].

The focus of this article is on working principles of bio-adhesives like lignin, plant protein, fatty acids and carbohydrates. This paper provides an overview of the working principles and accessibility of raw material for these adhesives. The current situation and possible technologies for the development of a bio-binder and the basis of previous research are reviewed in this article.

2. WHAT MAKES CHEMICALS STICKY

Adhesives have the properties to stick materials together – whether it is surface to surface or internally in the material [7]. Adhesion principles vary; hence it is important to be acquainted to them before choosing the right adhesive for a specific application.

The smallest unit of a substance – a molecule is held together by covalent bonds between its atoms. At the macro level the substance is held together by hydrogen, van der Waals or electrostatic forces. Such interactions in a substance are called cohesion and are influenced by cohesion forces. The effect between the surfaces of substances, on the other hand, is called adhesion – the forces of adhesion determine the specific work required to separate these surfaces [8]. The sum of these two forces – cohesion and adhesion, determines whether surface wetting will occur when a solid and a liquid interact.

Drops of the same volume of different substances on the same surface will form different shapes – with different contact area and droplet geometry. On hygroscopic surface the water drop will be more compact, while the olive oil drop will be rounder. A contact angle will form between the air layer, the surface, and the droplet. There is a direct relationship between this angle and adhesion – the narrower the angle, the greater the adhesion. Efficient adhesive has a strong cohesive, and strong adhesion [9]. Materials and their surface properties differ, hence different adhesives are created to adhere to specific surfaces.

Fluids that can act as an adhesive are also characterized by viscoelasticity. This means that these fluids are viscous – slow flowing and at the same time flexible – they try to return to their original state [10], [11]. The natural viscoelastic substance is honey – it is viscous and sticky. Honey appears sticky when taken between the fingers, it wets the skin and has strong cohesion and adhesion to skin.

The principle of adhesion includes both mechanical binding and specific binding. Mechanical binding occurs when the adhesive enters the texture of the surface on which it is poured. Specific adhesion includes electrostatic forces – van der Waals forces, hydrogen bonds [12], or even covalent bonds if chemical reactions also take place between the surface and the adhesive. It is often observed that the adhesion between two glued surfaces becomes stronger over time, this is because due to its viscosity it slowly flows into the finer grooves of the surface, increasing the surface between the glued materials and the adhesive, thus increasing the total adhesion.

There are cases when better mechanical adhesion can be achieved by diluting the adhesive with a more flowing solvent – thus reducing its viscosity. This approach allows the adhesive to fill the surface relief of the substrate faster, in this case the challenge is to get rid of the solvent, because only when the adhesive regains its original viscosity or even hardens, adhesion is ensured [13]. Some solvents, like acetone, evaporate rapidly, but solvents like water take longer time.

2.1. Types of fossil-based adhesives used in industry (e.g., polyvinyl acetate, urea-formaldehyde, and others)

High throughput production plants are characteristic to wood-based industry. Particleboard production plants can have as high throughputs as 500 thousand m^3/year [14]. Although adhesive comprises only 2 to 5 % of the final wood-based board, it makes up for up to 25 % of the product costs, therefore making a great impact on production profitability. This promotes the research and development of new and improved adhesives, nevertheless popular synthetic adhesives are industry standards – providing durability and resistance to water [3].

For gluing wood substrate, the popular polyvinyl acetate (PVA) water emulsion is produced in factory reactors from vinyl acetate monomers. The polymerization reaction is catalysed by the free radicals formed from decomposition of hydrogen peroxide, inorganic persulphates or organic hydroperoxides. Polymerization in this case is by-product free, as nothing else is created in the chemical reaction. As PVA glue is an aqueous solution of different concentrations of PVA, the glue only starts to hold the surfaces together when the water has evaporated [15], therefore it takes time for the process to take place passively, if faster curing is required, forced convection can be applied.

An alternative to increasing the adhesion strength of adhesive solutions is chemical hot-melt adhesives such as the well-known polyamide [16], polyolefins, polyester and polyurethane. The basic principle of these adhesives is similar to the already mentioned PVA adhesive – they are synthetic polymers that do not chemically react with the substrate. Depending on the adhesive, they have a specific melting temperature at which it passes into the liquid phase, but as the temperature decreases, it returns to the solid phase [11]. Choosing the wrong temperature to melt them can release volatile compounds from the polymer, creating an unpleasant ‘burnt plastic’ odour [17]. Hot melt adhesives have been available for many decades and are widely used, however, they have performance limitations such as poor heat resistance, low resistance to UV radiation, and water or solvent permeability [16]. However, the wide application of such adhesives is determined by their diversity – each type has copolymer variants, providing a range of performance properties according to the desired application. Depending on the application, many forms of hot melt adhesives (granules, blocks, films, tubes) [11] and application patterns (dots, spiral spraying or continuous lines, etc.) are available on the market [18]. Hot melt films are ideal for laminating a wide range of fabrics and making joints without seams, for example in the manufacture of fabric raincoats.

The variation of the glue application method allows to control costs – consuming only as much material and energy as needed for the specific case. As such, adhesives are generally difficult to spray due to the need for uniform temperature, contact with cooler air allows them to cool faster. Therefore, in practice it is customary to apply the adhesive in the form of a powder [11] – it provides less difficulty in storing the adhesive compared to the film, to ensure a thin layer of application on the substrate. Most hot melt adhesives are available in powder form in a variety of particle size ranges. Polyester and melamine urea formaldehyde in the form of fibres are used in the production of thermal insulation wool – for bonding glass, and stone, as well as various alternative ecological substrates [19].

Chemical adhesives are essentially like the adhesive solutions mentioned above, the difference being that the polymers are formed directly between the substrates and are not previously formed and dissolved to make a low viscosity solution. There are three polymer formation reactions:

1. Polymerization (unbound polyester adhesives, cyanoacrylates, anaerobic adhesives) [20];
2. Polycondensation (polyamides, phenolic adhesives and silicones) [19];
3. Polyaddition (epoxides, polyurethane, and silicone adhesives) [21].

Such adhesives consist of fillers, monomers, catalysts, and other additives such as reaction accelerators or inhibitors that promote a slower and more uniform formation of polymers. The properties of such adhesives have several advantages – resistance to high temperatures > 200 °C, silicone-based adhesives can withstand above 200 °C temperatures. These properties are suitable for aerospace applications where strength may not be compromised by high temperatures [22]. Most types of adhesives lose their strength at around 60 °C [23]. The high heat resistance can be used for improving plywood resistance to fire, by replacing the polyurethane adhesive in the outer most layers of veneer with silicone based elastomer with fire retardant additives [22].

Synthetic polymers can have high resistance to abrasion [24], and bending [25], withstanding up to 40 MPa mechanical forces. Therefore, such adhesives are used in cases where they must withstand heavy loads, such as in the production of particle board. Polyurethane adhesives have excellent flexibility withstanding repeated elongation – up to 60 % before breakage [26].

It is also possible to glue metals using adhesion forces, for this purpose resins are usually used, they are a type of anaerobic glue. Once they have hardened – polymerization has taken place, they are difficult to deform. They are used in the assembly of joints (by gluing metal screws) and are known for their 'locking' ability. The specificity of the resin is that the polymerization takes place only when oxygen has been removed from the system [27]. However, this is not difficult to achieve, as the compounds for which the resin is used are usually sealed.

2.2. Bio-based adhesives

The first adhesives were exclusively of organic origin, even back in the 20th century [28]. At the beginning of World War I, bio-based polymer solution in water was often used as adhesive. First analogue of PVA glue was a starch solution in water. This solution has the same working principle – when the water evaporates, long polymer molecules, in this case – starch, are left behind on the surface [28]. Starch is a polysaccharide made up of glucose molecules linked by α-1-4 or α-1-6 glycosidic bonds [29]. Therefore, similar to PVA, starch solution penetrates the pores of the substrate and, when the starch molecules intersect, they are mechanically bonded together when water has completely evaporated. Starch is formed in plants as energy reserves, so it is easily available, it is obtained from grains, legumes, potatoes and corn [29]. Bone glue was another bio-based polymer-water solution. Bone glue was obtained from animal connective tissues by boiling them. In this case, the polymer that acts as an adhesive is collagen, a protein that *in vivo* provides tissue elasticity. Collagen consists of long protein molecules that are usually linked together by sticky amino acid residues. When these bonds break under the influence of elevated temperatures, the sticky ends are released and as the temperature decreases, they again adhere chaotically to each other and to the substrate by electrostatic forces [10]. Additional benefit of such adhesive is the sustainability of raw material – as secondary bioresource, bones are residues and do not compete with food resources [30].

Over time, these protein adhesives were improved, and denaturants and crosslinkers were added to soybean protein adhesives to improve their water resistance, shelf life, and consistency of durability. The added substances were urea, sulphur compounds and inorganic salt complexes. Each of these groups of compounds reacts with the components of soybean meal, starch and protein [13]. Formaldehyde used to be additive to soy protein, as formaldehyde itself cures very well, but it hardens too quickly and is therefore difficult to control when used alone.

However, there are health risks associated with formaldehyde, so solutions are being sought to reduce the amount of formaldehyde in wood products used indoors. One such way, without significantly reducing the mechanical properties of the material is to replace part of the formaldehyde with lignin. This method is not new, however, with increasing public health concerns, a few MPa reductions in material strength are not as significant as the reduced health risks. Lignin is a natural aromatic polymer that contains cellulose fibres, forming lignocellulose found in the walls of plant cells and ensuring their firmness. Cellulose is mechanically bound to lignin - cellulose is structurally similar to starch – made from glucose molecules, which are bound together by β-1,4-glycosidic bonds, while lignin forms a complex lattice by tying filamentous cellulose fibres. The production of cellulose pulp produces significant residues of lignin, as it is found in wood in similar amounts as cellulose [31]. Depending on the pulp production method, several types of lignin are formed. The chemical extraction of pulp is either sulphite or alkaline. Sulphite pulp is pulverized with sulphite under acidic or alkaline conditions [32]. This process produces lignosulphonate, which is quite high in molasses, but the sulphonic acid in the solution keeps this lignin in solution. Sulphonic acid groups ensure the surfactant properties and hygroscopicity of lignosulphonate. These properties of lignin make it a suitable emulsifier and adhesive. However, in the context of adhesives, these properties, and the poor ability of the lignosulphonate to bind to, for example, phenol-formaldehyde adhesive mean that it is not suitable for application in formaldehyde resins. In turn, lignin obtained by alkaline pulping has several phenolic hydroxy groups, which allows it to bind to phenylpropanoid groups [33].

As the above-mentioned synthetic adhesives have been proven to be the most effective in achieving the performance of wood fibre panels, only reduction in the concentration of these adhesives in search for various natural fillers such as lignin can be seen in production [34].

2.3. Sources of bio-based adhesives

Bio-based adhesives and their corresponding sources are depicted in Table 1.

TABLE 1. BIOBASED ADHESIVES AND THEIR USES FROM SCIENTIFIC LITERATURE

Biological source	**Compound**	**Polymer formation reaction**	**Primary raw material***	**Uses**	**References**
Penicillium oxalicum	Anhydrous citric acid	Polycondensation	No	Wood composites	[35], [36]
Shrimp and other crustaceans	Chitosan (Carbohydrate)	Polycondensation	No	Medicine, wood composites	[37], [38], [46]
Vibrio parahaemolyticus	Exopolysaccharides	Polyaddition	No	Research, low technology readiness	[39]
Flowering plants	Latex (Isopropene)	Polymerization	Yes	Wood composites	[28], [40]–[42]

Biological source	Compound	Polymer formation reaction	Primary raw material*	Uses	References
Wood	Lignin (Aromatic polymer)	Polycondensation	No	Wood composites, foams	[43], [44]
Oleaginous plants	Polyols	Polyaddition	Yes	Wood composite, foam	[8], [45], [46]
			No	Wood composites	[45], [47]
Wheat	Protein	Polycondensation	Yes	Paper	[48], [49]
Fish	Protein	Polycondensation	No	Wood composites	[50]
Rapeseed cake	Protein, carbohydrates, and other residues after oil press	Polycondensation	No	Wood composites	[51]
Potatoes	Starch (Carbohydrate)	Polycondensation	Yes	Packaging	[29], [52], [53]
Tree bark, cork	Suberin	Polycondensation	No	Wood composites	[54], [44]
Potato tubers		Polycondensation	No	Research, low technology readiness	[35]
Flowering plants	Tannin (Polyphenol)	Polyaddition	Yes	Wood composites	[6], [55]
Wood	Hemicellulose (Carbohydrate)	Polycondensation	No	Wood composites	[44], [56]
	Vanillin (Phenol)	Polycondensation	No	High temperature environment	[57]
Vanilla planifola	Vanillin (Phenol)	Polycondensation	Yes	High temperature environment	[57], [58]

* Biological source marked as "No" is classified as secondary or tertiary raw material.

Additives such as citric acid and 1,2,3,4-butanetetracarboxylic acids may be added to increase the performance (strength and resistance to moisture) of natural binders and to facilitate their use [7]. The use of organic acids in adhesives or their production is a common approach. For example, citric acid as a crosslinker and a hydrolytic agent can be used as a plasticizer in starch matrices due to its structural properties. Another organic substance which can be used as an alternative to formaldehyde resins are tannins because they have many phenolic rings in their structure. Citric acid promotes the reaction of tannin and sucrose at lower temperatures, thus potentially reducing energy consumption. An alternative to citric acid can be ricinoleic acid, which can be obtained from renewable sources – castor oil [6]. Ricinoleic acid is a C18 fatty acid that is also used in the production of lubricants, its properties are made so different by the dual nature of fatty acids – their acid functional group makes them polar, while the long tail of the molecule has non-polar properties [59]. Tannins, in addition to greater mechanical strength, also help protect the material from water. To make the adhesive easier to work with, it is desirable to obtain a relatively flowing consistency to avoid unnecessary consumption and ensure the homogeneity of the material [6], [60]. As already mentioned, a more fluid adhesive that flows into the gaps in the surface of the substrate increases the contact surface between the surfaces of the substrate, thus also increasing the tensile strength and modulus of elasticity. Proportions vary, but experiments show that acid concentration in solution should be around 25 % in order to achieve the desired viscosity [6], [7].

Alternatively, it is possible to follow the path of the synthetic additive by adding vinyl acetate to the starch. In this case, the long starch molecules are crosslinked with smaller vinyl acetate molecules that could be linked to the hydroxyl group of glucose by ester bonds. This process is called grafting as the smaller monomers are added on the sides of starch polymer [61]. Such addition of synthetic excipients can increase not only the mechanical strength, but also the water repellence. Vinyl acetate prohibits water penetration, but starch on the other hand forms hydrogen bonds – it attracts water and swells very easily, which in turn reduces the mechanical strength of the material [61]. Samyn describes some biomimetic and gene engineering solutions for green adhesives, but at this point these approaches are at low technology readiness levels [62].

Starch structure – its branching intensity, also differ from plant to plant. Hence different results can be achieved from corn [63], cassava [64] and other starch sources [10], [65].

Chitin is a similar natural polymer to starch and cellulose. It forms the cell membranes of fungi as well as the exoskeletons of invertebrates. The chitin monomer is glucose, which, like cellulose, is linked by β-1,4-glycoside bonds, the difference being that the hydroxyl group at carbon 4 in the glucose monomer is replaced by an acetyl amine group. Chitin, unlike cellulose, also contains nitrogen. By treating chitin with alkali, it can be hydrolysed to smaller oligosaccharides. Chitosan is obtained in this way, but it must be deacylated by treatment with an organic acid, such as acetic acid, to make it sticky. The obtained glue can be used not only for gluing timber, but also for wound treatment, helping to stop bleeding. There is evidence that chitosan can be used as coagulant in wastewater treatment plants [66]. Chitosan is electrostatically attracted to negatively charged surfaces, which is possible because the deacylation of chitin leaves a free $-NH3^+$ group [67], [68]. The polarity of chitosan means that this adhesive also binds water well, so the properties of the wood deteriorate in the presence of water.

The positive aspect of chitosan is its production potential from the production residues of other products, so it can become a by-product, such as in production of shelled shrimp [67].

Another promising adhesive derived from natural raw materials is polyol adhesive. It can be obtained by transesterification of vegetable oil with glycosylated starch [8]. Higher hydroxyl content in polyol improve the bond strength, hence making these polyols more suitable for wood-based panel production [63], but are not compostable at the end of their life cycle [69]. Polyols are transesterified fatty acids, when they are joined by ester bonds, there are few microorganisms or enzymes in nature that could break them down. Polyurethane, on the other hand, is obtained by reacting isocyanate with fatty acids, the biggest negative aspect of which is toxic cyanide [55] when it is formed during combustion, so flame retardants are always added to polyurethanes, which makes it more difficult to process at the end of its life [70]. Due to cyanide safety issues, nonisocyanide polyurethanes (NIPUs) are developed by using tannins as isocyanide replacement [55].

With the push and support from policy makers to green chemistry, safer adhesives have been developed but at this point there are only few available on the market [71], [72], but at this time they do not reach the >95 % bio-based components requirements. Most of the adhesives' summarized in Table 1 working principle is based on condensation reactions as in urea-formaldehyde. Research in bio-based adhesives field could be divided into multiple groups – specific compounds (latex, vanillin), compound groups (e.g., lignin, hemicellulose, suberin), and non-specific substances with adhering properties (e.g., bark powder). Although all might result in good adhering properties, the specific compound development would be favourable in industry as can ensure the most persistent product quality for the user.

3. CONCLUSION

Finding a sustainable raw material, and persistent product quality are the main challenges in the field of bio-based adhesives. Nevertheless, research papers rarely investigate potential costs and possible production volumes. As discussed in this review, adhesive costs make up a considerable part of total wood composite production costs. In addition, large throughput of wood composite production plants requires adhesives that are available in required quantities and for a price that cannot be higher than synthetic fossil-based options already used in the industry.

Product integrity is still and will continue to be a topical issue, as bio-based adhesives are prone to damage from water. There is more success with bio-based adhesives in medicine and food production where the water attraction is beneficial. According to the bio-based adhesives state of the art, lignin and polyols are the most suitable for wood-based panel applications. Biotechnology and biomimicry approaches are rarely used in adhesives research, hence at this point, it is unclear whether these fields will have a significant impact on bio-based adhesives' further development.

Plant material has been the main raw material for research on bio-based adhesives. Adhesives are widely used and sold for relatively low prices as bulk chemicals, hence research on plant-based adhesives should be propelled by the availability of secondary plant biomass, possible production volumes of the bio-based adhesive and potential market price of the bio-based adhesive.

ACKNOWLEDGMENT

This work has been supported by the European Social Fund within the Project No 8.2.2.0/20/I/008 «Strengthening of PhD students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization» of the Specific Objective 8.2.2 "To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialization Areas" of the Operational Programme "Growth and Employment".

REFERENCES

[1] De Almeida T. H., de Sousa A. M., Martins A. S. M., Christoforo A. L., de Almeida D. H., Lahr F. A. R. Effect of service temperature on shear strength of Pinus wood for roof structures. *Acta Scientiarum. Technology* 2018:40. https://doi.org/10.4025/actascitechnol.v40i1.30913

[2] Ferreira A. M. *et al.* Biosourced binder for wood particleboards based on spent sulfite liquor and wheat flour. *Polymers (Basel).* 2018:10(10). https://doi.org/10.3390/polym10101070

[3] Irle M., Thoemen H., Sernek M. Wood-based panel technology. An Introduction for Specialists. Brunel University Press, 2010.

[4] Salem M. Z. M., Böhm M., Barcík Š., Beránková J. Emisija formaldehida iz drvnih ploča s različitim ljepilima na Bazi formaldehida. (Formaldehyde emission from wood panels with different formaldehyde-based adhesives). *Drv. Ind.* 2011:62(3):177–183. https://doi.org/10.5552/drind.2011.1102 (In Croatian).

[5] Solt P. *et al.* Technological performance of formaldehyde-free adhesive alternatives for particleboard industry. *Int. J. Adhes. Adhes.* 2019:94:99–131. https://doi.org/10.1016/j.ijadhadh.2019.04.007

[6] Teixeira D. E., Pereira D. D. C., Nakamura A. P. D., Brum S. S. Adhesivity of bio-based anhydrous citric acid, tannin-citric acid and ricinoleic acid in the properties of formaldehyde-free medium density particleboard (MDP). *Drv. Ind.* 2020:71(3):235–242. https://doi.org/10.5552/drvind.2020.1917

[7] Zheng P., Lin Q., Li F., Ou Y., Chen N. Development and characterization of a defatted soy flour-based bio-adhesive crosslinked by 1,2,3,4-butanetetracarboxylic acid. *International Journal of Adhesion and Adhesives* 2017:78:148–154. https://doi.org/10.1016/j.ijadhadh.2017.06.016

[8] Desai S. D., Patel J. V., Sinha V. K. Polyurethane adhesive system from biomaterial-based polyol for bonding wood. *International Journal of Adhesion and Adhesives* 2003:23(5):393–399. https://doi.org/10.1016/S0143-7496(03)00070-8
[9] Drelich J. W. Contact angles: From past mistakes to new developments through liquid-solid adhesion measurements. *Adv. Colloid Interface Sci.* 2019:267:1–14. https://doi.org/10.1016/j.cis.2019.02.002
[10] Huang T. *et al.* Fish gelatin modifications: A comprehensive review. *Trends Food Sci. Technol.* 2019:86:260–269. https://doi.org/10.1016/j.tifs.2019.02.048
[11] Malysheva G. V., Bodrykh N. V. Hot melt adhesives. *Polymer Science Series D* 2011:4:301–303. https://doi.org/10.1134/S1995421211040095
[12] Xu C. *et al.* Soy protein adhesive with bio-based epoxidized daidzein for high strength and mildew resistance. *Chem. Eng. J.* 2019:390:124622. https://doi.org/10.1016/j.cej.2020.124622
[13] Zhang Y. *et al.* Preparation and characterization of a soy protein-based high-performance adhesive with a hyperbranched cross-linked structure. *Chem. Eng. J.* 2018:354:1032–1041. https://doi.org/10.1016/j.cej.2018.08.072
[14] Tarling L. Global industry review. Surrey, 2015.
[15] Koral J., Ullman R., Eirich F. R. The adsorption of polyvinyl acetate. *J. Phys. Chem.* 1958:62(5):541–550. https://doi.org/10.1021/j150563a007
[16] Yamaguchi M., Takatani R., Sato Y., Maeda S. Moisture-sensitive smart hot-melt adhesive from polyamide 6. *SN Appl. Sci.* 2020:2(9):1567. https://doi.org/10.1007/s42452-020-03400-y
[17] Bravo A., Hotchkiss J. H., Aeree T. E. Identification of Odor-Active Compounds Resulting from Thermal Oxidation of Polyethylene. *J. Agric. Food Chem.* 1992:40(10):1881–1885. https://doi.org/10.1021/jf00022a031
[18] Pomposo J. A., Rodríguez J., Grande H. Polypyrrole-based conducting hot melt adhesives for EMI shielding applications. *Synth. Met.* 1999:104(2):107–111. https://doi.org/10.1016/S0379-6779(99)00061-2
[19] Pilato L. *Phenolic resins: A century of progress*. 2010. https://doi.org/10.1007/978-3-642-04714-5
[20] Zhang C., Wu Y., Xu X. U., Li Y. A. N., Feng L. I., Wu G. Synthesis of Polyisobutylene with Arylamino Terminal Group by Combination of Cationic Polymerization with Alkylation. *Journal of Polymer Science Part A: Polymer Chemistry* 2008:46(3):936–946. https://doi.org/10.1002/pola.22437
[21] Capar Ö., Tabatabai M., Klee J. E., Worm M., Hartmann L., Ritter H. Fast curing of polyhydroxyurethanes: Via ring opening polyaddition of low viscosity cyclic carbonates and amines. *Polym. Chem.* 2020:11(43):6964–6970. https://doi.org/10.1039/D0PY01172J
[22] Marques E. A. S., Magalhães D. N. M., Da Silva L. F. M. Experimental study of silicone-epoxy dual adhesive joints for high temperature aerospace applications. *Materwiss. Werksttech.* 2011:42(5):471–477. https://doi.org/10.1002/mawe.201100809
[23] Müller M., Chotěborský R. Impact strength behaviour of structural adhesives. *Agron. Res.* 2016:14:1078–1087.
[24] Marasinghe L., Croutxé-Barghorn C., Allonas X., Criqui A. Effect of reactive monomers on polymer structure and abrasion resistance of UV cured thin films. *Prog. Org. Coatings* 2017:118:22–29. https://doi.org/10.1016/j.porgcoat.2017.09.020
[25] Chen C. *et al.* Structure–property–function relationships of natural and engineered wood. *Nat. Rev. Mater.* 2020:5(9):642–666. https://doi.org/10.1038/s41578-020-0195-z
[26] Yang Z., Zhang X., Liu X., Guan X., Zhang C., Niu Y. Flexible and stretchable polyurethane/waterglass grouting material. *Constr. Build. Mater.* 2017:138:240–246. https://doi.org/10.1016/j.conbuildmat.2017.01.113
[27] Corigliano P., Ragni M., Castagnetti D., Crupi V., Dragoni E., Guglielmino E. Measuring the static shear strength of anaerobic adhesives in finite thickness under high pressure. *J. Adhes.* 2019:97(8):783–800. https://doi.org/10.1080/00218464.2019.1704271
[28] Thuraisingam J., Gupta A., Subramaniam M. Natural Rubber Latex (NRL) and rice starch as an alternative binder in wood composite industry. *Aust. J. Basic Appl. Sci.* 2016:10(17):101–106.
[29] Tester R. F., Karkalas J., Qi X. Starch structure and digestibility Enzyme-Substrate relationship. *Worlds. Poult. Sci. J.* 2004:60(2):186–195. https://doi.org/10.1079/WPS20040014
[30] Suresh G., Sebastian J., Brar S. K. Waste as a Bioresource. In Waste Valorisation: Waste Streams in a Circular Economy, Lin, C., Kaur, G., Li, C., Yang, X. (eds). Wiley 2015:13–32. https://doi.org/10.1002/9781119502753.ch2
[31] Patel A., Arora N., Sartaj K., Pruthi V., Pruthi P. A. Sustainable biodiesel production from oleaginous yeasts utilizing hydrolysates of various non-edible lignocellulosic biomasses. *Renew. Sustain. Energy Rev.* 2016:62:836–855. https://doi.org/10.1016/j.rser.2016.05.014
[32] Roffael E., Behn C., Dix B. On the formaldehyde release of wood particles. *Eur. J. Wood Wood Prod.* 2012:70(6):911–912. https://doi.org/10.1007/s00107-012-0625-8
[33] Ponomarenko J., Lauberts M., Dizhbite T., Lauberte L., Jurkjane V., Telysheva G. Antioxidant activity of various lignins and lignin-related phenylpropanoid units with high and low molecular weight. *Holzforschung* 2015:69(6):795–805. https://doi.org/10.1515/hf-2014-0280
[34] Çetin N. S., Özmen N. Use of organosolv lignin in phenol-formaldehyde resins for particleboard production: II. Particleboard production and properties. *Int. J. Adhes. Adhes.* 2002:22(6):481–486. https://doi.org/10.1016/S0143-7496(02)00059-3

[35] Järvinen R., Rauhala H., Holopainen U., Kallio H. Differences in suberin content and composition between two varieties of potatoes (Solanum tuberosum) and effect of post-harvest storage to the composition. *LWT - Food Sci. Technol.* 2011:44(6):1355–1361. https://doi.org/10.1016/j.lwt.2011.02.005

[36] Sawant O., Mahale S., Ramchandran V., Nagaraj G., Bankar A. Fungal Citric acid production using waste materials: A mini-review. *J. Microbiol. Biotechnol. Food Sci.* 2018:8(2):821–828. https://doi.org/10.15414/jmbfs.2018.8.2.821-828

[37] Kleekayai T., Suntornsuk W. Production and characterization of chitosan obtained from Rhizopus oryzae grown on potato chip processing waste. *World J. Microbiol. Biotechnol.* 2011:27(5):1145–1154. https://doi.org/10.1007/s11274-010-0561-x

[38] Qu J., Zhao X., Liang Y., Zhang T., Ma P. X., Guo B. Antibacterial adhesive injectable hydrogels with rapid self-healing, extensibility and compressibility as wound dressing for joints skin wound healing. *Biomaterials* 2018:183:185–199. https://doi.org/10.1016/j.biomaterials.2018.08.044

[39] Satpute S. K., Banat I. M., Dhakephalkar P. K., Banpurkar A. G., Chopade B. A. Biosurfactants, bioemulsifiers and exopolysaccharides from marine microorganisms. *Biotechnol. Adv.* 2010:28(4):436–450. https://doi.org/10.1016/j.biotechadv.2010.02.006

[40] Agrawal A. A., Konno K. Latex: A model for understanding mechanisms, ecology, and evolution of plant defense against herbivory. *Annu. Rev. Ecol. Evol. Syst.* 2009:40:311–331. https://doi.org/10.1146/annurev.ecolsys.110308.120307

[41] Triveni Soubam and Arun Gupta. Eco-friendly natural rubber latex and modified starch-based adhesive for wood-based panels application. A review. *Maejo Int. J. Energy Environ. Commun.* 2021:3(1):49–53. https://doi.org/10.54279/mijeec.v3i1.245163

[42] Epping J. *et al.* A rubber transferase activator is necessary for natural rubber biosynthesis in dandelion. *Nat. Plants* 2015:1:15048. https://doi.org/10.1038/nplants.2015.48

[43] Alinejad M. *et al.* Lignin-Based Polyurethanes: Opportunities for Bio-Based Foams, Elastomers, Coatings and Adhesives. *Polymers (Basel).* 2019:11(7):1202. https://doi.org/10.3390/polym11071202

[44] Isikgor F. H., Becer C. R. Lignocellulosic biomass: a sustainable platform for the production of bio-based chemicals and polymers. *Polym. Chem.* 2015:25:4497–4559. https://doi.org/10.1039/C5PY00263J

[45] Pan X., Tian Y., Li J., Tan Q., Ren J. Bio-based polyurethane reactive hot-melt adhesives derived from isosorbide-based polyester polyols with different carbon chain lengths. *Chem. Eng. Sci.* 2022:264:118152. https://doi.org/10.1016/j.ces.2022.118152

[46] Heinrich L. A. Future opportunities for bio-based adhesives-advantages beyond renewability. *Green Chemistry* 2019:8:1866–1888. https://doi.org/10.1039/C8GC03746A

[47] Cui S., Luo X., Li Y. Synthesis and properties of polyurethane wood adhesives derived from crude glycerol-based polyols. *Int. J. Adhes. Adhes.* 2017:79:67–72. https://doi.org/10.1016/j.ijadhadh.2017.04.008

[48] Fahmy Y., El-Wakil N. A., El-Gendy A. A., Abou-Zeid R. E., Youssef M. A. Plant proteins as binders in cellulosic paper composites. *Int. J. Biol. Macromol.* 2010:47(1):82–85. https://doi.org/10.1016/j.ijbiomac.2010.03.012

[49] Flambeau M., Redl A., Respondek F. Proteins From Wheat: Sustainable Production and New Developments in Nutrition-Based and Functional Applications. *Sustainable Protein Sources* 2016:67–78. https://doi.org/10.1016/B978-0-12-802778-3.00004-4

[50] Cheng H. N., He Z., Li C. H., Bland J. M., Bechtel P. J. Preparation and evaluation of catfish protein as a wood adhesive. *Int. J. Polym. Anal. Charact.* 2021:26(1):60–67. https://doi.org/10.1080/1023666X.2020.1844361

[51] Yang I., Han G. S., Ahn S. H., Choi I. G., Kim Y. H., Oh S. C. Adhesive properties of medium-density fiberboards fabricated with rapeseed flour-based adhesive resins. *J. Adhes.* 2014:90(4):279–295. https://doi.org/10.1080/00218464.2013.793161

[52] Kokel A., Török B. Sustainable production of fine chemicals and materials using nontoxic renewable sources. *Toxicol. Sci.* 2018:161(2):214–224. https://doi.org/10.1093/toxsci/kfx214

[53] Muizniece I., Blumberga D. Thermal Conductivity of Heat Insulation Material Made from Coniferous Needles with Potato Starch Binder. *Energy Procedia* 2016:95:324–329. https://doi.org/10.1016/j.egypro.2016.09.014

[54] Santos J., Delgado N., Fuentes J., Fuentealba C., Vega-Lara J., García D. E. Exterior grade plywood adhesives based on pine bark polyphenols and hexamine. *Ind. Crops Prod.* 2018:122:340–348. https://doi.org/10.1016/j.indcrop.2018.05.082

[55] Aristri M. A. Bio-based polyurethane resins derived from tannin: Source, synthesis, characterisation, and application. *Forests* 2021:12(11):f12111516. https://doi.org/10.3390/f12111516

[56] Norström E., Fogelström L., Nordqvist P., Khabbaz F., Malmström E. Xylan - A green binder for wood adhesives. *Eur. Polym. J.* 2015:67:483–493. https://doi.org/10.1016/j.eurpolymj.2015.02.021

[57] Sini N. K., Bijwe J., Varma I. K. Thermal behaviour of bis-benzoxazines derived from renewable feed stock 'vanillin'. *Polym. Degrad. Stab.* 2014:109:270–277. https://doi.org/10.1016/j.polymdegradstab.2014.07.015

[58] da Silva B. R. F. *et al.* Properties of cross-laminated timber bonded with an adhesive based on tannins from the bark of Mimosa tenuiflora Trees. *Rev. Arvore* 2022:46:1–10. https://doi.org/10.1590/1806-908820220000020

[59] Zheng D., Wang X., Zhang M., Liu Z., Ju C. Anticorrosion and lubricating properties of a fully green lubricant. *Tribol. Int.* 2018:130:324–333. https://doi.org/10.1016/j.triboint.2018.08.014

[60] Umemura K., Kawai S. Development of Wood-Based Materials Bonded with Citric Acid. *For. Prod. J.* 2015:65(1–2):38–42. https://doi.org/10.13073/FPJ-D-14-00036

[61] Gadhave R. V., Mahanwar P. A., Gadekar P. T. Starch stabilized polyvinyl acetate emulsion: Review. *Polym. from Renew. Resour.* 2018:9(2):75–84. https://doi.org/10.1177/204124791800900203

[62] Samyn P. A platform for functionalization of cellulose, chitin/chitosan, alginate with polydopamine: A review on fundamentals and technical applications. *International Journal of Biological Macromolecules* 2021:178:71–93. https://doi.org/10.1016/j.ijbiomac.2021.02.091

[63] Ferdosian F., Pan Z., Gao G., Zhao B. Bio-based adhesives and evaluation for wood composites application. *Polymers* 2017:9(2):polym9020070. https://doi.org/10.3390/polym9020070

[64] Monroy Y., Rivero S., García M. A. Sustainable panels design based on modified cassava starch bioadhesives and wood processing byproducts. *Ind. Crops Prod.* 2019:137:171–179. https://doi.org/10.1016/j.indcrop.2019.04.062

[65] Nordqvist P., Lawther M., Malmström E., Khabbaz F. Adhesive properties of wheat gluten after enzymatic hydrolysis or heat treatment. A comparative study. *Ind. Crops Prod.* 2012:38(1):139–145. https://doi.org/10.1016/j.indcrop.2012.01.021

[66] Wu T. Y., Mohammad A. W., Jahim J. M., Anuar N. Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes. *Journal of Environmental Management* 2010:91(7):1467–1490. https://doi.org/10.1016/j.jenvman.2010.02.008

[67] Ningsi D. W., Suhasman, Saad S. Characteristic of Chitosan Adhesive from Shell Shrimp Litopenaeus vannamei and Their Application for Producing Particleboard. in *IOP Conference Series: Materials Science and Engineering* 2019:593(1):012015. https://doi.org/10.1088/1757-899X/593/1/012015

[68] Tokura S., Tamura H. Chitin and Chitosan. *Compr. Glycosci. From Chem. to Syst. Biol.* 2007:2–4:449–475. https://doi.org/10.1016/B978-044451967-2/00127-6

[69] Hou L., Majumder E. L. W. Potential for and distribution of enzymatic biodegradation of polystyrene by environmental microorganisms. *Materials (Basel)* 2021:14(3):ma14030503. https://doi.org/10.3390/ma14030503

[70] Superti V., Forman T. V., Houmani C. Recycling thermal insulation materials: A case study on more circular management of expanded polystyrene and stonewool in switzerland and research agenda. *Resources* 2021:10(10):10100104. https://doi.org/10.3390/resources10100104

[71] United Soybean Board. NU Green soya® particleboard scores environmental certifications. 2016. [Online]. [Accessed: 15.11.2022]. Available: https://soynewuses.org/case-study/nu-green-soya-particleboard-scores-environmental-certifications/

[72] Solenis. SOYAD^{TM} Adhesive Technology. 2022. [Online]. [Accessed: 15.11.2022]. Available: https://www.solenis.com/en/research-and-development/innovations/soyad-adhesive-technology

Article

Logging residues as a future for engineered wood

Janis Andris Krumins[1], **Ilze Vamza** [1] , **Arnis Dzalbs**[1,*] **and Dagnija Blumberga** [1]

[1] Institute of Energy Systems and Environment, Riga Technical University, 12-k1 Azenes street, Riga, LV-1048, Latvia
* Correspondence: arnis.dzalbs@rtu.lv

Abstract: Engineer wood is widely used in the building industry starting from plywood forms for concrete forming to building materials e.g. cross-laminated timber and mass timber. Engineered wood chipboards with lower durability requirements are widely used in dwelling spaces from furniture to decorative paneling. This investigation is focused on the potential of woodchip board transition to 100% bio-based materials from forest logging residues. Research is done by making woodchip boards in a laboratory setting from logging residues and bio-based carbohydrate binder. Durability of produced woodchip boards are determined according to the European standard EN 323:1996. Results show that fine particles in conifer logging residues increase the durability of such woodchip material confirming the potential for engineered wood transition from fossil-based adhesives to more sustainable adhesives potentially made from bark. Investigation shows that logging residues can be further investigated as a viable source of woodchip as the durability reached in this study reaches more than 70% of the durability required by the market.

Keywords: Logging residues, bioeconomy, value-added, 100% bio-based, transition, resource efficiency, greener building

1. Introduction

Replacing conventional building materials with wood alternatives can have a great reduction of atmosphecic carbon [1]. As building with wood has experianced renensance led by cross-laminated timber and glued laminated timber [2], it is time to take the next step and improve the sustainability of engineered wood materials as almost all conventianal engineered wood materials are produced using some kind of fossil binders [3]. Chipboards are one of the main wood products in international trade. Although the current process of wood particle board production has been modernized for a long time, in essence production of boards still involves the use of fossil additives [4] and toxic binders or their components [5], as well as the use of quality wood [3]. Production efficiency has been improved and solutions have been sought to reduce the impact on the environment during the entire product life cycle [6]. Chipboards have multiple variations and according to market research reports, these materials are mostly used for construction and furniture [7]. Particleboard is one of the main wood products in international trade. Its global demand and production has seen an upward trend in recent years. Particleboard is an engineered wood product produced from high-quality wood chips by bonding them together with synthetic resin or other suitable adhesive at a certain temperature and pressure. Particle board consists of three layers: two surface layers and one base layer between the surface layers. The surface layers consist of fine particles, while the base layer is made of larger and coarser particles. Fine particles usually do not add to material integrity, but is very important for the final material lamination

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Received: date
Revised: date
Accepted: date
Published: date

process as smooth surface is crucial for efficiant coverage. Materials for the lamination significantly impacts the final material functionality as it can increase scratch resistance and water repelancy [8].

Although low-quality wood is being integrated into chipboards, it is not the preference of industry but rather necessity due to intense deforestatio and need for the biomass [3]. Referring to the United Nations (UN) Food and Agriculture Organization (FAO) report, the global production of roundwood in 2020 (including fuelwood and industrial roundwood) was estimated at 3,966 million m^3 (fuelwood - 1,945 million m^3 and industrial roundwood – 2,021 million m^3). Compared to the year 2000, the global timber production intensity has increased by about 24%. Timber market models and estimates developed so far show that if the world's population reaches 10 billion, the demand for wood will be greater than the global supply of this raw material, which could lead to an increase in wood prices and uncontrolled cutting of protected forest areas for illegal timber trade. The importance of forests and the need to protect their resources is only one of the reasons to move towards environmental sustainability as one of the main parameters of the timber industry when choosing raw materials for industrial production needs. In order to maintain a stable and steady production of roundwood and timber and to protect wood resources, necessary steps should be taken to increase the productivity by using the raw material more efficiently or explore completely new and alternative raw materials to replace high-quality wood [9]. Aditionally, wood use in higher value added product production has gained traction e.g. fibres for textile [10].

Forseing the future needs for resources in general, there has been multiple research and innovations oriented towards alternative biomass and adhesives for the engineered wood market [11]. Pędzik (2021) and colleagues have reported the potential of cipboard production using residues from forest management, tackling the need for sustainable raw material. Although the team concluded, that the produced boards are applicable to P2 functionality (suitable for dry environment), the adhesive used in this research is urea-formaldehyde based [9]. Mirski and colleagues recently has explored the pine bark as an additive for chipboards using the urea-formaldehyde and melamine-urea-formaldehyde resins [12]. Both of these adhesives are fossil-based. Formaldehyde compounds are most often used in adhesives. One of the most important areas of its production is urea-formaldehyde resin, but formaldehyde is classified as a compound that can cause cancer (class 3 carcinogen), poisonous, corrosive and allergenic [13], [14], [15, p. 5], [16], [17]. The wood particles are first mixed with glue and then formed from them into an inlay, which is then hot-pressed to form a panel product [9], [12].

Although some types of panels are relatively new to the market, others were developed and successfully implemented more than a hundred years ago. However, even for those types of boards and panels that have long existed in the timber industry, the optimization of the manufacturing parameters is still not complete. Technological developments and new market and regulatory requirements, in combination with the raw material situation, drive continuous improvements in wood panels and their manufacturing processes [18].

Traditionally, plywood and oriented strand board (OSB) mechanical properties have been characterized by strength and rigidity. They are resistant to various types of deformation and impact damage. Thanks to their split resistance, wood boards for various types of structures have excellent fastener retention properties. In addition, it is possible to nail and screw fasteners very close to the edges of the boards. For most applications, stiffness and strength is one of the biggest advantages of wood panels. Ultimate stiffness is measured as resistance to deformation under uniform and concentrated loads and forces that would deform the plate from its inherent shape in the plane of the panel. Stiffness often makes it possible to use wood structural panels without additional reinforcements with other materials. Load-bearing wood panels are perfectly suited for applications of bulky dimensions and loads, which are commonly used in construction Industry [13], [19]. Particleboards on the other hand are more sutied for indoor applications like furniture and some instances decorative panneling. As previously described, these types of boards are mainly used for their smooth surface allowing for variations in finishes by laminating them [8]. Therefore the integrity of the board itself can be lower compared to OSB or plywood. Making the particleboards the most realistic product for green imporvements.

Significant innovations have been made to ensure that wood panels do not have a negative impact on human health or the environment. In particular, formaldehyde emissions from the manufacturing process of various panels have been significantly reduced in recent decades, and further reduction remains the focus of effort and investment for panel manufacturers, adhesive suppliers, and researchers. In addition, a relatively recent problem observed in the manufacturing process is the detection and reduction of volatile organic compound (VOC) emissions. Several developed studies on the analysis of the life cycle of wood chipboards (life cycle assessment), replacing synthetic resins with biological binders, such as soy protein, lignin, tannin, etc., show a reduction in the impact on the environment [6], [16]–[18], [20].

One of the main driving forces for the continuous development of wood panels and, accordingly, their production processes, is the continuous change in the availability of raw materials and permits for use. The basic composition of the biomass used to make the boards usually depends on what raw material is available regionally. Therefore, the composition of the biomass and the final product may vary between plants in different regions. In addition, there are not only regional differences in raw materials, but also their changes over time, caused by several factors, for example, the management plans of forest areas are regularly changed. In addition, the demand for wood, which until now was mainly used in the production of boards, has increased significantly in several regions in other sectors, especially in the energy sector. As a result of these changes, wood panel manufacturers are beginning to pay more attention to optimizing their production processes and switching to alternative biomass types, including recycled and other lower quality wood. However, the variability of the quality and composition of wood raw material creates significant difficulties in ensuring quality uniformity. Studies analyzing the effect of the chemical composition of wood on the strength of wood chipboards show that different board strength can be obtained with changes in the content of wood particle cellulose, lignin, hemicellulose, tannin, as well as extractive substances and at different particle pH, particle porosity and permeability, as well as for changes in the anatomical and chemical properties of other wood particles [18], [21].

The cost of the raw materials used, namely adhesive and wood chips, make up the largest part of the cost of finished chipboard. Total material costs account for 40-60% of total production costs. Research to date indicates that adhesive costs account for 30-50% of the total material cost of particleboard production, with the remaining 50-70% of the material cost being wood chips, chips or logs. Therefore, glue and wood chips are assumed to account for 15-30% and 30-40% of the total production cost, respectively. Other cost components such as energy, labor and chipboard processing costs account for approximately 15-20%, 5-20% and 25-30% respectively. According to various authors of scientific literature, material costs account for approximately 66% of total production costs. Undeniably, the cost of materials, which includes the cost of adhesive and wood chips, most often accounts for more than half of the total cost of production. Consequently, replacing wood chips with alternative raw materials other than high-quality wood could lead to significant cost savings [13].

According to EN 312 – 2:1997 and *EN 312 – 3:1997* standards, the limit of the minimum modulus of rupture (MoR) for plates under 6 mm thickness is 11.5 N/mm^2 or 1150 N/cm^2 and the limit of the modulus of elasticity (MoE) is 1600 N/mm^2 or 160000 N /cm^2. On the other hand, the minimum permissible value of MoR for plates with a thickness of 6 mm - 13 mm is 12.5 N/mm^2 or 1250 N/cm^2.

In this research efforts are made to elucidate potential for chipboards made only from loggig residues using biogenic binders from external and potentially the same source as wood chips. Thus opening the possibility to make boards without negative impacts on environement and human healt.

2. Materials and Methods

Logging biomass was delivered in 50L to 100L polyethylene bags as wood chips from forest felling where branches were chipped with needles intact. Although the content of wood chips varied depending on the location and environment in which the wood chipping was carried out, as well as on the proportions of wood biomass, after visual assessment it was concluded that the wood chips mainly contained the heartwood and sapwood, bark, needles, fresh and decayed biomass particles, and mineral particles. To determine the mineral contents, chemical analysis of different supplied biomasses was carried out, placing a small part of selected biomass in a 500 ml polyethylene bag and taking it to the Waste products and fuel research and testing laboratory of Ltd "Virsma" for analysis. Along with mineral content, the volatile substances in biomass was determined according to the LVS EN ISO 18123:2016 standard and was between 72.2% and 79.2%. The amount of sand in the ash ranged from 4.2% to 50.2%.

Xanthan powder or xanthan resin purchased from the store of Ltd. "BBFactory Cosmetics" was used as a binder for the production of wood chip boards from logging residues. Xanthan was added to the biomass in the form of powder or solution during its preparation.

Biomass moisture content determination

Chips delivered from forest fellings contained varying but significant amounts of moisture. The different amount of moisture in the wood chips was observed under different weather conditions during chipping and delivery of logging residues. Therefore, first the wood chips were removed from polyethylene bags and placed indoors for drying to an air-dry moisture content of approximately 8% to 10%. The average time for biomass drying was one calendar week, but it depended on the initial moisture content. The moisture content of the wood chips before and after drying was determined with a Greisinger GMH 3830 probe by inserting it into the wood chips and reading the moisture content value from the device interface.

Milling

In order to obtain the required biomass particle size or size range, the dried wood chips were ground using a hammer mill. The initial grinding of the chips was carried out with a two-horizontally rotating axis chipper to grind it into smaller particles, which, if necessary, could be sieved immediately to separate larger particle sizes or placed in a "Vibrotehnik PM-120" hammer mill to obtain even smaller particles.

Size seperation

Depending on the required particle size, two methods were used to obtain desired particle size. (1) After the chips were crushed in the horizontal axis chipper, the chips were placed in a hammer-type mill, with integrated metal screen. (2) Sieving of the crushed particles was performed using a Retsch AS-400 sieve shaker, and metal sieves with different mesh opening sizes.

A disadvantage of the sieving process for obtaining different sizes of wood chips is that when sieves of a certain size are used in sieving, the particles are obtained not in one size, but in a range of sizes. In addition, when separating the particles with a metal sieves, not all the dimensions of the particles are smaller than the size of the mesh holes, because a particle with a size smaller than the mesh size in width but larger in length may fall through the mesh.

Mixing

Depending on the type of adhesive used in the plate pressing experiment group, it was either added to the biomass in the form of a ready-made powder, or the powder was first dissolved in water to obtain the adhesive in a viscous form according to the established production protocol, and then added to the biomass. In both variants, the binder was added to the logging residue particles no longer than 48 h prior biomass pressing to prevent mold formation, moisture change, and other aspects that would potentially cause unwanted additional effects on the investigated parameters.

Board preparation

Referring to the information obtained in the scientific literature and the descriptions of the production processes of wood chip boards, the following equipment and materials were used in the laboratory for the production of boards in the framework of the development of this work: Hydraulic press with hand pump (Hansa Flex - 10 t); Analog pressure gauge (Hansa Flex - 600 bar, ± 50 bar); Digital manometer (Hansa Flex - 1000 bar, ± 1 bar); Cylindrical heating elements (alternating currents); Temperature sensors; Heating metal blocks/surfaces; Plate drying stand; Metal frames: metal frame without perforations for holding biomass, and metal frame with perforations for biomass retention and steam discharge; Metal lining for steam removal; Teflon fabric.

The production of boards was carried out using previously prepared logging residue biomass with the required particle size (mm), moisture mass fraction (%). The board formation process was carried out in the following stages:

1. Digital pressure gauge was turned on and reset. In case of using analog pressure gauge, no power-up or reset was done.
2. The required temperature was set using the heating element control controller.
3. When the temperature shown by the temperature sensors indicated that the set temperature (± 5 °C) has been reached, a metal frame was placed on the lower heating surface and the Teflon cloth inserted into it. After that, the prepared biomass was formed into the frame by hand and a metal screen for steam discharge, and a Teflon fabric was laid on top.
4. Pressing was performed by squeezing the hand pump until the required pressure was displayed on the manometer (±10 bar for the digital manometer and ±50 bar for the analog manometer).
5. The countdown was started, and the pressure controlled with the hand pump during pressing.
6. After the desired time, the pressure was released evenly by carefully turning the pressure release valve on the hand pump.
7. Finally, the produced board was removed from the press and placed in the drying rack overnight.

Referring to the information provided in the scientific literature, the size, geometry or shape of the wood particles and the relative position of the particles significantly affect the mechanical strength of particle board. In this group of experiments, the effect of particle size of logging residues on the strength of the manufactured boards was tested. To determine the impact of logging residue particles on strength, the particle size was divided into three parts: < 2.8 mm, 2.8-8 mm, and 8.0-10.0. The hot pressing pressure was chosen to be 600 bar at a temperature of 140 °C and 160 °C.

Board testing

Density

The European standard EN 323:1996 has been developed for determining the density of wooden boards. With reference to EN 323:1996, the density of timber boards was determined as the ratio of the mass of each test specimen board to its volume. Both plate parameters were determined at the same moisture content of the sample. A caliper with an accuracy of ± 1 mm was used to determine the dimensions of the plates. On the other hand, for mass determination - laboratory scales with an accuracy of ± 0.01 g. The width and thickness of each logging residue plate and sheet was determined at three points - at the extreme longitudinal edges of the plates and sheets, and at the midpoint and at its edges according to the European Standardisation Organisations' (1993) EN 323:1993 standart "Wood-based panels - Determination of modulus of elasticity in bending and of bending, applicable at the European level".

Mechanical properties

For determining the bending strength and modulus of elasticity of wooden boards, the standard EN 310:1993 was used. This standard defines a method for testing the modulus of elasticity (MoE) and bending strength of horizontally placed boards in the bending of timber boards with a nominal thickness of ≥ 3 mm. The modulus of elasticity and flexural strength are determined by applying a load to the center of the test specimen supported at two external points. The modulus of elasticity is calculated using the slope of the linear region of the load-deflection curve. The calculated value is the apparent modulus rather than the true modulus because the test method includes both shear and bending. The bending strength of each sample is calculated by determining the strength of the maximum bending load F_{max} of the full cross-section of the sample until the mechanical collapse of the sample.

To determine the strength of plates according to the EN 310:1993 standard, following steps were taken: (1) Sawing lines of the sheets were marked on the prepared boards according to the dimensions determined in the methodology so that the midpoint of the marked sheets was as close as possible to the midpoint of the board; (2) Sheets from the prepared board were cut out using a stationary circular saw; (3) Placement of the distance of the outer support points of the stand for determining the resistance according to the approach determined in the standart methodology; (4) The plates were placed symmetrically on the support points of the strength test stand; (5) The load tube on the plate was placed at its longitudinal midpoint, perpendicular to the longitudinal direction of the sheet; (6) Predetermined load to the sheet was applied in a certain time interval (kg/min) depending on the deformation of the sheet at the initially applied load.

Data analysis

Each composition and parameters were replicated at least two times and achieved boards sawn in three equal parts for MoE testing, and density calculations, resulting in at least six repetitions. Calculated standartdeviations are depicted in graphs, confidence value of 95% (P-vaule < 0.05) was used in the analysis.

3. Results

Analyzing the strength results of the boards whose wood particles were obtained using the two-horizontally rotating axis chipper, no strong relationship between the particle size and the obtained strength result was observed. In addition, there was a significant standard deviation in the durability results for the same manufacturing parameters. Initial durability results for three particle size boards are depicted in Figure 1. The highest strength was obtained for plates with a particle size of 2.8 mm, and the highest inconsistency was detected under high pressure board preparation for medium particle size boards. Boards prepared from the 8.0-10.0 size fraction was generally less durable than the rest, but as seen from the statistical analysis the difference between MoE of 2.8-8.0 and 8.0-10.0 particle size boards in 660 bar pressure was not significant (P=0.27).

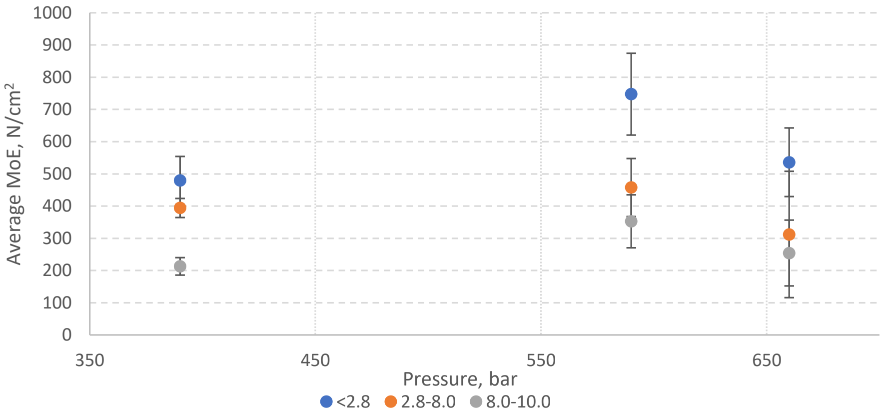


Figure 1. Modulus of elasticity depending on pressure for and particle size : <2.8 mm particle size boards; 2.8-8.0 mm particle size boards; 10.0 mm particle size boards. MoE – Modulus of Elasticity

There was no significant impact of the chosen pressure extremes to board durability (P=0.43) for the <2.8 mm particle boards, the boards produced by applying 590 bar pressure showed significantly higher durability compared to 390 bar (P=0.002) and 660 bar (P=0.01) pressures. For the further tests 600 bar setting was chosen. According to biomass tests conducted in external laboratory, some supplied biomass had a high sand content in the ash (ashing at 550 °C) showing up to 26% and around 2% sand content in the raw biomass. Therefore, further tests were done by using the hammer mill approach by milling the previously chipped and sifted >1mm fractions. Larger particles were combined to prepare boards in the range of 2.8 mm to 10 mm particle size as initial tests did not show significant difference between these two fraction in the chosen pressure range. Boards were prepared using 140 °C and 160 °C temperature regimes to assess temperature and particle size impacts on board mechanical properties. Initial tests for temperatures were done prior to this study, elucidating the 140 °C and 160 °C temperature range as the most suitable for further testing, as lower range temperatures produced boards that weren't truly bonded and higher temperatures produced burnt boards. Results from 140 °C and 160 °C temperature tests are depicted in Figure 2.

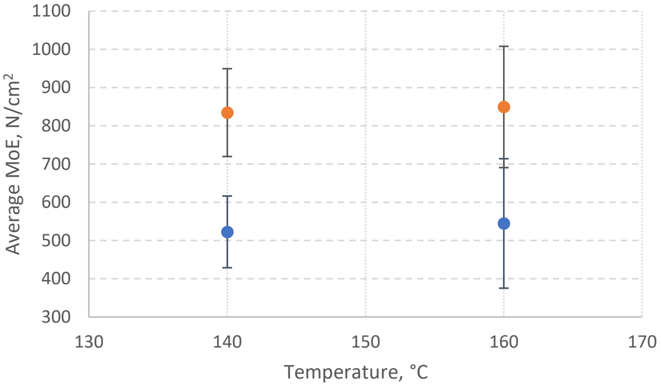


Figure 2. Modulus of elasticity of <2.8 mm particle size boards (blue), and for 2.8-10.0 partice size boards (orange) depending on hot press temperature

The results from combining 2.8-8.0 and 8.0-10.0 fractions showed a great increase in board durability, showing better results than prior. Nevertheless, smaller fraction boards showed decrease in durability, this might be explained by bark removal from the biomass. By separating sand from the biomass, other smaller particles got removed from the raw material – including finer bark and needle particles. To explain such change, temperatures were further tested by combining the hammer milled biomass with chipped and sieved particles. Results depicted in Figure 3 shot that although the larger particle size boards show roughly the same results as the standard deviations overly in the same areas on the graph, smaller particle size boards show increased results, with one outlier even reaching the minimum MoE threshold determined by European standard for wood chip materials EN 312-2:1997.

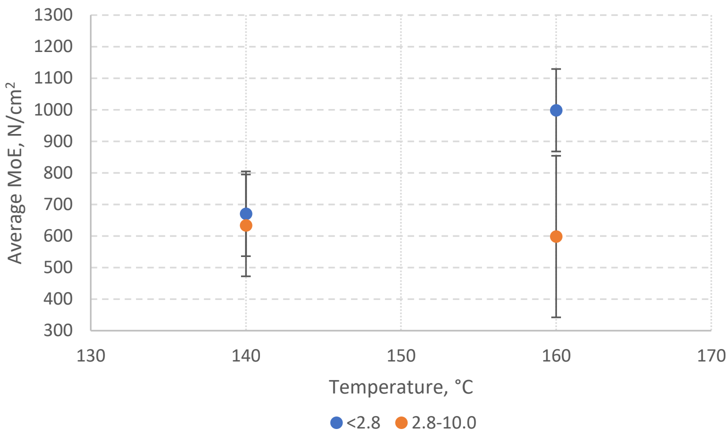


Figure 3. Modulus of elasticity of <2.8 mm particle size boards (blue), and for 2.8-10.0 partice size boards (orange) depending on hot press temperature for combined particles. Highest result from 2.8mm particle size boards (transperent dot)

Smaller particles pressed together makes the final product more dense loosing the desirability of such woodchip boards. Nevertheless there was no corelation of overall density increase and increased durability when boards from all particle sizes were compared. Density and mechanical durability of prepared samples are depicted in Table 1.

Table 1. Overview of the durability and density of produced samples.

Pressure, bar	Temperature, °C	Particle size, mm	MoE, N/cm^2	Density, kg/m^3
HC[1]				
390	140	<2.8	480 ±74	775 ±30
590	140	<2.8	747 ±127	872 ±52
660	140	<2.8	536 ±107	894 ±51
390	140	2.8-8.0	394 ±30	759 ±34
590	140	2.8-8.0	458 ±90	882 ±46
660	140	2.8-8.0	312 ±196	774 ±71
390	140	8.0-10.0	213 ±27	660 ±38
590	140	8.0-10.0	353 ±82	796 ±28
660	140	8.0-10.0	254 ±102	784 ±87
HM[2]				
600	140	<2.8	523 ±94	824 ±53
600	140	2.8-10.0	835 ±115	913 ±14
600	160	<2.8	545 ±169	885 ±40
600	160	2.8-10.0	849 ±159	913 ±58
Sifted combined				
600	140	<2.8	670 ±134	795 ±81

600	140	2.8-10.0	634 ±161	759 ±62
600	160	<2.8	999 ±131	892 ±26
600	160	2.8-10.0	598 ±256	843 ±58

Particle size achieved by HC-horizontal 2-axis chipping and sifting, HM – Hammermilling with screen on particle outlet.

4. Discussion and Conclusions

Although other research groups have been testing logging residue and pine bark applications for chipboard production the possibility of completely excluding fossil-based adhesives [9], [12]. With todays climate objectives it is crucial to compleatly rethink construction and housing approaches by compleatly excluding fossil carbon from the market [1]. Therefore scientific community and industry need to find working alternatives. This research provided insights on logging residue usefullenes for chipboard production and provides a few usefull takeaways confirming previous work on logging residue potential application in chipboard production even without fossil based adhesives. Although laboratory research has been done using particle size separation using sieves, it might be useful to consider gravimetric separation by cyclones as this would result in more even particle dimensions [18] and therfore lead to more consistent results. It was shown that the smallest conifer logging residue particle size might have a positive impact on 100% bio-based chipboard durability and methods for mineral separation from the bark material could be explored, perhaps by using flotation. There already is research on creating adhesives from bark extractables along other bio-based adhesives [11], and this research confirms the potential of chipboard transition away from fossil resources and towards completely bio-based materials.

Bio-based carbohydrate adhesive was used in this research as previous tests without any adhesive, materials showed low durability and other unwanted effects like bulging and burning of the material. Chosen adhesive showed promising results, but search for more efficient adhesive is still open. Previously done literature review on adhesives elucidates multiple bio-based options, even potential adhesives from other industry residues. Successful research in this direction could potentially result in chipboards from mostly residue based raw materials – biomass and adhesive.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, Janis Andris Krumins, Ilze Vamza and Dagnija Blumberga; methodology, Janis Andris Krumins; data analysis Janis Andris Krumins and Ilze Vamza; resources, Arnis Dzalbs; data curation Ilze Vamza.; writing—original draft preparation, Janis Andris Krumins; writing—review and editing, Ilze Vamza, and Arnis Dzalbs; supervision, Dagnija Blumberga; funding acquisition, Arnis Dzalbs. All authors have read and agreed to the published version of the manuscript."

Funding: Please add: "This research received no external funding" or "This research was funded by NAME OF FUNDER, grant number XXX" and "The APC was funded by XXX". Check carefully that the details given are accurate and use the standard spelling of funding agency names at https://search.crossref.org/funding. Any errors may affect your future funding.

Acknowledgments: Arņa grants!

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] A. H. Buchanan and S. B. Levine, "Wood-based building materials and atmospheric carbon emissions," *Environ. Sci. Policy*, vol. 2, no. 6, pp. 427–437, 1999, doi: 10.1016/S1462-9011(99)00038-6.

[2] O. Espinoza and U. Buehlmann, "Cross-Laminated Timber in the USA : Opportunity for Hardwoods ?," *Curr. For. Rep.*, vol. 4, no. 1, pp. 1–12, 2018.

[3] T. Nishimura, "6 - Chipboard, oriented strand board (OSB) and structural composite lumber," in *Wood Composites*, M. P. Ansell, Ed., Woodhead Publishing, 2015, pp. 103–121. doi: 10.1016/B978-1-78242-454-3.00006-8.

[4] R. Mújika-Garai *et al.*, "Stabilization of Paraffin Emulsions Used in the Manufacture of Chipboard Panels by Liquid Crystalline Phases," *J. Dispers. Sci. Technol.*, vol. 28, no. 6, pp. 829–836, Jul. 2007, doi: 10.1080/01932690701341777.

[5] A. Marcon *et al.*, “Outdoor Formaldehyde and NO2 Exposures and Markers of Genotoxicity in Children Living Near Chipboard Industries,” *Environ. Health Perspect.*, vol. 122, no. 6, pp. 639–645, Jun. 2014, doi: 10.1289/ehp.1307259.

[6] A. Arias, S. González-García, S. González-Rodríguez, G. Feijoo, and M. T. Moreira, “Cradle-to-gate Life Cycle Assessment of bio-adhesives for the wood panel industry. A comparison with petrochemical alternatives,” *Sci. Total Environ.*, vol. 738, p. 140357, Oct. 2020, doi: 10.1016/j.scitotenv.2020.140357.

[7] “Particle Board Market Size, Share, Growth Analysis, By Application, End-Use - Industry Forecast 2023-2030.” https://www.skyquestt.com/report/particle-board-market (accessed Aug. 09, 2023).

[8] G. Nemli and G. Çolakogˇlu, “The influence of lamination technique on the properties of particleboard,” *Build. Environ.*, vol. 40, pp. 83–87, Jan. 2005, doi: 10.1016/j.buildenv.2004.05.007.

[9] M. Pędzik, K. Tomczak, D. Janiszewska-Latterini, A. Tomczak, and T. Rogoziński, “Management of Forest Residues as a Raw Material for the Production of Particleboards,” *Forests*, vol. 13, no. 11, Art. no. 11, Nov. 2022, doi: 10.3390/f13111933.

[10] L. Melani and H.-J. Kim, “The surface softness and mechanical properties of wood pulp–lyocell wet-laid nonwoven fabric,” *J. Text. Inst.*, vol. 112, no. 8, pp. 1191–1198, Aug. 2021, doi: 10.1080/00405000.2020.1805962.

[11] “A Review of Bio-Based Adhesives from Primary and Secondary Biomass for Wood Composite Applications - ProQuest.” https://www.proquest.com/openview/fb15004e0a1b7adca03fa6536009000c/1?pq-origsite=gscholar&cbl=626454 (accessed Aug. 10, 2023).

[12] R. Mirski, A. Derkowski, J. Kawalerczyk, D. Dziurka, and J. Walkiewicz, “The Possibility of Using Pine Bark Particles in the Chipboard Manufacturing Process,” *Materials*, vol. 15, no. 16, Art. no. 16, Jan. 2022, doi: 10.3390/ma15165731.

[13] S. H. Lee *et al.*, “Particleboard from agricultural biomass and recycled wood waste: a review,” *J. Mater. Res. Technol.*, vol. 20, pp. 4630–4658, Sep. 2022, doi: 10.1016/j.jmrt.2022.08.166.

[14] A. Pizzi and K. Mittal, *Handbook of Adhesive Technology, Revised and Expanded*. CRC Press, 2003. doi: 10.1201/9780203912225.

[15] Q. Yuan, Z. Liu, K. Zheng, and C. Ma, “Chapter 5 - Wood,” in *Civil Engineering Materials*, Q. Yuan, Z. Liu, K. Zheng, and C. Ma, Eds., Elsevier, 2021, pp. 239–259. doi: 10.1016/B978-0-12-822865-4.00005-2.

[16] M. A. H. Mohd Azman *et al.*, “Life Cycle Assessment (LCA) of Particleboard: Investigation of the Environmental Parameters,” *Polymers*, vol. 13, no. 13, Art. no. 13, Jan. 2021, doi: 10.3390/polym13132043.

[17] M. Puettmann, E. Oneil, and J. Wilson, “Cradle to Gate Life Cycle Assessment of U.S. Particleboard Production,” 2013.

[18] H. Thoemen, M. Irle, and M. Sernek, *Wood-based panel technology*. 2010.

[19] “Strength & Stiffness - Performance Panels.” https://www.performancepanels.com/strength-stiffness (accessed Aug. 07, 2023).

[20] J. E. McDevitt and W. J. Grigsby, “Life Cycle Assessment of Bio- and Petro-Chemical Adhesives Used in Fiberboard Production,” *J. Polym. Environ.*, vol. 22, no. 4, pp. 537–544, Dec. 2014, doi: 10.1007/s10924-014-0677-4.

[21] S. Bardak, G. Nemli, T. Bardak, S. Bardak, G. Nemli, and T. Bardak, “The quality comparison of particleboards produced from heartwood and sapwood of European larch,” *Maderas Cienc. Tecnol.*, vol. 21, no. 4, pp. 511–520, Dec. 2019, doi: 10.4067/S0718-221X2019005000407.

Environmental and Climate Technologies
2021, vol. 25, no. 1, pp. 58–70
https://doi.org/10.2478/rtuect-2021-0005
https://content.sciendo.com

Life Cycle Assessment of Reprocessed Cross Laminated Timber in Latvia

Ilze VAMZA[1]*, Fabian DIAZ[2], Peteris RESNAIS[3], Antra RADZIŅA[4], Dagnija BLUMBERGA[5]

[1,2,4,5]*Institute of Energy Systems and Environment, Riga Technical University, 12-k1 Azenes street, Riga, LV-1048, Latvia*

[3]*SIA FUNDUSS, 'Tiltakrogs', Ieriķi, Drabešu parish, Amatas reg. LV-4139, Latvia*

Abstract **– It is expected that Cross-laminated timber (CLT) and other engineered wood products will experience rapid growth in the coming years. Global population growth is requiring more housing units, at the same time the negative impact of construction industry cannot stay in the same level as today. Alternatives for concrete and steel reinforced structures are being explored. CLT has proven to be an excellent substitution for concrete regarding construction of buildings up to eight storeys high. In addition to much lower environmental impact, construction process using CLT takes significantly less time due to pre-cut shapes required for specific project. Despite mentioned benefits, there are considerable amount of CLT cuttings generated in this process. Due to irregular shape and small dimensions of these cuttings they are useless for further use in construction. By applying re-processing technology described in this paper, around 70 % of generated cuttings can be re-processed into new CLT panels. In this paper we are evaluating the environmental benefits of re-processing these cuttings into new CLT panels versus business-as-usual scenario with waste disposal. Life cycle assessment results showed significant reduction of environmental impact for the scenario of CLT cutting re-processing.**

Keywords **– Avoided burden; construction; green buildings; eco-efficiency; engineered wood products**

1. INTRODUCTION

In lines with the Europe's Green Deal and overall ambition to reduce the carbon footprint of human activities, building and construction industries are a good direction to look. According to life cycle assessment on environmental impact of a dwelling in EU, individual family houses have the biggest negative impact per person per m^2. Significant negative impact is from building construction – mainly due to the metal that has been used for concrete reinforcement, used metal has 40 % effect on Human toxicity. Additionally, production of conventional building materials like concrete and bricks has considerable negative environmental impact [1]. According to European Commission, building construction and use consumes half of all the extracted materials and produced energy [2]. Hence improvements in construction and building industries could bring significant positive change regarding environmental impact of human activities. Promising field of improvement is the use of innovative building materials with less negative environmental impact but comparable functional properties.

---

* Corresponding author.
E-mail address: ilze.vamza@rtu.lv

As abovementioned, concrete and steel have the most negative impact. In order to reduce the global warming potential (GWP) of building construction and exploitation, alternatives to reinforced concrete are being explored. For comparison – GWP of concrete with ~40 MPa strength is from 120 to 60 kg CO_2/m^3 for some greener concrete variations [3], in contrast cross-laminated timber with the same strength has only 40 kg CO_2/m^3 GWP [4]. Wood based products were popular in the mid-twentieth century but increasing fire safety concerns and demand for high-rise buildings motivated the use of steel reinforced concrete. Up to 2014 cement industry experienced steady growth globally reaching 4 Gt of annual production, since then the annual production volumes have not changed [5]. Search for more sustainable options have led to engineered wood products (EWP), these materials are made out of various types of primary and secondary timber. Wood biomass has become desirable again, this time it is due to its added benefit of carbon storage. Naturally timber has great load bearing capabilities, EWP exploit these properties and offer structural materials with much lower environmental impact than concrete. Wood-based panel market is growing globally, by the estimates the size of it in 2019 was 124.416 billion euros and it continues to grow. Geographically the biggest market share is held by Asia Pacific region, it accounts for around 54 %. Europe holds around 24 % of the wood-based panel market [6]. Wood-based panel market can be divided in terms of application or product category. Some of the most popular products are medium density fibreboards, particleboards, plywood, softboard and hardboard. Product popularity varies in different regions, for example – oriented strand boards (OSB) are the most popular products in United States. In Europe the most popular ones are particleboards and medium density boards (MDF) holding around 75 % of Europe's market. Cross laminated timber is product that can serve as an alternative in construction, this product is developed in Central Europe and at this point its market share have not even reached half a billion. Nevertheless, material like cross-laminated timber (CLT) is a good example of EWP [7]. CLT boards are produced from planks adhered together layer by layer. To ensure higher mechanical strength, layers are oriented on top of each other to 90° in relation to bottom layer. Mechanical properties of the final panels are dependent on used adhesive, thickness of the separate layers and type of wood. Lower grade planks can be used, but in order to achieve uniformity of the material, knots are usually cut out of the planks before gluing them together [8]. Overall EWP category is becoming more popular in the construction industry [9]. Another benefit of CLT and other EWP is their low density, this is important factor for building mid- and high-rise buildings as the structures of lower levels need to hold up all the weight above them. Higher strength to weight ratio is more desirable [10].

Hemström *et al.* 2011 [11] research concluded that stakeholder attitudes towards wood in construction are changing. In Sweden restrictions on mid-rise wood constructions have been lifted since 1994 [11], in Latvia only since 2015 it is allowed to build up to six story buildings from wood, but only if evacuation routes are fire proofed and equipped with sprinklers [12]. Sprinkler systems increase the price of the project; hence developers can steer away from wood solutions and seek cheaper options. Nevertheless, 15 years after lifting restrictions architects in Sweden still considered concrete as the most reliable material in comparison to steel and wood, even if wood ranked highest in environment, design and project categories. Project category included costs, construction time, work environment and transport [11].

Despite the stakeholder attitude towards building with wood, EWP like medium-density fiberboard, CLT and laminated veneer lumber (LVL) have proven that their physical properties are similar to widely used materials with higher negative impacts on environment. For example – wood fiber insulation materials thermal conductivity matches the one of rockwool, with the added benefit of increased heat capacity. Due to LVL considerable compressive strength this material can replace steel beams however CLT has considerable compressive and flexural strength, hence it can be used in weight bearing wooden constructions [9]. According to OECD [13] globally life quality is increasing, as mentioned by FAO [14] this is one of the factors demand for wood-based boards are expected to rise even more – as people choose to build bigger houses and change their furniture more often [1]. Hence wood-based solutions that could provide consumers with the same functional qualities could be well accepted not only by environmentally conscious consumers, but developers who will need to find a way to meet the growing customer demand.

In the mid-rise wood building segment popular choice has become CLT, there are multiple examples of eight-story projects [10], [11]. As noted by Hemström *et al.* pre-made panels is one of the reasons construction with CLT is significantly faster than with other materials like bricks [11]. Specific shapes can be cut prior material transportation to construction site. This approach allows to cut down the onsite operation time and reduces the transported mass and fuel consumption in return. Nevertheless, all the cuttings are sent to waste stream as their dimensions are useless for application in construction. These cuttings account for around 15 % of produced CLT [15]. Usual treatment of CLT waste is incineration as added chemical inhibit biodegradation making it unsuitable for landfills [10].

Life cycle assessment have been often used to compare environmental impact during construction, exploitation and end of life stages of reinforced concrete structures versus CLT structures [16]. At this point many papers have been published on this topic evaluating various geographical cases [4], [10], [16], [17]. Nevertheless, the amount of cuttings and their impact have not yet been studied. In this paper we are looking into environmental impacts of reprocessing CLT cuttings into functional full size CLT panels in comparison with business-as-usual scenario of CLT waste disposal. Technology for CLT reprocessing is developed in lines with industrial research and all the mass flows are based on the results of it.

2. METHODS

2.1. Cross-Laminated Timber Reuse

Reprocessing of the panels consisted of five main steps: squaring, finger-joint profiling, adhesive application, pressing and cutting to required dimensions. Custom made set of production machinery was used for carrying out the CLT reprocessing process. Formatting was done manually by using hand tools. Finger joint milling and pressing was done on specifically designed prototype machinery. Electric saw with 77 % efficiency consumed 0.01 kWh/m, hydraulic press (82 % efficiency) was able to press maximum of three panels consuming 0.09 kWh per pressing. Finger joint cutting required feeder and cutter with 77 % and 89 % efficiencies, respectively, overall finger joint cutting required 0.16 kWh/m. CLT cuttings left from construction were reprocessed into new master panels with dimensions of 3 by 6 meters. In order to make the reuse of CLT panels efficient, leftover cuttings had to be sorted in order to organize them by thickness. Developed technology allows recycling of CLT boards with maximum thickness of 160 mm. Machinery is limited to only process cuttings wider than 800 mm. Cuttings with smaller dimensions are redirected to waste. By the estimates it is feasible to process cuttings that have reusable surface area above 1 m^2, otherwise adhesive consumption is too high to be rational. All cuttings were cut to 90° corners. Only panels with identical layering and surface layer orientation were pressed together to guarantee the same mechanical strength. In this scenario, only spruce wood CLT is used. After multiple tests, *Henkel Purbond S109/S309* adhesive was chosen for reprocessing of the cuttings. To maximise the working area for adhesive, 50 mm horizontal finger joint cuts with 12 mm step were made (Fig. 1), after manual application of the adhesive, panels were pressed together continuously and cut to required master panel dimensions.

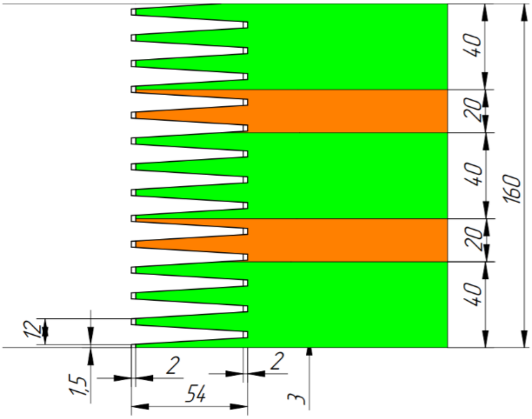


Fig. 1. Schematic representation of finger joint cut of 5-layer CLT (green – perpendicular cut to wood grain, orange – parallel cut to wood grain). Units in mm.

2.2. Scenario of Individual House Project

To illustrate the amount of available CLT for reprocessing, individual house project (Fig. 2) was chosen. Load bearing structure is entirely created from CLT. Doors and windows are cut out creating considerable amount of cutting waste.

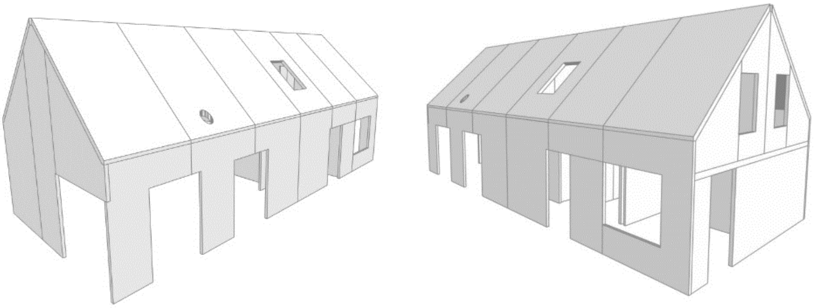


Fig. 2. 3D representation of individual house CLT weight bearing construction.

Not all the cuttings were suitable for new master panel production. Important criteria for cutting reuse was their flat surface area. Complicated geometrical shapes were sorted out, leaving the ones with reusable surface area above 1 m^2 with dimensions along X axis (example shown in Fig. 3(A) not less than 800 mm.

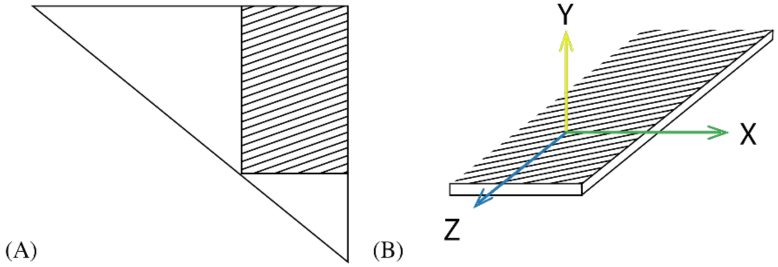


Fig. 3. (A) Reusable area of cutting represented with striped pattern. Width of the reusable area is 810 mm and length 1056 mm; (B) schematic representation.

In chosen scenario for each house eight of the irregular cuttings were suitable for reprocessing into new master panels. To ensure efficient reprocessing, firstly the cuttings were calibrated to adjust the width (X axis) so they could be adhered together and pressed perpendicular to Z axis, cut to desired master panel length of 3 m and after that gluing and pressing could be continued perpendicular the X axis (Fig. 3(B)). In this manner around 70 % of the cuttings can be reprocessed into new 3×6 m CLT panels. All the CLT cuttings from chosen individual house project.

As can be seen in Table 1, there are three types of CLT panels used – 80 mm, 120 mm and 150 mm. By evaluating scenario of cutting re-processing from 10 individual houses, we are generating scenario where cuttings can be re-processed straight away, otherwise panels with 120 mm and 150 mm thickness will need to be stored in order to accumulate adequate quantity for reprocessing.

In order to continue with LCA, calculations based on acquired data were conducted. As a result, 18 (29.7 m^3) pieces of re-processed master panels (3×6 m) were produced and additional 6.23 m^3 incomplete panels with 3 m by length that could be further used for new master panel production.

TABLE 1. CLT CUTTING ORIGINS AND DIMENSIONS

Origin	**Thickness,**	**Cutting dimensions**		**Dimensions after squaring**	
	mm	**Width, mm**	**Length, mm**	**Width, mm**	**Length, mm**
Door	80	1525	2400	1525	2200
Door	80	1525	2400	1525	2200
Door	80	1525	2400	1525	2200
Door	80	1525	2400	1525	2200
Door	80	1237	2420	1025	2220
Door	80	1025	2400	1025	2200
Window	80	825	1425	810	1025
Window	80	825	1425	810	1025
Door	80	817	2400	810	2200
Door	80	825	2400	810	2200
Door	80	810	2220	810	2020

Door	80	810	2220	810	2020
Geometrical cutting	80	irregular	irregular	810	1526
Geometrical cutting	80	irregular	irregular	810	1478
Geometrical cutting	80	irregular	irregular	810	1056
Geometrical cutting	80	irregular	irregular	810	1016
Geometrical cutting	80	irregular	irregular	810	921
Geometrical cutting	80	irregular	irregular	810	1396
Geometrical cutting	80	irregular	irregular	810	866
Geometrical cutting	80	irregular	irregular	810	848
Window	80	1625	1625	1625	1225
Window	120	840	1520	840	1120
Floor slab	150	2420	3380	2420	2980

2.3. Life Cycle Assessment Methodology

The life cycle assessment (LCA) methodology is the most common tool used to quantify and compare in a quantitatively manner the impacts from different products or processes such as the one under study. Every product (good or service) has a life cycle, from its design, then the resource extraction, transporting, production or manufacturing, commercialization, consumption or use, and final disposition. The LCA core is to collect and group the resource consumption, emissions to the environment and environmental exchanges in all activities, that are needed to produce a determined good, and translate them into comprehensive environmental impact categories [1], [2].

This allows to think beyond climate change, which is usually the main parameter judged when assessing environmental issues. The main advantage of LCA is the ability to analyse impacts from a global perspective, avoiding “burden-shifting” [3] by allowing the assessment in many and diverse impact categories, regularly summarized in climate change, stratospheric ozone depletion, tropospheric ozone creation (smog), eutrophication, acidification, toxicological stress on human health and ecosystems, resource depletion, water use, land use, noise, and others [4].

The most used methodology for performing LCA is the LCA ISO standard 14040 and 14044 where the principles and framework for LCA are described and the requirements and guidelines to perform the assessment presented. It is in ISO 14044, where the key four steps are defined: goal and scope, life cycle inventory, life cycle impact assessment, and life cycle interpretation [5]. Such steps will be covered in detail in the next section.

2.4. Goal and Scope Definition

The scope requires a clear description of the function and functional unit, system boundaries, methodology, and data requirements to sufficiently address the stated goal. This study was done as a comparative one where the waste treatment in the conventional scenario is assumed to be the same as reported in [6], meaning it is assumed the CLT cuttings are used for energy recovery, more specifically in district heating and electricity production. However, transport of cuttings is not considered neither in this nor in the new proposed scenario, where cuttings are re-processed in-situ to generate new CLT pieces. Thus, the scope of this study is to evaluate only the activities related to the use given to cuttings in both scenarios despite of the geographical location with respect to the waste treatment facility.

This is an attributional model where output data from [6] is normalized to the current scenarios considering the specific activities, material and energy flows required to conduct the re-process of cuttings for a specific residential construction project in Latvia. Then, the results of this study are only applicable to this scenario as foreground data was obtained directly from construction companies and the amount of cuttings subject to waste or re-process may vary from one project to another, as well as foreground data related to materials and energy.

For the baseline scenario, the intended waste treatment is energy recovery, and the values for electricity, and heat generated are taken directly from [6] as well as the related impact from this End-of-Life (EoL) stage. Then, the impact results are normalized to the amount of waste expected from the construction project under evaluation, and these values are understood as the environmental impact results in the different mid-point categories resulting from the Environmental Product Declaration (EDP) methodology. For the proposed scenario, the same amount of cuttings resulting from the construction site, instead of being sent to the waste treatment plant, are re-processed to create useful new CLT units that could be even sold to other projects or used internally within the same building site. However, despite of the re-processing activity, there are cuttings still left for waste, and it is assumed those leftovers are disposed in the same way as in the baseline scenario.

The EDP method has been recently updated (2018) including water scarcity footprint category, yet since the 2013 EDP version under which the Environmental Product Declaration was obtained for this CLT material did not include such category, this one has been left out of this study to keep comparison consistency. The LCA performed in this project was completed using *Simapro 9.0* software integrated with *Ecoinvent 3.6* database.

2.4.1. Functional Unit

The functional unit (FU) is a measure of the performance of the functional outputs of the product system and its main objective is to give a reference to which the inputs and outputs are related. Such a reference is needed to guarantee the equivalence of LCA results. The definition of a functional unit must then include both the quantitative and the key qualitative aspects to prevent subjectivity when subsequently defining an equivalence. In this case, the functional unit is one cubic meter (1 m^3) of CLT material used in the construction site.

2.4.2. System Boundaries

Considering the Environmental Product Declaration system boundaries for the material under study and the system boundaries considered there, the scheme presented in Fig. 4 has been developed for this LCA.

The system boundaries in the baseline scenario only covers the waste treatment of cuttings generated in the construction site without bearing in mind transport to waste treatment plant since the distance is considered an uncertainty due to variability of possible geographical locations of building sites. Please notice although phases A1–B7 are displayed in the figure, only those phases inside the dashed box are the ones within the study's system boundaries. Extra phases are only informative to show the overall life cycle of CLT.

For the proposed scenario, the re-process activity is carried out in-situ, without any need for transport to another location. The remaining cuttings not fitted to be re-processed are disposed using the same treatment technology considered for the baseline scenario, and again, the transport to the waste treatment facility is not considered due to distance uncertainty.

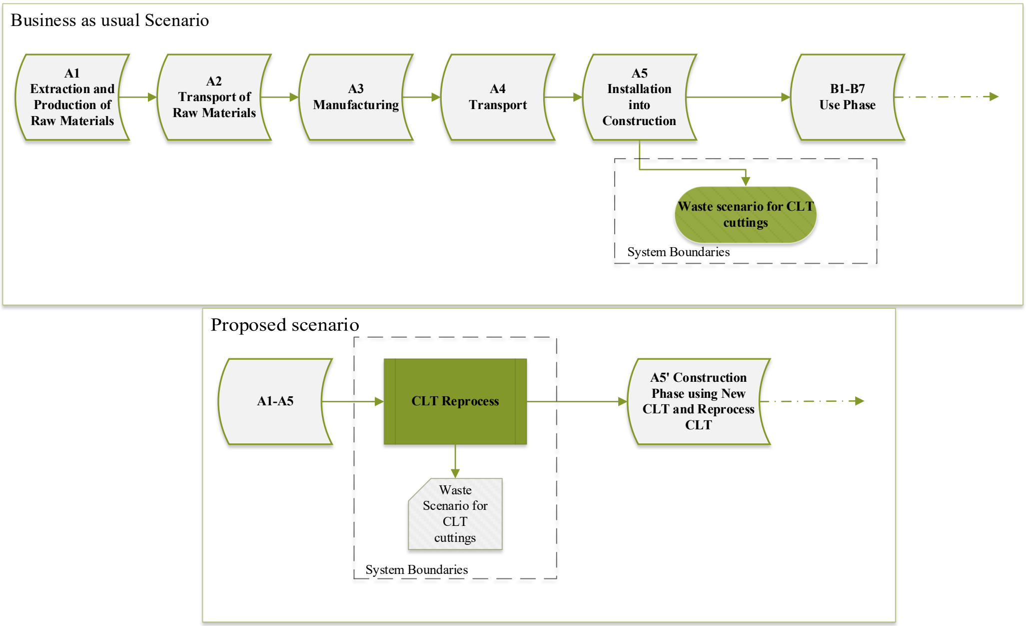


Fig. 4. System boundaries for the business as usual and proposed scenarios.

2.4.3. Limitations and Assumptions

Among the limitations that apply for the two scenarios under comparison, the exclusion of transport activities is the main one due to the uncertainty on both: the geographical location of the waste treatment facility and the construction site as it varies depending on the project. However, it is important to notice, that transporting wastes does come with an environmental burden from the vehicle itself and the fuel combustion, moreover, the higher the amount of waste to be transported, the higher the environmental impact will be; hence it is likely that by reducing the amount of waste subject to transported, an additional environmental benefit might be perceived despite not been accounted for in this study.

Another assumption to bear in mind is the fact of the re-process being carried out in the same location as the construction of the residential houses is taking place. This is important since it might be possible, under different case studies, that cuttings leftover after construction need to be sent to another location for re-processing and then dispatched back to the same location or sold to another construction project in a different one. For this cases study, since the re-processing activities are conducted in the same place, no additional environmental toll from transport is created.

2.5. Life Cycle Inventory

For the baseline scenario, the results from the energy recovery at the end of life (EoL) stage in [6] were taken directly for 1 m3 and normalized to the amount of waste generated in the particular construction site. According to the foreground data collected, per each cubic meter of CLT used, 0.128 m^3 end up as cuttings leftover to waste. The benefits resulting from the energy recovery of 1 m^3 are estimated in 612 MJ of electricity and 4208 MJ of thermal energy for district heating. Their associated environmental impact is shown in Table 2 for a whole cubic meter of material disposed. Nevertheless, the values within the model are normalized to the actual amount of cuttings sent to waste in each scenario.

TABLE 2. IMPACT ASSESSMENT FOR 1 M^3 OF CLT DISPOSED

Impact category	Unit	Total per m^3
Acidification Potential	kg SO_2 eq	–0.1786
Eutrophication Potential	kg PO_4 eq	–0.04186
Global Warming Potential	kg CO_2 eq	–32.51
Formation potential of tropospheric photochemical oxidants	kg C_2H_4 eq	–0.01664
Abiotic depletion potential for non-fossil resources	kg Sb eq	–0.000112
Abiotic depletion potential for fossil resources	MJ	–0.04217
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	0.000004012

For the proposed scenario where re-process activities allow to recover part of the cuttings by making new CLT units, the inventory collection goes toward gathering impacts from 3 stages:

1. Production of brand new CLT units;
2. Materials and energy required for the re-process activity itself;
3. The waste treatment of the unrecoverable cuttings.

Since by creating new CLT units from cuttings, brand new CLT units are potentially replaced in a construction site, the impact of such new re-processed CLT units are considered as an avoided product, hence the environmental impact results from phases A1–A3 (Fig. 1) are normalized and mathematically treated consequently with this approach. Impacts of stages A1–A3 for 1 m^3 are shown in Table 3.

TABLE 3. IMPACT ASSESSMENT OF PRODUCING 1 M^3 OF CLT (A1–A3 STAGES)

Impact category	Unit	Total
Acidification Potential	kg SO_2 eq	0.6272
Eutrophication Potential	kg PO_4 eq	0.1116
Global Warming Potential	kg CO_2 eq	–0.05673
Formation potential of tropospheric photochemical oxidants	kg C_2H_4 eq	0.1144
Abiotic depletion potential for non-fossil resources	kg Sb eq	0.0002468
Abiotic depletion potential for fossil resources	MJ	1497
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	0.0000125

The inventory of material and energy required for re-processing 0.128 m^3 of leftover cuttings (value per FU), are normalized to the following: 0.0904 kg of adhesive (polyurethane adhesive) and 0.466 kWh of electricity taken from the national grid. According to the foreground data obtained, 69.72 % of the cuttings re-processed are successfully converted into new CLT modules while the remaining 30.28 % are not suitable for re-process and must be left as waste material for treatment. Again, the impact related to such treatment is taken from Table 1 and normalized to the corresponding value in this scenario.

3. LIFE CYCLE IMPACT ASSESSMENT AND INTERPRETATION

The proposed case scenario where cuttings from CLT are re-processed was modelled in *SimaPro* according to the defined FU and the results are presented first in a comparative way with the business-as-usual scenario, and then it is disaggregated by unit process. The impact assessment is presented at midpoint level (kg of substance equivalent) as recommended by the EDP method and ISO standards in Table 4. Results in business-as-usual scenario correspond to the energy recovery phase for 0.128 m^3 of CLT; on the other hand, the results in the proposed scenario correspond to the sum of the three considerations aforementioned: impact from the re-process activity, avoided impact from putting in the market new CLT modules, and the impact related to the energy recovery of remaining cuttings not re-processed.

TABLE 4. CHARACTERIZATION RESULTS COMPARISON BETWEEN SCENARIOS

Impact category	**Unit**	**Business as usual**	**Proposed scenario**
Acidification Potential	kg SO_2 eq	–0.023	–0.059
Eutrophication Potential	kg PO_4 eq	–0.005	–0.011
Global Warming Potential	kg CO_2 eq	–4.155	–0.524
Formation potential of tropospheric photochemical oxidants	kg C_2H_4 eq	–0.002	–0.008
Abiotic depletion potential for non-fossil resources	kg Sb eq	–1.43E–05	–2.35E–05
Abiotic depletion potential for fossil resources	MJ	–0.005	–122.457
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq	5.13E–07	–9.20E–07

In the business-as-usual scenario, most of the impact categories show a benefit to the environment since it is understood, that the electricity and thermal energy generated from the incineration of CLT material would replace conventional electricity production in Latvia, according to the market for electricity mix in the *Ecoinvent 3.6* database. In the proposed scenario, even higher benefits to the environment are obtained, due to the still energy recovery for 30.28 % of the leftover cuttings and the delivered avoided impact from new CLT modules.

Percentual changes of moving from a business-as-usual scenario towards the proposed one are easily seen in Fig. 5.

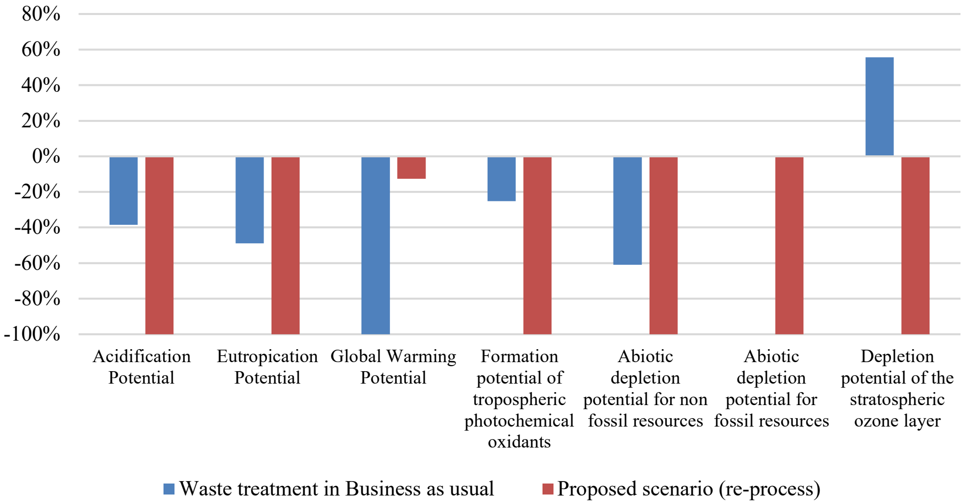


Fig. 5. Characterization results.

In general, the nowadays EoL stage or waste treatment of CLT delivers benefits to the environment in almost all the impact categories assessed within the EDP method, but for the ozone layer depletion one. Nevertheless, the proposed new set of activities that give birth to new CLT panels reducing the amount of waste to be incinerated, aids to increase the already delivered benefits in all areas except for the global warming potential, this as result of the lower electricity production that would have eventually substitute the production from conventional sources in the specific Latvian market. It is worth to notice that the GWP benefits under the business-as-usual scenario is due to the fact of substituting energy production from the local market by the energy recovery from a one hundred percent renewable source such as wood. In all other areas benefits from the new approach surpasses the original ones.

Regarding the proposed re-processing of CLT cuttings scenario, the adverse effects to the environment are coming from the re-process activity, since the waste scenario is the same as for the business as usual, thus resulting in an environmental benefit, and the new produced CLT modules are considered as an avoided product. Under the evaluation of the proposed scenario, it was found the main driver in most of the evaluated impact categories is the use of polyurethane adhesive (Fig. 6), except in the ozone layer depletion one.

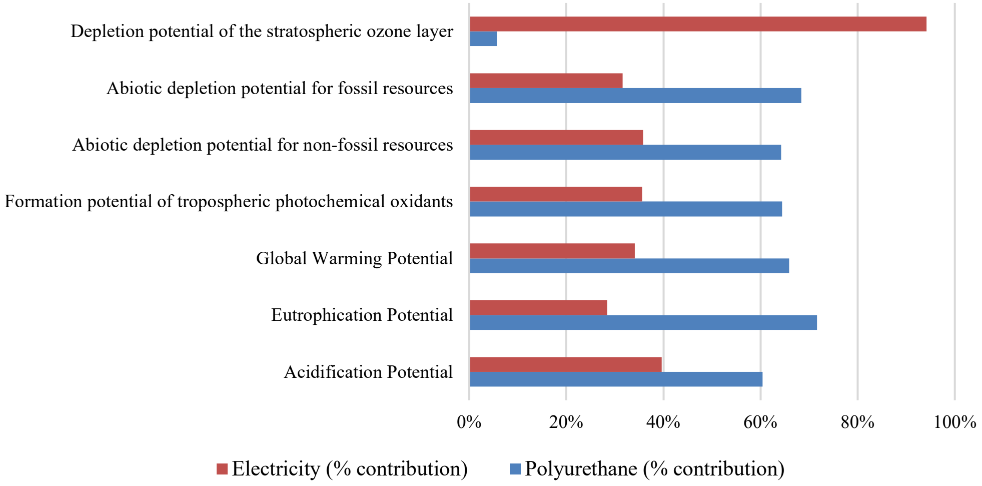


Fig. 6. Environmental impact contribution per re-processing activity/flow.

4. DISCUSSION

Several studies regarding the environmental impact of using CLT as a substitute material for concrete or just as a building material, from cradle to grave are found in the literature for different geographic scenarios such as Australia [10], The United States [15], Europe [16] and Japan [17] just to mention some. In most cases it is stated that the use of CLT is advantageous as its main raw material can be linked to a renewable source, which promotes Bio Energy Carbon Capture and storage, circular economy by implementing energy recovery in the EoL stage, and in general, all LCA prove CLT to be environmentally friendly.

Still, the construction activities deal with a lot of cuttings that result in CLT material waste, hence most of the quantitative environmental benefit linked to it that comes from the comparison with typical building supplies is now lost, and the benefit of CLT can only be related to how it is disposed. In this work, a new way of dealing with CLT wastes from construction sites is addressed to and evaluated using LCA and the EDP method to allow comparison with the EoL stage reported in the EDP declaration for the CLT manufacturer in Latvia case [18].

The results of conducted LCA show that eco-efficiency regarding CLT cutting reprocessing is beneficial, as cutting re-processing allows for considerable amount of avoided product. Data showed that re-processing consumes considerably less resources than new CLT production in turn leading to lower environmental impact. Only impact category where business as usual showed better results is global warming potential category, as explained previously – this is due to thermal and electric energy recovery from business-as-usual waste treatment. As almost 30 % of CLT cuttings goes to waste after reprocessing, proposed scenario benefits from incineration activities as well. At this point CLT re-processing technology is limited to 800 mm width dimensions and arguably it will not be viable to process smaller cuttings, as this approach would increase the consumption and end concentration of adhesive. As results (Table 4) show, greatest driver of impact in all categories is PU adhesive. Literature shows that conventional adhesives like urea-formaldehyde have significantly negative impacts on emissions, toxicity, eutrophication and acidification. Even if most of EWP contain resins like urea-formaldehyde, environmental impacts of EWP are lower than other types of building materials [19]. Nevertheless, as the adhesive creates the biggest environmental burden, materials with higher adhesive amount does as well. Hence from environmental point of view smaller cutting re-processing will not be feasible.

Positive results regarding the reduction of environmental impact shows that CLT re-processing technology should be explored further as it can potentially reduce the environmental impact of all CLT industry. As mentioned in this paper, rapid growth is predicted for CLT and another EWP. Building with CLT instead of concrete will allow for construction industry to transition towards more sustainable model. Recent signals from European Union [20] as well as older ones from United Nations [21] confirm the policy changes regarding efficient material use and re-processing. Hence, developing technology for CLT waste re-processing whilst the CLT technology is being developed itself corresponds to 21st century's green approach and aligned with the European and global goals of achieving sustainability and carbon neutrality.

ACKNOWLEDGMENT

This study was carried out with the support of CFLA contract No. 1.2.1.1/18/A/004 between "Forest Sector Competence Centre of Latvia" Ltd. and the Central Finance and Contracting Agency, the study is conducted by "FUNDUSS" Ltd. with support from the European Regional Development Fund (ERDF) within the framework of the project "Forest Sector Competence Centre"

REFERENCES

[1] M. Lavagna *et al.* Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock. *Build. Environ.* 2018:145:260–275. https://doi.org/10.1016/j.buildenv.2018.09.008

[2] Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions On Resource Efficiency Opportunities In The Building Sector. Brussels: European Commission, 2014.

[3] Müller H. S., Haist M., Vogel M. Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime. *Constr. Build. Mater.* 2014:67(C):321–337. https://doi.org/10.1016/j.conbuildmat.2014.01.039

[4] Athena Sustainable Materials Institute. A Life Cycle Assessment of Cross-Laminated Timber Produced in Canada. Ottawa: Athena Sustainable Materials Institute, 2013.

[5] IEA. Global cement production, 2010-2019 – Charts – Data & Statistics - IEA [Online]. [Accessed 30.10.2020]. Available: https://www.iea.org/data-and-statistics/charts/global-cement-production-2010-2019

[6] Wood Based Panel Market Size & Share | Industry Report, 2018-2025 [Online]. [Accessed 09.02.2021]. Available: https://www.grandviewresearch.com/industry-analysis/wood-based-panel-market

[7] Panels & Furniture Asia May/Jun 2020 [Online]. [Accessed: 28.10.2020]. Available: http://www.panelsfurnitureasia.com/ebook/PFA_MayJun2020/index.html

[8] Cherry R., *et al*. Out-of-grade sawn pine: A state-of-the-art review on challenges and new opportunities in cross laminated timber (CLT). *Constr. Build. Mater.* 2019:211:858–868. https://doi.org/10.1016/j.conbuildmat.2019.03.293

[9] Hildebrandt J., Hagemann N., Thrän D. The contribution of wood-based construction materials for leveraging a low carbon building sector in europe. *Sustain. Cities Soc.* 2017:34:405–418. https://doi.org/10.1016/j.scs.2017.06.013

[10] Jayalath A., *et al.* Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia. *Energy Build.* 2020:223:110091. https://doi.org/10.1016/j.enbuild.2020.110091

[11] Hemström K., Mahapatra K., Gustavsson L. Perceptions, attitudes and interest of Swedish architects towards the use of wood frames in multi-storey buildings. *Resour. Conserv. Recycl.* 2011:55(11):1013–1021. https://doi.org/10.1016/j.resconrec.2011.05.012

[12] Cabinet of Ministers. Ministru kabineta noteikumi Nr. 333: Noteikumi par Latvijas būvnormatīvu LBN 201-15 "Būvju ugunsdrošība" (Regulations of the Cabinet of Ministers No. 333: Regulations on the Latvian construction standard LBN 201-15 "Fire safety of buildings"). *Latvijas Vēstnesis* 2015. (in Latvian)

[13] OECD. *How's Life? Measuring well-being*. Paris: OECD, 2017.

[14] Barboutis I. Kamperidou V. Properties of two different thicknesses 3-ply plywood of tree-of-heaven veneers. *Proceedings of the 22nd Int. Sci. Conf. Wood is Good - EU Preaccession Challenges Sect. Proc.* 2011:6–19.

[15] Chen C. X., Pierobon F., Ganguly I. Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) produced in Western Washington: The role of logistics and wood species mix. *Sustain.* 2019:11(5):1278. https://doi.org/10.3390/su11051278

[16] Guardigli L., Monari F., Bragadin M. A. Assessing environmental impact of green buildings through LCA methods: A comparison between reinforced concrete and wood structures in the European context. *Procedia Eng.* 2011:21:1119–1206. https://doi.org/10.1016/j.proeng.2011.11.2131

[17] Passarelli R. N. Environmental Benefits of Reusable Modular Mass Timber Construction for Residential use in Japan: an LCA Approach. *Modul. Offsite Constr. Summit Proc.* 2019:2017:157–164. https://doi.org/10.29173/mocs89

[18] Giels E. *Cross laminated timber panels*. Oslo: Epd-Norge, No. 2017.

[19] Sathre R., González-García S. Life cycle assessment (LCA) of wood-based building materials. Eco-Efficient Construction and Building Materials. Life Cycle Assessment (LCA), Eco-Labelling and Case Studies. Woodhead Publishing, 2014:331–337. https://doi.org/10.1533/9780857097729.2.311

[20] Tubert-Brohman I., Sherman W., Repasky M., Beuming T. Improved Docking of Polypeptides with Glide *J. Chem. Inf. Model.* 2013:53(9):1689–1699. https://doi.org/10.1021/ci400128m

[21] Ichimura M., *et al.* Eco-efficiency Indicators: Measuring Resource-use Efficiency and the Impact of Economic Activities on the Environment. Bangkok: United Nations publication, 2009.

Environmental and Climate Technologies
2021, vol. 25, no. 1, pp. 1101–1113
https://doi.org/10.2478/rtuect-2021-0083
https://content.sciendo.com

Complete Circularity in Cross-Laminated Timber Production

Ilze VAMZA[1] *, Karlis VALTERS[2], Ilze LUKSTA[3], Peteris RESNAIS[4],
Dagnija BLUMBERGA[5]

[1–3,5]*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV-1048, Latvia*

[4]*SIA FUNDUSS, 'Tiltakrogs", Ieriķi, Drabešu parish, Amatas reg. LV-4139, Latvia*

***Abstract* – Many authors have discussed the paradigm shift in economy from linear to circular. Population growth and climate change caused resource scarcity are the main driving forces of shifting to circularity approach. Although consumers have been slower regarding transitioning to more sustainable economy, production companies are the ones who have felt the scarcity of resources first. In this paper we are exploring cross-laminated timber (CLT) production residue utilization possibilities for new product production and using multi-criteria analysis calculating the most promising recycling alternative from the perspective of companies working with wood as raw material. Data matrix for multi-criteria analysis was constructed from literature analysis gathering data on five criteria: (1) production costs; (2) energy consumption; (3) CO_2 emissions; (4) product market price and (5) final product to wood residues ratio. Multi-criteria analysis showed that production of mycelium insulation material is the most promising alternative for CLT production residue recycling.**

***Keywords* – Cascades; green growth; multi-criteria analysis; sustainable building; wood residue**

Nomenclature

SME	Small and medium enterprise	–
CLT	Cross-laminated timber	–
PWH	Peat, woodchip, and hemp shave composite	–
MDF	Medium density fiberboard	–
HDF	High density fiberboard	–
PB	Particleboard	–
CO_{2eq}	Carbon dioxide equivalent	–
AHP	Analytical hierarchy process	–
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution	–
UF	Urea-formaldehyde	–

---

* Corresponding author.
E-mail address: Ilze.Vamza@rtu.lv

1. INTRODUCTION

Circularity principles in economy are gaining momentum with The Paris Agreement [1] and the European Green Deal [2]. United Nations in their 2011 report advocated that decoupling of economic growth from resource consumption along with the negative impact on environment is a key to sustainable future. Every region has its limits on how much natural resources can be extracted, nevertheless all nations have the desire to grow and develop [3]. It comes down to consumers and production companies to make more sustainable choices and work on resource efficiency [4]. Bocken *et al.* in her 2017 commentary published 9-year keyword analysis on major global companies' press releases, showing the gradual appearance of words like 'zero-waste' and 'resource efficiency' [5]. Recent analysis on how small and medium enterprises (SME) participate in the circular economy elucidated eight approaches, with the main six:

- Maximize efficiency and productivity of material and energy;
- Increase the proportion of bio-based and renewable material use;
- Create value from waste;
- Develop industrial symbioses and transparent supply chains;
- Encourage sufficiency;
- Develop scale-up solutions [6].

For the SME to be able to adopt the abovementioned approaches research and development is required. Another study by Zihare *et al.* elucidate the complex network of factors impacting bioeconomy – network illustrates the links between research and development, technology, and bioresource [7]. Another important driving force of innovation is policies [4], [7]. Major sector regarding resource consumption is building sector. Global efforts are aimed towards reduction of impact of building construction, exploitation and demolition [8]. Important aspects in greener building, especially in construction phase, is the choice of materials – materials made from bio-based raw materials [6], lightweight and easy to use materials result in faster production times, reduction of overall impact of construction phase on the environment [9]. National efforts of transition to greener building process include various policies with varying tools in the form of stimulus or incentives. Nevertheless, it often comes down to material producers and project developers to invest in green innovations, often encouraged by social demand [8], [10]. It is important not only to create greener supply chains of renewable raw material but to use the created production residues in other economic activities, hence promoting resource efficiency [11]. Resource cascading principles imply reuse, recycling, and recovery in the described order. When possible, production residues should be reused as a raw material for the same product production where they were generated. In this way the demand for new raw material would be reduced. If there are technological limitations for production residues to be reused, they can be recycled – transferred to a relevant recycling company or a company that can use it as raw material. Recovery should be used only as a last resort when nothing else other than energy recovery is possible [12]. Recycling is part of open-loop lifecycle – on this basis industrial synergies can be created. Depending on the material, receiving companies may need to acquire license for accepting waste in their plant [13].

Regarding building industry's circularity (and sustainability) wood is still one of the most promising raw materials. Although used for many centuries, wood has regained its popularity due to its sustainability and physical properties [10]. Deeper understanding of the mechanics behind timber strength along with stronger binders [14], [15] have led to engineered wood products like fiberwood, particleboards, laminated beams [16] and cross-laminated timber (CLT) [17].

CLT is a promising construction material, its mechanical properties and renewable raw material makes it attractable mineral building block replacement [17]. With today's technology it is possible to build midrise buildings using renewable laminated wood constructions [9]. Building with CLT is a fast process due to its pre-fabrication possibilities. CLT panels are made by gluing wooden planks together in cross-wise manner, as a result large panels can be made and cutouts for openings like doors and windows can be made in production plant, this approach makes working on site much easier. The downside of this pre-fabrication is the generated cuttings – around 20 % of CLT panels are entering production residue streams. Our previous work explored the environmental impact and possibilities of reusing CLT cuttings for new CLT panel production. With the developed CLT reprocessing technology, around 70 % of the generated cuttings can be reused for new full-size panel production [18]. Work shows how industrial innovation would be applied in CLT production plants allowing for CLT producers to operate in line with the circular economy principles [12]. Nevertheless, to develop a full cascade for CLT production, it is crucial to explore the possibilities for CLT residue recycling. As specific research on CLT residues have not been done, in this work we will explore the options for other wood residue utilization.

CLT residues comprise sawdust from cutting and finger-jointing, and cuttings made from cross-wise laminated planks. These larger cuttings (Fig. 1) have around 2 % of adhesive. Today CLT is mainly produced using urea-formaldehyde (UF) or polymer iso-cyanine adhesives like polyurethane [17]. UF resins cause toxic fumes, hence the use of polyurethane can reduce the negative impact of the final product [19]. In addition, fatty acids in polyurethane production can be replaced by renewable canola oil [17] reducing the negative environmental impact of polyurethane itself.

Fig. 1. Cross laminated timber non-reusable cuttings.

With the emerging paradigm shift in economy from linear to circular [11], [20], [21], it is necessary to work on full circularity of products. This research explores the possibilities for full circularity of CLT production, ensuring recycling of production residues unsuitable for reuse. In this paper we are exploring CLT production residue utilization alternatives for various product production and using multi-criteria analysis to elucidate the most promising one from the perspective of companies working with wood products.

1.1. Materials from Wood Residues

Using production residues when primary raw material runs out is not anything new, wood particleboards were mass produced during World War II when supply for sawn wood could not meet the demand [22]. To achieve similar structural integrity to sawn wood, wood particles are bonded together with formaldehyde, urea or phenolic resins. Despite formaldehyde's toxicity UF resin is the one that is most often used and particleboards are the most popular wood-based composite [23]. Consumer demand for particleboards have made this industry so profitable that good quality timber was used as raw material. Research have shown that recycled wood raw material negatively impacts the mechanical strength of the final product [24]. Only in recent decade companies are looking into steering away from timber to wood residue as raw material [24], [25]. Lumber is the preferred choice of raw material because it can be broken down into particles with necessary geometry and size. Wood residues usually come in various forms – sawdust, dust or woodchip. Research have shown that larger particles than sawdust are preferable in order to achieve better mechanical strength of particleboard [26].

Popular wood-based panels are medium (MDF) and high (HDF) density fiberboards. Annually around 9 million m^3 of fiberboards are produced in European Union alone [27]. Fine cellulose fibers are glued together with UF resin [28]. To acquire the cellulose fiber, wood is treated using thermo-mechanical pulping during which cellulose is separated from lignin. The overall strength of wood is compromised when lignin absorbs water, making it easier to separate cellulose from lignin with mechanical force. Thermomechanical pulping is carried out at ~180 °C temperatures and 60–120 % humidity [29]. After fiber refining they are dried to around 7 % water content [28].

Typically, MDF is made from production residues (e.g. green and dried sawdust, veneer and plywood cuttings) of primary wood products – lumber and plywood. As plywood is made from veneer sheets glued with UF resin in a cross-wise manner [28], [30] it can be speculated that CLT cutting residues could be used for MDF production despite the varying directions of wood grain.

Another material where wood residues can be used is thermal insulation composite of peat, woodchip and hemp shaves (PWH) [31]. Material has been tested in laboratory setup on heat conductivity, showing 0.056 to 0.060 W/(m·K) thermal conductivity. Benefits of this technology implies that less energy is needed to produce it in comparison to medium density fiberboards (MDF) or mineral wool. Curing PWH requires only 75 °C [31] temperatures where MDF requires 175 °C [32], nevertheless, PWH requires 24 hours of 75 °C but MDF only 275 seconds [31], [32] resulting in 3.36 MWh versus 0.02 MWh respectively. Another thermal insulation material made from wood residue is mycelium based, with its first iterations material was made from agricultural residues by cultivating specific fungi on it. In addition to material's excellent thermal conductivity of 0.039 W/(m·K), its light weight, mycelium insulation material can be produced using less energy than PWH or conventional mineral wool insulation as solar dryers can supply sufficient amount of energy for curing the material [33].

Physical properties of wood make it an attractive building material, it can be used on its own, for example in log houses [34], or as engineered wood in a form of a CLT [35] or in composites as described above with thermal insulation material [31]. Relatively low density of wood and its thermal properties makes it an excellent filler as wood ignition temperature is in the range of temperatures used for brick burning. Burning bricks to cure them result in sawdust filler burning, as a result density of the mineral blocks decreases, reducing the dead load of final construction [36]. Heavy building loads are a safety issue in regions within

Earth's earthquake zones [36], in regions like Latvia reduced material weight leads to lower emissions during construction phase as less energy is needed for transportation [37] and other manipulations with the material. Recently researchers have been exploring the benefits of polypropylene and wood composite materials. By placing the wood sawdust in specific areas, material with disparate stiffness in its sections can be achieved. At this point it is expected that this kind of material could be used in snap fit parts in connections or quick release parts [38]. This kind of parts could be used in products compliant with eco-design principles [39] replacing polypropylene with biodegradable plastic like polylactic acid.

Solid fuel in the form of wood pellets can be produced from various wood residues [40]. Although, wood burning is considered more sustainable, it generates considerable amount of CO_2 emissions. Each generated GJ of energy from wood pellets releases 11.76 kg CO_2eq in the atmosphere [41].

In line with the European Union's Green Deal and global trends of circular economy and resource efficiency, it is important for companies developing new products to utilize their production residues in the best possible way. In this work we are exploring potential opportunities for CLT cutting recycling into four alternatives – medium density fiber-board, mycelium thermal insulation material, particleboard, or solid fuel. All the alternatives have their benefits and downfalls, hence multi-criteria decision making tools will be utilized in order to find the best alternative. Our goal is to elucidate the best possible alter-native for CLT cutting use according to expert opinions and literature analysis.

2. MATERIALS AND METHODS

2.1. Criteria and Data Gathering

Products were analysed from green economy perspective, hence criteria that would represent it was chosen. Overall, five criteria:

1. Production costs;
2. Energy consumption;
3. CO_2 emissions;
4. Product market price;
5. Final product to wood residues ratio were chosen.

Values for analysed criteria were gathered from scientific literature, market data [42] and life cycle inventories [43], [44] on the chosen products.

Production costs included energy, raw material, and labour costs to produce one metric ton of the product. Energy consumption and CO_2 emissions during production process of one metric ton of product was calculated from energy consumption and source (grid or cogeneration). 'New product to raw material' criterion represented the extra material needed for the production of new product (one of alternatives). Ratio of new product to raw material also represented how much of the raw material originally used for production could be replaced with wood resides. Product market price represents value what the consumer pays to acquire the material from market.

Data were gathered from life cycle inventories and other works. In case of life cycle inventories of PB and MDF data were reflected using functional unit or one square meter, hence values were converted to tonne using material density.

2.2. Multi-Criteria Decision Making

Many multi-criteria decision-making (MCDM) methods have been developed to provide decision makers with tools based on mathematical logic. All MCDM methods have some subjectivity aspect to them and many MCDM methods provide different results as shown by Zlaugotne *et al.* [45] Siksnelyete *et al.* recognized Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method as the one having the most benefits in comparison to PROMETHEE, PROMETHEE II, VIKOR, WASPAS, WASPAS-G and Fuzzy Sets. AHP had the second best benefit count [46]. In addition, Lee *et al.* 2012 have used AHP specifically for technology transfer adoption in companies, hence showing the compatibility of AHP to organizational decision making [47]. In this work we are looking for the best alternative closest to the ideal solution, hence TOPSIS was chosen in combination with AHP. TOPSIS method not only elucidates the best alternative but gives the closeness to the ideal solution coefficient [48]. Hence, by using TOPSIS more detailed picture of 'How ideal all the alternatives are' can be acquired. To acquire weights for TOPSIS, Analytical hierarchy process (AHP) was used. AHP is one of the most widely used MCA methods because it allows to easily compare criteria with each other [49]. In this work, the Saaty's scale was used to compare the criteria, in which nine degrees of importance were verbally denoted, indicating the importance of one criterion over another. The scale of nine ratings starts with 1, which stands for equal importance, and ends with 9 which stands for extreme importance [50].

To evaluate the importance of each criterion, experts with experience on CLT production were asked to rate reciprocal relations of criteria. For evaluation, experts were acquainted with Saaty's scale and criteria plotted in Excel to generate questionnaires for experts to fill. Questionnaires were sent out via e-mail.

The acquired ranking was used in AHP in order to calculate the normalized eigenvectors representing the importance of each criterion [50]. Criteria and their ranking were plotted in Excel in a comparison matrix as shown by Delvere *et al.* [51]. Consistency ratio <0.2 was determined, and the calculated weights were used in further MCA.

AHP was used in combination with TOPSIS.

TOPSIS decision-making method was based on previously calculated weights for AHP, and data collected from the literature. Four alternatives for CLT residue utilization were considered:

- MDF;
- Mycelium insulation;
- Solid fuel;
- PB.

For comparison, the considered alternatives and their criteria were arranged in a decision-making matrix and the matrix data were normalized, Eq. (1).

$$\begin{array}{c} A_1 \\ A_2 \\ A_3 \\ A_4 \end{array}\begin{bmatrix} v_{11} & v_{12} & v_{13} & v_{14} \\ v_{21} & v_{22} & v_{23} & v_{24} \\ v_{31} & v_{32} & v_{33} & v_{34} \\ v_{41} & v_{42} & v_{43} & v_{44} \end{bmatrix}, \tag{1}$$

where A_n alternative uses of wood residue, v_n criteria, normalized matrix.

The obtained normalized values were multiplied by the weights obtained by AHP and the distance of each criterion to the ideal solution was determined.

Sensitivity analysis was conducted to evaluate robustness of the TOPSIS results. To compare sensitivity of the assigned weights (ω), Li *et al.* described TOPSIS method was used [52]. Changes in the importance of product market price was calculated by introducing unity variation βpm that represents the changes in product market price weight. After changes the product market price weight (ω’pm), all the other criteria weights (ω) were recalculated according to:

$$\begin{cases} \omega_1' = \dfrac{\omega_1}{1+(\gamma_{pm}-1)\cdot\omega_{pm}} \\ \omega_{pm}' = \dfrac{\omega_{pm}\cdot\gamma_{pm}}{1+(\gamma_{pm}-1)\cdot\omega_{pm}}, \\ \omega_n' = \dfrac{\omega_n}{1+(\gamma_{pm}-1)\cdot\omega_{pm}} \end{cases} \tag{2}$$

where

ω'_{pm} Product market price criteria weight after changes;

ω'_{n} Other criteria weights after changes in ω_{pm};

γ_{pm} Initial variation, calculated according to:

$$\gamma_{pm} = \frac{\beta_{pm} - \beta_{pm}\cdot\omega_{pm}}{1-\beta_{pm}\cdot\omega_{pm}}, \tag{3}$$

where β_{pm} unity variation, calculated according to:

$$\beta_{pm} = \frac{\omega_{pm}'}{\omega_{pm}}. \tag{4}$$

In addition, sensitivity on the production costs of the ideal CLT cutting recycling alternative was conducted.

3. RESULTS

Based on the conducted AHP weights for criteria of wood residue, recycling was calculated and used in TOPSIS analysis to elucidate the best alternative from companies working with CLT perspective.

According to expert evaluation, production costs are the most important when considering potential applications of wood residue. Production costs are followed by product market price, and wood residue to new product ratio. Results of AHP are shown in Fig. 2.

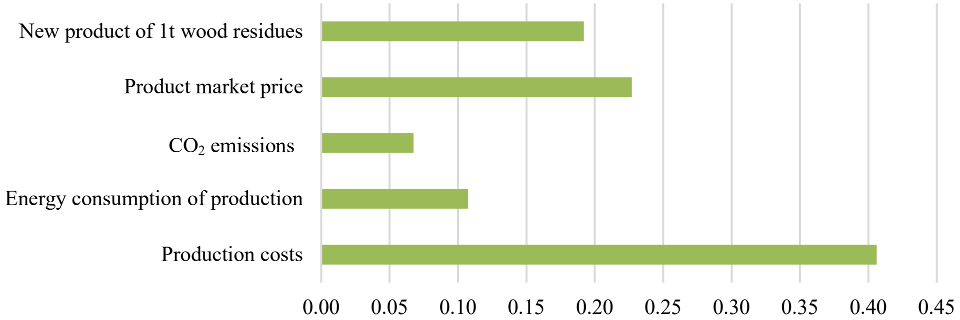


Fig. 2. Weighed criteria. Weights of criteria are determined using analytical hierarchy process un input form expert interviews. The sum of all weights is equal to 1.

Calculated weights were used for TOPSIS analysis as described in section 2. Data matrix of alternatives and their corresponding criteria are depicted in Table 1. along with calculated weights.

TABLE 1. DATA MATRIX WITH CONSIDERED ALTERNATIVES (A_N) AND CORRESPONDING DATA OF WEIGHED CRITERIA (X_N)

	(x_1) Production costs	(x_2) Energy consumption	(x_3) CO_2 emissions	(x_4) Product market price	(x_5) New product to wood waste ratio	Reference
Criteria weights (ω)[1]	0.41	0.11	0.07	0.23	0.19	
Units	€/tonne	MWh/t	kg CO_2/t	€/tonne	t	
(A_1) Medium density fiberboard	250	1.6	1088	586	0.9	[42], [44]
(A_2) Mycelium insulation material	68	0.28	47	140	0.9	[42], [53]
(A_3) Solid fuel	113	0.02	38	204	1	[42]
(A_4) Particle boards	147	0.77	150	350	0.9	[42]

Note: [1] Weights calculated with analytical hierarchy process approach.

TOPSIS approach elucidated the mycelium thermal insulation material as the most promising wood residue utilization option and MDF production as the least preferable option (Fig. 3). Mycelium thermal insulation gained closeness coefficient (CC) of 0.65 to the ideal solution. According to expert evaluation and literature data, solid fuels gained CC of 0.59 showing that solid fuel production is still closer to ideal than non-ideal solution. Nevertheless, when raw material cascades are considered, burning the by-product is considered as the least preferable option, especially if the by-product could still be recycled for other purposes [12].

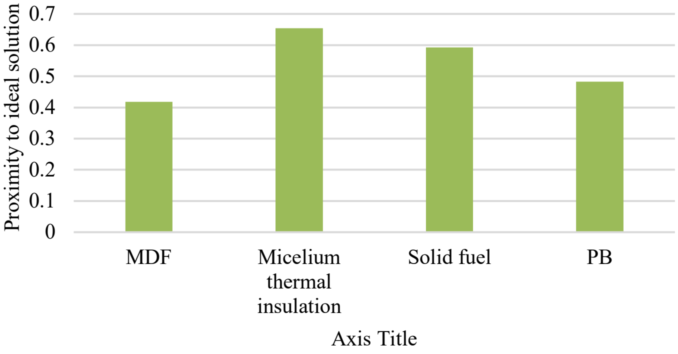


Fig. 3. Multi-criteria analysis results, showing options considered and their proximity to the most preferable alternative represented on y-axis. (PB-particleboard; MDF- medium density fiberboard).

Sensitivity analysis of criteria weight showed the similarity of two preferable options – mycelium thermal insulation and solid fuel. By changing the weight of product market price according to unity variation β_{pm}, mycelium thermal insulation material and solid fuel alternatives experienced the same trend. When the weight of product market price doubles, these two alternatives lose their positive proximity to the ideal solution. MDF experience mirrored trend to mycelium thermal insulation and solid fuel alternatives, but PB is the least impacted by the changes in product market price.

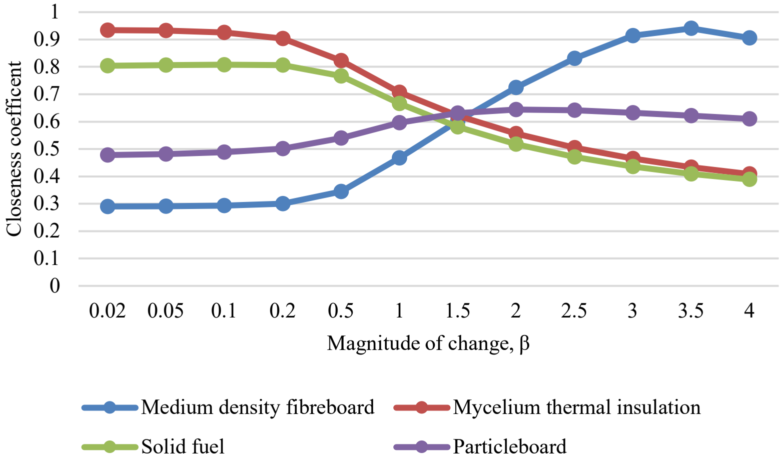


Fig. 4. TOPSIS results sensitivity analysis. Sensitivity analysis is conducted by changing weight of product market price and re-calculating the rest of assigned weights. X-axis depicts magnitude (β) of change of product market weight and y-axis depicts the closeness coefficient of all alternatives to the ideal solution.

Additional sensitivity analysis on product market price change was conducted to evaluate how the most ideal alternative – mycelium thermal insulation material's closeness coefficient to the ideal solution and how the closeness coefficient of other alternatives would be impacted. A step of 10 % change was chosen and results are depicted in Fig. 5. Despite of the product market price reduction of 50 %, mycelium thermal insulation was still the most preferable alternative, gaining greater distance from the second best alternative – solid fuel.

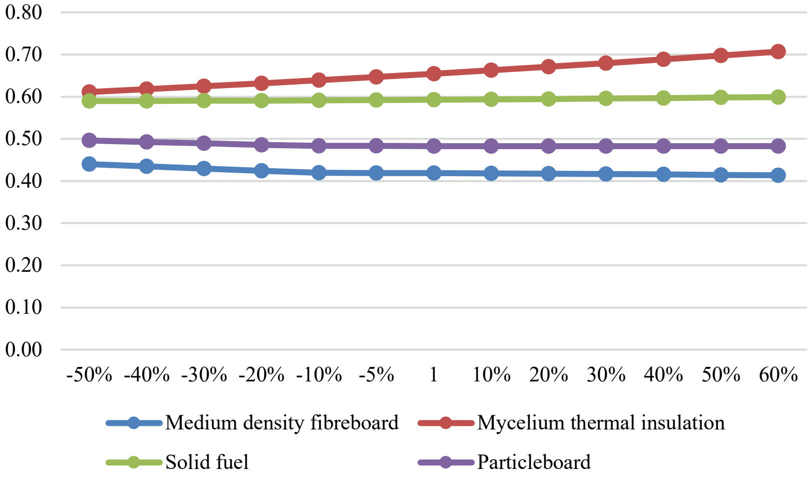


Fig. 5. Sensitivity analysis on mycelium thermal insulation's market price change on the closeness coefficient to the ideal solution change.

As production costs were the only criterion where mycelium thermal insulation material took the lead from the start, sensitivity analysis was conducted to find out how big should be the changes in mycelium thermal insulation production for the material to lose its most preferred rank. Sensitivity analysis on mycelium thermal insulation production cost (depicted in Fig. 6) show that 60 % increase on production costs would make mycelium alternative less desirable as solid fuel production.

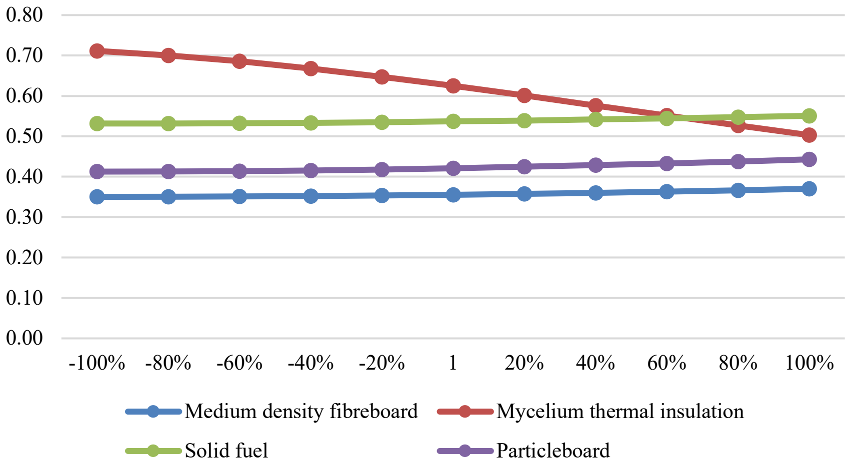


Fig. 6. Sensitivity analysis on mycelium thermal insulation's production cost changes.

4. DISCUSSION

Objectives of this paper was to conduct literature analysis on existing wood residue recycling technologies and compare them from the perspective of the company generating CLT residues. Although specific CLT residue utilization alternatives have not yet been published, in this paper we explored known wood residue utilization options. PB and MDF alternatives had closest proximity to un-ideal solution when analysed from the perspective of CO_2 emissions and economy. In addition, there might be technical limitations of CLT recycling into specific dimensions of chips and fibers due to heterogeneous nature of CLT layers [17].

Conducted analysis showed that the most energy intensive solution – MDF production, is the least preferable one as well. Energy intensive production process is reflected in CO_2 emissions more than seven times higher than PB production, this is due to the required MDF setting temperatures that are 20 °C higher in comparison to PB production. In addition, wood fiber separation required steam, making it energy and water intensive process.

Amongst considered alternatives for wood residue use the mycelium insulation material was recognized as the best, despite it having the most preferable result only in one criterion – production costs. According to sensitivity analysis, production costs of mycelium thermal insulation material would need to increase by 60 % in order for it to lose its preferability over solid fuel production. As a second best alternative solid fuel was elucidated. It is understandable as wood pellet production requires almost no other raw material and relatively small energy consumption. Nevertheless, wood pellets generate 205.8 kg of CO_2 emissions per tonne during exploitation. On the contrary, the rest of considered alternatives provide carbon storage during their exploitation phase. As shown in the introduction of this paper, energy recovery is the very last step in cascading. To make the CLT production as sustainable as possible, production residues should be recycled if possible. In case of mycelium insulation material, it could be used for energy recovery at its end-of-life cycle, as a result prolonging CLT residue life cycle.

This research provides insights into promising CLT residue recycling options. Although MCA elucidated mycelium insulation material the most promising alternative, practical research is needed to test capabilities of various fungi to grow on timber with polyurethane residues.

ACKNOWLEDGEMENT

Funding: This research was carried out with the support of CFLA contract No. 1.2.1.1/18/A/004 between 'Forest Sector Competence Centre of Latvia' Ltd. and the Central Finance and Contracting Agency, the study is conducted by 'FUNDUSS' Ltd. with support from the European Regional Development Fund (ERDF) within the framework of the project 'Forest Sector Competence Centre'.

REFERENCES

[1] UNFCCC. The Paris Agreement [Online]. [Accessed 30.05.2021]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[2] EU Commission. The European Green New Deal Annex. *J. Chem. Inf. Model.* 2013:53(9):1689–1699.

[3] Fischer-Kowalski M., *et al.* Decoupling Natural Resource Use and Environmental Impacts from Economic Growth. Paris: UNEP DTIE, 2011.

[4] Sanyé-Mengual E., *et al.* Assessing the decoupling of economic growth from environmental impacts in the European Union: A consumption-based approach. *J. Clean. Prod.* 2019:236:117535. https://doi.org/10.1016/j.jclepro.2019.07.010

[5] Bocken N. M., Ritala P., Huotari P. The Circular Economy Exploring the Introduction of the Concept Among. *J. Ind. Ecol.* 2017:21(3):487–490. https://doi.org/10.1111/jiec.12605

[6] D'Amato D., Veijonaho S., Toppinen A. Towards sustainability? Forest-based circular bioeconomy business models in Finnish SMEs. *For. Policy Econ.* 2020:110:101848. https://doi.org/10.1016/j.forpol.2018.12.004

[7] Zihare L., *et al.* Triple factor nexus in bioeconomy through indicator analysis. *N. Biotechnol.* 2020:61:57–68. https://doi.org/10.1016/j.nbt.2020.11.008

[8] Olubunmi O. A., Xia P. B., Skitmore M. Green building incentives: A review. *Renew. Sustain. Energy Rev.* 2016:59:1611–1621. https://doi.org/10.1016/j.rser.2016.01.028

[9] Jayalath A., *et al.* Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia. *Energy Build.* 2020:223:110091. https://doi.org/10.1016/j.enbuild.2020.110091

[10] Hildebrandt J., Hagemann N., Thrän D. The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. *Sustain. Cities Soc.* 2017:34:405–418. https://doi.org/10.1016/j.scs.2017.06.013

[11] Suzanne E., Absi N., Borodin V. Towards circular economy in production planning: Challenges and opportunities. *Eur. J. Oper. Res.* 2020:287(1):168–190. https://doi.org/10.1016/j.ejor.2020.04.043

[12] Kalverkamp M., Pehlken A., Wuest T. Cascade use and the management of product lifecycles. *Sustain.* 2017:9(9):1540. https://doi.org/10.3390/su9091540

[13] Golev A., Corder G. D., Giurco D. P. Barriers to Industrial Symbiosis Insights from the Use of a Maturity Grid. *Journal of Industrial Ecology* 2014:19(1):141–154. https://doi.org/10.1111/jiec.12159

[14] Alinejad M., *et al.* Lignin-Based Polyurethanes: Opportunities for Bio-Based Foams, Elastomers, Coatings and Adhesives. *Polymers (Basel)* 2019:11(7):1202. https://doi.org/10.3390/polym11071202

[15] Magalhães de Souza A., *et al.* Performance Assessment of OSB Wood Composites with Added Wire Mesh. *Int. J. Mater. Eng.* 2014:4(3):88–91.

[16] Hemmila V., *et al.* Development of sustainable bio-adhesives for engineered wood panels – A Review. *R. Soc. Chem.* 2017:7:38604–38630. https://doi.org/10.1039/c7ra06598a

[17] Brandner R., *et al.* Cross laminated timber (CLT): overview and development. *Eur. J. Wood & Wood Prod.* 2016:74(3):331–351. https://doi.org/10.1007/s00107-015-0999-5

[18] Vamza I., *et al.* Life Cycle Assessment of Reprocessed Cross Laminated Timber in Latvia. *Environ. Clim. Technol.* 2021:25(1):58–70. https://doi.org/10.2478/rtuect-2021-0005

[19] Chaudhary A., Messer A. Life cycle assessment of adhesives used in wood constructions Life cycle assessment (LCA) of adhesives used in wood constructions. Zurich: ETH, 2015.

[20] Masi D., *et al.* Towards a more circular economy: exploring the awareness, practices, and barriers from a focal firm perspective. *Prod. Plan. Control* 2018:29(6):539–550. https://doi.org/10.1080/09537287.2018.1449246

[21] Homrich A. S., *et al.* The circular economy umbrella: Trends and gaps on integrating pathways. *J. Clean. Prod.* 2018:175:525–543. https://doi.org/10.1016/j.jclepro.2017.11.064
[22] Popescu C. M. *Wood as bio-based building material*. 2017.
[23] Teixeira D. E., *et al.* Adhesivity of bio-based anhydrous citric acid, tannin-citric acid and ricinoleic acid in the properties of formaldehyde-free medium density particleboard (Mdp). *Drv. Ind.* 2020:71(3):235–242. https://doi.org/10.5552/drvind.2020.1917
[24] Iždinský J., Vidholdová Z., Reinprecht L. Particleboards from recycled wood. *Forests* 2020:11(11):1166. https://doi.org/10.3390/f11111166
[25] Yang T. H., *et al.* Characteristics of particleboard made from recycled wood-waste chips impregnated with phenol formaldehyde resin. *Build. Environ.* 2007:42(1):189–195. https://doi.org/10.1016/j.buildenv.2005.08.028
[26] Mirski R., *et al.* By-products of sawmill industry as raw materials for manufacture of chip-sawdust boards. *J. Build. Eng.* 2020:32:101460. https://doi.org/10.1016/j.jobe.2020.101460
[27] Eurostat. Medium/high density fiberboard production in EU [Online]. [Accessed 3.06.2021]. Available: https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do
[28] Wilson J. B. CORRIM: Phase II Final Report. Module G Medium Density Fiberboard (MDF): A Life-Cycle Inventory of Manufacturing Panels from Resource through Product. 2008.
[29] Irle M., Thoemen H., Sernek M. Wood-based panel technology: An introduction for Specialists. London: Brunel University Press, 2010.
[30] Wilson J. B., Sakimoto E. T. Gate-to-gate life-cycle inventory of softwood plywood production. *Wood Fiber Sci.* 2005:37:58–73.
[31] Korjakins A., *et al.* Application of Peat, Wood Processing and Agricultural Industry By-products in Producing the Insulating Building Materials. *J. Sustain. Archit. Civ. Eng.* 2013:1(2):62–68. https://doi.org/10.5755/j01.sace.1.2.2884
[32] Gul W., Khan A., Shakoor A. Impact of hot pressing temperature on Medium Density Fiberboard (MDF) performance. *Adv. Mater. Sci. Eng.* 2017:2017:4056360. https://doi.org/10.1155/2017/4056360
[33] Bruin S. Mycelium: A Building Block for Parkstad Limburg. Delft: Delft University of Technology, 2008.
[34] Grossi P., *et al.* Analysis of timber log-house construction system via experimental testing and analytical modelling. *Constr. Build. Mater.* 2016:102:1127–1144. https://doi.org/10.1016/j.conbuildmat.2015.10.067
[35] Epd-Norge.No. Cross laminated timber panels. Oslo: Epd-Norge, 2017.
[36] Ahmed M., *et al.* Production of Lightweight Bricks Using Saw Dust. *Sch. J. Eng. Technol.* 2020:8(7):132–140. https://doi.org/10.36347/sjet.2020.v08i07.003
[37] Gurtu A., Searcy C., Jaber M. Y. Emissions from international transport in global supply chains. *Manag. Res. Rev.* 2017:40(1):53–74. https://doi.org/10.1108/MRR-09-2015-0208
[38] Bahri M. A. S., Ratnam M. M., Khalil H. A. Functionally graded wood filler–recycled polypropylene composite: Effect of mechanical loading on deflection of cantilever beam. *Adv. Compos. Lett.* 2020:29: 2633366X2092285. https://doi.org/10.1177/2633366X20922856
[39] Luttropp C., Lagerstedt J. EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *J. Clean. Prod.* 2006:14(15–16):1396–1408. https://doi.org/10.1016/j.jclepro.2005.11.022
[40] Trømborg E., *et al.* Economic sustainability for wood pellets production - Acomparative study between Finland, Germany, Norway, Sweden and the US. *Biomass and Bioenergy* 2013:57:68–77. https://doi.org/10.1016/j.biombioe.2013.01.030
[41] Wang C., *et al.* A life-cycle comparison of the energy, environmental and economic impacts of coal versus wood pellets for generating heat in China A life-cycle comparison of the energy, environmental and economic impacts of coal versus wood pellets for generating heat. *Energy* 2016:120:374–384. https://doi.org/10.1016/j.energy.2016.11.085
[42] Group A. M. R. Biomass Markets: Weekly biomass markets news and analysis. 2022. [Online]. [Accessed 23.03.2021]. Available: https://www.argusmedia.com/-/media/Files/sample-reports/argus-biomass-markets.ashx?la=en&hash=872E2C03A0A78FE3F236BBF00E7729E3114326E0
[43] Rivela B., *et al.* Life Cycle Inventory of Particleboard: A Case Study in the Wood Sector. *J. LCA* 2006:11(2):106–113. https://doi.org/10.1065/lca2005.05.206
[44] Rivela B., Moreira M. T., Feijoo G. Life Cycle Inventory of Medium Density Fibreboard. *J. LCA* 2007:12(3):143–150. http://dx.doi.org/10.1065/lca2006.12.290
[45] Zlaugotne B., *et al.* Multi-Criteria Decision Analysis Methods Comparison. *Environ. Clim. Technol.* 2020:24(1):454–471. https://doi.org/10.2478/rtuect-2020-0028
[46] Siksnelyte I., *et al.* An overview of multi-criteria decision-making methods in dealing with sustainable energy development issues. *Energies* 2018:11(10):2754. https://doi.org/10.3390/en11102754
[47] Lee S., *et al.* Using AHP to determine intangible priority factors for technology transfer adoption. *Expert Syst. Appl.* 2012:39(7):6388–6395. https://doi.org/10.1016/j.eswa.2011.12.030
[48] Ishizaka A., Nemery P. Multi-Criteria Decision Analysis. Methods and software. Wiley, 2013.
[49] Pubule J., *et al.* Finding an optimal solution for biowaste management in the Baltic States. *J. Clean. Prod.* 2015:88:214–223. https://doi.org/10.1016/j.jclepro.2014.04.053

[50] Saaty T. L., Sodenkamp M. The Analytic Hierarchy and Analytic Network Measurement Processes: The Measurement of Intangibles: Decision Making under Benefits, Opportunities, Costs and Risks. In Zopounidis C., Pardalos P. (eds) *Handbook of Multicriteria Analysis*. *Applied Optimization* 2010:103:91–166. https://doi.org/10.1007/978-3-540-92828-7_4

[51] Delvere I., *et al.* Evaluation of polymer matrix composite waste recycling methods. *Environ. Clim. Technol.* 2019:23(1):168–187. https://doi.org/10.2478/rtuect-2019-0012

[52] Li P., *et al.* Sensitivity analysis of TOPSIS method in water quality assessment: I. Sensitivity to the parameter weights. *Environ. Monit. Assess.* 2013:185(3):2453–2461. https://doi.org/10.1007/s10661-012-2723-9

[53] Jones M., *et al.* Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Mater. Des.* 2020:187:108397. https://doi.org/10.1016/j.matdes.2019.108397

Environmental and Climate Technologies
2021, vol. 25, no. 1, pp. 382–391
https://doi.org/10.2478/rtuect-2021-0028
https://content.sciendo.com

Criteria for Choosing Thermal Packaging for Temperature Sensitive Goods Transportation

Ilze VAMZA[1]*, Karlis VALTERS[2], Arnis DZALBS[3], Edgars KUDURS[4], Dagnija BLUMBERGA[5]

[1–5]*Institute of Energy Systems and Environment, Riga Technical University, 12-k1 Azenes iela, Riga, LV-1048, Latvia*

Abstract **– Today cold chain transportation has become more important than before, as countries rely on cold chain logistics to store and transport SARS-CoV-2 vaccines and other temperature-sensitive goods. The cold chain is usually associated with the use of non-renewable materials and higher energy consumption than the regular supply chain. An important part of cold chain sustainability is thermal packaging. Up to now one of the most popular thermal packaging materials is polystyrene – made from fossil raw material. Polystyrene has low thermal conductivity and density, but it breaks down into micro- and nano plastics when exposed to sunlight making it environmentally unsustainable. To determine which factors are important for cold chain regarding thermal packaging, 12 criteria were compared to determine their ranking. Further multi-criteria analysis was used to compare polystyrene to four alternative biodegradable thermal packaging options: mycelium-based, corn starch, non-woven wool, and non-woven feathers. Polystyrene gained only 3rd place with a 0.70 proximity to ideal solution 1, but non-woven wool showed the best result with 0.88 proximity to ideal solution.**

Keywords **– Cold chain; logistics; non-woven materials; sustainable packaging; polystyrene**

1. INTRODUCTION

Temperature sensitive products have been challenging commodities as their transportation requires more energy and resources. In many cases temperature monitoring is required to guarantee the quality of the product. Commodities like meats [1] can spoil if temperatures rise, vaccines require even stricter temperature regimes as they can lose efficiency when exposed to higher or lower temperatures than recommended [2]. In both cases temperature fluctuations out of the required range require recall of the product. This can be very expensive and sometimes life threatening [3] in case of vaccines and first aid kits.

Temperature sensitive product logistics require cold chain – continuous low temperature regime from storage after production to transport and final storage before getting to the end consumer. Usually, logistics managers are responsible that the cold chain is not broken at any point, ensuring the required temperature regime. Additionally, there are costs, CO_2 footprint and other factors that need to be considered when cold chain logistics is being developed. There are multiple aspects logistics management need to consider – required temperature regime, available infrastructure, time frame and available financial resources [4]. In every case risk assessment needs to be conducted and precautions weighed. Multiple tools can help

---

* Corresponding author.
E-mail address: Ilze.Vamza@rtu.lv

to ensure efficient product transportation - the Global Positioning System [5] along with temperature logging [3] can provide real-time information on the location and temperature of the product. Temperature logging can provide information, but in no way, is it a tool that can impact the situation, it only helps to elucidate the weak points in the cold chain. Temperature fluctuations of transported goods can be prevented by using dry ice or cold packs [3] and thermal insulation packaging [6].

All the above mentioned equipment and tools impact the carbon footprint of the whole cold chain. The most popular thermal insulation material used in temperature sensitive product transportation is polystyrene [41] – styrene is synthesized from ethylene and benzene and then polymerized [7], [8]. Ethylene and benzene are chemicals acquired in petroleum refining process [9] making polystyrene a non-renewable polymer. In addition, its carbon footprint is considerable making up 64.98 kg of CO_{2eq} per m^3 expanded polystyrene with thermal conductivity of 0.031 W/m/K [10]. Polystyrene has a negative impact on the environment not only in production process, but at the end of its use as well. Song *et al.* experiment results show that polystyrene can lose its mass for as much as 5 % after a month of exposure to the sun and outdoor weather, nevertheless polystyrene's mineralization can take hundreds or even thousands of years [11]. This polymer breaks down when exposed to UV light, natural exposure from the sun is sufficient for polystyrene to break down in microplastics and even nanoplastics [11]. In this form it is dispersed in natural bodies of water where it is ingested by marine life and ends up in the food chain leading to humans [12].

To address the environmental issues regarding cold chain and logistics overall, green logistics approach has been implemented. Green logistics deals with reduction of the negative aspects of goods transportation – like noise, air pollution, greenhouse gas emissions, accidents resulting in wastage and so on [13]. In many companies the necessity for temperature sensitive product transportation is so rare that it is outsourced, leaving the decision making regarding packaging, vehicles and the rest of logistics in the hands of another company [14]. According to Lammgard and Andersson (2014), around 70 % of companies claim that the environmental aspect is important when outsourcing the transportation service for their goods [15].

The World Health Organization (WHO) has recognized the impact of global vaccine cold chains on the environment. Inefficient fuel use, poor quality insulation of buildings, fossil fuel use and many more factors contribute to a negative environmental impact [16]. Packaging has been recognized as another important contributor to the negative impact on the environment, hence the WHO is in search of more sustainable packaging regarding vaccine logistics, including thermal packaging used for temperature sensitive product shipment [17].

Already 10 years ago corn-based packaging was highlighted by the WHO as a sustainable choice in vaccine transportation [17]. Today there are companies like 'Greencellfoam' [18] that offer biodegradable solutions made from corn, this material is often provided by logistics companies under a generic name – starch-based packing peanuts. The technology behind starch-based packing peanuts is similar to polystyrene extrusion. Usually, some kind of blowing agent (air or supercritical CO_2) is used to enable air bubble production in the extruded material [19], [20]. Although this material is completely compostable with lower negative impact at the end of its life in comparison to conventional plastic foams, it is denser [19], hence more expensive to use in air cargo shipping. In addition, the hydrophilic properties of starch-based foams make them prone to size reduction in humid environments and even dissolving if the material comes in contact with water. To counteract the hydrophilic nature, there are attempts to merge starch with small amounts of plastics, as this reduces the carbon footprint in comparison to conventional plastic foams while increasing the product water resistance [21].

Another commercially available thermal insulation material for packaging use is mycelium based. 'Ecovative' were the first pioneers leading this material to the market in 2007. Agricultural and wood waste can be used to produce mycelium-based insulation material [22]. As seen in nature, fungus weaves through the substrate and interlocks the substrate particles in a rigid structure. This can happen due to fungus morphology – its cells are making filamentous structures called hyphae – these strand-like structures allow for fungus to connect with each other and create a network [23]. Substrate locking with hyphae can result in stiff material with better strength than polystyrene. In addition to mycelium-based materials produced from agricultural and wood waste being biodegradable, production technology consumes considerably less energy than polystyrene production - 652 MJ and 4667 MJ, respectively [22]. The downside of mycelium insulation materials is production time as it is limited to the slow growth of mycelium [24].

Another thermal insulation material produced from waste is feather insulation found on the market under the brand name of 'Pluumo' [25]. In the European Union alone around 3 million tonnes of feather waste are created from poultry farms annually. Feathers contain natural fibers that can be used in non-woven form to achieve low thermal conductivity of 0.030 W/m·K providing better thermal insulation than polystyrene foam. Feather insulation has the same weakness as other thermal insulation materials already discussed – water. The fibre structure makes it easy for water to seep into the material with capillary forces [26]. Hence waterbirds constantly preen their feathers with a waxy secretion to make them water resistant [27]. Plucked and processed feathers lose their coating making them prone to water absorption. The weak spot of thermal packaging from feather mat is the base of the box where all the weight of transported goods is pushing down – reduced thickness of feather mat greatly impacts the quality of packaging by increasing the thermal conductivity [26]. A similar material prone to the same problem is made out of sheep wool – on the market under the name 'Woolcool' [28]. Although the macroscopic structure of wool is different from feathers, it is made of the same protein fibers called keratin, making the material hydrophilic. Like the bird uropygial gland, sheep have glands on the skin that produce waxy substance called lanolin, impregnating the wool to make it water repellent. Sheep wool has good thermal insulation properties of 0.033 W/m/K [29].

As shown above, there are multiple new and innovative thermal packaging solutions on the market, but none have been as successful as polystyrene boxes. There are many criteria that logistics management need to consider while choosing the right packaging. Some of the more environmentally sustainable packaging solutions provide more efficient thermal insulation than others but all fall short in some respects, hence it is necessary to elucidate the most important criteria evaluated from the industry's perspective that is dealing with temperature sensitive product transportation. In this paper we are using pairwise comparison to determine the most important factors regarding thermal packaging from the perspective of logistics managers in Latvia's biotechnology, pharmacology, and fine chemical enterprises.

2. METHODS

2.2. Criteria identification

Initial criteria for thermal packaging comparison were identified in open interviews with representatives of companies working in the pharmaceutical and fine chemicals and logistics field. By allowing representatives to answer to open questions like 'How is thermal packaging chosen?', criteria and their indicators were elucidated. In many cases it became clear that industry is not using numerical indicators for each criterion. For example, criterion ‘sustainable’ was often described as non-fossil raw material without any numerical value assigned to the corresponding criterion. Further, literature and product data sheets were analysed to validate the criteria. The analysed product data sheets contained information based on performance, for example, hours held in temperature below +8 °C [25], [28], [30], indicators like thermal conductivity and density were found in scientific literature on corresponding materials [19], [22], [26].

2.3. *Weighing*

To determine the importance of 12 criteria, pairwise comparison was conducted. As it is impossible for humans to grasp the reciprocal relationships of 12 criteria at the same time, the method for pair analysis was chosen. Using this approach, experts were asked to compare only two criteria at a time, each expert did a total of 66 comparisons. Comparison was done verbally as suggested by Saaty *et al.* 2010 [31] by determining, is one criteria equally important as the other, less important or more important. After verbal comparison, numerical values were assigned to each compared pair using a scale of 1 to 9. In the chosen scale 9 was signifying very high importance, 6 – strong to very strong importance, 3 – moderate importance and 1 – equal importance [32].

TABLE 1. THERMAL PACKAGING CRITERIA USED FOR PAIRWISE COMPARISON

Criteria	**Description**
Odour	Material has no considerable scent
Resistance to humidity	Material does not dissolve or get damaged to the point it loses its thermal resistance
Vapour resistance, m	S_d value of thermal insulation material. Represents the resistance to water vapour taking up certain air layer thickness [m]. Mostly relevant for shipments with dry ice
Branding opportunities	Material can be printed on
Sustainability	Raw material of thermal packaging is renewable
Ability to hold temperature, hours	Packaging can hold specific temperature for more than 24 hours. Criterion represents in situ measurements of temperature in relevant environment and packed test goods – representing goods that would be transported.
Thermal conductivity, W/m/K	In line with this study, 0.04 W/m/K was considered the threshold for thermal conductivity to be considered low. Thermal conductivity characterizes the material by its ability to conduct heat energy. Heat energy is always transferred down the gradient.
Reusability	Material can be re-used multiple times
Available in multiple sizes	Multiple dimension options are available
Price, EUR per 39l box	Per packaging solution
Durability	Material can be used without supportive tertiary packaging (e.g., cardboard box)
Density, kg/m^3	Weight to volume ratio of packaging solution

Overall, 10 questionnaires were disseminated among the identified pharmaceutical and fine chemical industry enterprises in Latvia, including big companies like Grindex and Olainfarm. It was expected that the approached companies were heavily impacted by the global pandemic, only five responded and three were eligible to questions as companies made their own decisions regarding temperature sensitive product logistics. Two companies outsourced this service hence were unsuitable for multi criteria analysis and criteria comparison, nevertheless their reported practice will be discussed in the Results part of this study. The chosen companies assigned the questionnaire to logistics team experts within the company. All the criteria experts comparisons are compiled in Table 1.

Mathematically all the chosen criteria are plotted on a matrix and by solving them, eigenvalues can be found. These values, also called eigenvectors, represent the importance of each criteria – a higher value means higher importance in the final decision. Indicative eigenvalues were calculated in Microsoft Excel [33] and used for further analysis. A consistency threshold of 0.2 was used, as done before [34] when multiple stakeholders were surveyed.

2.4. Multi criteria analysis

To compare thermal packaging materials, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used. TOPSIS allows to compare multiple options by multiple criteria. The first stage of TOPSIS was gathering data set of indicators for each thermal packaging material. Data were acquired from product data sheets [25], [28], [30] and patent claims. In the second step, normalization of indicators was performed. Values were weighed based on responses from experts as described in section 2.2. In the next step normalized values were weighed, directions of vectors and their proximity to desirable and avoidable results were calculated. The final step was to calculate the proximity to the ideal solution represented by a value of 1 [35].

TOPSIS methodology was chosen because it requires only a few indicators, while providing comparable data to draw conclusions. For further multi-criteria analysis, only criteria with comparable numerical values were chosen, reducing the number of criteria from 12 to 5. Chosen criteria were density, thermal conductivity, environmental sustainability, ability to hold temperature, and price. Criteria like odour, availability in multiple dimensions were determined as on-off type of criteria – if material would have considerable odour, it would not be used, the same with availability in multiple dimensions – most of the companies needed the thermal packaging to be available in at least 3 different sizes. Cases where the thermal packaging producer does not offer multiple sizes, the product was not considered further. Resistance to humidity and vapour resistance are both important for certain kinds of transportation – transportation where there is a high humidity risk e.g. transportation with ice, and transportation using dry ice accordingly. Reusability and durability were excluded as expert principles for determining material's accordance for reuse differed. Durability as material's ability to be used without supporting cardboard box was excluded from further analysis as this option was rarely used by experts in their represented companies.

The basic assumption of TOPSIS methodology is that the most preferred solution is one with the shortest distance to the desirable result and greatest distance from the result to be avoided. Multiple innovative packaging materials along with conventional polystyrene were compared regarding five criteria.

3. RESULTS

3.1. Importance of criteria

Weighing process using pairwise comparison of all 12 criteria gives an overall look on the importance of each criterion in relation to the rest. The results of weighing are shown in Fig. 1.

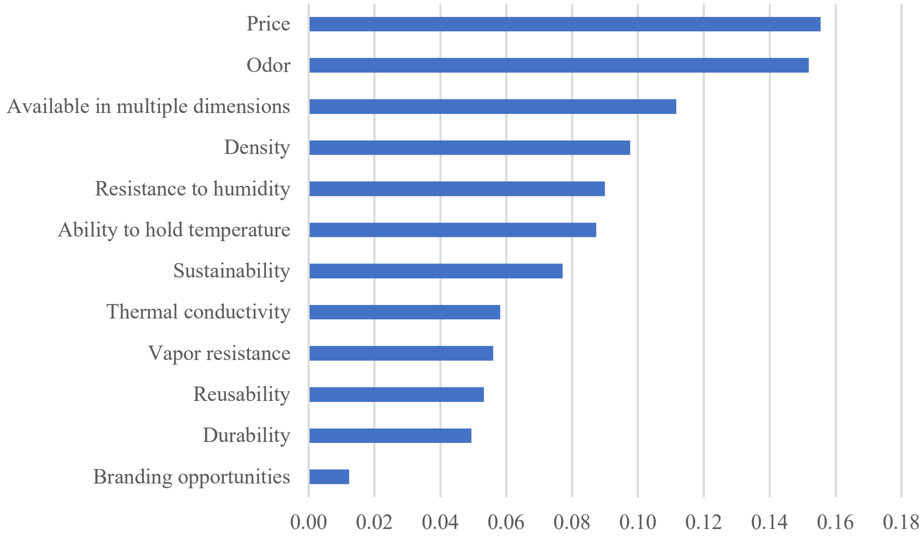


Fig. 1. Weighed criteria in ascending order regarding their importance.

Interestingly, enterprises with specialty in fine chemicals and companies using thermal packaging for internal use, like sample transfer among branches, expressed the importance of reusable packaging. In these cases, companies are preferring thermal packaging that can withstand at least 10 application times. On the contrary – pharmaceutical companies claimed that packaging was used only one time, as its visual appearance after one use is no longer suitable for medication.

To compare the thermal packaging options available on the market, only five criteria were chosen for further analysis. Criteria like neutral smell was excluded as none of the materials available on the market reported to have a scent and this would be only an on-off criteria. Availability of dimensions was not analysed as experts from different companies were interested in various sizes, making this criterion specific to each case.

Water resistance was considered as being an important criterion, but it covers a lot of aspects: (1) water absorption; (2) water release after absorption; (3) whether material stays intact after being exposed to water. The third aspect is very important, at the same time it should be considered for each specific case. For example, corn-starch foam could be the most preferred option for shipping electronics, as it can absorb mechanical shock and protect the goods, but as it dissolves in water, it cannot be used in shipments with higher humidity, e.g., iced products, as humidity would destroy the packaging. At the same time water resistance is not important in the case of electronics as usually the cargo is protected from such and in cases where the cargo is compromised by water, the shipment is recalled.

Additionally, criteria for durability were excluded along with vapour resistance, repeated use, and graphical identity. Vapour resistance was excluded as it is most important for shipments with dry ice and companies are avoiding this shipping option due to the hazardous nature of dry ice. Each company considered various re-use times as optimal – experts from testing laboratories and other companies who use the packaging only internally admitted that they reuse the packaging at least ten times and it can look quite scuffed but its functionality is the most important. On the contrary, pharmaceutical companies used the packaging only one time as its visual appearance was compromised after use. Graphical identity was the least important criterion and similarly as scent – it is an on-off criterion, so it was left out of further analysis. Criteria chosen for further analysis were weighed and results are depicted in Fig. 2.

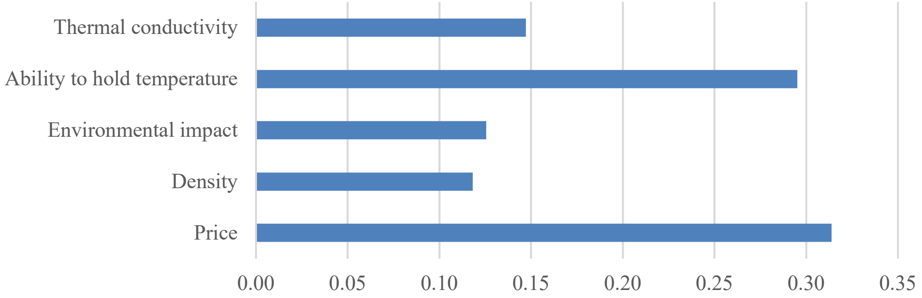


Fig. 2. Chosen quantitative criteria and their weights showing the importance of each criterion in the final decision making.

As shown above, after narrowing down to five criteria, price, and ability to hold temperature took a considerable lead as being the two most important criteria, they together accounted for more than a half of the impact on the final decision.

3.2. Most preferable material

To evaluate the most preferable 'green' thermal packaging available on the market, four products were compared to polystyrene packaging. Using previously determined weights, the following thermal insulation materials were compared: non-woven feathers, non-woven wool, starch foam, mycelium, and polystyrene (Fig. 3).

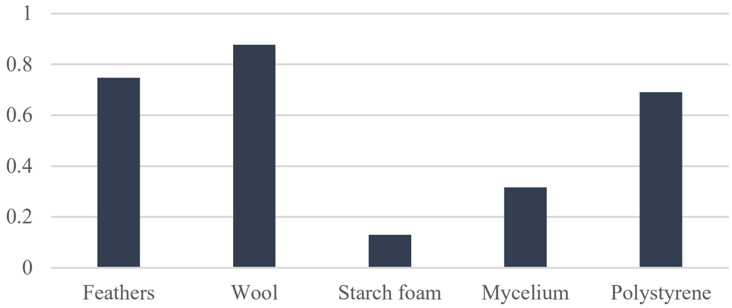


Fig. 3. Technique for Order of Preference by Similarity to Ideal Solution ranking of thermal packaging materials. Y axis represents the proximity to ideal solution 1.

Among the thermal packaging options, the closest proximity to ideal solution (represented by 1 on Y axis in Fig. 3) by applying TOPSIS method was assigned to non-woven wool followed by feathers and polystyrene, the lowest rank was assigned to starch foam and mycelium was second-to-last in the ranking.

4. DISCUSSION

The findings of the study show that price is the most important factor when choosing thermal packaging for temperature sensitive pharmacology and fine chemical applications. Nevertheless, performance of holding temperature in a specific range was the second most important criterion in the reduced criteria set. Among obvious factors like density and availability in multiple sizes, the scent of the material was elucidated as a factor of considerable importance. Experts explained that material cannot have any strong odours to be used as thermal packaging. Concern that scent might linger and compromise the neutral scent of product itself was expressed.

Due to the high number of criteria analysed, a consistency ratio of 0.2 was chosen [34], although according to Saaty [31] 0.1 is considered as the optimal threshold. Saaty's approach is based on crisp values – criteria can be ranked in linear order. Authors like Ju [36], Ishizaka and Nguyen [35], and recently Lin [37] have argued that humans cannot comprehend complex relationships between many criteria and fuzzy numbers should be used for more representative comparison. Fuzzy values are characterized by coordinates representing area, opposite to crisp values representing vectors with one direction.

Inconsistencies in this research mainly arose from the unrealistic evaluation of the importance of the sustainability criterion – when other criteria were compared to the sustainability criterion, higher importance was assigned to sustainability, however, when sustainability was compared to other criteria its importance was scored lower, hence the inconsistency.

Analytical hierarchy process was conducted according to Satty's principles with crisp values, as fuzzy values have not yet gained consensus amongst the mathematics community [38]. Nevertheless, inconsistency level and data analysis showed experts struggle to prioritize sustainability versus price and other criteria, criteria used for choosing thermal packaging at this point might not have a consistent hierarchy at all. Environmental aspects are important as shown by survey that showed – around 70 % of enterprises claim that environmental aspects often signified by environmental certification is an important factor when considering transportation services [15], however the results show a different situation. In a single case, one logistics company expert explained that a company can boost its environmental performance by reducing the administration's impact on the environment, like – reduce the printed paper amount and implement other office-oriented policies. The example shows that environmental certificates do not always manifest the transportation part of the business and, although sustainability is important, at this point it is hard to determine the hierarchy of sustainability and price and other criteria.

Another finding in this study confirms that industry values higher the actual *in situ* performance over laboratory tested attributes. Actual performance measured by hours the material could hold the temperature in a specific range was twice as important as thermal conductivity. Final performance or ability to hold temperature is dependent on thermal conductivity, specific heat capacity and thickness of the insulation layer. As discussed above, even deformation of the thermal insulation layer can impact the ability to hold temperature, soft materials like wool and feather get compressed under the weight and their thermal conductivity increases, seeing their performance in a real life situation can help to evaluate overall performance. As discussed before, time is crucial for the quality of many products, e.g., meats and vaccines [1], [2]. Overall performance of the thermal packaging is impacted by thermal conductivity [22], heat capacity [39] and, in some cases, vapour resistance [22]. Performance tests in +30 °C temperature surroundings are preferred, final packaging performance is impacted not only by thermal insulation layer properties, but the product and the chosen cooling agent as well. So-called gel packs are ubiquitous cooling agents, hence performance testing is conducted by using gel packs for maintaining temperature levels[6]. Thermal packaging-producing companies have discovered the importance of time and depict multiple temperature regime tests in their datasheets [28]. The World Health Organization has developed an independent type-testing protocol for thermal packaging in various conditions for various cold and hot ambient temperatures [40]. For thermal packaging producers these guidelines only serve as advice for the testing setup – weight and dimensions for tested thermal insulation packaging were not specified in any of the analysed data sheets. Avoiding factoring in weight might lead to completely different results while in use, as mentioned before, deformation of packaging can lead to compromised thermal resistance.

Despite polystyrene's popularity, our research shows that thermal packaging made from expanded polystyrene is not the most preferable choice when compared to some environmentally sustainable thermal packaging options. Two products – 'Woolcool' and 'Pluumo' outperformed polystyrene packaging when compared in price, density, ability to hold temperature, environmental impact, and thermal conductivity. Our research elucidates the discrepancy between theoretically preferable and actual choices made by logistics managers. Results signal that environmentally preferable solutions have caught up conventional packaging and it is worthwhile for logistics managers to consider switching to new thermal packaging solutions. Multi criteria analysis using crisp numbers could be used by logistics managers to decide on the most preferrable thermal packaging option. Although this paper provides general results regarding most preferable thermal packaging, each company can tailor the weights of criteria to align them with company values. Consequently, research teams developing sustainable alternatives to conventional thermal packaging materials could use the weights calculated in this study to gain perspective on respective material's performance regarding industry needs. Although sustainability criterion is important, according to calculated weights – price and ability to hold temperature prevails. Although ability to hold temperature will not lose its importance, the price criterion will continue to be impacted by green initiatives and the national natural resource tax.

REFERENCES

[1] Singh S., Gaikwad K. K., Lee M., Lee Y. S. Temperature sensitive smart packaging for monitoring the shelf life of fresh beef. *J. Food Eng.* 2018:234:41–49. https://doi.org/10.1016/j.jfoodeng.2018.04.014

[2] Hanson C. M., George A. M., Sawadogo A., Schreiber B. Is freezing in the vaccine cold chain an ongoing issue? A literature review. *Vaccine* 2017:35(17):2127–2133. https://doi.org/10.1016/j.vaccine.2016.09.070

[3] Kartoglu U., Milstien J. Tools and approaches to ensure quality of vaccines throughout the cold chain. *Expert Rev. Vaccines* 2014:13(7):843–854. https://doi.org/10.1586/14760584.2014.923761

[4] Mariano E. B., Gobbo J. A., Camioto F. de C., do N. Rebelatto D. A. CO_2 emissions and logistics performance: a composite index proposal. *Journal of Cleaner Production* 2017:163:166–178. https://doi.org/10.1016/j.jclepro.2016.05.084

[5] Pan C., Yu S., Li S. Research on the development mode and evaluation system of green cold chain logistics in China. *Chinese Control Conf. CCC*. 2017. https://doi.org/10.23919/ChiCC.2017.8028547

[6] Wang K., Yang L., Kucharek M. Investigation of the effect of thermal insulation materials on packaging performance. *Packaging Technology and Science* 2020:33(6):227–236. https://doi.org/10.1002/pts.2500

[7] Vaughan B. A., Webster-Gardiner M. S., Cundari T. R., Gunnoe T. B. A rhodium catalyst for single-step styrene production from benzene and ethylene. *Science* 2015:348(6233):421–424. https://doi.org/10.1126/science.aaa2260

[8] Pei D., Mo Z.-H., Xu R. W., Zhang S., Wu Y. X. Cross-Linked Quaternized Poly(styrene-b-(ethylene-co-butylene)-b-styrene) for Anion Exchange Membrane: Synthesis, Characterization and Properties. *ACS Appl. Mater. Interfaces* 2016:8(31):20329–20341. https://doi.org/10.1021/acsami.6b04590

[9] Wei W., Lv Z., Yang G., Cheng S., Li Y., Wang L. VOCs emission rate estimate for complicated industrial area source using an inverse-dispersion calculation method: A case study on a petroleum refinery in Northern China, *Environ. Pollut.* 2016:218:681–688. https://doi.org/10.1016/j.envpol.2016.07.062

[10] Lewis E. Environmental Product Declaration. In Lewis E. *et al.* (eds) *Sustainaspeak.* Routledge, 2018:106–107. https://doi.org/10.4324/9781315270326-75

[11] Song Y. K., Hong S. H., Eo S., Han G. M., Shim W. J. Rapid Production of Micro- And Nanoplastics by Fragmentation of Expanded Polystyrene Exposed to Sunlight. *Environ. Sci. Technol.* 2020:54(18):11191–11200. https://doi.org/10.1021/acs.est.0c02288

[12] Jovanović B. Ingestion of microplastics by fish and its potential consequences from a physical perspective. *Integr. Environ. Assess. Manag.* 2017:13(3):510–515. https://doi.org/10.1002/ieam.1913
[13] Dekker R., Bloemhof J., Mallidis I. Operations Research for green logistics – An overview of aspects, issues, contributions and challenges. *Eur. J. Oper. Res.* 2012:219(3):671–679. https://doi.org/10.1016/j.ejor.2011.11.010
[14] Rogerson S. Influence of freight transport purchasing processes on logistical variables related to CO_2 emissions: a case study in Sweden. *Int. J. Logist. Res. Appl.* 2017:20(6):604–623. https://doi.org/10.1080/13675567.2017.1308472
[15] Lammgård C., Andersson D. Environmental considerations and trade-offs in purchasing of transportation services. *Res. Transp. Bus. Manag* 2014:10:45–52. https://doi.org/10.1016/j.rtbm.2014.04.003
[16] Need T. H. E. *et al.* Green supply chains: a glimpse into the future? [Online]. [Accessed: 16.04.2021]. Available: https://path.azureedge.net/media/documents/TS_opt_green_supply_chains.pdf
[17] Newland S. Sustainability in Vaccine Packaging Draft. 2011.
[18] Greencellfoam, Greencellfoam. 2021. [Online]. [Accessed: 15.04.2021]. Available: https://greencellfoam.com/
[19] Mariam I., Cho K. Y., Rizvi S. S. H. Thermal properties of starch-based biodegradable foams produced using Supercritical Fluid Extrusion (SCFX). *Int. J. Food Prop.* 2008:11(2):415–426. https://doi.org/10.1080/10942910701444705
[20] Kalambur S. B., Rizvi S. S. Starch-based nanocomposites by reactive extrusion processing. *Polym. Int.* 2004:53(10):1413–1416. https://doi.org/10.1002/pi.1478
[21] Kalambur S., Rizvi S. S. H. An overview of starch-based plastic blends from reactive extrusion. *J. Plast. Film Sheeting* 2006:22(1):39–58. https://doi.org/10.1177/8756087906062729
[22] Bruin S. Mycelium: a Building Block for Parkstad Limburg. 2018.
[23] Schmieder S. S. *et al.* Bidirectional Propagation of Signals and Nutrients in Fungal Networks via Specialized Hyphae, *Curr. Biol.* 2019:29(2):217–228. https://doi.org/10.1016/j.cub.2018.11.058
[24] Boswell G. P., Jacobs H., Davidson F. A., Gadd G. M., Ritz K. Growth and function of fungal mycelia in heterogeneous environments. *Bull. Math. Biol.* 2003:65(3):447–477. https://doi.org/10.1016/S0092-8240(03)00003-X
[25] Home – pluumo. [Online]. [Accessed: 29.03.2021]. Available: https://www.pluumo.com/home
[26] Dieckmann E., Nagy B., Yiakoumetti K., Sheldrick L., Cheeseman C. Thermal insulation packaging for cold-chain deliveries made from feathers, *Food Packag. Shelf Life* 2019:21:1003609. https://doi.org/10.1016/j.fpsl.2019.100360
[27] Braun M. S., Sporer F., Zimmermann S., Wink M. Birds, feather-degrading bacteria and preen glands: The antimicrobial activity of preen gland secretions from turkeys (*Meleagris gallopavo*) is amplified by keratinase. *FEMS Microbiol. Ecol.* 2018:94(9):1–14. https://doi.org/10.1093/femsec/fiy117
[28] Woolcool Thermal Insulated Packaging Company. Food & Pharmaceutical. [Online]. [Accessed: 29.03.2021]. Available: https://www.woolcool.com/
[29] Tuzcu T. M. Hygro-Thermal Properties of Sheep Wool Insulation. 2007.
[30] High Performing Foam Packaging – Green Cell Foam. [Online]. [Accessed: 15.04.2021]. Available: https://greencellfoam.com/data
[31] Saaty T. L., Sodenkamp M. The Analytic Hierarchy and Analytic Network Measurement Processes: The Measurement of Intangibles. In Zopounidis C., Pardalos P. (eds) *Handbook of Multicriteria Analysis. Applied Optimization,* vol. 103. Springer, Berlin, Heidelberg, 2010. https://doi.org/10.1007/978-3-540-92828-7_4
[32] Saaty T. L. Deriving the ahp 1-9 scale from first principles. *Proc. – 6th ISAHP*, 2001. https://doi.org/10.13033/isahp.y2001.030
[33] Goepel K. D. Implementing the Analytic Hierarchy Process as a Standard Method for Multi-Criteria Decision Making in Corporate Enterprises – a New AHP Excel Template with Multiple Inputs. *Proceedings of the International Symposium on the Analytic Hierarchy Process*, 2013. https://doi.org/10.13033/isahp.y2013.047
[34] Adem Esmail B., Geneletti D. Multi-criteria decision analysis for nature conservation: A review of 20 years of applications. *Methods Ecol. Evol.* 2018:9(1):42–53. https://doi.org/10.1111/2041-210X.12899
[35] Ishizaka A., Nguyen N. H. Calibrated fuzzy AHP for current bank account selection. *Expert Syst. Appl.* 2013:40:(9):3775–3783. https://doi.org/10.1016/j.eswa.2012.12.089
[36] Ju Y., Wang A., Liu X. Evaluating emergency response capacity by fuzzy AHP and 2-tuple fuzzy linguistic approach. *Expert Syst. Appl.* 2012:39(8):6972–6981. https://doi.org/10.1016/j.eswa.2012.01.061
[37] Lin C. N. A fuzzy analytic hierarchy process-based analysis of the dynamic sustainable management index in leisure agriculture. *Sustain.* 2020:12(13)5395. https://doi.org/10.3390/su12135395
[38] Kubler S., Derigent W., Voisin A., Robert J., Le Traon Y., Viedma E. H. Measuring inconsistency and deriving priorities from fuzzy pairwise comparison matrices using the knowledge-based consistency index. *Knowledge-Based Syst.* 2018:162:147–160. https://doi.org/10.1016/j.knosys.2018.09.015
[39] Singh S., Gaikwad K. K., Lee Y. S. Phase change materials for advanced cooling packaging. *Environ. Chem. Lett.* 2018:16(3):845–859. https://doi.org/10.1007/s10311-018-0726-7
[40] PQS Independent type-testing protocol. 2010.
[41] Insulated Packaging Market - Growth, Trends, Forecasts (2020–2025). [Online]. [Accessed: 16.04.2021]. Available: https://www.globenewswire.com/news-release/2020/12/16/2146158/0/en/Insulated-Packaging-Market-Growth-Trends-Forecasts-2020-2025.html

New BIOTECHNOLOGY 61 (2021) 57–68

Contents lists available at ScienceDirect

New BIOTECHNOLOGY

journal homepage: www.elsevier.com/locate/nbt

Full length Article

Bioeconomy triple factor nexus through indicator analysis

Lauma Zihare *, Anna Kubule, Ilze Vamza, Indra Muizniece, Dagnija Blumberga

Institute of Energy Systems and Environment, Riga Technical University, Azenes Iela 12/1, Riga, LV-1048, Latvia

ARTICLE INFO

Keywords:
Bioeconomy
Indicators
Sustainable development
Benchmark
MCDA

ABSTRACT

The transition to a sustainable bioeconomy by a customized approach would speed up its development and make it more targeted. There is still no common international method for determining, measuring and comparing the extent of sustainability. The aim of this research is to develop a methodology for the assessment of bioeconomy-influencing factor interlinkages, and creation of benchmarks through a top-down approach. The main output is the assessment of factor interlinkages that could be further used for composite index creation. A case of triple factor nexus is presented: policy, research and innovations, and technology nexus for EU countries. As a result, the empirical model presents the mathematical description of policy, research and innovation, and technology link benchmark.

Introduction

Global transition towards sustainable development has been one of the major goals of recent years [1], which has led to the development of national or regional bioeconomy strategies [2]. Bio-based economy could be one of the main instruments for such transition, although critical views have been raised in scientific publications about how truly sustainable a bioeconomy is [3,4]. Research and innovation has a significant role in stepping closer to sustainable development, for example, the EU Horizon 2020 programme investments to support bioeconomy reached €4B in the period 2014–2020 [5] and investments by the Bio-based Industries Joint Undertaking reached €3.7B [6]. Several factors impact the development of bioeconomy, for example, at the outset, biotechnology was assumed to be bioeconomy's main driver [7]. While it is one of the factors that should be taken into account [8], focusing only on biotechnologies would not lead to successful development [2]. Currently the main focus is on the agricultural and forestry sectors and sustainable development, but there is no one best way for bioeconomy development. There is still no common international method for determining, measuring and comparing the extent of sustainability [9]. Several methods have been developed and all are based on three main pillars of sustainability - environmental, economic and social. Although this is the fact, the exact criteria and factors used in each sustainability assessment method are different and the results are not comparable. There have been studies that identified bioeconomy principles, drivers and distinctive visions of strategies, and they have concluded that three main visions exist: bio-resource, bio-technology and bio-ecology [2]. There are opinions that focus on bioeconomy as political vision [10] or biorefinery vision (techno-economic concept) [11]. All visions are strongly related to research and innovation policies [11]. It is understood that every country has its own resource pool, opportunities, workforce, policies, etc.; therefore, the transition to sustainable bioeconomy development needs to have a customized approach for each country. If the main factors influencing bioeconomy are analysed by the strength of their influence, it becomes clear which ones have an indirect influence through other important factors; building a model to highlight each factor's exposure to bioeconomy could help countries to evolve the stronger and indicate the weaker, but nevertheless important, factors.

Our previous study [12] focused on the assessment of factors affecting bioeconomy. Within current research, although each of the factors is analysed individually, the main output is the assessment of factor interlinkages. The chief novelty of the study is the use of the nexus approach for factor analysis. Also multicriteria decision analysis (MCDA) methods are used within the novel approach by creating consolidated results between different methods to achieve a broader view on decision-making results. The main aim is to propose a methodology for identification of a bioeconomy nexus and to define factors, links and their indicators that could be further assessed.

Abbreviations: MCDA, multi criteria decision analysis; TOPSIS, Technique for Order of Preference by Similarity to Ideal Solution; AHP, analytical hierarchy process; PROMETHEE, the preference ranking organization method for enrichment of evaluations; TRL, technological readiness level; GHG, greenhouse gases; CC, climate change.

* Corresponding author.
E-mail address: lauma.zihare@rtu.lv (L. Zihare).

https://doi.org/10.1016/j.nbt.2020.11.008

Research methodology

The development of bioeconomy has become one of the main drivers of overall economic development. In previous studies [12–14] on key factors affecting bioeconomy, a transdisciplinary approach has been applied, and based on those results seven factors have been selected for interlinkage analysis and benchmarking. Here, we propose the methodology for the assessment of bioeconomy-influencing factor interlinkages and to create benchmarks through a top-down approach (Fig. 1).

The method algorithm for this research consisted of five main steps:

1) First step: Based on scientific literature analysis and by the use of the Delphi method, seven primary factors were selected from a set of 24 affecting bioeconomy, and a graphical representation of their interlinkages was built by determining whether the link is direct (represented by a straight line) or indirect (broken line), and whether it is an influencing or dependent link (direction of an arrow). Indirect links mean that more than two factors are involved in the linkage, therefore, the derivative has been reached through another factor or with more than two factors together.

2) Second step: Multi-criteria decision making analysis (MCDA) is applied as a quantitative approach for determination of factors with the highest impact on bioeconomy development. This is a preliminary assessment and does not imply that other factors should be excluded from assessment; on the contrary, this assessment will only give an overall notion of which factors have the strongest impact on bioeconomy. As is well known, different MCDA approaches give very different results [15], so that to get a better perspective it is advisable to use at least two MCDA methods for the same decision. We proposed using the consolidated result for decision making. Two MCDA approaches were used: the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and the Analytical Hierarchy Process (AHP), which are two of the most commonly used MCDA analysis methods in the context of sustainable development [16].

2.1) MCDA analysis was conducted based on four criteria: direct influencing links, direct dependent links, indirect. influencing links, indirect dependent links. Values for seven factors (alternatives) were based on the number of linkages described. Link weights were based on assumptions, i.e. for both methods the weight of link strength was assumed to be 2:1, where direct links (both influencing and dependent) are twice as significant as indirect links (both influencing and dependent).

A) AHP analysis method based on pairwise comparison [17] ***(Figure B.1. supplementary information)***

Analytical Hierarchy Process (AHP) was calculated separately for each link type for more consistent results. For each sub-link type, the results were normalised and the priority vector obtained. Thereafter, the results of each alternative were summarized to acquire final results. AHP

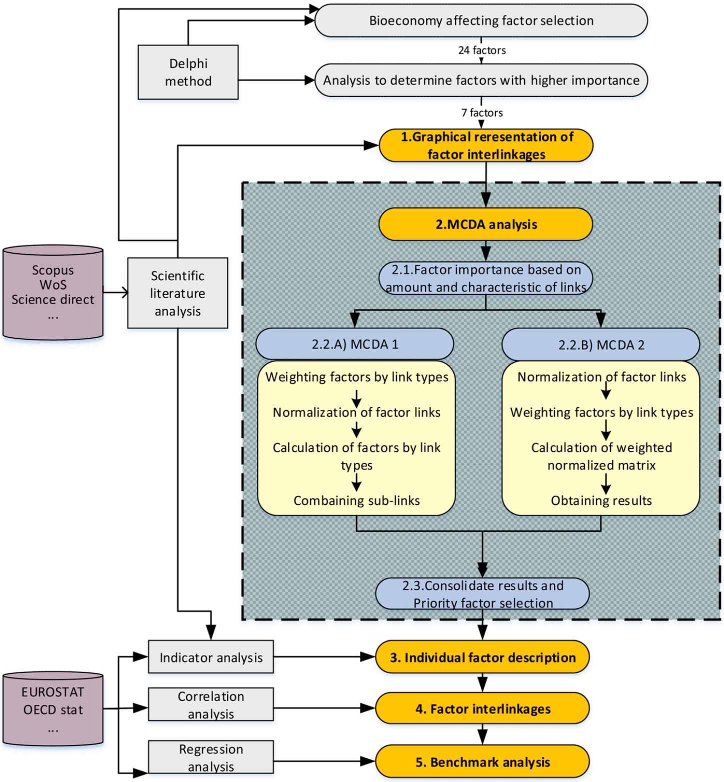


Fig. 1. Methodology algorithm for factor interlinkages and benchmark determination.

values were obtained by division between link amounts to determine which factor was more important than others. That is the main difference made in AHP calculations, where the typically used ranking, e.g., based on fundamental scales from 1 to 9, is not applied, but exact values are calculated between criteria pairs instead. Pairwise comparison was performed for each sub-link type individually, where one weighted alternative value was divided by another weighted alternative value, gaining the importance value for each factor in the AHP matrix

2.2. B) The TOPSIS - Technique for Order of Preference by Similarity to Ideal Solution analysis method [18], which is based on Euclidean distance evaluation, gives the result as a closeness to the ideal solution. TOPSIS calculations can be found in the previous work [19]. The preferred outcome (ideal solution) for all criteria is the max and anti-ideal for all criteria is the min amount. As stated previously, weights were identical for both methods.

2.3.) As MCDA methods vary, and often give slightly different results, a novel approach was used by creating a consolidated result between two methods. If this is used in other studies, more than two MCDA analysis methods can also be applied if necessary; in addition, different approaches can be used according to the specifics of the problem to be solved.

3)Third step: Individual factor analysis. To obtain an in-depth characterization of factors, each selected factor was analysed separately in the context of bioeconomy. Each was described through indicator analysis and grouped as environmental, economic, social or technological aspect indicator.

4)Fourth step: The application of a nexus approach, aimed at finding a way of determining link strength, e.g., by overlapping indicators related to bioeconomy-influencing factors. This could provide an insight and correlation between each two or more factors.

5)Fifth step:

The final step was to find benchmarks that best characterise linkages between two factors. They are expressed as mathematical regression models that characterize the link and its strength.

Results

Graphical representation of bioeconomy factor interlinkages

Twenty four bioeconomy-affecting factors had been obtained previously [12]. After expert evaluations and application of the Delphi method, seven primary bioeconomy-affecting factors and their linkages were identified (see Fig. 2). The linkages discussed were based on scientific literature and are described as direct or indirect based on how they affect factors. In future research it is advised to use triple or quadruple factor link assessment to gain more insight into linkage characteristics based on the factors that the link is connecting.

Modern technologies have an impact on the environment; one of the most noticeable effects is reached by energy efficiency [20]. The industry has gone a long way from burning coal with efficiency as low as 0.5 % [21] to around 90 % efficiency in recent decades [22]. In addition, technologies play an immense role in the industry by allowing

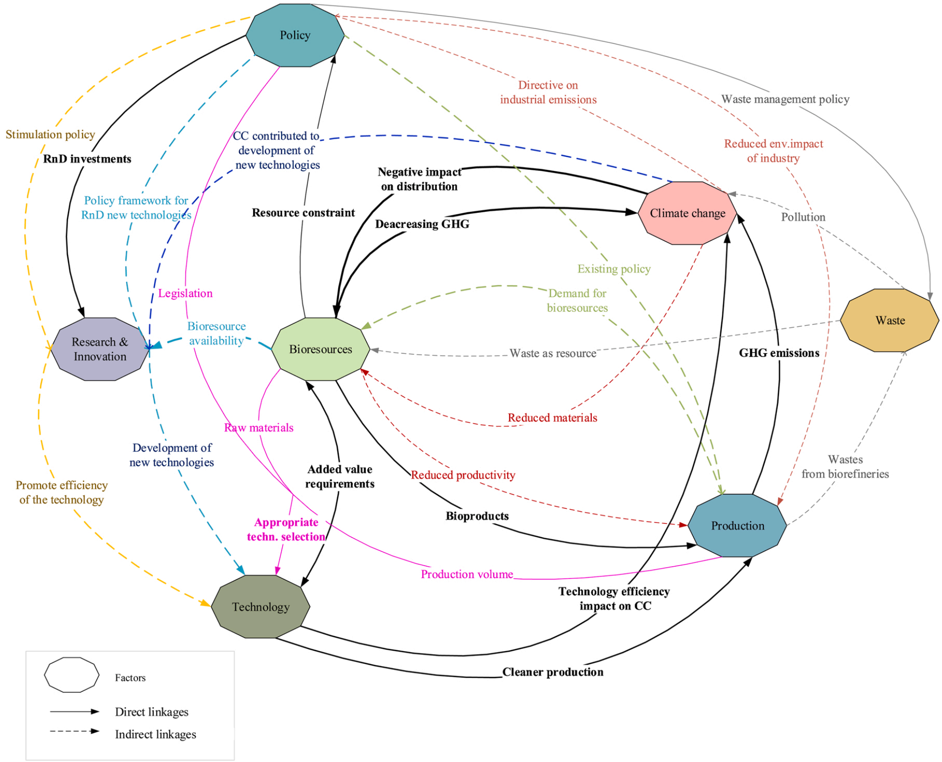


Fig. 2. Graphical representation of seven bioeconomy influencing factors interlinkages.

production of bioproducts from raw materials, thus creating a strong link between bioresources, technologies and bioproducts [23]. Preference for specific technology is impacted by production volume and raw materials used, as well as regional legislation [24].

Policy has a strong role in technology development as strategic incentives to research and development lead to their improved production efficiency of technologies. Their adoption in new and existing production plants could lead to growing demand for biomass feedstock [25]. Due to existing legislation it is expected that the demand for biomass feedstock for production will indeed grow in local, EU, and even at the global level [26] reducing the negative impact of production on climate [27]. However, biomass cannot substitute for fossil resources to the same amount needed to satisfy demand for products and energy, so that European requirements are now focusing on more effective biomass usage and biowaste management. Nevertheless, biorefinery causes pollution in the forms of gas, liquid waste and solids [28].

One of the many negative aspects of the climate change is altered temperatures and water cycles [29] leading to change of bioresource distribution in regions [30]. Popular example of this negative effect on the industry is the predicted decrease in coffee bean productivity [31]. Despite the fact that climate change negatively impacts industry (in most cases), specific policies aimed at reduction of industry's negative impact on climate need to be implemented [32]. They are made to endorse innovations that prevent industrial emissions, including pollution [33].

Burning of fossil fuel releases the carbon sequestered millions of years ago back into the atmosphere, hence increasing the amount in the active carbon cycle [21]. To slow down climate change, fossil resources would need to be completely replaced by bioresources [34] and alternative energy sources, such as hydrogen. This would require an immense commitment on the part of industry, as demand dictates supply. Demand not only dictates the amount of available bioresources, but also stimulates the development of new greener technologies [35]. Unlike fossil resources, bioresources vary in composition, requiring more variable technologies and demanding a more flexible approach from industry [26]. In addition, various biomass leads to different products with varying value per ton of raw material [25]. Therefore production of biomass with higher added value is so important, and technology development of new and underused biomass in order to raise its value.

Recognizing the crucial role of research and development (R&D) in innovative technology development [25], the EU allocates considerable resources to promoting R&D biotechnologies [26].

The main nexus identified from graphical representation linkages (Fig. 3) are:

- o Policy – Research and Innovations - Technology;
- o Production – Waste – Climate change;
- o Production – Waste – Bioresources;
- o Policy – Production – Bioresources;
- o Technology – Production – Climate change;
- o Climate change – Policy – Production;
- o Policy- Technology - Production – Bioresources;
- o Climate change – Bioresources – Production.

MCDA results on bioeconomy factor linkages

MCDA for all seven selected bioeconomy factors was performed with the AHP and TOPSIS methods. which are two of the most used in MCDA [36]. A TOPSIS matrix with initial values is seen in Table 1 and is then normalized using the vector normalization method and weighted accordingly. Distances for positive and negative solutions by Euclidean distance helps to rank the alternatives [37].

Assumptions made about the link type strength are included in both analysis methods. Both direct links (direct influencing and direct dependent) are assumed to be twice as important than indirect links (indirect influencing and indirect dependent links). Therefore, the weights are 1/3 (0.33) for direct links and 1/6 (0.17) for indirect links.

From the evaluation in Table 1, it is seen that there are more indirect than direct links between factors. For example, for R&D, the largest share of the AHP analysis result was due to indirectly influencing links (see Fig. 3), which can be understood as this factor is more of an instrument (driver) for bioeconomy development and works in close connection with other factors. The highest share of direct links is for bioresources, which is the one that bioeconomy is based on. Policy and technology factors in AHP analysis also show great impact.

Fig. 4. shows the final results of three methods that differ based on the approach used. After a pairwise comparison (AHP) it was determined that the highest impact is for research and innovation, technology and bioresources, that can be confirmed by bioeconomy's definition as a knowledge and bio-based economy [38] and that in 2012,

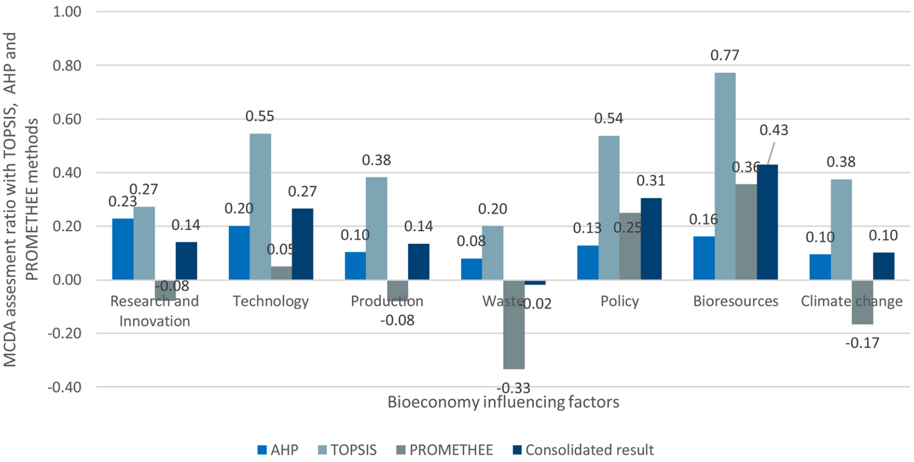


Fig. 3. MCDA analysis results for seven bioeconomy influencing factor importance based on their interlinkages.

Table 1
TOPSIS matrix for factor evaluation based on link type and amount.

Alternatives, $A_{n,\ n=1\ldots7}$ Criteria, $i_{m,\ m=1..4}$	A_1 *Research and Innovations*	A_2 *Technology*	A_3 *Production*	A_4 *Waste*	A_5 *Policy*	A_6 *Bioresources*	A_7 *Climate change*	$\sum$ Total number of links
Direct influencing link, $\boldsymbol{i_1}$	1	2	2	1	1	3	2	12
Direct dependent link, $\boldsymbol{i_2}$	0	3	1	1	3	4	1	13
Indirect influencing link, $\boldsymbol{i_3}$	4	2	3	1	1	2	1	14
Indirect dependent link, $\boldsymbol{i_4}$	2	0	2	1	4	2	3	14
Total number of links $\sum$	7	7	8	4	9	11	7	

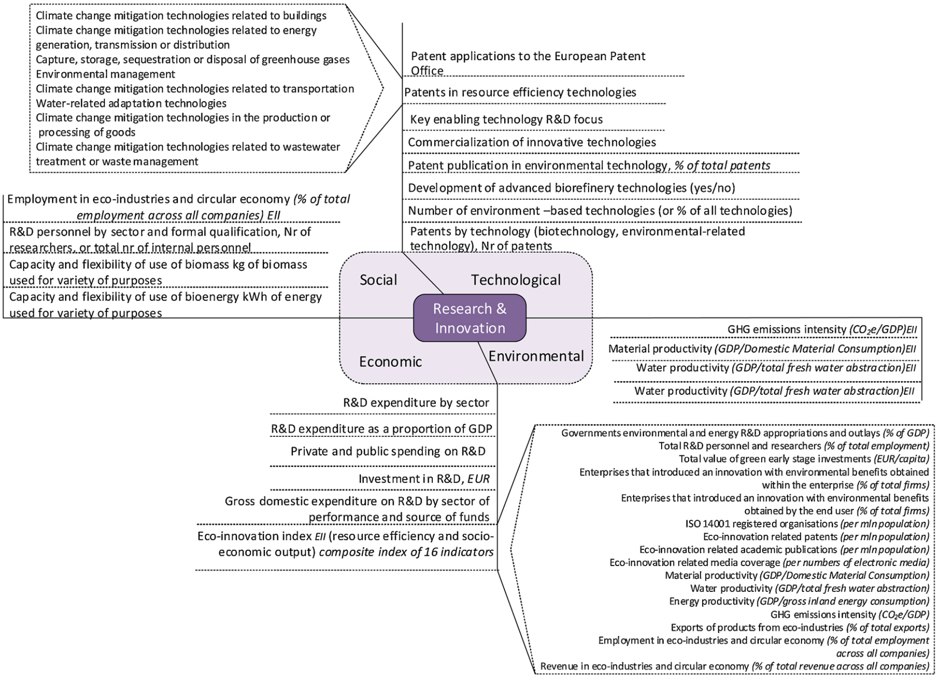


Fig. 4. Indicators that characterize Research & Innovation factor in bioeconomy context (social, technological, economic and environmental dimension).

biotechnology was set as the priority driver for bioeconomy development [39]. Analysis by PROMETHEE (The Preference Ranking Organization METHod for Enrichment of Evaluations) shows the greatest impact on bioresources, policy and technology. In spite of the fact that, according to TOPSIS analysis, bioresources have the highest score, technology and policy factors are also important. Bioresources play an important role in bioeconomy, as they are based on biomass and its sustainable use. Technology factor has high results in all methods, as it ensures sustainable use of resources, as well as providing a more effective use and development of new technologies and bioproducts. The lowest score in all methods was for waste. However, looking back at interlinkages between these factors (Fig. 3), policy has indirect linkages through research and innovation that lead to technology factor. Therefore, it is proposed to take into account the consolidated results when selecting priorities for further assessment on factor analysis and linkage selection.

Interval scales for TOPSIS analysis results varied from 0.2 (waste) to 0.77 (bioresources), and AHP analysis results from 0.08 (waste) to 0.23 (research and innovation); PROMETHEE varies from -0,33 (waste) to 0,36 (bioresources).

Case study. Triple factor nexus in EU bioeconomy

To better understand the proposed methodology, a case study has been performed for EU countries. Triple factor nexus has been assessed between the following factors: policy, research & innovation and technology. Each factor has been described through indicator analysis. Main overlapping factor indicators were used to characterize the linkage. Based on statistical data and correlation analysis, the benchmark was determined.

Individual factor analysis

In order to build triple nexus evaluation, each factor was first analysed through indicator analysis.

Research and innovation factor characteristics

Technology transfer organisations are the way to bridge the gap between industry and academia [40], but countries and regions that rely on transnational science and technology transfer organisations to advance the development of new bioproducts [30] should also consider governmental support.

There are two stages for transition to bioeconomy innovation: incremental and gradual innovations (through new products and processes) and implementation of diverse, radically new and disruptive innovations [38,41]. For an effective transition to a sustainable bioeconomy, there is a need for second type innovations. This means that radical innovations will be necessary to make a global change towards desirable goals. This includes redesigned business models, reconfigured supply chains, a setup of new value chains, such as development of new sustainable products, and technology needs, knowledge and skills outside industries' fields of expertise. Universities and research institutions are especially conceived as the cornerstones in accomplishing these radical innovations [38,41].

Innovations can be described by type [42], stage of development, technological readiness level (TRL), extent to which they are disruptive or radically new [38,43], level of complexity in the knowledge base for the innovation development [38], degree of cooperation between different actors in such development [41], level of complexity in the policy framework (European Commission Bioeconomy strategy 2012) and level of nonlinearity in the development. HORIZON 2020 has been one of the main instruments for promoting innovation in the bioeconomy [38], and now it can be seen how efficiently that has worked.

Fig. 4 Shows the main indicators of the research and innovation factor, where two of the indicators have been explained in more detail by sub-indicators: patents in resource efficiency technologies and eco-innovation index (EII). For indicator references see Appendices A.1 (supplementary information).

Number of patents is the best quantitative indicator that characterizes the research and innovation factor, especially, patents for biotechnologies and resource efficiency technologies. The number of patents on resource efficiency technologies includes several sub-indicators (from OECD database) [44]:

- o Climate change mitigation technologies related to buildings
- o Climate change mitigation technologies related to energy generation, transmission or distribution
- o Capture, storage, sequestration or disposal of greenhouse gases
- o Environmental management
- o Climate change mitigation technologies related to transportation
- o Water-related adaptation technologies
- o Climate change mitigation technologies in the production or processing of goods
- o Climate change mitigation technologies related to wastewater treatment or waste management

All of these sub-indicators focus largely on climate change and greenhouse gases (GHG) mitigation technologies. Therefore, they do not cover all the technologies the development of which impacts bioeconomy.

Patent data are available and easily collected for analysis. However, they do not capture all innovations [45]. Patents are the main research and innovation output that can reflect the efficiency of innovations. Fig. 5 shows the results for the indicator patent applications to the European Patent Office (EPO) according to gross domestic expenditure on R&D by sector from 2010 to 2016 (available data from EUROSTAT database). The EU 28 average is taken as the benchmark and countries exceeding the benchmark are selected as the top for research and innovation factor benchmarking, namely Germany (explicitly higher), France, Italy, UK, Netherlands and Spain. The lowest countries are Malta, Cyprus, Croatia, Lithuania, Estonia, Bulgaria, Latvia, Luxembourg, Slovenia and, Slovakia.

The distance between highest and lowest countries (Table 2) in 2010 was 8581 (distance between leader position – Germany and lowest results - Malta), the smallest distance between benchmark and top country in 2010 was 5 (Spain), and the smallest distance from benchmark to runner up countries was 167 (Sweden). All values in 2017 were lower and the distance between highest and lowest country in 2017 was 6138 (distance between leader position – Germany and lowest results - Malta), the smallest distance from benchmark till to countries was 424 (Spain) and from benchmark to runner up countries was 102 (Sweden). It seems

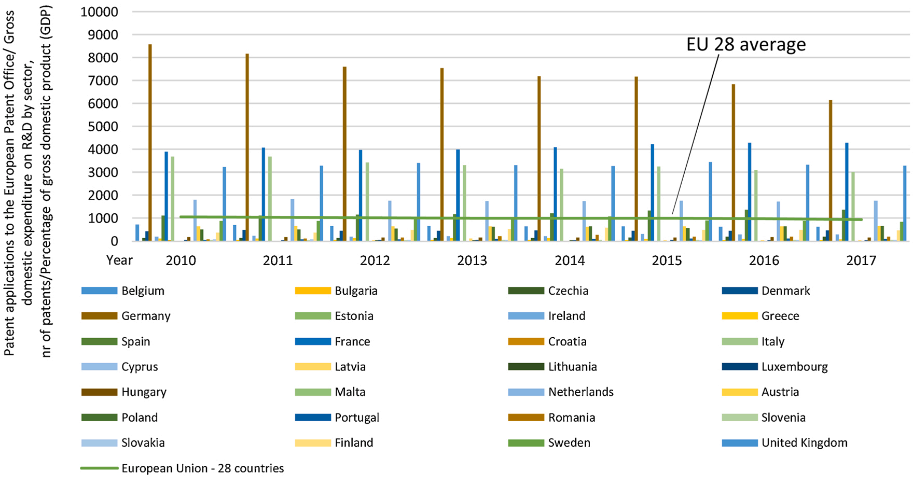


Fig. 5. Benchmark for patent applications to the European Patent Office/ gross domestic expenditure on R&D by sector, nr of patents/percentage of gross domestic product (GDP) (Data: Eurostat).

Table 2
Patent applications to the European Patent Office/ Gross domestic expenditure on R&D by sector, nr of patents/Percentage of gross domestic product (GDP) in EU countries.

Patent applications to the European Patent Office/ Gross domestic expenditure on R&D by sector, nr of patents/Percentage of gross domestic product (GDP)							
	2010		2013		2016		2017
Germany	8587.5	Germany	7544.8	Germany	6849.7	Germany	6150.4
France	3894.4	France	4005.7	France	4304.2	France	4299.9
Italy	3689.2	United Kingdom	3314.4	United Kingdom	3339.4	United Kingdom	3295.2
United Kingdom	3244.4	Italy	3308.7	Italy	3096.5	Italy	3027.7
Netherlands	1799.9	Netherlands	1745.1	Netherlands	1726.2	Netherlands	1756.3
Spain	1111.2	Spain	1181.9	Spain	1379.4	Spain	1367.4
Benchmark	1056.0	Benchmark	1008.5	Benchmark	980.1	Benchmark	942.9
Sweden	888.5	Sweden	990.5	Sweden	892.4	Sweden	840.7
Belgium	735.5	Belgium	659.3	Poland	653.5	Poland	666.6
Austria	648.5	Austria	648.7	Austria	649.1	Austria	665.4
Poland	501.9	Poland	629.0	Belgium	630.6	Belgium	622.3
Denmark	441.6	Finland	533.7	Finland	483.4	Finland	475.1
Finland	375.2	Denmark	456.9	Denmark	444.1	Denmark	464.8
Ireland	203.8	Romania	218.2	Ireland	304.1	Ireland	302.0
Hungary	171.5	Ireland	209.6	Romania	206.1	Czechia	199.7
Czechia	143.7	Hungary	155.1	Czechia	189.7	Romania	199.1
Greece	109.2	Czechia	131.9	Hungary	169.1	Hungary	147.9
Slovakia	76.2	Greece	129.1	Portugal	108.7	Portugal	107.8
Romania	75.3	Latvia	110.1	Greece	93.1	Greece	79.9
Portugal	61.7	Portugal	90.0	Slovakia	68.6	Slovakia	62.0
Slovenia	51.8	Bulgaria	62.2	Slovenia	55.9	Slovenia	61.1
Luxembourg	51.1	Slovakia	60.7	Latvia	49.2	Luxembourg	43.7
Croatia	41.0	Luxembourg	50.0	Luxembourg	48.8	Latvia	43.6
Bulgaria	29.8	Slovenia	50.0	Bulgaria	40.3	Bulgaria	39.6
Latvia	25.9	Lithuania	42.8	Estonia	26.4	Estonia	28.4
Estonia	24.8	Croatia	22.8	Croatia	24.5	Lithuania	24.0
Lithuania	20.1	Estonia	16.3	Lithuania	22.8	Croatia	23.2
Cyprus	17.4	Cyprus	16.2	Cyprus	17.9	Cyprus	16.5
Malta	5.7	Malta	6.3	Malta	11.7	Malta	11.4

Gross domestic expenditure on R&D by sector [SDG_09_10] EUROSTAT Percentage of gross domestic product (GDP).
Patent applications to the European Patent Office (source: EPO) [SDG_09_40] EUROSTAT Number [NR].

that Sweden was closer to the benchmark in 2017, but almost all the values decreased over time, with lowering of benchmark; Sweden values in 2010 was 888, but in 2017 only 840. In contrast for Spain, the values were increasing from 1111 in 2010 to 1367 in 2017, see Fig. 6. Therefore, the distances between these two countries are increasing.

Patent applications are used in various statistical analyses and are one of the most important indicators of innovation in the EUROSTAT sustainable development goals database [46]. Although the volume of

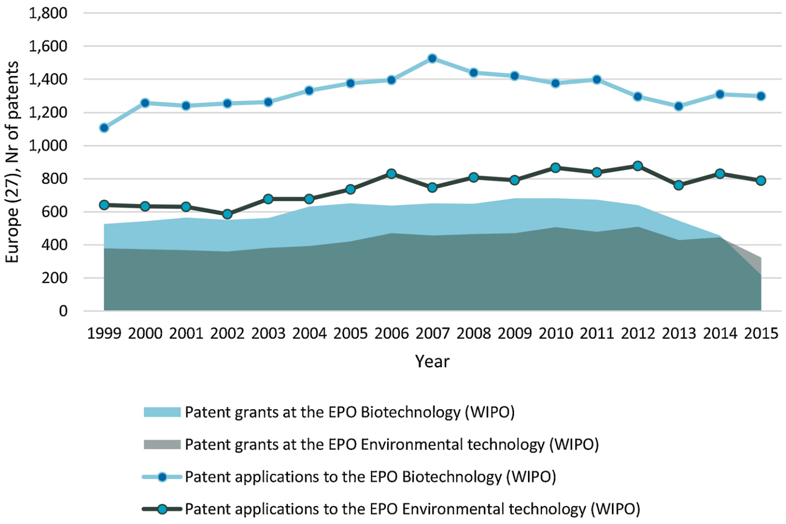


Fig. 6. Patent applications vs granted patents in fields of biotechnology and environmental technology (data: OECD stat).

patent applications is one of the indicators of patent productivity and, consequently, a comparable indicator of innovation at the national level, it should be taken into account that the number of approved patents is much lower. Statistics on approved patents show that environmental technology patents are granted for more than 50 % (54%–61%) of the filed applications, but in biotechnology are below 50 % (44%–47%). In 2015, there was a decrease in patents granted for both biotechnology and environmental technologies, where only 17 % of biotechnology patents were approved and 41 % of environmental technologies patents **(Figure B2, supplementary information).**

Patent applications related to bioeconomy sectors in Eurostat sustainability development goal indicators (no granted patents included) shows a very stable tendency of about 51,000 per year. The OECD database provides data related to environmental management (7–10,000 per year), biotechnology (4–12,000) and selected environmentally - related technologies (20–31,000) and it is possible to get data about granted patents. As noted previously, patent applications vs granted patents can differ by at least 50 %. If the trend for patent applications is not decreasing over the years, then granted patents are. Data values provided by Eurostat covers all sectors related to bioeconomy and were therefore used in further analysis.

Policy factor characteristics

Policy is defined as a general set of actions and measures that are planned and set at the highest level of management and which include approved attitudes and regulations that must be followed when managing the operations of an organization [47]. Another policy understanding states that “a policy is a statement of intent to change behaviour in a positive way, while an [policy] instrument is the means or a specific measure to translate that intent into action” [48] [49]. It is one of the strongest and most significant factors influencing the implementation of a sustainable bioeconomy. Bioeconomy development depends on a country’s political system and preferred policy instruments [50]. The EU Bioeconomy strategy (2012) and its updated version (2018) [27] both emphasize the significance of policy for the development of bioeconomy. The general types of policy instruments are: constraining and control measures, innovation promotion, product pricing mechanisms, information measures (such as public information campaigns), enabling actors, supporting investment [49].

Policy interventions may enable the transition to sustainability and bioeconomy, but no single policy can ensure full systemic implementation of such transition. [32] A combination of various policy instruments is required to ensure the development of bioeconomy [25]. Those intended to promote the development of bioeconomy can generally be classified into four groups:

- Legal, i.e., necessary changes in regulations and/or quality standards to allow and advance the sale of bioproducts,
- Support for voluntary initiatives and requirements for public sector regarding implementation of biological waste collection,
- Provide financial incentives for private investments in biorefineries (e.g. green certificates or feed-in tariffs),
- Public financial support for R&D [25].

Referring to the last two groups of instruments, policy is related to

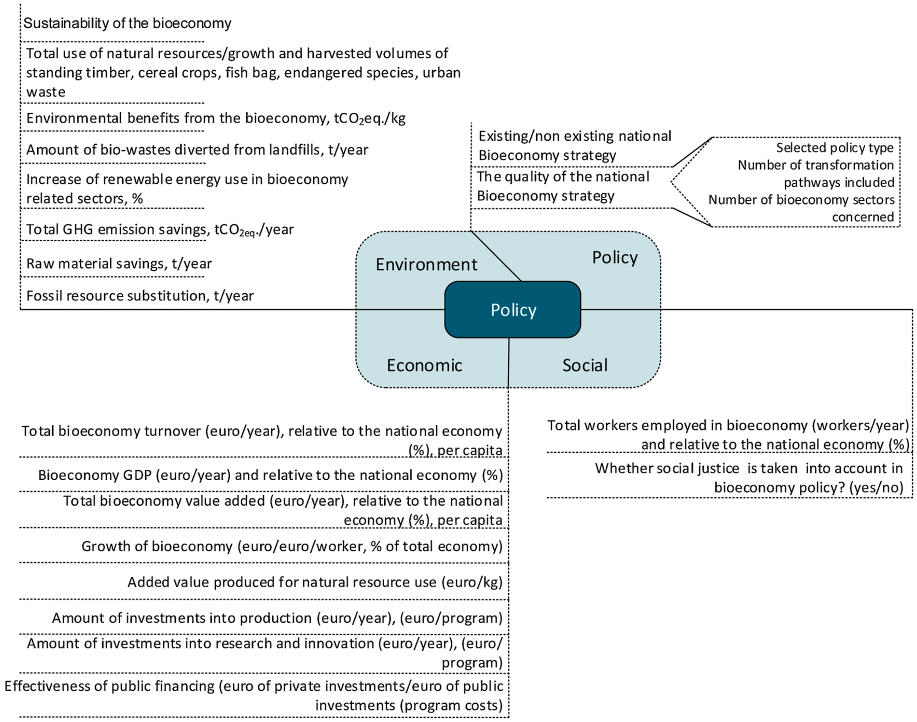


Fig. 7. Indicators that characterize policy factor in bioeconomy context (social, policy, economic and environmental dimension).

production and research and innovation, as the subsidies prescribed by a bioeconomy-enhancing policy are commonly directed towards industry or research and innovation.

By providing performance measurement, reporting and communicating to stakeholders, policy indicators help to ensure a consistent and transparent consideration of sustainability within public policy [51]. Indicators that can be used for assessment of bioeconomy policy are those that characterize bioeconomy development (for references, see annex A.2, supplementary information.). Fig. 7 provides a graphical summary of indicators related to policy factors. Better indicator performance as a result of the implemented policy would support the effectiveness of a policy, while no change or even decrease of indicator performance indicates inefficiency of the applied policy.

Regarding policy instrument assessment, another aspect to consider is that various countries may have preferences for different policy measures. Nevertheless, policy effectiveness should be assessed in respect to the chosen indicator, not based on the type of instruments used [49]; longevity of certain policies [52], for instance, change of a left-wing to a right-wing government, might affect the policies.

Technology factor characteristics

Technologies are one of the main pillars of bioeconomy. They bridge the gap between innovations and production and between unused or underused biomass and bioresources. They include environment-related technologies that allow mitigation of climate-change, and biotechnologies and existing technology improvements that either solve the possibility of using biomass that otherwise could not be collected, or help to advance the efficiency of resource use.

One of the greatest emphasis of the technology factor in the context of bioeconomy is for biotechnologies. By collecting a list of biotechnology definitions, the OECD has made a single statistical definition of biotechnology as “The application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services.” [53] Biotechnology has an important potential not only for economic development, but also for sustainable bioeconomy development acceleration [54]. Biotechnology cannot be advanced without specific knowledge, and therefore there is a strong link to education and research institutions. As the main outcome from technology development is intellectual property, there should be a correlation between promotion of patent production at local and international levels, to succeed in technology commercialization [54].

Technology indicators shown in Fig. 8 are derived from OECD statistics as key indicators for technology (biotechnology). The number of active biotechnology firms in Latvia (including medical, environmental, industrial and agricultural biotechnology) according to the data in the OECD database for 2016–2017 was 9 and 12 accordingly [55]. That is the smallest number in respect of the other countries for which data has been provided. However, in order to see the true situation, normalization should be applied.

Triple factor nexus: policy, research and innovations and technology

An effective policy framework is essential to ensure innovation and the development of new technologies and production methods. In [25, 32] it is stated that R&D investments are crucial for the development of innovative technologies. [25]. also states that technology and machinery knowledge and organisation of biomass logistics are required for the development of bio-based solutions. The dynamic relationship between Policy, Innovation, Technology, Production and Bioresource factors are explained in [26]. A stimulation policy that provides incentives to R&D, would promote an improved production efficiency of the technology; this would in turn result in installation of those technologies in existing and new production plants and sequentially, the requirements of the biomass feedstock would grow. Resource constraints are in fact one of the main concerns in the study [25].

One indicator that clearly overlaps policy and research and innovation factors is investments in R&D. Countries are committed to significantly increase public and private R&D expenditures and the number of researchers by 2030 as part of Sustainable Development Goals [56]. In more detail, the dynamic loops of R&D expenditure and dynamics of innovation diffusion and technology adaption are described in [57].

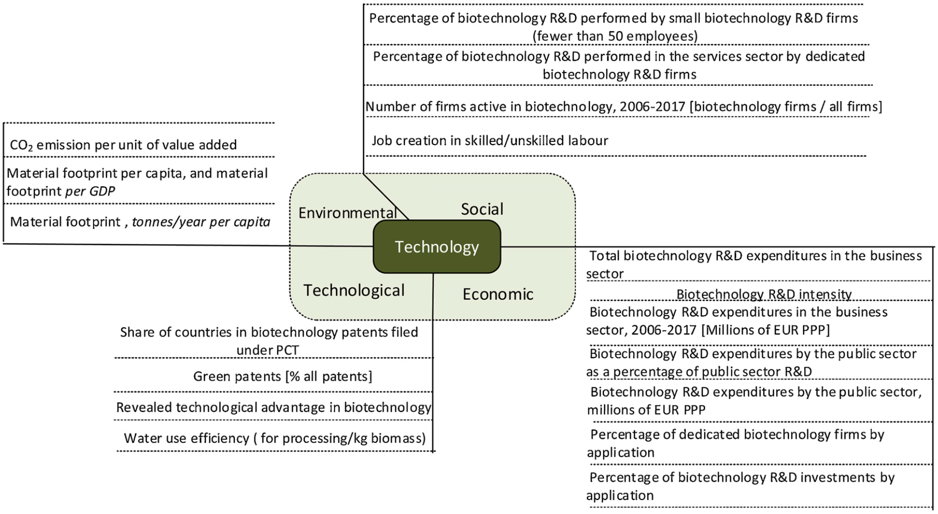


Fig. 8. Indicators that characterize technology factor in bioeconomy context (social, technological, economic and environmental dimension) [55,61].

Environmental policy has an effect on technological innovation. It can be manifested through tax measures or quota obligations with an impact on patent activity [58]. Patent data aids examination of eco-innovations and suggestions for future policy. Resource (input) indicators are R&D expenditures and personnel (in terms of knowledge acquisition), R&D intensive goods or expenditure for licences; the output indicators for R&D results are patents. To ensure innovation transfer to industrial production patent should be in place, therefore in this case amount of publications has not been included, however it is also a good indicator for innovation measurement. Patent data are more commonly used as output indicators and key measure of innovations [58]. Policy frameworks should search for optimal solutions to innovation rate and direction. Market-based instruments may affect the technological trajectory of the economy. The use of subsidies in support of environmental R&D could be in form of grants or tax credits. [59] (Fig. 9).

Looking at the graphical representation in Fig. 3, the connection between policy and research and innovation links factor "policy" through framework for new technologies, measured as R&D expenditure (public sector (government, see Fig. 10), with factor "research & innovation" and "technology" through development of new technologies (that can be measured with patent applications). Assessing the nexus in-depth, there are additional factors that ensure the existence of these linkages as presented in Fig. 9.

The indicator of this link coincides with Sustainable Development Goal 9 (SDG9) [60], and is therefore considered a strong link towards bioeconomy sustainable development.

Benchmark analysis

Benchmark analysis is one of the effective analysis methods for description of bioeconomy performance at national level. In this case, the existing performance in each EU country is analyzed and compared with the practice in leading EU countries to adapt or improve its existing policy, moving towards sustainable bioeconomy development. In a triple factor nexus, two indicators that have been selected for the assessment of one of the possible link benchmarks are R&D expenditures (that characterize the link between policy and R&D) and the number of patent applications (that characterize the link between R&D and Technology).

Top countries (UK is excluded from analysis due to Brexit and to provide a reliable future benchmark) over the benchmark (set as the EU 28 country average) in patent applications to the EPO (SDG_9_40; Eurostat) attributed to the gross domestic expenditure on R&D by sector (SDG_09_10; Eurostat) are selected for the link indicator benchmark analysis. For these top countries (Germany, France, Italy, Netherlands and Spain) data correlation is good at the intra-country level, as well as inter-country (see Figure 12), providing the EU with the best practice benchmark, with a strong correlation (R = 0.8).

The empirical model (1) presents the mathematical description of

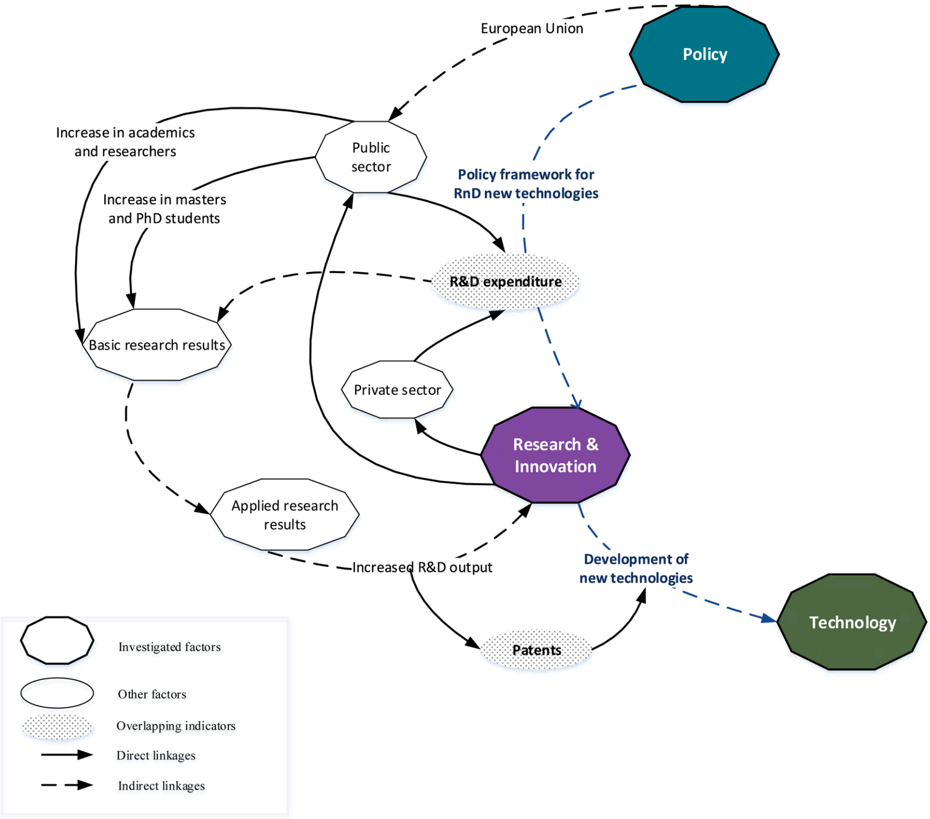


Fig. 9. Triple factor nexus: Policy, Research and Innovation and Technology interlinkages.

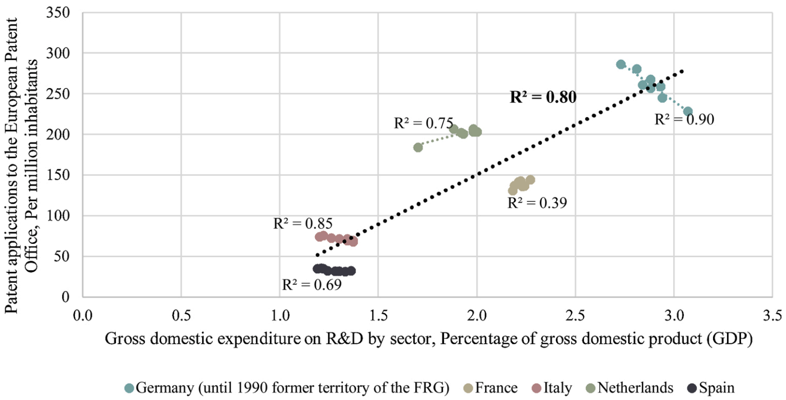


Fig. 10. Benchmark for Policy, Research & Innovation and Technology factor linkages.

policy, research & innovation and technology link benchmark.

$$P = 122{,}13\ c - 92{,}97, \tag{1}$$

where

P- patent indicator: applications to the EPO per million inhabitants,
c-gross domestic expenditure on R&D by sector

With the use of this empirical model, each country can calculate their situation, based on the benchmark.

Some countries that are not in the top list prove that there is an imbalance between these two indicative parameters at intra-country level. Therefore, a more detailed assessment is needed to address appropriate policy measures or strategy that could accelerate patent applications as a result of expenditure for R&D. Policies in different countries may affect these trends, for instance, different national incentives for researchers in academic institutions to apply for patents.

Conclusions

MCDA analysis can be integrated during system dynamic model development to quantify indirect and direct link parameters. In the current analysis, bioresources, technology and research & innovation factors acquired the highest scores of all seven factors considering the consolidated result. This quantitative analysis could help when setting priorities and determine which factors are more linked with others.

The methodology for a bioeconomy factor nexus approach presented is a means to move towards measuring sustainable bioeconomy development. The collection of each factor-related indicator facilitates finding continuous linkages between factors and indicators and, consequently, establishing benchmarks. Several benchmarks could be addressed for each linkage characteristic. The empirical model presents the mathematical description of policy, research & innovation and technology link benchmarks, as in this case for the triple factor nexus: policy, research and innovations and technology indicator sets are used for creation of this benchmark - policy and innovations as gross domestic expenditure on R&D by sector and innovations and technology as patent production. Future research could focus on technology and production factor interlinkage, that could determine how productive the patent applications are in bioeconomy – how many granted patents are actually commercialised and reached the production stage.

Assessments of additional nexus in future research would provide a more comprehensive view. Limitations of using a top-down approach could be reached when statistical data are not available or have not yet been created (for example, for biorefineries or biowaste); for such situations a bottom-up approach could be applied, e.g. companies' cases could provide an idea of which data are needed in order to develop the appropriate indicators and build a complete bioeconomy factor nexus. Such research could provide important recommendations for additional statistical data collection. The methodology created can be used as a starting point for holistic bioeconomy assessment, and it can be further expanded in system dynamic modelling or complex index distribution.

Funding

This work was supported by the Latvian Council of Science, project "Bioresources Value Model (BVM)", grant No. lzp-2018/1-0426.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.nbt.2020.11.008.

References

[1] Guo M, Song W. The growing U.S. bioeconomy: drivers, development and constraints. N Biotechnol 2019;49:48–57. https://doi.org/10.1016/j.nbt.2018.08.005.

[2] Wreford A, Bayne K, Edwards P, Renwick A. Enabling a transformation to a bioeconomy in New Zealand. Environ Innov Soc Transitions 2018:1–16. https://doi.org/10.1016/j.eist.2018.11.005.

[3] Pülzl H, Kleinschmit D, Arts B. Bioeconomy - an emerging meta-discourse affecting forest discourses? Scand J For Res 2014;29:386–93. https://doi.org/10.1080/02827581.2014.920044.

[4] Heimann T. Bioeconomy and SDGs: Does the Bioeconomy Support the Achievement of the SDGs? Earth's Futur 2019;7:43–57. https://doi.org/10.1029/2018EF001014.

[5] Bell J, Paula L, Dodd T, Németh S, Nanou C, Mega V, et al. EU ambition to build the world's leading bioeconomy—uncertain times demand innovative and sustainable solutions. N Biotechnol 2018;40:25–30. https://doi.org/10.1016/j.nbt.2017.06.010.

[6] Dupont-Inglis J, Borg A. Destination bioeconomy – the path towards a smarter, more sustainable future. N Biotechnol 2017:6784. https://doi.org/10.1016/j.nbt.2017.05.010.

[7] Patermann C, Aguilar A. The origins of the bioeconomy in the European Union. N Biotechnol 2017. https://doi.org/10.1016/j.nbt.2017.04.002.

[8] Woźniak E, Twardowski T. The bioeconomy in Poland within the context of the European Union. N Biotechnol 2018;40:96–102. https://doi.org/10.1016/j.nbt.2017.06.003.

[9] Ramcilovic-Suominen S, Pülzl H. Sustainable development – a 'selling point' of the emerging EU bioeconomy policy framework? J Clean Prod 2018;172:4170–80. https://doi.org/10.1016/j.jclepro.2016.12.157.

[10] European Commission. A sustainable Bioeconomy for Europe: strengthening the connection between economy. society 2018:13. https://ec.europa.eu/knowledge4policy/publication/sustainable-bioeconomy-europe-strengthening-connection-between-economy-society_en.

[11] Schütte G. What kind of innovation policy does the bioeconomy need? N Biotechnol 2018;40:82–6. https://doi.org/10.1016/J.NBT.2017.04.003.

[12] Muizniece I, Zihare L, Blumberga D. Obtaining the Factors Affecting Bioeconomy 2019;23:277–91. https://doi.org/10.2478/rtuect-2019-0018.

[13] Muizniece I, Kubule A, Blumberga D. Towards understanding the transdisciplinary approach of bioeconomy nexus. Energy Procedia 2018:175–80. https://doi.org/10.1016/j.egypro.2018.07.052.

[14] Kubule A, Indzere Z. Muizniece I. Modelling of the bioeconomy system using interpretive structural modelling. Agron Res 2019;17:1665–78. https://doi.org/10.15159/AR.19.170.

[15] Lee H-C-C, Chang C-T-T. Comparative analysis of MCDM methods for ranking renewable energy sources in Taiwan. Renewable Sustainable Energy Rev 2018;92:883–96. https://doi.org/10.1016/J.RSER.2018.05.007.

[16] Kandakoglu A, Frini A, Ben Amor S. Multicriteria decision making for sustainable development: a systematic review. J Multi-Criteria Decis Anal 2019;26:202–51. https://doi.org/10.1002/mcda.1682.

[17] Saaty RW. The analytic hierarchy process—what it is and how it is used. . Math Model 1987;9:161–76. https://doi.org/10.1016/0270-0255(87)90473-8.

[18] Hwang Ching-Lai, Yoon K. Multiple attribute decision making: methods and applications a State-of-the -art survey, vol. 186. Berlin Heidelberg: Springer; 1981. https://doi.org/10.1007/978-3-642-48318-9.

[19] Zihare L, Gusca J, Spalvins K, Blumberga D. Priorities determination of using bioresources. Case study of Heracleum sosnowskyi. . Environ Clim Technol 2019;23:242–56. https://doi.org/10.2478/rtuect-2019-0016.

[20] Salar-García M, de Ramón-Fernández A, Ortiz-Martínez VM, Ruiz-Fernández D, Ieropoulos I. Towards the optimisation of ceramic-based microbial fuel cells: a three-factor three-level response surface analysis design. Biochem Eng J 2019;144:119–24. https://doi.org/10.1016/J.BEJ.2019.01.015.

[21] Wrigley EA. Energy and the English industrial revolution. . Energy English Ind Revolut 2015:1–272. https://doi.org/10.5860/choice.48-4603.

[22] David Pimentel. Handbook of energy utilization in agriculture. 2018. https://books.google.lv/books?hl=en&lr=&id=7zSoDwAAQBAJ&oi=fnd&pg=PA15&dq=coal+plant+energy+efficiency&ots=ZjxQGvZlgl&sig=DmA6YXBEy9n2vmT9p8-4d5mtoZ8&redir_esc=y#v=onepage&q&f=false.

[23] Lewandowski I. Bioeconomy: Shaping the transition to a sustainable, biobased economy. In book Bioeconomy. 2017. https://doi.org/10.1007/978-3-319-68152-8.

[24] European Comission. BREF n.d. https://eippcb.jrc.ec.europa.eu/reference/ (accessed February 11, 2020).

[25] Maes D, Van Passel S. Effective bioeconomy policies for the uptake of innovative technologies under resource constraints. Biomass Bioenergy 2019;120:91–106. https://doi.org/10.1016/j.biombioe.2018.11.008.

[26] European Commission. The Bioeconomy Strategy. A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment 2018. https://ec.europa.eu/knowledge4policy/node/33004_lv (accessed February 11, 2020).

[27] Handayani K, Krozer Y, Filatova T. From fossil fuels to renewables: an analysis of long-term scenarios considering technological learning. Energy Policy 2019;127:134–46. https://doi.org/10.1016/J.ENPOL.2018.11.045.

[28] Lin R, Man Y, Lee CKM, Ji P, Ren J. Sustainability prioritization framework of biorefinery: a novel multi-criteria decision-making model under uncertainty based on an improved interval goal programming method. J Clean Prod 2020;251:119729. https://doi.org/10.1016/j.jclepro.2019.119729.

[29] Gibson CA, Meyer JL, Poff NL, Hay LE, Georgakakos A. Flow regime alterations under changing climate in two river basins: implications for freshwater ecosystems. River Res Appl 2005;21:849–64. https://doi.org/10.1002/rra.855.

[30] Haarich S. Bioeconomy development in EU regions – mapping of EU Member States' / regions' Research and Innovation plans & Strategies for Smart Specialisation (RIS3) on Bioeconomy. European Commission; 2017. https://ec.europa.eu/research/bioeconomy/pdf/publications/bioeconomy_development_in_eu_regions.pdf.

[31] Bunn C, Läderach P, Ovalle Rivera O, Kirschke D. A bitter cup: climate change profile of global production of Arabica and Robusta coffee. Clim Change 2015;129:89–101. https://doi.org/10.1007/s10584-014-1306-x.

[32] Ladu L, Imbert E, Quitzow R, Morone P. The role of the policy mix in the transition toward a circular forest bioeconomy. For Policy Econ 2020;110:101937. https://doi.org/10.1016/j.forpol.2019.05.023.

[33] European Union. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). 2010 (accessed February 11, 2020), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32010L0075.

[34] Gaurav N, Sivasankari S, Kiran G, Ninawe A, Selvin J. Utilization of bioresources for sustainable biofuels: a Review. Renewable Sustainable Energy Rev 2017;73:205–14. https://doi.org/10.1016/J.RSER.2017.01.070.

[35] Engelmann F. Use of biotechnologies for the conservation of plant biodiversity. Vitr Cell Dev Biol - Plant 2011;47:5–16. https://doi.org/10.1007/s11627-010-9327-2.

[36] Zyoud SH, Fuchs-Hanusch D. A bibliometric-based survey on AHP and TOPSIS techniques. Expert Syst Appl 2017;78:158–81. https://doi.org/10.1016/j.eswa.2017.02.016.

[37] Shih H-S, Shyur H-J, Lee ES. An extension of TOPSIS for group decision making. Math Comput Model 2007;45:801–13. https://doi.org/10.1016/J.MCM.2006.03.023.

[38] Golembiewski B, Sick N, Bröring S. The emerging research landscape on bioeconomy: What has been done so far and what is essential from a technology and innovation management perspective? Innov Food Sci Emerg Technol 2015;29:308–17. https://doi.org/10.1016/j.ifset.2015.03.006.

[39] Ahn MJ. High technology in emerging markets Building biotechnology clusters. capabilities and competitiveness in India 2012. https://doi.org/10.1108/17574321211207953.

[40] Zihare L, Muizniece I, Spalvins K, Blumberga D. Analytical framework for commercialization of the innovation: case of thermal packaging material. Energy Procedia 2018;147:374–81. https://doi.org/10.1016/j.egypro.2018.07.106.

[41] Boehlje M, Bröring S. The increasing multifunctionality of agricultural raw materials: three dilemmas for innovation and adoption. Int Food Agribus Manag Rev 2011;14:1–16.

[42] OECD/Eurostat/European Union. Proposed guidelines for collecting and interpreting technological innovation data: Oslo manual. The measurement of scientific and technological activities. Paris: OECD Publishing; 1997. https://doi.org/10.1787/9789264192263-en.

[43] Boons F, Montalvo C, Quist J, Wagner M. Sustainable innovation, business models and economic performance: an overview. J Clean Prod 2013;45:1–8. https://doi.org/10.1016/j.jclepro.2012.08.013.

[44] OECD. R-D expenditure by sector of performance and type of R-D n.d. https://stats.oecd.org/Index.aspx?DataSetCode=RD_ACTIVITY (accessed February 11, 2020).

[45] Oltra V, Kemp R, De Vries FP. Patents as a measure for eco-innovation. Int J Environ Technol Manag 2010;13:130–48. https://doi.org/10.1504/IJETM.2010.034303.

[46] Eurostat. Sustainable development goal (SDG) indicators. 2020. https://ec.europa.eu/eurostat/web/sdi/indicators.

[47] UNDP. European Union dictionary of terms. 2004 (accessed February 11, 2020), http://termini.lza.lv/term.php?term=policy&lang=EN.

[48] Mees HLP, Dijk J, van Soest D, Driessen PPJ, van Rijswick MHFMW, Runhaar H. A method for the deliberate and deliberative selection of policy instrument mixes for climate change adaptation. Ecol Soc 2014:19. https://doi.org/10.5751/ES-06639-190258.

[49] Jacob K, Mangalagiu D, King P. Approach to assessment of policy effectiveness. Policies, goals, object. Environ. Gov. An assess. Their eff. Downloaded, vol. 21. Cambridge University Press; 2020. p. 273–81. https://www.researchgate.net/profile/Klaus_Jacob2/publication/331773232_Approach_to_Assessment_of_Policy_Effectiveness/links/5c8b7cf045851564fade7cd1/Approach-to-Assessment-of-Policy-Effectiveness.pdf.

[50] Dietz T, Börner J, Förster JJ, Von Braun J. Governance of the bioeconomy : a global comparative study of national bioeconomy strategies. 2018. https://doi.org/10.3390/su10093190.

[51] Ramos TB, Alves I, Subtil R, Joanaz de Melo J. Environmental performance policy indicators for the public sector: the case of the defence sector. J Environ Manage 2007;82:410–32. https://doi.org/10.1016/J.JENVMAN.2005.12.020.

[52] OECD. The Bioeconomy to 2030: designing a policy agenda. 2009.

[53] Friedrichs S, va Beuzekom B. Revised proposal for the revision of the statistical definitions of biotechnology and nanotechnology. . OECD 2018:1–22.

[54] Barragán-Ocaña A, Gómez-Viquez H, Merritt H, Oliver-Espinoza R. Promotion of technological development and determination of biotechnology trends in five selected Latin American countries: an analysis based on PCT patent applications. Electron J Biotechnol 2019;37:41–6. https://doi.org/10.1016/J.EJBT.2018.10.004.

[55] OECD. Key biotechnology indicators n.d. https://www.oecd.org/innovation/inno/keybiotechnologyindicators.htm (accessed February 13, 2020).

[56] UNESCO. How much does your country invest in R&D? n.d. http://uis.unesco.org/apps/visualisations/research-and-development-spending/ (accessed February 18, 2020).

[57] Uriona M, Maldonado M, Grobbelaar S, Uriona MM, Grobbelaar S. System dynamics modelling in the innovation systems literature. 15th globelics int conf. 2017. Conference:32, https://www.researchgate.net/publication/319545608_System_Dynamics_modelling_in_the_Innovation_Systems_literature.

[58] OECD. Environmental Policy, Technological Innovation and Patents. 2008. https://doi.org/10.1787/9789264046825-en.

[59] OECD. OECD Studies on Environmental Innovation n.d. https://doi.org/https://doi.org/10.1787/20743483.

[60] Ronzon T, Sanjuán AI. Friends or foes? A compatibility assessment of bioeconomy-related Sustainable Development Goals for European policy coherence. J Clean Prod 2020:254. https://doi.org/10.1016/j.jclepro.2019.119832.

[61] Green patents - OECD n.d. https://www.oecd.org/env/indicators-modelling-outlooks/green-patents.htm (accessed February 18, 2020).

Environmental and Climate Technologies
2022, vol. 26, no. 1, pp. 1158–1168
https://doi.org/10.2478/rtuect-2022-0087
https://content.sciendo.com

CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios

Gustavs VIKSNE[1], Ilze VAMŽA[2], Viktorija TERJANIKA[3*], Tereza BEZRUCKO[4],
Jelena PUBULE[5], Dagnija BLUMBERGA[6]

[1–6]*Riga Technical University, Institute of Energy Systems and Environment, Azenes iela 12/1, Riga, LV 1048, Latvia*

Abstract **– Woody logging residues produced by logging activities are currently an underutilised resource that is mainly burned for energy production or left in the forest to decay, thus releasing CO_2 into the atmosphere. This resource could be used to manufacture long-lasting products and store a significant amount of CO_2, promoting CO_2 valorisation in rural areas. In this study, potential use for logging residues is proposed – the production of low-density wood fibreboard insulation panels. The new material's potential properties, manufacturing method and combined heat and power (CHP) plant parameters were proposed. The potential climate benefits of the new product were analysed using various biogenic carbon accounting methods. As energy production for manufacturing can be a significant source of emissions, possible energy production scenarios were analysed for manufacturing the product. However, an economically and environmentally viable energy production scenario should be chosen. By conducting a multi-criteria analysis, three possible energy production scenarios were analysed – wood biomass CHP plant, a natural gas CHP plant and a standalone wood biomass combustion plant combined with Solar photo-voltaic (PV) panels. The scenarios were analysed in terms of technological, economic, and environmental performance to determine the best strategy in this case.**

Keywords **– CO_2 storage; energy production; logging residues; wood products.**

1. INTRODUCTION

Forestry practices produce large amounts of waste and residues from the harvestable yield. This can present significant management problems, as the discarded biomass can hurt the environment. Meanwhile, sustainable energy sources and raw material feedstock are required with increasing global population and rising demand for construction products and materials. Forestry waste and logging residues are under-utilized resources for energy and material production. To date, there has been little activity to utilise these resources in a 'low carbon' way. It is estimated that for every cubic meter of logged wood material removed, a cubic meter of wastes and residues (e.g., stumps, branches, greenery) is left in the forest. Currently, of all wood-derived biomass produced globally, 20 % can be accounted as primary production loss left in the woods to decay, which could instead be used as a feedstock for a variety of products, including the production of fuels, polymers and building materials and products [1].

Wood, like products made from it, has a significant advantage over other building materials – they are an essential source of CO_2 sequestration. It has been observed that there exists a direct correlation between the amount of CO_2 sequestered and the amount of wood-derived

---

[*] Corresponding author.
E-mail address: viktorija.terjanika@rtu.lv

biomass harvested to produce high-added value products – with increasing amounts of wood harvested or rising efficiency of timber used, the amount of carbon sequestration is also increased [2]. The overall decarbonisation solutions can be achieved if sustainable carbon cycles, including using Carbon Capture and Utilisation technologies, are implemented (see Fig. 1) [3]–[6].

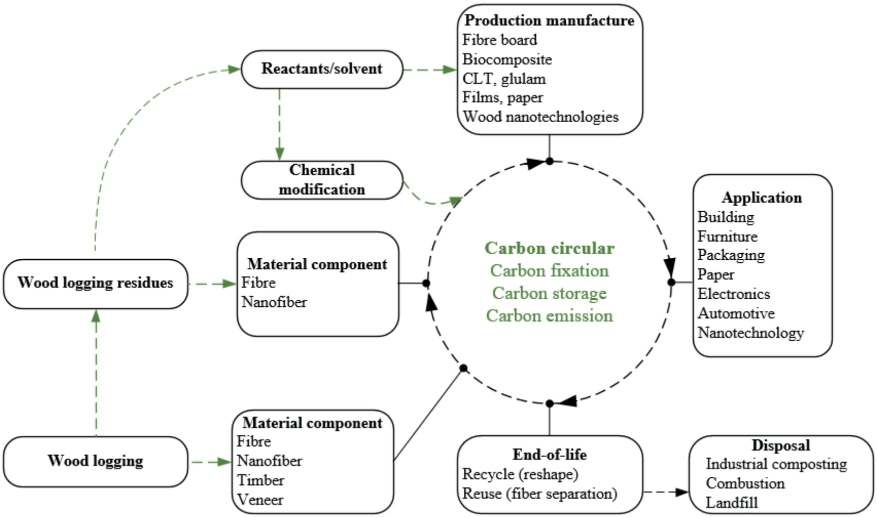


Fig 1. The sustainable carbon cycle of wood logging residues [1].

In the wood-based product sector, significant potential for CO_2 sequestration can be attributed to the production of wood-based panels and engineered wood products [7], [8]. In a 2017 study about carbon storage in wood products, the carbon sequestration potential of three different wood-based panels was reviewed – oriented strand board (OSB), particleboard (PB) and medium density fibreboard (MDF). According to the IPCC methodology, all three of these products are included in the national inventory reports as harvested wood products that store carbon, thus decreasing the overall CO_2 balance in the atmosphere. It was calculated that a cubic meter of PB and OSB sequester 720 kg of CO_2 each and that a cubic meter of MDF sequesters 820 kg of CO_2, considering the number of emissions from material production [9].

However, despite this advantage, producing such panels is quite an energy-intensive process. The Best Available Techniques (BAT) Reference Document to produce Wood-based Panels states that the average amount of thermal energy required to produce one cubic meter of the material is 0.955 MWh for PB, 0.4 MWh for OSB and 1.65 MWh for MDF panels. The average amount of electrical energy required to produce one cubic meter of the material is 0.155 MWh for PB, 0.115 MWh for OSB and 0.505 MWh for MDF panels [9], [10]. In turn, producing such thermal insulation materials as Ecowool and mineral wool requires 0.00416 MWh and 0.200 MWh of electricity per cubic meter of product. Although rigidboards are popular insulation material, they are mostly produced from expanded polystyrene or polyurethane foam – both are produced from fossil resources eliminating the opportunity to store CO_2 in such products. Nevertheless, rigid and flexiboards from wood fibres are becoming more popular. Production technology of such materials is similar to other wood fibre materials, in detail described further in this paper.

Although the CO_2 sequestration benefits of one cubic meter of rigid board insulation material will be lower than that of OSB, PB and MDF panels, considering the lower density of wood in the material, it will require less energy and raw materials to manufacture. The low-efficiency and uninsulated buildings in Latvia and many other countries are still tall, meaning that building insulation materials will remain a high-demand product for the foreseeable future. There is a wide range of insulation materials available today, each with its advantages and disadvantages. However, modern consumers care not only about the physical and mechanical properties of the material but also about the environmental impact. Manufacturing insulation materials could become one of the future opportunities of the forestry industry of Latvia. Generating by-products and residues in the harvesting and manufacturing processes is inevitable. Currently, forestry companies mainly use these by-products to produce energy or sell them to other companies. Exporting these by-products is still inefficient since they are now sold as low-added value products. As companies in the forestry sector move to increase the efficiency and productivity of their production, the utilisation of wastes and residues previously considered low value is becoming an increasingly attractive option. Using these by-products to manufacture thermal insulation is one of the potential solutions for increasing their value [11], [12].

Mitigation of CO_2 emissions has become a top question in the last decades. Therefore, understanding processes within rural CO_2 economy sectors, factors, interconnections and effects on the environment and nature quality and guidelines for future activities are crucial. Valorisation of CO_2, including direct capture and utilization, transformed CO_2 utilization or pre-processed CO_2 utilization, can positively affect the reduction of CO_2 emission and the development of rural areas [3]–[6]. The changes in wood waste treatment practices and production of the rigid board from wood logging residues can have a positive effect on mitigating CO_2 emissions, providing its storage in the products. This work aims to analyse the environmental impact of this insulating material. Using an underestimated resource to produce thermal insulation material can be viable from economic and technological perspective. The practice could be favourable from product demand, and raw material supply perspective by adding value to wood value-chain.

2. METHODS AND METHODOLOGY

For this study, the production of rigid board wood insulation material was chosen. The production methodology consists of steps like a description of the production process and needed feedstock calculation of the amount of CO_2 that can be stored in the final product. As for the energy sources for the rigid board production. Three different scenarios have been compared using the multicriteria analysis method. All steps of the methodology are seen in Fig. 2.

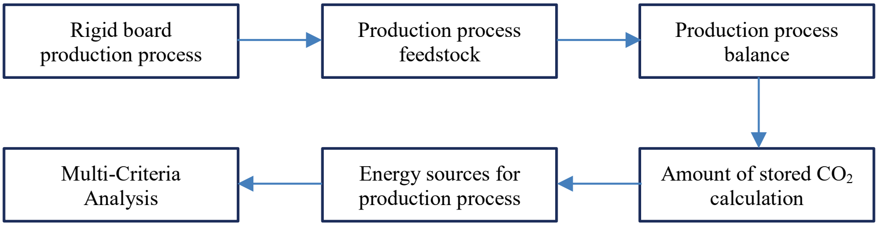


Fig. 2. Algorithm of the methodology.

The rigid board is produced similarly to other wood fibre boards e.g., MDF and LDF. The same dry process is used for refining the dried wood fibres derived from wood chips. After drying, the material goes through forming, pressing and profiling. A simplified manufacturing process of rigid board insulation panels is shown in Fig. 3. The refined and dried wood fibres are mixed with resin, formed into a mat, and then pressed and cured. Curing occurs by passing steam through the mat to heat it slightly. In comparison to general MDF production, the working pressure is lower and process does not require heated press. The slight temperature increase and the small amount of water cure the resin. The resin used for rigid board production is exclusively pMDI (polymeric methylene diphenyl diisocyanate). Rigid board is produced in various thicknesses ranging 18–244 mm and in densities ranging 100–220 kg/m^3. It is mainly used for insulation purposes, and the raw boards are passed through a profiler to produce a tongue-and-groove finish [10].

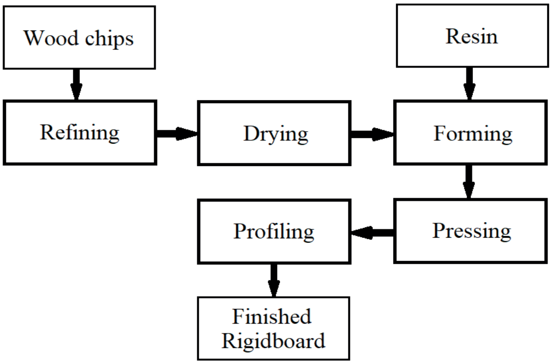


Fig. 3. Simplified rigidboard manufacturing process [10].

The primary feedstock for manufacturing the new rigidboard is logging residues, mainly from coniferous trees, the dominant tree group harvested in Latvia. The logging residues used for the production of chips will especially be branches, smaller logs and possibly stumps that are not used in conventional production. It is assumed that all needles and other greenery will fall off or be removed from the feedstock while in storage and manufacturing. To produce fibreboard insulation panels, wood fibres of strong and uniform quality must be obtained. Although MDF and other fibreboard producers traditionally use roundwood as a raw feedstock, novel methods of cleaning and sorting waste wood or production residues from other woodworking industries have enabled alternative sources of wood materials on dedicated production lines [10]. A 2013 study about the chase characteristics of wood chips produced from logging residues concluded that wood chips produced from logging residues have a moisture content of 50 % and are suitable for use in small and medium size boilers [13]. It is assumed that the wood chips obtained from logging residue feedstock will be of sufficient quality to produce fibreboard panels.

The material balance of the new fibreboard insulation panel is shown in Table 1. Material density is assumed maximum for rigid board production from the BAT Reference Document for Wood-based Panels [10]. Material balance was chosen based on fibreboard and insulation board data from the Forest Product Conversion Factors document [14], assuming an increased bark and decreased wood content. The weight content of bark, binders and fillers, moisture and wood in one cubic meter of the finished insulation panel were calculated based on the chosen material density and material balance.

For the new fibreboard insulation material manufacturing process, the standard dry manufacturing process was chosen from the BAT Reference Document for the Production of Wood-based Panels [10], modified for rigid board production (Fig. 2).

TABLE 1. FIBREBOARD INSULATION MATERIAL BALANCE

	Content, kg/m^3	**Balance, %**	**Source**
Density	220	100	[10]
Bark	6.6	3	[14]
Binders and fillers	11	5	[14]
Moisture	13.2	6	[14]
Wood	189.2	86	[14]

It is assumed that the new plant would produce 300 000 m^3 of fibreboard insulation material annually, based on average plant capacities in the industry [10]. To calculate the specific amounts of heat and electric energy needed to produce one cubic meter of the material, existing insulation material manufacturing plant data was used. Assuming that an existing plant has an electrical capacity of 5 MW and a heat capacity of 10 MW [15] and operates for 8000 hours annually, the manufacturing plant would require 0.13 MWh of electricity and 0.26 MWh of thermal energy to produce one cubic meter of fibreboard insulation material. Energy consumption for the most energy-intensive manufacturing processes is shown in Table 2. The drying of the wood fibres consumes the most energy, mainly in the form of thermal energy, as the fibres need to be dried from a moisture content nearing 100 % to 5 %. The dryers also need to be ventilated, using mechanical ventilators that consume electricity. The second most energy-intensive process is refining the fibres, which requires powerful motors that consume the most electricity. Thermal energy is also needed for refining to supply hot steam for cooking and washing wood chips. The pressing of the fibreboard mat requires thermal energy in the form of steam and electricity for the press rollers; however, for the production of rigid board insulation, the energy consumption is minimised, as the temperature required is relatively low. Lastly, all other processes requiring electricity are grouped, such as chipping, sawing and profiling [10].

TABLE 2. ENERGY CONSUMPTION FOR PRODUCTION

Manufacturing process	**Electricity, MWh/m^3**	**Thermal energy, MWh/m^3**
Drying	0.03	0.16
Refining	0.08	0.08
Pressing	0.01	0.02
Chipping, sawing, profiling	0.01	–
Total	0.13	0.26

To calculate the possible amount of CO_2 stored in the material, eight different standards for biogenic carbon accounting in products were reviewed and used. Many different technical standards for Life Cycle Analysis (LCA) with other methods and approaches for carbon accounting. Still, in this case, only standards relevant to forest-based building materials and biogenic carbon were used. The standards used can be grouped into those that deal only with building materials (ISO-21930, EN-15804, CEN/TR-16970, EN-16485) and those which cover all products (PAS-2050, ISO/TS-14067, PEF). The standards can also be distinguished by geographical coverage, as some are international standards (ISO-21930, PAS-2050, ISO/TS-14067), and others are specific to Europe (EN-15804, CEN/TR-16970, EN-16485, PEF) and have stronger links to government regulation [16]–[18]. As there currently exists no scientific consensus on which standard and method are the most appropriate for use, an average value derived from all standards was proposed.

The initial calculation for CO_2 stored in the material is assumed to be the same for all standards and is calculated [17]:

$$mCO_2 = \mathrm{m_{dry}}(\mathrm{timber}) \cdot \mathrm{C}_f \cdot \frac{m.mCO_2}{m.m_\mathrm{C}}, \tag{1}$$

where

mCO_2	mass of CO_2 sequestered, $kgCO_2$;
$m_{dry}(\mathrm{timber})$	dry weight of timber in the finished product, kg;
C_f	percentage of carbon in dry matter (for timber = 0.5);
$m.mCO_2$	molecular mass of CO_2 = 44 g/mol;
$m.m_C$	atomic mass of carbon = 12 g/mol.

By substituting the masses of carbon and CO_2, Eq. (1) becomes:

$$mCO_2 = m_{dry}(\mathrm{timber}) \cdot 0.5 \cdot \frac{44}{12} = m_{dry}(\mathrm{timber}) \cdot 1.833, \tag{2}$$

where mCO_2 is the mass of CO_2 sequestered in the finished product and $m_{dry}(\mathrm{timber})$ is the dry weight of timber in the finished product.

Only the CO_2 sequestered from the wood and bark content for the new product is calculated. The carbon content for bark is assumed to be the same as wood (50 %).

To maximise the CO_2 storage potential of the new fibreboard insulation material, the energy production sources for the manufacturing process need to be reviewed and analysed, as energy production is the single most significant source of emissions and can potentially offset the avoided CO_2 stored in the product material. Indeed, producing heat and power from the most environmentally friendly renewable sources would be the best way to minimise emissions from manufacturing. However, this may not always be the most technologically and economically viable option. Thus, energy production for product manufacturing needs to be assessed from an environmental point of view while considering the technological and economic aspects. Three energy production scenarios were evaluated based on the proposed manufacturing plant capacity of 5 MW electrical capacity and 10 MW heat capacity [16], current trends in the sector and possible future technologies. Technological, economic and environmental data for the three proposed scenarios are shown in Table 3. The capacities of the energy production plants were chosen according to the required minimum heat capacity of the manufacturing plant of 10 MW, as all the process heat needs to be produced on-site to meet heat and steam requirements. The electrical power of the energy production plant can be lower than the electrical demand of the manufacturing plant, as electricity can also be supplied from the grid. The first proposed scenario is to produce heat and power with a biomass combined heat and power (CHP) plant, which would use wood chips as fuel. The chosen CHP technology is a wood chip boiler combined with a steam turbine. The second proposed scenario is a natural gas CHP plant with a gas turbine technology well suited for industrial processes. The third proposed scenario is a wood biomass combustion plant (CP) producing only thermal energy, using wood chips as fuel, combined with Solar Photo-voltaic (PV) panels for electricity production.

To evaluate environmental impacts, five different emission values were considered for each scenario: NO_X (nitrogen oxides), CO (carbon monoxide), VOC (volatile organic compounds), PM (particulate matter) and CO_2 (carbon dioxide).

TABLE 3. TECHNOLOGICAL, ECONOMIC AND ENVIRONMENTAL PARAMETERS OF PROPOSED ENERGY PRODUCTION SCENARIOS

Parameter	**Wood biomass CHP**	**Natural gas CHP**	**Wood biomass CP + PV panels**	**Sources**
Electrical capacity, MWe	5	7.5	4	[19], [20], [21]
Thermal capacity, MWth	12	10.7	12	[19], [20]
Electrical efficiency, %	25	29.2	–	[20], [22]
Thermal efficiency, %	60	41.4	85	[20], [22]
Total efficiency, %	85	70.6	85	[20], [22]
Capital costs, EUR/kW[a]	3310	1510	965[b]	[23]
O&M costs, $\%_{CAPEX}$	2	2.5	2[b]	[23]
Fuel cost, EUR/MWh	25	81.2	25	[24], [25]
NO_X emissions, g/MWh[c]	29	27	9.1	[20], [26]
CO emissions, g/MWh[c]	8	31.5	2.5	[20], [26]
VOC emissions, g/MWh[c]	0	27	0	[20], [26]
PM emissions, g/MWh[c]	44	0	13.6	[20], [26]
CO_2 emissions, kg/MWh[d]	0	202	0	[27]

[a] Based on the electrical capacity for CHP and thermal capacity for CP

[b] Does not include the cost of PV panels

[c] Applies to electricity produced for CHP and thermal energy for CP

[d] Applies to both electrical and thermal energy produced

The capital costs of the standalone biomass combustion plant are assumed to be 30 % lower than the costs of the same thermal capacity CHP plant. Still, they are recalculated according to the thermal capacity of the combustion plant. Similarly, emission levels for the standalone biomass combustion plant are assumed to be the same as for the biomass CHP plant. Still, they are recalculated for a total thermal efficiency of 85 % instead of 60 % and apply only to the thermal energy produced.

The capital costs and O&M costs for the Solar PV panels are chosen according to the peak capacity of Solar PV panel installation. A Solar PV panel installation with an electrical capacity of 4 MWe is assumed to have a peak capacity of 5.4 MWp. The capital costs for an installation of this size are 510 EUR/kWp, and O&M costs 6.5 EUR/kWp [21].

A multicriteria analysis using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method compares the three energy production scenarios. Using the TOPSIS method, the proposed scenarios or alternatives are evaluated for the ideal possible solution. The alternative that is the closest to the ideal solution is considered to be the best scenario [28]. The criteria were selected according to the opinion of experts whose work profile is directly related to construction, sustainability and innovation, as well as the literature analysis. The criteria chosen for the analysis are shown in Table 4. The values of the criteria were calculated using data from Table 3 and applied to the manufacturing plant's selected electrical and thermal energy demand parameters, with the annual plant production capacity of 300 000 m^3 of fibreboard insulation material. The criteria values were calculated relative to one cubic meter of the finished product.

To perform the multicriteria analysis, the criteria weights need to be determined. The criteria weights were determined using the Analytical Hierarchy Process (AHP) method [28]. The criteria were first ranked in importance, prioritising economic and technological criteria, and then ranking the environmental criteria by their global warming potential. The weights of each criteria were then determined according to their rank, consequently comparing them to each other.

TABLE 4. CHOSEN CRITERIA FOR THE MULTICRITERIA ANALYSIS

Technological criteria	Economic criteria	Environmental criteria
Fuel energy content, GJ/m^3	Capital costs, EUR/m^3	NO_X emissions, g/m^3
	Fuel costs, EUR/m^3	CO emissions, g/m^3
	O&M costs, EUR/m^3	VOC emissions, g/m^3
	Bought/sold electricity, EUR/m^3	PM emissions, g/m^3
		CO_2 emissions, kg/m^3

With the obtained criteria weights, the results of the multicriteria analysis were calculated. The result is shown as a relative closeness coefficient to the ideal solution. The results can have a value ranging from 0 to 1, with the ideal solution being a value of 1. The closer the coefficient of a proposed alternative is to the maximum value of 1, the closer it is to the ideal solution.

3. RESULTS

The amount of stored biogenic CO_2 in the new fibreboard insulation material for the eight different accounting standards is shown in Table 5. The stored amount has been calculated for one cubic meter of the new fibreboard insulation material.

TABLE 5. STORED BIOGENIC CO_2 DEPENDING ON ACCOUNTING STANDARD

Technical standard	Stored CO_2, kg/m^3	Source
EN-15804 (2012)	359	[18]
ISO/DIS-21930 (2015)	251	[29]
EN-15804 (2012) +A1:2013	359	[18]
CEN/TR-16970 (2016)	359	[18]
EN-16485 (2014)	359	[18]
ISO/TS-14067 (2013)	90	[30]
PEF v2.2 (2016)	90	[30]
PAS-2050 (2011)	291	[31]

For standards EN-15804 (2012), EN-15804 (2012) +A1:2013, CEN/TR-16970 (2016) and EN-16485 (2014) the calculated amount of stored CO_2 is the same, as they are all based om the same standard of EN-15804 (2012) and assume that the amount is calculated with the formula shown in Eq. (2), with no further elaboration. ISO/TS-14067 (2013) and PEF v2.2 (2016) standards are based on the previous ISO-14040/44 standard for LCA, and do not differ in calculating the stored CO_2.

Standards-based on the EN-15804 standard offer the highest amount of CO_2 stored in one cubic meter of the product – 359 $kgCO_2/m^3$, while the lowest amount of CO_2 stored can be attributed to standards based on the previous ISO-14040/44 LCA standard – 90 $kgCO_2/m^3$. Considering all standards, an average value of 270 $kgCO_2/m^3$ stored can be assumed as the final result if no single carbon accounting method is chosen.

The calculated criteria values and weights for the multicriteria analysis of three different energy production scenarios are shown in Table 6.

TABLE 6. CRITERIA VALUES AND WEIGHTS

	Wood biomass CHP	**Natural Gas CHP**	**Wood biomass CP + PV panels**	**Criteria weight**
Fuel energy content, GJ/m^3	1.56	2.26	1.10	0.079
Capital costs, EUR/m^3	12.68	38.01	8.45	0.210
Fuel costs, EUR/m^3	55.17	37.75	47.80	0.288
O&M costs, EUR/m^3	1.10	0.94	0.89	0.152
Bought/sold electricity, EUR/m^3	3.84	−9.45	19.77	0.110
NO_X emissions, g/m^3	3.14	4.95	2.36	0.028
CO emissions, g/m^3	0.86	5.78	0.64	0.016
VOC emissions, g/m^3	0	4.95	0	0.020
PM emissions, g/m^3	4.7	0	3.5	0.040
CO_2 emissions, kg/m^3	0	90	0	0.057

The results of the multicriteria analysis of three different energy production scenarios are shown in Fig. 4.

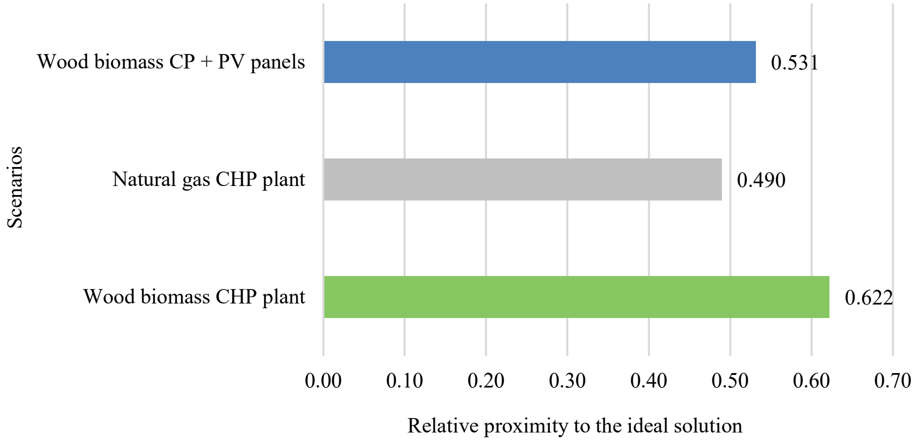


Fig. 4. Multicriteria analysis results.

The results of the multicriteria analysis show that the best scenario for energy production for the manufacturing plant is the wood biomass CHP plant (0.622). In second place are the wood biomass combustion plant and Solar PV panel scenario (0.531), barely beating out the natural gas CHP plant scenario (0.490). While currently, the multicriteria analysis shows that the fossil resource use scenario of natural gas is relatively close in valuation compared to the renewable resource use scenarios of wood biomass, it is evident that the evaluation of the natural gas CHP plant scenario could decrease in the future, as the world moves to use more renewable resources. Nevertheless, the natural gas CHP plant scenario still needs to be reviewed and considered, so it can be clearly shown that there are better renewable resource alternatives, which are the wood biomass CHP and combustion plants. To emphasise this further, more detailed studies should be carried out, which should consider both quantitative and qualitative data, including data and opinions of experts and companies in the field. Social and political aspects should also be reviewed in further studies. This, in turn, could significantly impact the evaluations of the different energy production scenarios, possibly increasing the assessment of the renewable energy source scenarios to mark them as the clear favourite over fossil resource use.

4. CONCLUSION

This study proposed a new possible wood fibreboard insulation material product made from a currently underutilised wood resource – logging residues. The material balance of the new product was presented, along with the manufacturing technology, manufacturing plant capacity and energy resource demands. The possible amount of CO_2 stored in the new product was calculated and reviewed using eight standards and their methods for biogenic carbon accounting.

The amount of stored CO_2 in the material varies considerably depending on the accounting method. Ideally, one of the eight possible standards should be chosen and prioritised. If no standard can be selected, an average value of stored CO_2 calculated from all eight standards could be proposed.

As the single largest source of emissions for the manufacturing of the new product is energy production, different energy production scenarios were analysed based on current trends in the industry. The scenarios were analysed regarding technological, economic, and environmental performance. Renewable energy scenarios should be considered a priority. However, fossil resource use was also considered, as the technical and financial benefits might outweigh the environmental disadvantages.

Three energy production scenarios were analysed: wood biomass combined heat and power (CHP) plant, a natural gas CHP plant and a standalone wood biomass combustion plant combined with solar photo-voltaic (PV) panels. The analysis results show the wood biomass CHP plant as the best scenario for energy production for the new manufacturing plant. However, the other scenarios are relatively close in evaluation.

ACKNOWLEDGEMENT

This research is funded by the Latvian Council of Science, project CO2 Deal: Effective Valorisation of CO_2 for Decarbonised Regional Development, project No. lzp-2020/1-0302.

REFERENCES

[1] Montanari C., Olsén P., Berglund L. A. Sustainable Wood Nanotechnologies for Wood Composites Processed by In-Situ Polymerization. *Front. Chem.* 2021:9:1–12. https://doi.org/10.3389/fchem.2021.682883

[2] Blumberga D., *et al*. Forest biomass – new products and technologies. Riga: Riga Technical University, Institute of Energy Systems and Environment, 2016.

[3] Terjanika V., Pubule J. Barriers and Driving Factors for Sustainable Development of CO_2 Valorisation. *Sustainability* 2022:14(9):5054. https://doi.org/10.3390/su14095054

[4] Terjanika V., *et al*. Analysis of CO_2 Valorisation Options for Regional Development. *Environmental and Climate Technologies* 2021:25(1):243–253. https://doi.org/10.2478/rtuect-2021-0017.

[5] Terjanika V., Blumberga D., Pubule J. Regional Development Scenarios and Model Boundaries for CCU in Energy Sector in Latvia. *Proceedings of the IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON* 2021. https://doi.org/10.1109/RTUCON53541.2021.9711727.

[6] Singh T., *et al*. Emerging technologies for the development of wood products towards extended carbon storage and CO_2 capture. *Carbon Capture Science & Technology* 2022:4:100057. https://doi.org/10.1016/j.ccst.2022.100057

[7] Xu X., *et al*. Bamboo construction materials: Carbon storage and potential to reduce associated CO_2 emissions. *Science of the Total Environment* 2022:814:152697. https://doi.org/10.1016/j.scitotenv.2021.152697

[8] Tripathi N., *et al*. Biomass waste utilisation in low-carbon products: harnessing a significant potential resource. *Npj Climate and Atmospheric Science* 2019:2:35. https://doi.org/10.1038/s41612-019-0093-5

[9] Kazulis V., *et al*. Carbon storage in wood products. *Energy Procedia* 2017:128:558–563. https://doi.org/10.1016/j.egypro.2017.09.009

[10] Raunkjaer Stubdrup K., *et al*. Best Available Techniques (BAT) Reference Document for the Production of Wood-based Panels. Seville: JRC, 2016.

[11] Veitmans K., Grinfelds U. Wood fibre insulation material. *Research for Rural Development* 2016:2:91–98.

[12] Vamza I., *et al*. Bioresource utilization index – A way to quantify and compare resource efficiency in production. *Journal of Cleaner Production* 2021:320:128791. https://doi.org/10.1016/j.jclepro.2021.128791

[13] Gruduls K., *et al*. 2013. Characteristics of wood chips from logging residues and quality influencing factors. *Research for Rural Development* 2013:2:49–54.

[14] FAO, ITTO, United Nations. Forest product conversion factors. Rome: FAO, 2020.

[15] Dieffenbacher GmbH. Fibre Insulation Board lines [Online]. [Accessed 20.04.2022]. Available: https://www.environmental-expert.com/products/fibre-insulation-board-lines-190613

[16] Tellnes L. G. F., *et al*. Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: A review study for construction materials based on forest products. *ISEF – Italian Society of Silviculture and Forest Ecology* 2017:10(5):815–823. https://doi.org/10.3832/ifor2386-010

[17] Pubule J., *et al*. Analysis of the environmental impact assessment of power energy projects in Latvia. *Management of Environmental Quality* 2012:23(2):190–203. https://doi.org/10.1108/14777831211204930.

[18] BRE Ltd. BRE Global Product Category Rules for Type III environmental product declaration of construction products to EN 15804:2012+A1:2013. Watford: BRE Group, 2014.

[19] Balkan Green Energy News. 5 MWe biomass cogeneration plant officially opened in the city of Slatina. 2019 [Online]. [Accessed 20.04.2022]. Available: https://balkangreenenergynews.com/5-mwe-biomass-cogeneration-plant-officially-opened-in-the-city-of-slatina/

[20] U.S. Department of Energy. Combined Heat and Power Technology Fact Sheet Series: Gas turbines. Washington: DoE, 2016.

[21] Danish Energy Agency. Technology Data for Energy Plants for Electricity and District Heating generation. Copenhagen: DEA, 2019.

[22] Abbas T., Issa M., Ilinca A. Biomass Cogeneration Technologies: A Review. *Journal of Sustainable Bioenergy Systems* 2020:10(1):1–15. https://doi.org/10.4236/jsbs.2020.101001

[23] Tsiropoulos I., Tarvydas D., Zucker A. Cost development of low carbon energy technologies. Luxembourg: Publication Office of European Union, 2018.

[24] Zalamane D. Pieaug koksnes šķeldas cena, apkure ar šķeldu ir 5 reizes lētāka nekā ar dabasgāzi (The price of wood chips is rising, heating with wood chips is 5 times cheaper than with natural gas.). 2022 [Online]. [Accessed 20.04.2022]. Available: https://lr1.lsm.lv/lv/raksts/eiro-fokusa/pieaug-koksnes-skeldas-cena-apkure-ar-skeldu-ir-5-reizes-letaka-.a155970/ (in Latvian)

[25] 'Latvijas gaze' brīdina par dabasgāzes biržas cenas trīskāršu pieaugumu aprīlī ('Latvian gas' warns of a threefold increase in natural gas exchange prices in April). 2022 [Online]. [Accessed 20.04.2022] Available: https://www.lsm.lv/raksts/zinas/ekonomika/latvijas-gaze-bridina-par-dabasgazes-birzas-cenas-triskarsu-pieaugumu-aprili.a446800/ (in Latvian)

[26] Darrow K., *et al*. Catalogue of CHP technologies. Boston: EPA, ICF International, 2017.

[27] Cabinet of Ministers. Methodology for calculating greenhouse gas emissions. *Latvijas Vestnesis* 2018:18.

[28] Ishizaka A., Nemery P. Multi-criteria Decision Analysis: Methods and Software. USA: Wiley, 2013.

[29] American Center for Life Cycle Assessment. ACLCA Guidance to Calculating Non-LCIA Inventory Metrics in Accordance with ISO 21930:2017. Washington: ACLCA, 2019.

[30] European Commission, Joint Research Centre, Institute for Environment and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook. General guide for Life Cycle Assessment. Detailed guidance. Luxembourg: Publications Office of the European Union, 2010.

[31] British Standards Institution. 2011. PAS 2050:2011: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.

System dynamics thinking to optimize carbon storage in the wood-based economy.

Ilze Vamza, Aleksandra Kasakovska, Armands Gravelsins, Dagnija Blumberga, Toms Prodanuks

Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV-1048, Latvia

Carbon has emerged as a crucial metric for monitoring the advancement of new technologies and the use of existing ones. Comparing different biomass types by mass is often unfeasible, given their distinct properties and potential applications. However, carbon can function as a normalization factor, enabling us to compare the potential impact of various biomass types on climate change. It has been established through political consensus that carbon emissions need to be reduced and that resources have been utilized in an irrational manner. Today we understand that the achievement of future economic growth can only be facilitated by the adoption of more efficient resource consumption practices. The bioeconomy has been overlapping with the circular economy, indicating that bio-based materials can be repurposed, recycled, and remain a part of the economy for a longer period. The objective of this paper is to assess the carbon flux within Latvia's wood-based economy, as well as the potential influence of introducing novel product integration into the wood-based value chain. Ministry of Environmental Protection and Regional Development of the Republic of Latvia have developed a “Strategy for Low-Carbon Development in Latvia until 2050” (OMA Strategy). The goal of the OMA strategy is to reduce Latvia's national economy's greenhouse gas (GHG) emissions by 80% compared to 1990 levels and achieve carbon neutrality by fully offsetting the remaining anthropogenic GHG emissions with increased carbon sequestration measures by 2050. The importance of accurate information is emphasized in the OMA Strategy in order for policymakers to help guide consumption decisions. Emphasizing that data sheets aren’t enough and the impact of resource use throughout the life cycle is needed. Over the past decade, numerous studies have been conducted to investigate possibilities for enhancing the efficient utilization of wood biomass[1]–[3]. In certain instances, life cycle assessments (LCAs) have been employed to illustrate potential environmental benefits[4], [5]. Although LCA is an excellent method for evaluating a product's environmental impact across multiple categories, this technique is static and only provides a limited snapshot of one product-specific part of the economy. To depict and project carbon fluxes in the whole economy, system dynamics modelling can be employed[6], [7]. In system dynamics modelling, the system's behaviour is depicted using stocks, flows, and feedback loops, the model itself is founded on a mathematical model that unites differential and integral calculus. Differential calculus is employed to model the rate of change of variables over time, while integral calculus is utilized to model the accumulation of variables over time. Stocks denote the amassed quantity of a variable over time, such as carbon in forest biomass[8], carbon in extracted timber, and carbon in manufactured products. By scrutinizing the carbon dynamics through system dynamics modelling, it becomes possible to evaluate the long-term impacts on carbon flux done by novel technology integration in the economy. During the research phase, multiple innovative wood-based products were integrated into the system dynamics model, illustrating the system dynamics modelling as a valuable tool for long-term carbon policy planning. In the future the developed system dynamics model could be further developed making it suitable for policy planning and resource allocation, favouring innovations with bigger carbon offset potential in the long run.

---

[1] E. Trømborg, T. Ranta, J. Schweinle, B. Solberg, G. Skjevrak, and D. G. Tiffany, “Economic sustainability for wood pellets production - Acomparative study between Finland, Germany, Norway, Sweden and the US,” *Biomass Bioenergy*, vol. 57, pp. 68–77, 2013, doi: 10.1016/j.biombioe.2013.01.030.

[2] B. Rivela, M. T. Moreira, and G. Feijoo, “Wood and Other Renewable Resources (Subject Editor : Jörg Schweinle) Life Cycle Inventory of Medium Density Fibreboard,” no. May, 2007, doi: 10.1065/lca2006.12.290.

[3] M. Alinejad *et al.*, “Lignin-Based Polyurethanes: Opportunities for Bio-Based Foams, Elastomers, Coatings and Adhesives,” *Polymers*, vol. 11, no. 7, p. 1202, 2019, doi: 10.3390/polym11071202.

[4] C. X. Chen, F. Pierobon, and I. Ganguly, “Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) produced in Western Washington: The role of logistics and wood species mix,” *Sustain. Switz.*, vol. 11, no. 5, 2019, doi: 10.3390/su11051278.

[5] R. Sathre and S. González-García, “Life cycle assessment (LCA) of wood-based building materials,” *Eco-Effic. Constr. Build. Mater. Life Cycle Assess. LCA Eco-Label. Case Stud.*, pp. 311–337, 2013, doi: 10.1533/9780857097729.2.311.

[6] R. Azis, A. Blumberga, and G. Bazbauers, “The role of forest biotechonomy industry in the macroeconomic development model of the national economy of Latvia: A system dynamics approach,” *Energy Procedia*, vol. 128, pp. 32–37, 2017, doi: 10.1016/j.egypro.2017.09.011.

[7] A. Blumberga, G. Bazbauers, P. I. Davidsen, D. Blumberga, A. Gravelsins, and T. Prodanuks, “System dynamics model of a biotechonomy,” *J. Clean. Prod.*, vol. 172, pp. 4018–4032, 2018, doi: 10.1016/j.jclepro.2017.03.132.

[8] J. Liepiņš, “Latvijas Kokaudžu Biomasas Un Oglekļa Uzkrājuma Novērtēšanas Metodes Forest Stand Biomass and Carbon Stock Estimates in Latvia,” 2020, [Online]. Available: www.silava.lv

Journal of Cleaner Production 320 (2021) 128791

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Bioresource utilization index – A way to quantify and compare resource efficiency in production

Ilze Vamza [*], Anna Kubule, Lauma Zihare, Karlis Valters, Dagnija Blumberga

Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV, 1048, Latvia

ARTICLE INFO

Handling editor; M.T. Moreira

Keywords:
Bioeconomy
Value-added
By-products
Enterprise
Bio-based value
Bioresource utilization index

ABSTRACT

The efficiency of renewable bioresources is becoming increasingly important. Along with the European Union's Green Deal and plans to decouple economic growth and prosperity from resource consumption, a new way of thinking must be adopted. Resource efficiency is no longer limited to electricity, heat or non-renewable resources. Previous studies have described the classification of the value of bioresources, which is usually formed as a pyramid depicting the values of the obtained products and the demand for their volume. The approach of the circular economy in the bioeconomy with its principles - reuse, recycle and regenerate - is also widely described in the scientific literature. Combining these two approaches, we created a bioresource utilization index, which would show the efficiency of bioresource use in an enterprise, along with the enterprise's contribution to the bioeconomy. In open interviews with representatives from multiple companies, we identified bioresource flows and mapped the factors that influence these flows in an enterprise. The proposed bioresource utilization index gives an insight into resource efficiency in a specific enterprise by quantifying the incoming raw material, the outgoing product, by-products, and waste. The elucidated factor nexus could be used as a map for easier detection of place for improvement.

1. Introduction

Although environmentally friendly consumer choice is an important driver toward sustainability, production companies have the biggest impact on resource efficiency. With the global efforts of disjointing economic growth and resource consumption it has come clear that resource efficiency is the most reasonable approach (Wood et al., 2018). Today bioeconomy is viewed not only as bioresource based economy, but bioeconomy also implies sustainable bioresource consumption by adding value to society.. Although, European Union directive 2008/98/EC (European Parliament and Council, 2008) defines that by-products of production are not classified as waste, in reality often by-products of production are treated as waste in enterprises and sent to waste streams or to low value streams like biogas or solid fuel production. Often small and medium-sized enterprises lack the skills, knowledge and capacity for scrutinous bioresource flow tracking, leading to inefficient by-product utilization and an increased enterprise's impact on the environment(Khalili et al., 2015). In this study we have evaluated various factors impacting by-product utilization or redirection to waste or low value product streams. All factors are interlinked in "bioresource nexus" and specific indicators can be used to describe these linkages (Fang and Chen, 2017). We propose a simple calculations' method to determine the by-product utilization efficiency describing the "Waste – bioresource" linkage. In conventional economics demand creates supply, in bioeconomy the demand for bioresource is often limited to technological capabilities and knowledge base of stakeholders. One resource can be used to produce products with various added value levels (Stegmann et al., 2020) and cascading is viewed as the most sustainable way of bioresource utilization. Cascading refers to bioresource utilization for higher added value product production where the created leftovers are redirected to production of another, usually lower value, product (Höglmeier et al., 2015). Cascading can be done in a production company by creating product driven biorefinery, but also it can be implemented by cooperation between enterprises and creation of industrial synergies(Ubando et al., 2020).

While technological approaches in food manufacturing have offered new markets and opportunities, they must also respond to the changing environmental concerns (Wu et al., 2010). Conservation of resources, recycling and reuse of materials, utilization of by-products and bioconversion of waste materials in addition to reduction of

---

[*] Corresponding author.
E-mail address: ilze.vamza@rtu.lv (I. Vamza).

https://doi.org/10.1016/j.jclepro.2021.128791
Received 26 March 2020; Received in revised form 19 August 2021; Accepted 21 August 2021

environmental loadings are contributing to sustainability (Afonso R.G. de Azevedo et al., 2019; Afonso Rangel Garcez de Azevedo et al., 2020; Kroyer, 1995). Waste is quite a broad term including wastewaters, agricultural residues as well as residues from slaughterhouses (Evans, 2013). Each of these types of waste burdens environment in different ways. Wastewaters might bring toxic pollutants within them causing stress to aquatic ecosystems and reducing biodiversity (Kuzmanović et al., 2016). In addition, elevated biological oxygen demand (BOD) can cause dead zones (Muñoz et al., 2006). Organic matter, like manure and agricultural residues, but mainly food waste are causing methane production due to anaerobic digestion taking place in landfills (Clemens and Cuhls, 2003). 18–68% of municipal solid waste can be organic (Ismail and Yusuff, 2013), moreover households with higher income level are producing more organic waste linking waste production with socio-economic factors (Bandara et al., 2007). Despite this link it is almost impossible to assess the waste to bioresource flow on national scale due to limitations of available data. Waste burden on the environment has led to development of various technologies to relieve the stress, the most noticeable being wastewater treatment, reducing BOD in natural waterbodies (Saad A, 2009) and landfill gas collection facilities (Trubaev et al., 2018). In many cases, reducing the burden on the environment has led to profit generation. For example, in Latvia, SIA “Getliņi Eko” – the biggest municipal solid waste management company has developed a profitable side business by collecting landfill gas. The use of heat energy and electricity generated from landfill gas combustion allowed them to successfully grow tomatoes (“Getliņi skaitļos | Getlini. Lv,” n.d.), in this case an energy intensive culture (Dorais, M., Schwarz, 2018) is produced entirely using organic waste. Nexus impacting this decision is further investigated in this study using other enterprises.

The abovementioned example is an apt representation of bioeconomy, showing that waste can serve as raw material for acquiring other products (Evans, 2013). According to the European Commission “bioeconomy […] encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy” (EUROPEAN COMMISSION, 2012). OECD in their definition concentrates on the benefits bioeconomy is providing to the society: “bioeconomy to be the aggregate set of economic operations in a society that use the latent value incumbent in biological products and processes to capture new growth and welfare benefits for citizens and nations” (OECD, 2006). Though expressed differently, one can argue that waste is the very embodiment of “latent value” as often waste is sent to polygon despite the possibilities for acquiring higher added value products, like reducing sugars(Jiang et al., 2014; Rosales et al., 2002; Van Wyk, 2011) that can further be used for ethanol or even enzyme production (Rosales et al., 2002). Perhaps the most obvious use of waste is biogas production (Zhang et al., 2014), this can be done straight in polygon of municipal waste (Trubaev et al., 2018) or in biogas plants (Rasi et al., 2007). So, despite absence of the term “waste” in the OECD definition, it is still considered a crucial bioresource and its value depends on the selected management approach.

The OECD project to design a bioeconomy policy agenda for governments is strongly concentrated on biotechnologies like gene engineering not once mentioning waste (OECD, 2006). The EU approach is more grounded and oriented on managing resources to their full potential – using every bit of raw material The OECD approach is oriented on using bioresource to their highest potential – creating products with the highest possible added value. When it comes to the actual situation, there are plenty of companies producing waste, but fewer companies are applying biotechnologies-gene editing or modified organisms. There are almost half a million manufacturing enterprises in the EU using bio-based raw materials, and accordingly producing waste (eurostat, 2015). The actual amount of produced waste is unknown.

In this study using bottom-up approach we have investigated the enterprise level of biomass utilization – enterprises using biomass to produce specific products. By using cleaner production principles an enterprise can not only reduce its negative environmental impact, but improve overall bioeconomy (Khalili et al., 2015). Hence, from research point of view it is important to elucidate factors affecting the resource flow and the indicators that would show comparable reflections of bioresource utilization in any enterprise dealing with organic resource flows. We have analyzed the nexus involving biomass, waste and bioproducts, as well as additional factors in this nexus. In addition, we are proposing an indicator for evaluation of by-product utilization in an enterprise.

Waste and bioresource can be one decision away from each other. So far industrial energy efficiency is studied as the main position to cut down CO_2 emissions and reduce the industry’s caused effect on climate change (Klemeš et al., 2012), “Our World in Data” reports that the electricity and heat production sector is the biggest CO_2 emitter (Ritchie and Roser, 2019). As our understanding of the natural carbon cycle and storage becomes broader, there are more policies aimed at preventing destruction of carbon rich biotopes (Janowiak et al., 2017; Sullivan et al., 2017) as well as stimulating circular economy. In 2015 the European Union adopted a whole Circular economy package including specific deliverables (European Commission, 2015). Nevertheless, there are ongoing discussions on how to evaluate and measure various factors impacting industrial energy efficiency (Cagno et al., 2013; Sorrell et al., 2011), but factors for bioeconomy have not been discussed enough. Industrial clusters have been drivers for development of various competences, there are clusters related to bioeconomy with respective key performance indicators (Axelsson et al., 2012), 78% of these indicators are economical in nature.

In line with bioeconomy, technology as a term covers a vast field – from mechanical technologies to biotechnologies like gene engineering. As bioeconomy is based on bioresources – increasing bioresource productivity means larger capital circulation in this field. In earlier stages of industrial development, increase of bioresource amount in economy was achieved by simply expanding land used for bioresource cultivation. With growing threats of climate change and decreasing area of wildlife habitats (Powers and Jetz, 2019), it has become clear that expansion is not an option anymore and other ways for acquiring greater amount of biomass needs to be found. Today it can be done by using biotechnology tools and techniques. Hence, there has been a great boost to bioeconomy from the field of life sciences. Possibilities for boosting lipid production in plants (Vanhercke et al., 2014) and microorganisms (Tai and Stephanopoulos, 2013) have been studied widely for further applications to biodiesel production, in addition, manipulations to achieve better lignin biomass for 2nd generation biodiesel production have been studied (Vanholme et al., 2012). EU is recognising the importance of technologies in life science. According to Deloitte research, EU has the biggest cited publication amount in the field of biotechnology in comparison to the United States and the major Asian countries (Deloitte, 2014). In addition, considerable amount of financial resources are dedicated to EU Food, Agriculture, Fisheries and Biotechnology programme Activity 2.3: “Life sciences, biotechnology and biochemistry for sustainable non-food products and processes” (Levidow et al., 2012).

When it comes to manufacturing companies, technologies usually are a crucial part of production. Applying effective technologies in the production process can reduce the amount of generated waste or simply increase the production yield. As food production companies are dealing with a considerable amount of organic matter, this could be a field with potential for bioeconomy development.

Nevertheless, there are multiple factors impacting bioeconomy adoption. In this study we elucidate factors affecting this segment of circular bioeconomy development and propose an indicator to characterize the utilization of bioresource’s potential. As a case study we analyze two producers using the same type of biological raw material but creating different products. Varying waste types allowed us to calculate various scenarios for by-product utilization. Although the EU have clearly defined the difference dividing waste from by-product, after interviewing managers in three enterprises, we concluded that terms by-product and waste are used interchangeably. Fig. 1 represents a scheme adopted from Eurostat Manual on waste statistics (eurostat, 2013), with our modification to show the dissolved border between by-products and waste.

To evaluate reasons behind decision making leading to various choices, multiple interviews were conducted with production managers as well as representatives from companies dealing with produced waste. In real-life situations by-products and primary waste are not so clearly divided, as companies often discard by-products as waste, in some cases by-products are used, but not to their full potential.

In bioeconomy resource value can be estimated from the bio-based value pyramid representing five ways for biomass use: (1) Pharmaceuticals and Fine chemicals (PFCs); (2) Food and Feed; (3) Bioplastics and Polymers; (4) Bulk chemicals, and (5) Energy, Heat and Fuels in descending order of value (Stegmann et al., 2020). Although biogas fits in the fifth category as a source of energy, we argue that the fourth category would be better fit for biogas. As in the burning process organic compounds are oxidised to carbon dioxide (a well-known greenhouse gas) leaving only ash, after biogas production the leftover digestate can be used to improve the nutrient content in soil (Pubule et al., 2015). This classification is used by Stegmann et al., representing energy recovery and composting as part of circular economy, partially feeding back resources into sustainable biomass sourcing (Stegmann et al., 2020). In EU, biogas for the heat production [ktoe] has increased six times in the last 15 years and solid biomas use has increased only by 20%. Trends show that raw biomass proportion for heat and energy production has been reduced (Banja et al., 2019). In this study we differentiate solid biomass fuels from biofuels like bioethanol and biobuthanol that both are considered as bulk chemicals.

The top of the bio-based value pyramid is occupied by PFCs as usually these products have higher economic value due to their importance and small concentrations in the raw biomass. Depending on the extraction method of PFCs' their by-products could be further used (Kumar et al., 2017). . One example of bioresource use in PFCs is potatoes – a product that is typically used for food and feed, but can also be processed into PFCs such as ascorbic acid and phenolic compounds (Priedniece et al., 2017; Singh and Saldaña, 2011). More importantly, some PFCs can be extracted from by-products, for example ascorbic acid and some phenolic compounds can be extracted from potato peels increasing the added value of the by-product from food industry.

The goal of this study was to elucidate factors affecting the production by-product flow from waste to bioresource as well as to develop an index for bioresource utilization efficiency in an enterprise. In line with this study we conducted a deeper investigation of by-product flows in two enterprises using the same raw material. Investigating specific by-products and identifying alternative applications for those products gave us the opportunity to evaluate various scenarios of bioresource by-product utilization. In addition, the conducted interviews allowed us to elucidate factors and their interlinkages impacting the development of bioeconomy.

2. Methods

2.1. Interviews

To evaluate the link between waste and bioresource, as well as various factors impacting the proposed indicator of this link, qualitative interviews with managers from involved enterprises were conducted. The interview format was semi-structured, as this type of interview lets the interviewer to ask open questions and gives the possibility to go deeper into various aspects of the revealed facts (Jamshed, 2014). Semi-structured interviews have been already used in bioeconomy research (D'Amato et al., 2020; Gârdan et al., 2018). During the interviews, the overall attitude and motivation regarding bioresource, by-product and waste utilization was determined. Efficiency of by-product utilization was determined by collecting data from enterprises, including real consumption of raw materials as well as the produced bio-waste and by-products. Technical directors of three enterprises using the same bioresource as raw material were interviewed. Due to sensitive information interviewees were providing, interviews were not recorded, instead the interviewer produced comprehensive notes on the acquired information.

2.2. Nexus building

Bioresource nexus was created by analyzing the information acquired in the interviews and validated with literature analysis and by-product data from the enterprises in question. Qualitative and quantitative data were collected from interviews (see section 2.1.). The overall methodology for building of bioresource nexus is shown in Fig. 2.

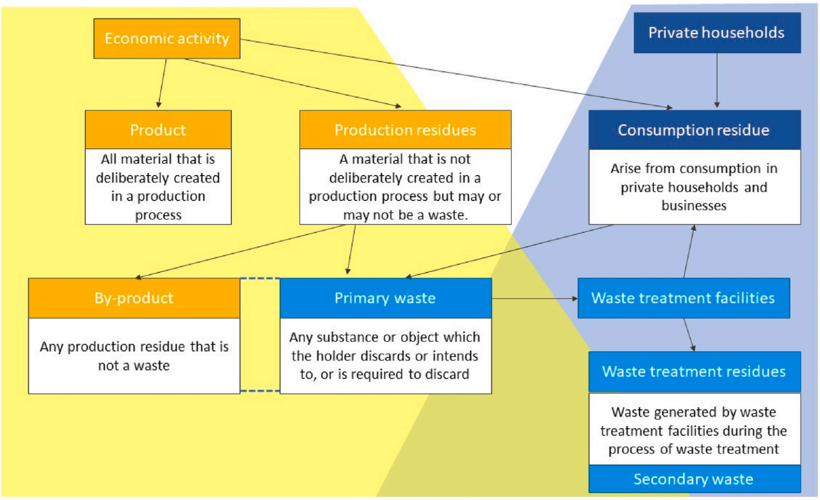


Fig. 1. Waste generation scheme (eurostat, 2013). Original source depicts waste generation streams represented by arrows. Scheme modifications include by-product-to-primary waste flow represented by dashed line, showing the fuzzy division of both. Flow is impacted by factors discussed further in this work. As in the original source, the economic activity excludes waste treatment facilities emphasizing the importance of keeping bioresource in the production sector represented by "Economic activity".

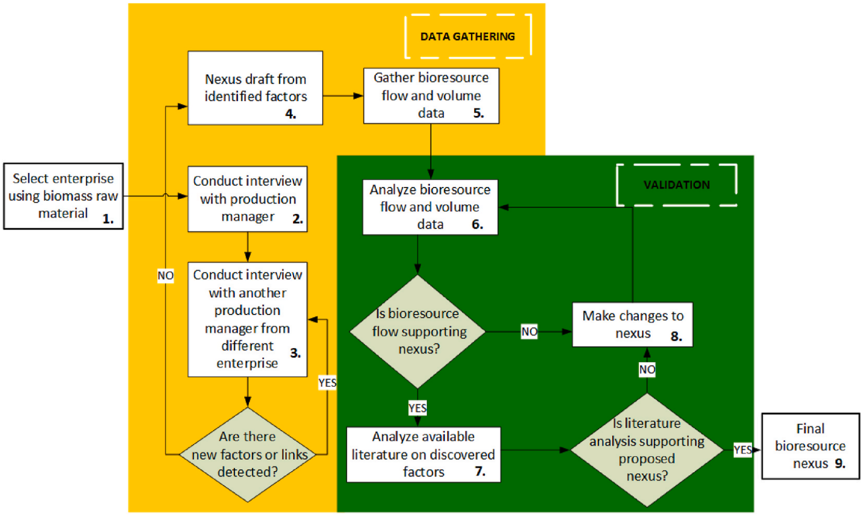


Fig. 2. Bottom-up approach for bioresource nexus building.

Following the algorithm, two interviews were conducted, then as the second interview elucidated new factors, a third interview was conducted. The created algorithm demands to continue interviews until there are no new factors. In this specific case study, three interviews were sufficient. Steps two and three represent the minimum interviews necessary to gain an overall idea of the factors impacting the specific subject. As during second interview some new factors were identified, third interview was conducted to see if more factors would be identified. If there are no new factors the algorithm continues. The research was divided in smaller modules for a structured approach. While picking enterprises for this research, various production companies using the same type of biomass as a raw material were considered. An important factor in choosing the enterprises was their willingness to participate. The overall methodology algorithm is depicted in Fig. 2. The study consisted of two parts: (1) data gathering and nexus building, as well as (2) nexus validation. Bioresource flow analysis was conducted, by analyzing bioresource and waste data acquired from the enterprises. After additional literature analysis nexus was completed.

The methodology depicted in Fig. 2 can be applied for evaluation and building of various nexus using a bottom-up approach. In this study the bottom-up approach allows to analyze factors for organic by-product flow back into bioeconomy through bioresource. Nexus provides information on factors impacting the system, but additional by-product data analysis provided information on effectiveness of this by-product – bioresource flow.

2.3. *Alternative scenario analysis*

Bioresource flow in an enterprise was evaluated by comparison with waste management hierarchy (Demirbas, 2011) and bio-based value pyramid (Stegmann et al., 2020) shown in Fig. 3 with the chosen coefficients from 0 representing no value and 1 representing the highest possible added-value to bio-based material. The bio-based value is assigned to the raw material or the by-product when it is used for the corresponding application in the bio-based pyramid.

For evaluation of bioresource utilization in the enterprise, alternative scenarios for two of the enterprises in study were designed. Only two out of three enterprises gave the consent for further data analysis,

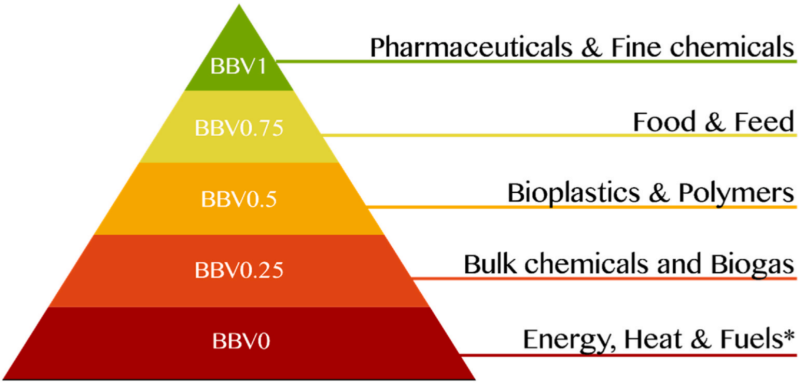


Fig. 3. Bio-based value pyramid. Five bioresource utilization options by categories and assigned coefficients corresponding to each group of bioresources (Stegmann et al., 2020) BBV – bio-based value and the corresponding coefficient, 1 representing the greatest value and 0 representing no value from the point of bioeconomy.

nevertheless due to the small number of enterprises in Latvia none of the companies gave the consent to reveal their company name. Hence, we could proceed with only two enterprises with specifics like enterprise name and specifics on production concealed. Each level in the bio-based value pyramid (Fig. 3.) was given a corresponding coefficient representing the value for bioresource utilization – coefficient of 1 was attributed to PFCs, coefficient of 0.75 to Food and Feed, 0.5 to Bioplastics and Polymers, 0.25 to Bulk chemicals and Biogas, but Energy, Heat and Fuels were assigned the value of 0. The bioresource utilization index provides insight into production efficiency regardless of the product type, hence no value is assigned to the product. The calculations were conducted with various generated by-product utilization options and attributing corresponding coefficients from the previously described bio-based value pyramid.

$$B_{u_{ind.}} = (P + BP_1 \times c1 + BP_2 \times c2 + BP_3 \times c3 + BP_4 \times c4 + BP_5 \times c5)/RM$$

$B_{uind.}$ – Bioresource utilization index; P – product [kg of dry weight]; BP_n – by-product [kg of dry weight]; c_n – coefficient assigned to bio-based value pyramid; RM – used raw material [kg of dry weight].

The calculations were made using dry weight. If there were no available data on the actual dry weight of the by-product, estimations were made by using values found in literature. To assign a specific bio-based value for each by-product, at first the data for by-product amounts were collected and the dry weight was determined by literature analysis. The main categories analyzed were peels, damaged raw material, raw material that does not meet production standards, products that do not meet the market standards, other production leftovers, dissolved sugars, and undissolved starch. As company managers disagreed to more detailed information disclosure, the raw material, product or production technology could not be described in this work.

3. Results and discussion

In this study, nexus of factors impacting waste to bioresource was built. In addition to the main bioeconomy impacting factors described by Zihare et al., (2020) (Zihare et al., 2020), a few new factors were detected using the bottom-up approach. Factors like Behaviour and Financial resources were elucidated only when bottom-up approach was used.

It is important to notice that a large proportion of biomass defined as waste is in fact by-products according to the EU definition, but in some cases, production managers are referring to by-products as waste. The by-product group might be referred to as waste only due to lack of technology – by-products might spoil due to inappropriate storage or they can be hard to retrieve, like sugars from waste after blanching. Nevertheless, behavior and knowledge strongly impact the by-product-to-waste flow. When enterprise's management does not want to deal with finding new applications or buyers of the by-products, the biomass is simply directed to waste stream. In addition, companies worry about disclaiming their practices publicly, this can slow down the progress and opportunities for innovation as there is no exchange of information amongst enterprises sticking to closed innovation.

According to Demirbas (2011), waste reduction is the most preferred waste management option (Demirbas, 2011), according to elucidated nexus, waste can negatively impact company's financial resources and positively impact available bioresource amount. In case of blanched, peeled, and ready to use vegetable production, more efficient peeling technologies might be implemented to reduce the total amount of peels generated. In many cases by-products properly treated would not become waste, hence proper utilization of them would reduce the relative waste amount in proportion to the product.

After analyzing links and respective products, we came to conclusion that indicators for these links might be economic or technologic in nature. An indicator can characterize the economic value of byproducts, energy efficiency of technology or efficiency of the production itself.

It is a frequent practice to motivate companies for research and development by providing incentives specifically for technologies reducing carbon emissions (Uyarra et al., 2016), alternatively fines are used as a tool to prevent companies from pollution.

In every enterprise there are already existing technologies affecting the overall production process. After interviews we concluded that the existing technologies are impacting the production efficiency, which is in turn affecting the amount of generated waste. As waste increases the risk of pollution (Van Wyk, 2011) and climate change due to methane production in landfills (Davidsson et al., 2007; Trubaev et al., 2018), these climate threats are leading to policy change from local authorities. Enforced policy might provide incentives for developing cleaner production, alternatively taxes might be enforced on the disposed waste (Dvulit et al., 2019). As these policies cause pressure on an enterprise's financial resources, enterprises are forced to invest in R&D to search for solutions that might reduce the amount of waste. This loop represents the decision making process, before implementing new technologies, their cost-benefit analysis is conducted. If a new technology costs more when introduced, causing new pressure on the financial resources, hence R&D phase continues starting the loop again. Two new technologies might be considered – one that reduces waste during production and another that allows to extract bioresources from waste. Both approaches can lead to reduction of waste. In terms of waste management – reduction is the most preferred option (Demirbas, 2011), but using waste to produce PFCs can be considered as a good option as well. As mentioned above – diverging by-product flows to production of another product group from the top of the bio-based value pyramid can lead to value cascading, hence prolong resource circulation in bioeconomy.

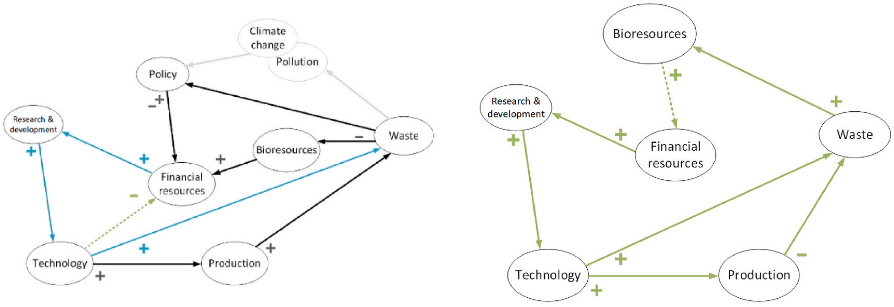
In the discussed examples of path B, the loop finishes with a positive feedback on financial resources. In this specific case study, two instances when R&D lead to path A and three leading to path B were detected. One instance from path A led to path B in a previously described manner (see Fig. 4).

The overall enterprise nexus was developed including additional factors. After analyzing information acquired in the interviews, we concluded that knowledge and behavior are crucial factors in this nexus. Although, companies are not always aware of this, knowledge and behavior in a company can lead to implementation of a new, more environmentally friendly, technology (Del Brío and Junquera, 2003). It is clear how financial resources in a company play a large role in environmental innovations (Uyarra et al., 2016), but behavior and company culture is often left out of the picture.

As can be viewed in Fig. 5, local policies, production as well as knowledge and decision makers in a company are impacting the link between waste and bioresources. The gray area in Fig. 5 represents factors that are out of enterprise scope, although climate change and pollution might have an impact on enterprise functionality – there could be a pressure to relocate the production site due to lack of resources (Gasbarro et al., 2016; Linnenluecke et al., 2011). These two factors have a long-term impact, hence policies imposing fiscal measures have a more noticeable and rapid impact. For bioeconomy evaluation a central core consisting of bioresources-production-waste leading back to bioresources was detected. In this case waste represents lost or disposed resources, by-products used efficiently lead back to bioresource and are used in the production of another product.

To evaluate company's added value to circular bioeconomy, a bioresource utilization index was calculated using the approach described in Methods section. For this analysis two enterprises from the three interviewed before were chosen. An overall bioresource utilization state in an enterprise is estimated – a bioresource utilization index closer to 1 shows better by-product (bioresource) utilization. The constructed scenarios with corresponding biomass utilization indexes are represented in Table 1.

Two studied cases and four alternative scenarios for each case. RM – raw material, BBV 1 to 0 represents bio-based value pyramid levels starting from the top. Percentages in the table represent the amounts of



(A) (B)

Fig. 4. Flows between various bioeconomy factors detected in the interviews. Path (A) on the left side is continuing and leading to path (B) on the right side of the illustration. Arrows illustrate the direction one factor is impacting the others. Dashed line represents a crucial place in enterprise for the change. Whether Technology impacts Financial resources in a positive or negative way and weather enough bioresources are retrieved from waste in order to be beneficial for Financial resources is shown with (+) – increases next factor (−) – decreases it.

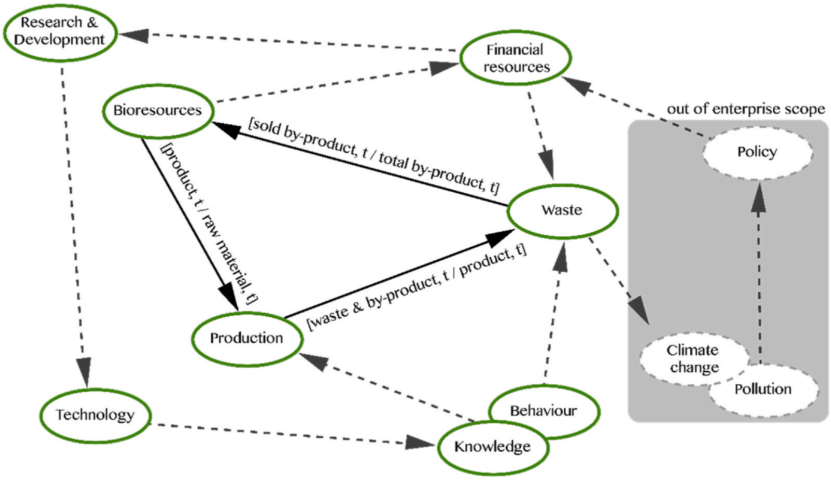


Fig. 5. The proposed nexus of bioresources flow in an enterprise showing all the relevant factors. Green – primary factors, gray dashed – secondary factors; arrows represent direction of what factors impact each other. Central arrows represent the bioresource-production-waste-bioresource factor cluster used for the proposed bioresource utilization index calculations.

Table 1
Alternative scenario representation by biomass allocation. By-product flows by dry weight. RM – raw material; BBV – bio-based value represents the added value to biomass. Added value is represented with corresponding coefficient 1-high value, 0.75- Moderately high value, 0.5-medium value, 0.25-low value and 0-no value. Table represents the allocation of biomass by dry weight in constructed scenarios (I, III to VIII and X) and detected scenarios (II$_{case}$ and IX$_{case}$) for Enterprise No. 1 and Enterprise No. 2.

Scenario		RM	BBV1	BBV0.75	BBV0.5	BBV0.25	BBV0	Waste	Product
Enterprise No. 1	I	100%	0%	0%	0%	0%	0%	34%	66%
	II$_{case}$	100%	0%	0%	0%	34%	0%	0%	66%
	III	100%	0%	5%	0%	12%	0%	17%	66%
	IV	100%	0%	0%	0%	12%	7%	16%	66%
	V	100%	9%	6%	7%	12%	0%	0%	66%
Enterprise No. 2	VI	100%	0%	0%	0%	0%	8%	32%	59%
	VII	100%	0%	0%	0%	0%	0%	41%	59%
	VIII	100%	0%	0%	0%	37%	0%	3%	59%
	IX$_{case}$	100%	0%	5%	0%	32%	0%	3%	59%
	X	100%	9%	32%	0%	0%	0%	0%	59%

dry biomass sent to a specific product, waste, or by-product stream. Scenarios represent by-product use for pharmaceuticals and fine chemicals BBV1, food and feed BBV0.75, bioplastics and polymers BBV0.5, bulk chemicals and biogas BBV0.25, energy and heat BBV0. Waste is dry mass of wasted organic by-products and waste as rotten raw material. BU_{ind} – the calculated bioresource utilization index. Actual situations in respective two enterprises: II $_{base}$ – the base scenario for the first enterprise, IX $_{base}$ - the base scenario for the second enterprise.

Each company is represented by five scenarios, I to V and VI to X for each company, respectively, with base scenarios II for the first and IX for the second. For each enterprise in the worst-case scenario II and VII it is assumed that damaged raw material and all generated by-products, products that do not meet market standards, and other production leftovers are sent to waste and sugars along with starches that are not retrieved from water or used in any other way. By calculating the worst-case scenario, it is possible to evaluate the general efficiency of production process, as the index shows how much product can be acquired from a certain amount of raw material. There might be two explanations if the index is exceptionally low; in this case – first, the raw material contains a small concentration of the product or second, the technology is inefficient and there could potentially be a place for improvement. Base scenario for both production companies included storage of raw material, in this step material could be lost as it might get damaged due to incorrect storage conditions or simply prolonged storage. The enterprise represented in cases VI to X does not store the raw material as long as the first enterprise. The damaged raw material is stored as waste and sent to a biogas production plant along with other raw material that has been sorted out due to being unfit for production needs.

Scenarios I to V included peeling where up to 5% of raw material is excluded from further production. As scenario II (actual situation) shows – at this point peelings are stored as waste and transferred to biogas production plant. In scenarios II to V and VIII to IX still at least 12% of the raw material or by-product is sent to biogas production, this is the amount that is damaged during storage or sorted out for not meeting the safety standards for being used as food. In scenarios III, V, IX and X a significant amount of created by-products is used as food and feed. Usually, the sorting process is meant for sorting out damaged raw materials or products that are not meeting the market standards. However, in many cases the raw material or product is in good condition, it is simply misshapen, or size does not match the production line requirements, hence it could still be used as food or feed. In scenarios III and V peels are used for animal feed, in addition, in scenario V a small portion of the raw material was used as a food product, because the amount of raw material was too small for production line. Although it is quite easy to redirect such by-products as peels and misshapen vegetables to livestock feed, it might be more feasible to sell these by-products to food producers. The well-known Yurosek case proves that even misshapen vegetables can be used to produce higher added value foods - in 1986 Yourosek as an entrepreneur decided to try out producing “baby-carrots” from overgrown and misshapen carrots by cutting and physically shaping them into bite-size shapes (Sidhu, 2010), hence increasing the economic value of this bioresource from animal feed to food. The smaller size of the raw material was in higher demand from restaurants. Scenarios IV and VI both show that a portion of by-products is being used to create solid fuels. as energy recovery is considered downcycling of a material (Passarelli, 2019), this is the least preferable utilization option of a material. This idea is supported by the proposed bioresource utilization index, as scenarios IV and VI generate one of the lowest bioresource utilization index, lower being only scenarios where all generated side streams are redirected to waste. A portion of the analyzed material is leached into water by blanching in the form of simple sugars or as starch during washing and cutting or grinding process. Best case scenarios V and X explore the option for these carbohydrates to be used for fine chemical production by the mixotrophic cultivation of algae(Mitra et al., 2012) (Heredia-Arroyo et al., 2011) or other microorganisms. In addition, scenario V explores the option of leached starch to be used for poly-lactic acid production as in this enterprise a considerable amount of starch was lost as suspended solids in wastewater. As mentioned before, BBW0.25 is assigned to by-products used for biogas production. This is the most popular choice in enterprises dealing with organic by-products. The lowest bioresource index represents scenario where all by-products are wasted, in this case the index is dependent only on product/raw material ratio. As can be seen in Fig. 5., the highest bioresource utilization index calculated was 0.88. The highest score in bioresource utilization index is affected by best available techniques as well as the demand from PFC industry as in most cases status quo in this industry is to purchase raw materials with the highest purity. As more environmentally sustainable and safe options are becoming more popular in the PFC industry, more options for wood biomass utilization are surfacing in the market. Wood used to be on the bottom of the bio-based value pyramid, but today there are plenty of fine chemicals being extracted from it, such as terpenes (Tanzi et al., 2012), lignin (Alinejad et al., 2019) and betulin (Dehelean et al., 2012). It is expected that opportunities for vegetable and fruit peels and other food production by-product utilization will grow, as more research trying to find possible uses for them is taking place (Rafiq et al., 2018; Singh and Saldaña, 2011).

As mentioned before, production companies often choose to direct by-product to biogas production (in this study represented by BBW 0.25 or 4th level from the top), although this study shows that often by-products rich in reducing sugars might be used for PFCs production (Escaramboni et al., 2018; Priedniece et al., 2017), if veterinarian standards are met, by-product can be used as feed for livestock.

The overall comparison between scenarios can be seen in Fig. 6. In food processing industry, sugars and soluble proteins are lost during blanching (SELMAN, PRICE, & ABDUL-REZZAK, 1983), retrieving these compounds from wastewaters requires too much energy for this process to be feasible. Organic compounds like starch can be extracted from production wastewaters (Da et al., 2008). In addition, after starch extraction from the raw material, juice is produced as by-product, it is a colloid substance that can be used for soil fertilization or proteins can be extracted and used as feed (Priedniece et al., 2017).

Hence in these calculations, the weight lost during blanching is considered as lost raw material. For determination of bioresource potential use in the enterprise, all biomass materials should be considered as bioresource.

4. Conclusions

The elucidated nexus can help to identify potential factors for enterprise development towards bioeconomy and effective bioresource utilization. Deeper exploration of the Core of nexus (bioresource-product-waste) led to mathematical descriptions of linkages within this core. The proposed bioresource utilization index puts the state of by-product management in perspective. This indicator could be used to gain the first insight into by-product management in relation to best available techniques. Production of different products will give differing maximal real index values. If the company is producing frozen produce, it is expected for them to have a different amount and type of by-products than a company producing baby food Because quality standards as well as volumes and types of by-products differ. The work on the bioresource utilization index could be continued by investigating the maximal real bioresource utilization index for production of specific products, for example, wood fiberboard. The calculated maximal index would be useful for all fiberboard producers who would be interested in their by-product management efficiency and overall production compliance with bioeconomy. The index is not restricted to wood biomass; it could be calculated for any type of biomass or biomass combinations. Another factor affecting the biomass utilization index is product to raw material ratio, this ratio can be increased by improving production technologies. For example, reduction of vegetable peel thickness can decrease the amount of wasted product, instead of directing the material to by-

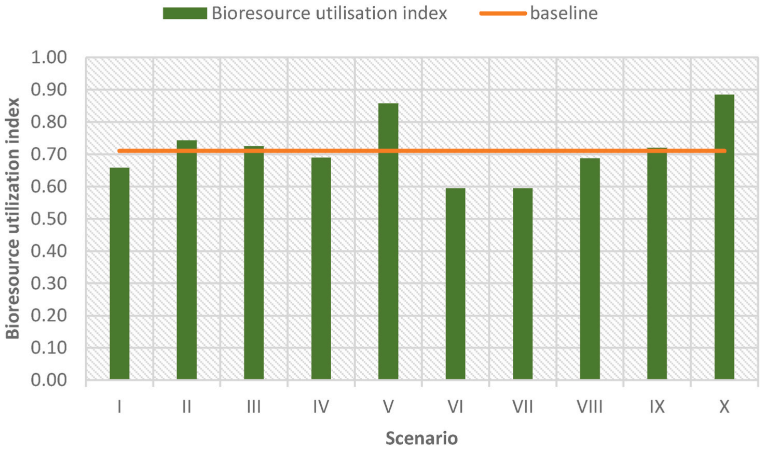


Fig. 6. Bioresource utilization index calculated for Enterprise No. 1 and 2. actual situations represented by case II and IX and four alternative scenarios (I, III to VIII and X). Baseline is represented by median from all ten scenarios as one bioresource is used in all cases. Baseline shows that actual scenarios are very close to median (orange), showing that actual situation is somewhat in-between of worst and best possible case.

product flow it could be used for target product production.

Policy trends in European Union are promoting waste reduction, in addition, reports on misclassification of waste have been published. With the coming years it is expected for enterprises to become more thoughtful with the by-product and waste utilization. We have shown that bioresources could be audited not only from the perspective of waste utilization but from the perspective of resources. Proposed bioresource utilization index gives an insight into resource efficiency in specific enterprise by quantifying incoming raw material, outgoing product, by-products, and waste. The elucidated factor nexus could be used as a map for easier detection of place for improvement. In the future work we plan to elaborate on the financial aspects of the utilization of production residues, to kick-start the bioresource evaluation discussion, in this paper we are offering coefficients based on existing bio-based value pyramid with 5 levels of values represented by five product groups.

CRediT authorship contribution statement

Ilze Vamza: Formal analysis, Conceptualization, Methodology, Original draft, Investigation, Visualization. **Anna Kubule:** Data curation, Investigation, Validation, review &editing. **Lauma Zihare:** Data curation, Investigation, Validation, review &editing. **Karlis Valters:** Conceptualization, Validation, Supervision. **Dagnija Blumberga:** Conceptualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research is funded by the Latvian Council of Science, project "Bioresource Value Model (BVM)", project No. lzp-2018/1–0426.

References

Alinejad, M., Henry, C., Nikafshar, S., Gondaliya, A., Bagheri, S., Chen, N., Nejad, M., 2019. Lignin-based polyurethanes: opportunities for bio-based foams, elastomers, coatings and adhesives. Polymers 11 (7), 1202. https://doi.org/10.3390/polym11071202.

Axelsson, L., Franzén, M., Ostwald, M., Berndes, G., Lakshmi, G., Ravindranath, N.H., 2012. Perspective: jatropha cultivation in southern India: assessing farmers' experiences. Biofuels, Bioproducts and Biorefining 6 (3), 246–256. https://doi.org/10.1002/bbb.

Bandara, N.J.G.J., Hettiaratchi, J.P.A., Wirasinghe, S.C., Pilapiiya, S., 2007. Relation of waste generation and composition to socio-economic factors: a case study. Environ. Monit. Assess. 135 (1–3), 31–39. https://doi.org/10.1007/s10661-007-9705-3.

Banja, M., Sikkema, R., Jégard, M., Motola, V., Dallemand, J.F., 2019. Biomass for energy in the EU – the support framework. Energy Pol. 131 (April 2019), 215–228. https://doi.org/10.1016/j.enpol.2019.04.038.

Cagno, E., Worrell, E., Trianni, A., Pugliese, G., 2013. A novel approach for barriers to industrial energy efficiency. Renew. Sustain. Energy Rev. 19, 290–308. https://doi.org/10.1016/j.rser.2012.11.007.

Clemens, J., Cuhls, C., 2003. Greenhouse gas emissions from mechanical and biological waste treatment of municipal waste. Environ. Technol. 24 (6), 745–754. https://doi.org/10.1080/09593330309385611.

D'Amato, D., Veijonaho, S., Toppinen, A., 2020. Towards sustainability? Forest-based circular bioeconomy business models in Finnish SMEs. For. Pol. Econ. 110, 101848. https://doi.org/10.1016/j.forpol.2018.12.004. June 2018.

Da, G., Dufour, D., Marouzé, C., Thanh, M. Le, Maréchal, P.A., 2008. Cassava starch processing at small scale in North Vietnam. Starch Staerke 60 (7), 358–372. https://doi.org/10.1002/star.200800202.

Davidsson, Å., Gruvberger, C., Christensen, T.H., Hansen, T.L., Jansen, J. la C., 2007. Methane yield in source-sorted organic fraction of municipal solid waste. Waste Manag. 27 (3), 406–414. https://doi.org/10.1016/j.wasman.2006.02.013.

de Azevedo, Afonso, R.G., Alexandre, J., Pessanha, L.S.P., Manhães, R. da S.T., de Brito, J., Marvila, M.T., 2019. Characterizing the paper industry sludge for environmentally-safe disposal. Waste Manag. 95, 43–52. https://doi.org/10.1016/j.wasman.2019.06.001.

de Azevedo, , Afonso Rangel Garcez, Alexandre, J., Marvila, M.T., Xavier, G. de C., Monteiro, S.N., Pedroti, L.G., 2020. Technological and environmental comparative of the processing of primary sludge waste from paper industry for mortar. J. Clean. Prod. 249, 119336. https://doi.org/10.1016/j.jclepro.2019.119336.

Dehelean, C.A., Şoica, C., Ledeţi, I., Aluaş, M., Zupko, I., Gălușcan, A., Munteanu, M., 2012. Study of the betulin enriched birch bark extracts effects on human carcinoma cells and ear inflammation. Chem. Cent. J. 6 (1), 1–9. https://doi.org/10.1186/1752-153X-6-137.

Del Brío, J.Á., Junquera, B., 2003. A review of the literature on environmental innovation management in SMEs: implications for public policies. Technovation 23 (12), 939–948. https://doi.org/10.1016/S0166-4972(02)00036-6.

Deloitte, 2014. Researcher's Report, DG Research and Innovation. Retrieved from. http://ec.europa.eu/euraxess/index.cfm/general/researchPolicies.

Demirbas, A., 2011. Waste management, waste resource facilities and waste conversion processes. Energy Convers. Manag. 52 (2), 1280–1287. https://doi.org/10.1016/j.enconman.2010.09.025.

Dorais, M., Schwarz, D., 2018. In: Heuvelink, E. (Ed.), Tomatoes, second ed. CAB International. Retrieved from. https://books.google.lv/books?hl=en&lr=&id=SVdoDwAAQBAJ&oi=fnd&pg=PA1&dq=tomatoes+energy+intensive+growing&ots=efWK9Xblt4&sig=RbyHxsGNNMTcVqN3T9yeiJIWr98&redir_esc=y#v=onepage&q=energy&f=false. Tomatoes.

Dvulit, Z., Melnyk, O., Chyrkova, Y., Petryshyn, N., Bortnikova, M., 2019. Diagnostics of the structural risk level in the sphere of waste management at Ukrainian railways.

MATEC Web of Conferences 294, 02005. https://doi.org/10.1051/matecconf/201929402005.

Escaramboni, B., Fernández Núñez, E.G., Carvalho, A.F.A., de Oliva Neto, P., 2018. Ethanol biosynthesis by fast hydrolysis of cassava bagasse using fungal amylases produced in optimized conditions. Ind. Crop. Prod. 112 (December 2016), 368–377. https://doi.org/10.1016/j.indcrop.2017.12.004.

European Commission, 2015. Circular Economy Strategy. Retrieved from. https://ec.europa.eu/environment/circular-economy/.

EUROPEAN COMMISSION, 2012. Innovating for sustainable growth: a bioeconomy for europe, Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions §.

European Parliament and Council, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives (Waste Framework. LexUriServ. Do, pp. 3–30. http://data.europa.eu/eli/dir/2008/98/oj.

eurostat, 2013. Manual on Waste Statistics A Handbook for Data Collection on Waste Generation and Treatment. https://doi.org/10.2785/4198.

eurostat, 2015. Business Economy - Size Class Analysis - Statistics Explained. Retrieved February 18, 2020, from. https://ec.europa.eu/eurostat/statistics-explained/index.php/Archive:Business_economy_-_size_class_analysis#Sectoral_analysis.

Evans, G., 2013. Biowaste and biological treatment. Journal of Chemical Information and Modeling. https://doi.org/10.1017/CBO9781107415324.004.

Fang, D., Chen, B., 2017. Linkage analysis for the water–energy nexus of city. Appl. Energy 189, 770–779. https://doi.org/10.1016/j.apenergy.2016.04.020.

Gârdan, D.A., Andronie, M., Gârdan, I.P., Andronie, I.E., Iatagan, M., Hurloiu, I., 2018. Bioeconomy development and using of intellectual capital for the creation of competitive advantages by Smes in the field of biotechnology. Amfiteatru Economic 20 (49). https://doi.org/10.24818/EA/2018/49/647, 947–666.

Gasbarro, F., Rizzi, F., Frey, M., 2016. Adaptation measures of energy and utility companies to cope with water scarcity induced by climate change. Bus. Strat. Environ. 25 (1), 54–72. https://doi.org/10.1002/bse.1857.

Getliņi skaitļos | Getlini.Lv. (n.d.). Retrieved March 19, 2020, from https://www.getlini.lv/.

Heredia-Arroyo, T., Wei, W., Ruan, R., Hu, B., 2011. Mixotrophic cultivation of Chlorella vulgaris and its potential application for the oil accumulation from non-sugar materials. Biomass Bioenergy 35 (5), 2245–2253. https://doi.org/10.1016/j.biombioe.2011.02.036.

Höglmeier, K., Steubing, B., Weber-Blaschke, G., Richter, K., 2015. LCA-based optimization of wood utilization under special consideration of a cascading use of wood. J. Environ. Manag. 152, 158–170. https://doi.org/10.1016/j.jenvman.2015.01.018.

Ismail, A., Yusuff, N.A., 2013. Public awareness campaigns in solid waste management through islamic approaches: review in kelantan, Malaysia. Istanbul International Solid Waste, Water and Wastewater Congress 2013, pp. 109–110. Retrieved from. https://s3.amazonaws.com/academia.edu.documents/32342596/Istanbul3WCongAbstracts2013EngInteraktif.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1527859798&Signature=Lcduh1Imeu7%2F0rPKJRusbqYO2qA%3D&response-content-disposition=inline%3B filename%3DMet.

Jamshed, S., 2014. Qualitative research method-interviewing and observation. J. Basic Clin. Pharm. 5 (4), 87. https://doi.org/10.4103/0976-0105.141942.

Janowiak, M., Connelly, W.J., Dante-Wood, K., Domke, G.M., Giardina, C., Kayler, Z., Buford, M., 2017. United States Department of Agriculture Considering Forest and Grassland Carbon in Land Management. Retrieved from. http://www.ascr.usda.gov/complaint_filing_cust.html.

Jiang, J., Gong, C., Wang, J., Tian, S., Zhang, Y., 2014. Effects of ultrasound pre-treatment on the amount of dissolved organic matter extracted from food waste. Bioresour. Technol. 155, 266–271. https://doi.org/10.1016/j.biortech.2013.12.064.

Khalili, N.R., Duecker, S., Ashton, W., Chavez, F., 2015. From cleaner production to sustainable development: the role of academia. J. Clean. Prod. 96, 30–43. https://doi.org/10.1016/j.jclepro.2014.01.099.

Klemeš, J.J., Varbanov, P.S., Huisingh, D., 2012. Recent cleaner production advances in process monitoring and optimisation. J. Clean. Prod. 34, 1–8. https://doi.org/10.1016/j.jclepro.2012.04.026.

Kroyer, G.T., 1995. Impact of food processing on the environment-an overview. LWT - Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.) 28 (6), 547–552. https://doi.org/10.1016/0023-6438(95)90000-4.

Kumar, S.P.J., Prasad, S.R., Banerjee, R., Agarwal, D.K., Kulkarni, K.S., Ramesh, K.V., 2017. Green solvents and technologies for oil extraction from oilseeds. Chem. Cent. J. 11 (9). Retrieved from. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5258651/.

Kuzmanović, M., López-Doval, J.C., De Castro-Català, N., Guasch, H., Petrović, M., Muñoz, I., Barceló, D., 2016. Ecotoxicological risk assessment of chemical pollution in four Iberian river basins and its relationship with the aquatic macroinvertebrate community status. Sci. Total Environ. 540, 324–333. https://doi.org/10.1016/j.scitotenv.2015.06.112.

Levidow, L., Birch, K., Papaioannou, T., 2012. EU agri-innovation policy: two contending visions of the bio-economy. Crit. Pol. Stud. 6 (1), 40–65. https://doi.org/10.1080/19460171.2012.659881.

Linnenluecke, M.K., Stathakis, A., Griffiths, A., 2011. Firm relocation as adaptive response to climate change and weather extremes. Global Environ. Change 21 (1), 123–133. https://doi.org/10.1016/j.gloenvcha.2010.09.010.

Mitra, D., van Leeuwen, J., Hans), Lamsal, B., 2012. Heterotrophic/mixotrophic cultivation of oleaginous Chlorella vulgaris on industrial co-products. Algal Research 1 (1), 40–48. https://doi.org/10.1016/j.algal.2012.03.002.

Muñoz, P., Drizo, A., Cully Hession, W., 2006. Flow patterns of dairy wastewater constructed wetlands in a cold climate. Water Res. 40 (17), 3209–3218. https://doi.org/10.1016/j.watres.2006.06.036.

OECD, 2006. OECD International Futures Programme the Bioeconomy to 2030: Designing a Policy Agenda. Retrieved from. http://www.oecd.org/sti/emerging-tech/34823102.pdf.

Passarelli, R.N., 2019. Environmental benefits of reusable modular mass timber construction for residential use in Japan: an LCA approach. Modular and Offsite Construction (MOC) Summit Proceedings 157–164. https://doi.org/10.29173/mocs89, 2017(MLIT 2016).

Powers, R.P., Jetz, W., 2019. Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. Nat. Clim. Change 9 (4), 323–329. https://doi.org/10.1038/s41558-019-0406-z.

Priedniece, V., Spalvins, K., Ivanovs, K., Pubule, J., Blumberga, D., 2017. Bioproducts from potatoes. A review. Environ. Clim. Technol. 21 (1), 18–27. https://doi.org/10.1515/rtuect-2017-0013.

Pubule, J., Blumberga, A., Romagnoli, F., Blumberga, D., 2015. Finding an optimal solution for biowaste management in the Baltic States. J. Clean. Prod. 88, 214–223. https://doi.org/10.1016/j.jclepro.2014.04.053.

Rafiq, S., Kaul, R., Sofi, S.A., Bashir, N., Nazir, F., Ahmad Nayik, G., 2018. Citrus peel as a source of functional ingredient: a review. J. Saudi Soc. Agric. Sci. https://doi.org/10.1016/j.jssas.2016.07.006.

Rasi, S., Veijanen, A., Rintala, J., 2007. Trace compounds of biogas from different biogas production plants. Energy 32 (8), 1375–1380. https://doi.org/10.1016/j.energy.2006.10.018.

Ritchie, H., Roser, M., 2019. CO_2 and Greenhouse Gas Emissions - Our World in Data from. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#co2-emissions-by-sector. (Accessed 11 February 2020).

Rosales, E., Rodríguez Couto, S., Sanromán, A., 2002. New uses of food waste: application to laccase production by Trametes hirsuta. Biotechnol. Lett. 24 (9), 701–704. https://doi.org/10.1023/A:1015234100459.

Saad A, A.J., 2009. COD and BOD Reduction of Dosmetic Wastewater Using Activated Sludge, Sand Filters and Activated Carbon in Saudi Arabia. *Biotechnology*. Retrieved from. http://docsdrive.com/pdfs/ansinet/biotech/2009/473-477.pdf.

Selman, J.D., Price, P., Abdul-Rezzak, R.K., 1983. A study of the apparent diffusion coefficients for solute losses from carrot tissue during blanching in water. Int. J. Food Sci. Technol. 18 (4), 427–440. https://doi.org/10.1111/j.1365-2621.1983.tb00285.x.

Sidhu, I., 2010. Profiles in Doing Both: Mike Yurosek, Father of the "Baby Carrot. " Retrieved March 20, 2020, from. https://www.forbes.com/sites/indersidhu/2010/11/04/profiles-in-doing-both-mike-yurosek-father-of-the-baby-carrot/#4b07b50228d9.

Singh, P.P., Saldaña, M.D.A., 2011. Subcritical water extraction of phenolic compounds from potato peel. Food Res. Int. 44 (8), 2452–2458. https://doi.org/10.1016/j.foodres.2011.02.006.

Sorrell, S., Mallett, A., Nye, S., 2011. Barriers to Industrial Energy Efficiency: a Literature Review. United Nations Industrial Development Organisation. https://doi.org/10.1016/j.rser.2015.03.002. Working pa).

Stegmann, P., Londo, M., Junginger, M., 2020. The Circular Bioeconomy: its elements and role in European bioeconomy clusters. Resour. Conserv. Recycl. X (6), 100029. https://doi.org/10.1016/j.rcrx.2019.100029. (Accessed July 2019).

Sullivan, M.J.P., Talbot, J., Lewis, S.L., Phillips, O.L., Qie, L., Begne, S.K., Zemagho, L., 2017. Diversity and carbon storage across the tropical forest biome. Sci. Rep. 7, 1–12. https://doi.org/10.1038/srep39102. July 2016.

Tai, M., Stephanopoulos, G., 2013. Engineering the push and pull of lipid biosynthesis in oleaginous yeast Yarrowia lipolytica for biofuel production. Metab. Eng. 15 (1), 1–9. https://doi.org/10.1016/j.ymben.2012.08.007.

Tanzi, C.D., Vian, M.A., Ginies, C., Elmaataoui, M., Chemat, F., 2012. Terpenes as green solvents for extraction of oil from microalgae. Molecules 17 (7), 8196–8205. https://doi.org/10.3390/molecules17078196.

Trubaev, P.A., Verevkin, O.V., Grishko, B.M., Tarasyuk, P.N., Shchekin, I.I., Suslov, D.Y., Ramazanov, R.S., 2018. Investigation of landfill gas output from municipal solid waste at the polygon. J. Phys. Conf. 1066 (1) https://doi.org/10.1088/1742-6596/1066/1/012015.

Ubando, A.T., Felix, C.B., Chen, W.H., 2020. Biorefineries in circular bioeconomy: a comprehensive review. Bioresour. Technol. 299 https://doi.org/10.1016/j.biortech.2019.122585. (Accessed December 2019).

Uyarra, E., Shapira, P., Harding, A., 2016. Low carbon innovation and enterprise growth in the UK: challenges of a place-blind policy mix. Technol. Forecast. Soc. Change 103, 264–272. https://doi.org/10.1016/j.techfore.2015.10.008.

Van Wyk, J.P.H., 2011. Biowaste as a resource for bioproduct development. Environmental Earth Sciences 19 (5), 875–883. https://doi.org/10.1007/978-3-540-95991-5-82.

Vanhercke, T., El Tahchy, A., Liu, Q., Zhou, X.R., Shrestha, P., Divi, U.K., Petrie, J.R., 2014. Metabolic engineering of biomass for high energy density: oilseed-like triacylglycerol yields from plant leaves. Plant Biotechnology Journal 12 (2), 231–239. https://doi.org/10.1111/pbi.12131.

Vanholme, R., Morreel, K., Darrah, C., Oyarce, P., Grabber, J.H., Ralph, J., Boerjan, W., 2012. Metabolic engineering of novel lignin in biomass crops. New Phytol. 978–1000.

Wu, T.Y., Mohammad, A.W., Jahim, J.M., Anuar, N., 2010. Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes. J. Environ. Manag. https://doi.org/10.1016/j.jenvman.2010.02.008.

Zhang, C., Su, H., Baeyens, J., Tan, T., 2014. Reviewing the anaerobic digestion of food waste for biogas production. Renew. Sustain. Energy Rev. 38, 383–392. https://doi.org/10.1016/j.rser.2014.05.038.

Zihare, L., Kubule, A., Vamza, I., Muizniece, I., Blumberga, D., 2020. Triple factor nexus in bioeconomy through indicator analysis. New BIOTECHNOLOGY 61 (November 2020), 57–68. https://doi.org/10.1016/j.nbt.2020.11.008.

Ilze Vamža was born in 1989 in Riga. She obtained a Bachelor's degree in Biology in 2016 and a Master's degree in Environmental Sciences in 2019 from the University of Latvia. Since 2019, she has been a researcher with the Institute of Energy Systems and Environment of Riga Technical University. Her scientific interests are related to bioeconomy and bioresource value chains.