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SUSTAINABILITY ASSESSMENT OF BIORESOURCES. LATVIAN CASES

Doctoral Thesis

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CONTENTS

INTRODUCTION

In the face of increasing global demand for bioresources and the pressing need for sustainable development, the assessment of bioresource sustainability has emerged as a critical area of scientific inquiry. This Thesis is dedicated to conducting a comprehensive evaluation of the sustainability of bioresources in Latvia. It aims to delve into their potential as a better alternative for and to scrutinize the environmental and economic implications that arise from their utilization in the local context.

As a case study for sustainable bioresources, among other examples, sea buckthorn plantation is analysed. This perennial bush embodies many of the challenges of bioresources and sustainability. The concept of sustainability is multidimensional, encompassing a wide array of considerations. Sea buckthorn, for example, is not only an income source for farmers but also a source of sustainable and healthy bioproducts in pharmacy, thus reducing climate changes and improving the wellbeing of people. As part of the cold supply chain, it requires a significant amount of energy not only during the growing phase but also during transportation and storage, thus also creating greenhouse gasses.

The decision-making process for end-products with low added value or as part of more sophisticated products in agriculture is analysed. In the context of bioresources, sustainability involves an intricate balance between their renewability, the carbon neutrality they offer, and the impact they have on biodiversity, investment desicions, and the prosperity of people around bioresources. During research, specific methodologies and tools are used to analyse the Latvian cases of bioresource usage.

Chapter 1 of this study concentrates on sea buckthorn - determining the existing impact on the sustainability of bioresources cold supply chain and processing and what improvements could be performed by analysing the specific Latvian case study of existing plantation and supply chain near the town of Cēsis. Also, market readiness for renewable energy sources among companies in Latvia is analysed.

In Chapter 2 of the Thesis, researches the future impacts of bioresources, namely the greenhouse gass emissions of the sea buckthorn plantation and new, sustainable future bioresources as alternative substitution for existing fossil-based products.

Finally, a decision-making tool for future bioresource trends in agriculture is researched to assist those in policy-making or business environments seeking more sustainable bioproducts to promote, research and develop.

The goal of this research is to pave the way for a more sustainable future. By shedding light on the sustainability of bioresources, it hopes to contribute to the transition towards renewable sources of energy and materials, a key pillar of sustainable development. This transition is not only about meeting our energy and resource needs but also about preserving our planet and ensuring the well-being of current and future generations.

The Relevance of the Doctoral Thesis

In the contemporary world, the relevance of sustainability assessment of bioresources cannot be overstated. Sustainability and resource availability have become an increasingly crucial factor in policymaking and investments. This is due to environmental, economic, and social concerns that have risen because of global population growth and climate change. Governments around the world are now recognizing the importance of sustainability and are implementing policies that support sustainable investment practices.

The increasing global demand for bioresources and the urgent need for sustainable development have brought this field to the forefront of scientific research, business, politics, and daily life. Bioresources are one of the pillars in many policy documents at the national level, like Latvian "The National Development Plan 2021–2027", European level "New Green Deal" and "Common agricultural policy" or international United Nations 17 sustainability goals.

In Latvia alone, for the next five years, more than nine billion EUR will be allocated, among others, to promote the usage of bioresources, thus promoting sustainability and long-term development. Bioresources can be analysed by countless metrics and criteria. During research, specific dimensions of bioresources sustainability are chosen – logistics and processing, greenhouse gas emissions, renewable energy, added value of materials and innovations and investments. Those dimensions are applied to various bioresources, including sea buckthorn plantation as a main case study.

During research, sustainability in bioproduction refers to the idea that economic activity should take place while preserving and enhancing environmental assets over time. This includes considering impacts on natural resources, energy source availability, greenhouse gas emissions, and justification for new economic investments. Investments in bioresources support responsible land use practices, seek to reduce negative environmental impact and support renewable energy, and ecologically sound practices. All those factors are everyday topics at the manufacturing level of bioresources, at policy-making level and at the investment planning level, thus clearly proving the relevance of the Thesis subject.

The findings of this Thesis are intended to contribute to the development of strategies and policies that promote the sustainable use of bioresources. By providing a thorough and objective assessment of bioresource sustainability, this Thesis aims to inform decision-making processes at multiple levels, starting from the farm level and providing tools for more general policy making.

Industry stakeholders can gain valuable insights to guide their operational and strategic decisions, enabling them to align their practices with sustainability principles. Policymakers can use the findings to craft informed and effective policies that encourage the sustainable use of bioresources. At the societal level, the research can contribute to raising awareness and understanding of bioresources sustainability, fostering informed public discourse and decision-making.

Objective and Tasks of the Thesis

The primary objective of this Thesis is to evaluate the environmental and economic impacts of utilizing sustainable bioresources. This analysis aims to shed light on the multifaceted influences driving sustainable practices uptake within the bioresource sector. By pinpointing the obstacles to widespread adoption and identifying the catalysts for change, this research endeavours to offer strategies for enhancing the promotion and integration of sustainable bioresources, thereby fostering more environmentally and economically viable choices.

Tasks:

- Identify sustainability dimensions. Outline the key sustainability dimensions pertinent to this research, encompassing environmental, economic, and social aspects.
- Gather data for case study analysis. Collect comprehensive data for a Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) focusing on a case study of a sea buckthorn plantation to understand the sustainability impact across its lifecycle.
- Engage with industry stakeholders. Conduct structured interviews with stakeholders in the business community to gather insights on current practices, challenges, and perceptions regarding the sustainability of bioresources.
- Experimental analysis of alternatives. Design and execute experiments to evaluate the viability and sustainability of alternative materials compared to conventional ones within the bioresource sector.
- Literature review and application of GHG calculations. Undertake a thorough literature review of greenhouse gas calculators tailored for horticulture plantations. Apply these tools to a localized scenario to validate their accuracy and relevance.
- Develop a system dynamics model. Create a system dynamics model for selecting bioresources to assess their sustainability. This model should help determine the most viable bioresources based on predefined sustainability criteria.

By accomplishing these tasks, the Thesis aims to contribute significant insights into the sustainable management of bioresources, inform policy, and guide industry practices towards more sustainable outcomes.

Theses

The thesis of the doctoral research are based on two distinct dimensions.

1. The sustainability dimension of products includes various characteristics, the metrics of which outline the sustainability of the use of bioresources:
    - parameters of the resource extraction process and logistics, which are based on the pilot project of sea buckthorn cultivation;
    - greenhouse gas emission parameter characterising the impact of bioresources on climate change based on agriculture;
    - parameter of the use of bioresources for the production of a product with high added value, which is based on examples of the use of logging residues;

- level of use of bioresources for energy production based on the readiness of entrepreneurs to renewable energy sources;
- an assessment of the role of investment and innovation towards the European Union's sustainability goals.

2. The sustainability dimension of the use of bioresources can be assessed by integrating and combining different analytical methods:
   - multi-criteria analysis;
   - surveys;
   - experiment;
   - fuzzy cognitive mapping approach;
   - life cycle and life cycle cost analysis.

Hypothesis of the Thesis

Faced with the global demand for bioresources toward sustainable development targets, this Thesis provides a multifaceted approach to evaluating the sustainability of bioresources. This can significantly enhance their utilization in an environmentally sound, economically viable, and socially beneficial manner. This comprehensive evaluation is crucial to identifying sustainable alternatives that mitigate environmental impact and foster economic prosperity.

The research hypothesis of this Thesis is that the implementation of sustainable practices with an emphasis on the cultivation, processing, and utilization of bioresources, exemplified by the case study of sea buckthorn plantation, can lead to an important reduction in greenhouse gas emissions, improvement in resource efficiency, and enhancement of socio-economic benefits for communities involved.

Scientific Novelty

The scientific novelty of the Thesis research lies in its tailored approach for specific and unique models made:

- LCA/LCCA model for a small-scale sea buckthorn plantation in Latvia, including creation, operations, and logistics up to a retail shelf of product.
- Market prospects for bioresource-based green thermal packaging based on an interview of Latvian stakeholders and the MCA method to quantify results.
- FCM to assess bioresources viability to the set of sustainability criteria for implementation in Latvia.
- Market maturity for investments in RES based on AHP and interviews of large energy consumers in Latvia.
- Parameters of farm-level GHG calculation tool for horticulture and result verification by local sea buckthorn farm.

Practical Significance of the Research

As a result of the research several models based on case studies were created. Those models can be used by stakeholders and policymakers to improve sustainable bioresource usage:

- development of a tool to assess future markets for bio-products and what criteria shape those markets in Latvia;
- A practical tool to analyse "green" solutions from the perspective of sustainability and feasibility, based on a case study of sea-buckthorn;
- methodology to analyse results of interviews to determine market maturity for renewable energy sources in the Latvian case study.

Also, new and unique bioresource material – particle boards from forest residue – was researched.

Research Framework

The sustainability of bioresource usage depends on locally available materials, impact on climate, and technological maturity.

Of high importance is not only the usability and characteristics of each separate bioresource but also the requirement to efficiently use other resources: energy, water, land, materials.

One of the core elements of sustainability is the impact on climate change, which is characterised by GHG emissions in all the stages of production.

As a summary of the previously mentioned, a research framework is formed. The framework is based on seven dimensions – two are background dimensions, and five are related to the field of research. The framework includes two background dimensions: "as-is" and "to-be". Those dimensions are used during business modelling, first, describing existing conditions and factors, while second, describing future trends or desired outcomes at some point in future.

Within time dimensions specific dimensions of sustainability are analysed:

- as-is (existing situation) analysis:
  - using sea buckthorn plantation and products' existing maintenance and operational costs, as well as existing infrastructure and energy consumption;
  - sustainable farming to verify GHG emission calculations using existing data and parameters;
- to-be (future) analysis:
  - integration of renewable energy sources in the bioproducts processing industry, based on companies' plans and expectations in future;
  - evaluation of the future of bioresources in manufacturing of products with high added value for products not in making now;
- the role of investment and innovation both in present and future models. For example, sea buckthorn's existing situation is based on actual, measured data of the present, but possible improvements are investments at some point in the future.

A summary of the research framework visualisation is shown in Fig. 1.

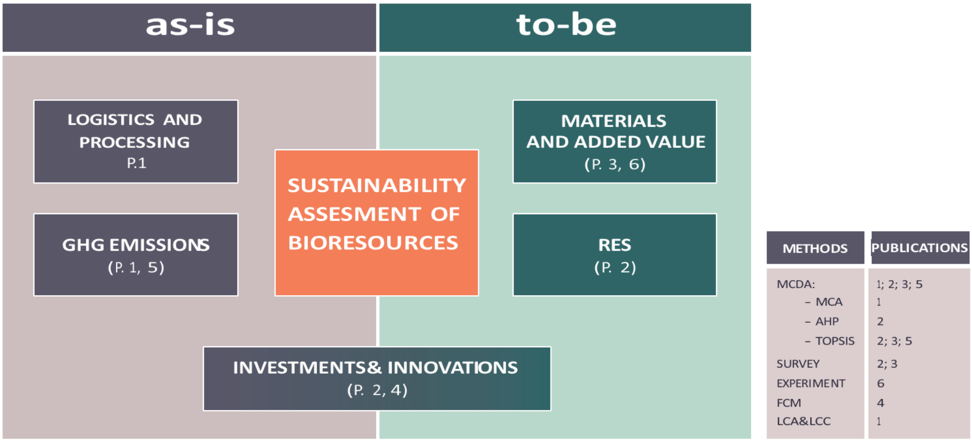

Fig. 1 Research framework

The methodology for each of the dimensions is chosen. In the Thesis, methodologies are used according to their relevance to data availability, and results are described in five dimensions, as shown above.

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Participation in conferences: Connect 2023

1. LITERATURE REVIEW

Sustainability as keyword is mentioned in more than 31 thousand articles in SCOPUS database in year 2023 alone. Literature review is organized in five sections according to dimensions from research framework – logistics and processing, greenhouse gas emissions, renewable energy, added value of materials and innovations and investments. This approach helps to narrow down the boundaries of literature research in accordance of scope of thesis.

1.1. Logistics and processing

The agricultural cold supply chain plays a pivotal role in ensuring the quality, safety, and shelf-life extension of perishable agricultural products. With the growing concerns over food security, environmental sustainability, and economic viability, there is an increasing focus on optimizing this supply chain. Investments in cold storage facilities and transportation infrastructure have been identified as critical for improving the efficiency and sustainability of the agricultural cold supply chain [1].

Upgrading these facilities with energy-efficient technologies and renewable energy sources not only reduces operational costs but also mitigates environmental impacts, contributing to overall sustainability [2].

Technological advancements such as IoT-enabled monitoring systems, RFID tracking, and predictive analytics have revolutionized cold chain management [3].

These innovations enable real-time monitoring of temperature and humidity, thereby minimizing food losses and ensuring product quality throughout the supply chain. Moreover, process optimization through the integration of data analytics enhances resource utilization and reduces carbon footprint [4].

Collaborative partnerships among stakeholders including farmers, producers, retailers, and logistics providers are essential for optimizing the cold supply chain [5].

By sharing resources, information, and best practices, these partnerships facilitate the implementation of sustainable practices such as coordinated delivery schedules and consolidation of shipments, leading to reduced emissions and waste. Government policies and regulatory frameworks play a crucial role in shaping the sustainability of the agricultural cold supply chain. Incentives for investment in sustainable infrastructure, subsidies for adopting green technologies, and stringent quality standards promote environmentally friendly practices and drive continuous improvement in the supply chain's sustainability performance. Investments in the agricultural cold supply chain hold immense potential for enhancing its sustainability by improving infrastructure, leveraging technological innovations, fostering collaborative partnerships, and implementing supportive policy frameworks. Future research should focus on evaluating the effectiveness of these investments in achieving long-term sustainability goals and addressing emerging challenges in the dynamic agricultural landscape.

1.2. Greenhouse gas emissions

Agriculture is a significant contributor to greenhouse gas (GHG) emissions, necessitating accurate measurement tools for mitigation strategies. Greenhouse gas calculators have emerged as essential tools for assessing emissions in agricultural systems. This literature review aims to explore the effectiveness of GHG calculators in agricultural contexts, highlighting their benefits, challenges, and areas for improvement.

Several studies have investigated the utility of GHG calculators across diverse agricultural settings. [6] conducted a study in USA egg production, revealing decrease of GHG emissions over years, emphasizing the importance of considering local conditions. [7] conducted a comparative analysis of GHG calculators, highlighting variations in emissions estimates due to differences in calculation methods and input parameters. Case study and performance of GHG calculators emphasize the role of uncertainty in emission estimates and recommending improved data collection and model validation. Furthermore, [8] evaluated the four alternative low carbon scenarios for Nigeria were developed, identifying expected future trends of GHG emission in country.

Greenhouse gas calculators offer valuable tools for assessing emissions in agricultural systems, aiding in the formulation of sustainable practices. However, challenges such as variability in estimates, uncertainty, and the need for localized calibration persist. Future research should focus on standardizing methodologies, improving model accuracy, and enhancing data collection to ensure effective GHG assessment in agricultural contexts.

1.3. Renewable energy sources

The agricultural sector is increasingly turning towards renewable energy sources to mitigate environmental impacts, reduce operational costs, and enhance sustainability. This literature review examines the investment perspectives surrounding the adoption of renewable energy technologies in agriculture, elucidating key considerations, benefits, and challenges.

Several studies have explored the financial implications of transitioning to renewable energy sources in agriculture. [9] conducted a cost-benefit analysis of renewable energy adoption on farms, highlighting significant long-term savings despite initial investment costs. They emphasized the importance of government incentives and financing options in facilitating adoption.

Similarly, [10] investigated the economic feasibility of wind and energy integration in agricultural greenhouses, emphasizing the potential for revenue diversification and risk management through energy production. However, they noted challenges related to intermittency and alternative sources in case of unfavourable climate conditions.

Moreover, [11] examined the investment attractiveness of bioenergy production in agriculture, considering factors such as feedstock availability, technology maturity, and market demand. Their study highlighted the importance of comprehensive feasibility assessments and risk management strategies for successful implementation. Furthermore, [12] analysed the financial viability of biogas generation from agricultural waste, emphasizing the role of government policies and carbon markets in incentivizing investment. They underscored the potential for revenue generation, waste management, and environmental benefits. Biomethanation and pyrolysis technologies may be economically and environmentally competitive over natural gas, still more advanced LCA models to be made.

Renewable energy adoption in agriculture presents compelling investment opportunities, offering long-term cost savings, revenue diversification, and environmental sustainability. However, challenges such as upfront costs, technology integration, and policy support remain significant barriers. Future research should focus on developing innovative financing mechanisms, improving technology efficiency, and enhancing policy frameworks to accelerate the transition towards renewable energy in agriculture.

1.4. Materials and added value

In recent years, there has been growing interest in utilizing bioresource materials in agriculture to enhance productivity, sustainability, and economic viability. Literature review aims to explore the added value of bioresource materials in agricultural practices, highlighting their diverse applications, benefits, and implications.

Numerous studies have investigated the potential of bioresource materials to add value to agricultural systems. [13] examined the use of biochar, a carbon-rich material derived from biomass, in soil amendment. Their study demonstrated the ability of biochar to improve soil fertility, water retention, and crop productivity, thereby enhancing agricultural sustainability.

Similarly, [14] explored the utilization of agricultural residues such as crop residues and animal manure for biogas production. They highlighted the dual benefits of bioenergy generation and waste management, emphasizing the potential for renewable energy integration in agricultural operations. Furthermore, [15] investigated the application of agricultural by-products, such as crop residues and agro-industrial wastes, in the production of bio-based materials. Their study showcased the potential of bio-based materials for diverse applications, including manufacturing of biofuels, enzymes, vitamins, antioxidants, animal feed, antibiotics, thereby promoting circular economy principles in agriculture. Moreover, [16] examined the use of biofertilizers derived from microbial inoculants in agricultural practices. They demonstrated the ability of biofertilizers to enhance nutrient uptake, soil health, and crop yield, offering a sustainable alternative to chemical fertilizers.

Bioresource materials offer significant added value to agriculture by enhancing soil fertility, promoting waste management, enabling renewable energy production, and facilitating the development of bio-based products. However, challenges such as scalability, technology adoption, and market penetration remain. Future research should focus on optimizing bioresource utilization pathways, improving technology efficiency, and fostering stakeholder engagement to realize the full potential of bioresource materials in agriculture.

1.5. Innovations and investments

The pursuit of sustainable agriculture necessitates strategic decision-making processes to guide innovations and investments towards environmentally friendly, economically viable, and socially equitable practices. This literature review delves into the complex landscape of decision-making frameworks utilized in the context of sustainable agriculture, exploring key factors, challenges, and emerging trends.

Several studies have examined decision-making processes related to innovations and investments in sustainable agriculture. [17]emphasized the importance of participatory approaches that involve stakeholders at various levels to ensure the relevance and acceptance of sustainable agricultural practices. Their study underscored the role of farmer knowledge, local contexts, and socio-economic factors in shaping decision-making processes.

Furthermore, [18] highlighted the need for holistic assessments that consider multiple dimensions of sustainability, including environmental, economic, and social aspects. They advocated for integrated decision-making frameworks that prioritize synergies and trade-offs among different sustainability goals. Moreover, [19] examined the role of technology adoption and innovation in driving sustainability transitions in agriculture. Their study emphasized the importance of risk management strategies, information dissemination, and incentive mechanisms to encourage the adoption of sustainable technologies. Policymakers and stakeholders must prioritize the adoption of advanced technologies to promote sustainable agriculture, bolster resilience, and mitigate the adverse impacts of greenhouse gas emissions.

Additionally, [20] investigated the economics of sustainable agriculture decision-making, emphasizing the complexities of balancing environmental stewardship with economic profitability. Integrating mathematical model-based decision making in the current land use planning and agricultural decision making will significantly improve the efficiency of agricultural production and contribute to achieving the goal of increase profitability in the face of climate change.

Decision-making for innovations and investments in sustainable agriculture requires a multifaceted approach that integrates stakeholder engagement, holistic assessments, technology adoption, and economic considerations. Future research should focus on developing decision support tools, fostering stakeholder collaboration, and enhancing policy frameworks to accelerate the transition towards sustainable agricultural systems.

Sustainable investments are important not only for the environment but also for socio-economic development. Investment in sustainable projects can create jobs, improve livelihoods, and reduce poverty rates. By investing in green technologies, businesses can also benefit from lower production costs while reducing their environmental footprint [21]. This can result in greater economic growth over time as well as improved health and well-being for local communities [22].

2. METHODOLOGY

A proper methodology in Thesis is crucial as it provides a clear and detailed plan of how the research has been conducted, enhancing the reproducibility of the study. It allows for the validation of the results, as others can follow the same procedures to arrive at similar conclusions. A well-defined methodology also increases the credibility of the research, demonstrating that the findings are not based on mere speculation but on systematic and rigorous investigation. Lastly, it contributes to the transparency of the research process, enabling reviewers and readers to understand and evaluate the soundness of the research design and execution.

2.1. Survey

In Publication 2 survey was conducted to identify which RES are most viable when mutually compared and determine RES with highest potential among Latvian companies. The target group of the survey is manufacturing enterprises. The survey was prepared using the online software "Typeform" and sent out to 2000 manufacturing enterprises consuming 500 MWh or more of electricity annually. As only criteria were energy consumption, companies represent various industries. The survey is based on the following questions:

1. Are renewable energy technologies used in your company;
2. Specify which RES is/are used;
3. What limits the use of RES;
4. What would facilitate the use of RES;
5. Which three RES technologies could have the most potential in your company;
6. What is the approximate monthly electricity consumption of your company;
7. Is energy consumption one of the top three cost positions in your company;
8. Would you be interested in the results of this survey and learning more about RES technologies.

When summarizing the result of question No. 5, in order to take into account whether the technology is indicated as the first, second or third priority, coefficients have been selected that are multiplied by the number of respondents who have indicated the specific RES technology at the respective priority level. This coefficient for first priority is 3, for second priority – 2 and for third priority – 1. The incidence of each RES technology is calculated using Eq. (2.1):

$$R_{RES} = \frac{p_1 \cdot 3 + p_2 \cdot 2 + p_3 \cdot 1}{\sum_{n=1}^{n} p_1 \cdot 3 + p_2 \cdot 2 + p_3 \cdot 1} \cdot 100, \quad (2.1)$$

where R_{RES} - incidence of specific RES technology among respondents, %;

p_1, p_2, p_3 - number of respondents who indicated RES technology as first priority (p_1), second priority (p_2) and third priority (p_3);

n - number of total RES technologies considered.

Another survey was used to determine optimal thermal packaging. 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 [23], [24], [25].

Indicators like thermal conductivity and density were found in scientific literature on corresponding materials [26], [27], [28].

2.2. Pairwise comparison

After survey the importance of 12 criteria conducted in pairwise fashion. As it is nearly impossible for humans to 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 [29].

By determining, is one criterion 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 [30].

Table 2.1

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 large 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. The chosen companies assigned the questionnaire to logistics team experts within the company. All the criteria experts comparisons are compiled in Table 2.1.

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 [31] and used for further analysis. A consistency threshold of 0.2 was used, as done before [32] when multiple stakeholders were surveyed.

2.3. Experiment

As described in Publication 6, to create new biomaterial an experiment was conducted to make a bio-based chipboard. Logging biomass was sourced from Latvian State Forests' logging sites, and the collection took place within two months following the conclusion of logging operations. The biomass was systematically gathered in polyethylene bags, ranging from 50 to 100 litters in capacity. These bags contained wood chips obtained from forest areas where branches, complete with needles, had undergone chipping. The biomass comprised logging residues primarily derived from Picea abies and Pinus sylvestris, including small branches and needles. It is important to note that the composition of wood chips varied based on factors such as the specific location, the environmental conditions during the chipping process, and the relative proportions of wood biomass.

Upon visual inspection, the assessment indicated that the wood chips predominantly consisted of:

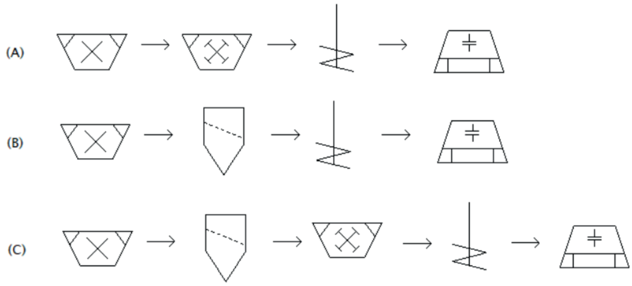
- Heartwood and sapwood
- Bark
- Needles
- Fresh and decomposed biomass particles
- Mineral particles

The following equipment and materials were used for board preparation:

1. Analog pressure gauge (Hansa Flex - 600 bar, ± 50 bar)
2. Digital manometer (Hansa Flex - 1000 bar, ± 1 bar)
3. Custom-made hot press, consisting of:
    - Cylindrical heating elements (alternating currents)
    - Temperature sensors
    - Heating metal blocks/surfaces
    - Plate drying stand

- Metal frames: one frame without perforations for biomass retention and an-other with perforations for steam discharge
- Metal lining for steam removal
- Teflon fabric

Xanthan powder acquired by glucose fermentation was produced by Fluid Science Ltd. and added to the biomass in the form of powder or solution during its preparation. Chips delivered from forest fallings contained varying but significant amounts of moisture. The different



amount of moisture in the wood chips was observed under different weather conditions during the 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. Two methods were used to obtain the desired particle size. Workflow is depicted in Fig.1. 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 integrated metal screen. Sieving of the crushed particles was performed using a Retsch AS-400 sieve shaker and metal sieves with different mesh opening sizes.

Fig. 2.1 Work flow for particle separation

Work flow for particle separation:

(A) horizontal 2-axis mill followed by hammer mill, particle mixing with binder and pressing;

(B) horizontal 2-axis mill followed by sieve for particle separation, mixing, and pressing;

(C) horizontal 2-axis mill followed by sieve for particle separation, particle >1 mm milling with hammer mill, mixing, and pressing.

The separation approach allowed to assess the bark and other fine particle impact 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.

Each composition and parameter were replicated at least two times and achieved boards sawn in three equal parts for MoR testing and density calculations, resulting in at least six repetitions.

2.4. Multiple-criteria decision analysis

Multiple-criteria decision analysis (MCDA) includes the following steps: target definition, definition of alternatives, selection of criteria, determination of their weight, and evaluation of alternatives. There are several variations of MCDA.

Analytic Hierarchy Process (AHP)

In Analytic Hierarchy Process (AHP) four main criteria are used for alternative evaluation: technical criteria, economic criteria, environmental criteria, and social criteria – these are the criteria that characterize a decision based on the principles of sustainable development.

The first step for the calculation of criteria weights is the pairwise comparison. For this comparison, the nine-integer value scale is used as presented in Table 2.2. The nine-integer value scale was initially suggested by Saaty [33].

Table 2.2

Scale for pairwise comparison [34]

Scale	Definition
1	Equal importance
3	Moderate importance of one over the other
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Extreme or absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

Each criterion is compared to all other criteria forming the comparison matrix. In order to determine the ranks of criteria, the next step is solving the eigenvector problem. There are three methods for solving the eigenvector problem – Saaty's method, the power method, and the geometric mean method. In this case, Saaty's method is chosen, given its simplicity compared to the other two methods. The first step is a normalization of the comparison matrix – the sum of each column of the pairwise comparison matrix is calculated, and the values in the corresponding column are divided by it. The next step is the calculation of eigenvectors of each matrix row – values in each row are summed and divided by the number of criteria. The eigenvectors give the ranking (weight) of the criteria [35].

However, so that these weight values can be used with some certainty for further evaluation, it is necessary to calculate the consistency index (CI) and consistency ratio (CR).

TOPSIS

TOPSIS methodology is useful because it requires only few indicators, while providing comparable data to draw conclusions. There is only one parameter, which is subjective – relative weight of each criteria.

The basic assumption of TOPSIS methodology is that the most preferred solution is one with shortest distance to desirable result and further distance from result to be avoided.

TOPSIS methodology is based on five calculation stages. First stage is gathering data set of indicators for each scenario. In second step normalization of indicators is performed. In next step normalized values are weighted and their proximity to desirable and avoidable results are calculated. Final step is to calculate proximity by ratio these distances [36].

Mathematical description of steps is described further. Step one gathers data from *n* alternatives a with chosen m criteria i in decision matrix X, where i=1,…,m and a=1,…n. Data is being normalized so that various units used are comparable. Distributive normalization, used for master thesis uses formula Eq. (2.2) [36].

$$r_{ia} = \frac{x_{ia}}{\sqrt{\sum_{a=1}^{n} x_{ia}^2}}, \text{ for } a = 1, \dots, n \text{ and } i = 1, \dots, m. \tag{2.2}$$

For second step weight of each criteria is taken into account using Eq. (2.3.)

$$V_{ai} = w_i \cdot r_{ai}, \tag{2.3}$$

In next step results from previous step will be used to compare each action to an ideal (zenith) and anti-ideal (or nadir or negative ideal) virtual action (Ishizaka, 2013). To perform comparison, formula Eq. (2.4.) and Eq. (2.5.) is used for zenith and nadir options.

$$A^{+} = (v_1^{+}, \dots., v_m^{+}), \tag{2.4}$$

$$A^{-} = (v_1^{-}, \dots., v_m^{-}), \tag{2.5}$$

From results v_i^+ is $\max_a(v_{ai})$ if criterion i is to be maximized and v_i^- is $\min_a(v_{ai})$ if criterion i is to be minimized.

It is by performer to determine which are with positive value, and which – negative value.

Fourth step calculates the distance to preferred result (Eq.2.6.).

$$d_a^{+} = \sqrt{\sum_i (v_i^{*} - v_{ai})^2}, a = 1, \dots., m. \tag{2.6}$$

Finally, relative proximity coefficient is calculated (Eq.2.7.).

$$C_a = \frac{d_a^{-}}{d_a^{+} + d_a^{-}}. \tag{2.7}$$

Obtained results show most preferable scenario with list desirable in numerical ranking.

TOPSIS has been used in Publication nr. 2 for the evaluation of different energy generation technologies [37].

TOPSIS main benefits are the choice of an unlimited number of criteria and alternatives, a relatively simple calculation process and no need for a specific software or special programming skills. TOPSIS results allow comparing alternatives in a convenient and easily understandable way.

The target of TOPSIS analysis in Publication Nr. 2 is to compare RES technologies in order to find technology that performs the best in terms of the criteria set. For the evaluation, six alternatives were selected: biomass technologies, solar PV panels, solar thermal technologies,

technologies that use renewable part of waste as an energy source, wind technologies, and geothermal technologies.

Technologies were assessed based on four criteria: technical, economic, social, and environmental. The technical aspect includes the level of technological development, also known as technology maturity, which characterizes how advanced the technology is, i.e., whether there is potential for efficiency gains or whether the theoretical maximum level of technological productivity has already been reached [38].

The technical aspect also includes the feasibility of innovation, process efficiency, and energy quality, which often is expressed as reliability, which describes the ability of technology to work continuously and independently – without unforeseen damage, interruptions, and additional monitoring. Reliability is one of the most commonly used criteria in the multi-criteria analysis and has always been a topical issue in the energy sector [39].

Reliability is affected by conditions such as the quality of technical equipment, required maintenance, the type of energy source used, etc. The economic aspect includes capital investments and operational costs, as well as costs related to additional costs of replacing equipment from an occasional source of energy at a time when energy is not available. Investment costs consist of several parts (equipment costs, installation costs, other system element costs, etc.). Operation and maintenance costs are regular costs associated with the maintenance and optimal operation of technological systems. These may include, for example, regular (scheduled) maintenance, system repairs, etc. These costs are often expressed as a percentage of the total investment costs. The social aspect covers issues of increased or declining employment as well as the impact of imports. The environmental aspect is linked to increasing or reducing impact on environmental pollution and climate change, also considering the production of technological equipment. This is expressed as life cycle emissions that consider the impact at all stages of the technology, which is essential in sustainable decision making. For each criterion, its individual weight representing the importance of the criterion shall be determined. The sum of all the criteria weights shall be equal to 1. For the TOPSIS analysis, the weight values from the AHP results were taken.

The first step using the TOPSIS method is the normalization of the decision-matrix, followed by the calculation of normalized decision-matrix and determination of the best and worst solution. The best solution corresponds to a theoretical option of the most desirable level of each criterion, while the worst solution corresponds to a theoretical option of the least desirable level of each criterion [40].

After that, the distance of each alternative from the best and worst solution is calculated in order to obtain the closeness coefficient, which is used for the ranking of alternatives.

2.5. Fuzzy cognitive map

System dynamics is a computerized approach to comprehend activity and behaviour of complex systems, such as cities, climate, and ecosystems, for policy analysis and development, which was originally developed by Jay W. Forester. System dynamics is related to how things change over time [41].

It embraces most of what seems important to some people. System dynamics include the interpretation of real-life systems in computer simulation models. This allows to see how the system's structure and decision-making policy shape its behaviour. Complex systems are any system with many mutually interacting components (agents, processes, etc.) that are often difficult to understand and solve and that require the development or use of new scientific tools, non-linear models, out-of-balance descriptions, and computer simulations. Complex social systems involve human behaviour and may have concepts that interact in a way that is quantitative (final) and/or qualitative (abstract), and the latter is particularly difficult to include into modelling tools due to their qualitative nature and the consequential challenges. The exclusion of such abstract qualitative concept may call into question the conclusions that were reached and the relation of the models to reality. In order to be able to explain, predict and understand complexity, it is argued that qualitative phenomenon that can play a significant role in systems must be included. Therefore, analysis of qualitative systems or qualitative modelling is increasingly used to analyse the dynamics of complex systems. Kosko [42] introduced fuzzy cognitive maps (FCM) as a tool for dynamic qualitative system behaviour perception and explanation. FCM is increasingly being used to model and analyse the behaviour of qualitative systems. Over the past 30 years, this fuzzy cognitive mapping (FCM) approach has become increasingly popular due to the simplicity of design and low computing requirements. In order to model the dynamics of the social system, two types of application are mainly used - deductive approach and inductive approach. The deductive approach uses the knowledge acquired by interviewing experts in the field of application, while the inductive approach is an automated and semi-automated approach designed to learn FCM rules based on historical data.

In general, it is considered that FCM has several advantages over traditional quantitative modelling approaches. The advantages of FCM include, for example, the ability to model data in limited environments using natural language, expressing knowledge, perception, experience or beliefs, as formulated by an expert or stakeholder, usually characterized by ambiguous information. Besides, the results of FCM are easy to interpret for the individuals and the public. However, if they're used to model qualitative System dynamics (SD) behaviour, traditional FCM also has several drawbacks. These shortcomings are largely due to incomplete: semantics of causation and thus the limited causation dynamics perception, depiction, and simulation; inclusion of time relations; diffusion detection, depiction, and simulation; dynamics simulation using single-layer perceptron mechanisms. Several FCM extensions have been developed to overcome these shortcomings, but most of the developed extensions are trying to solve specific problems with traditional FCM and do not try to solve the problems related to modelling FCM dynamics.

FCM consists of concepts (linguistic terms) that are expressed by nodes. Directed arrows with scales explain the relations between concepts. These weights describe the strength of causality with ({-1,0} and {0,1}), which, respectively, denotes the decrease and increase of causality. Concepts and their reciprocity are depicted by nodes and directed arrows with their weights explain the layout of a particular system. It is depicted in a matrix that allows to perform standard algebraic operations to find relations between nodes. The FCMs that were introduced by Kosko are simulated using a mathematical formula expressed in the equation (2.8).

$$C_j(t+1) = f(\sum_{\substack{i=1 \\ i \neq j}}^{n} w_{ij} * C_i(t)), \quad (2.8)$$

Where n is the number of concepts, C_j (t+1) is the value of the concept in the next iteration. Ci (t) is the value of the concept during the iteration t and w_{ij} is the wight of the reciprocity between cause and effect. Then it is mapped on a predetermined universe in discourse using transformation functions. It is then mapped to a predetermined universe in discourse using transformational functions, the most common are the achievements of the sigmoid and hyperbolic transformation function FCM in relation to modelling and simulation.

Ideally, when modelling a complex qualitative SD, it should have FCM and be able to capture and model causal dynamics, as experts believe. This includes integration and capture of certain causative dynamics properties, which may include, but are not limited to, the following:

- The cause can manifest itself in different conditions or in different ways;
- The cause cannot be two states or an example of strength in time (two states are possible only in quantum superposition);
- The cause is before the consequences, so time dependence is a characteristic;
- The influence of the cause must either increase or decrease;
- The cause in a certain condition can create consequences, which result because of the dynamic time lag, time delay or time reduction;
- The cause can create consequences that are dynamic as a result of changes in position or strength (i.e., they can be nonlinear, non-monotonic, and asymmetric);
- The effect is felt only when there is a change in the state or the strength of the process;
- Influence may be the result of relative causes.

In addition, ordinary FCMs and several achievements of single-layer perceptron are used to model and explain the dynamics of the quality system as a universal event. However, SD, causation can be conditional, probable or possible in terms. Lastly, in the best-case scenario FCM also reflects the uncertainty and indetermination of excerpt knowledge. They can be represented and simulated by using fuzzy systems and FCM, as it was foreseen by Kosko his approach is suggested and intended as a combination of fuzzy logic and artificial neural networks.

Methodology was used for evaluation of bioproducts. FCM modelling method was used in the study to compare different production processes methods and to understand which of them best meets the sustainability criteria and to identify potential barriers to obtaining reliable and objective results while using the FCM method and whether the use of this type of integrated analysis is appropriate to compare the different production process alternatives that were looked at in the study. FCM modelling requires a sequential set of activities that will ensure that the research objective is achieved in a transparent and understandable way to analyse 16 manufacturing processes.

In order to compare all the described production processes, it is necessary to define the most important criteria. A number of criteria are used in this process, making choices more efficient, rational, and clear. The aim of the analysis if to structure the processes to define the objectives, evaluate the possible alternatives and compare them from different perspectives. The following criteria were selected when evaluating the priority criteria:

1. Environment aspects;
2. Technological aspects;
3. Economic aspects;
4. Social aspects.

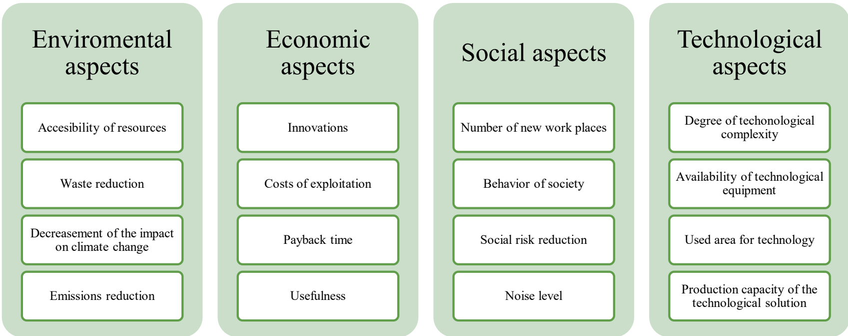


Fig. 2.2 Aspects of evaluation criteria

Considering the limitations of the information availability, sustainability, and usefulness indicators from the point of view of bioeconomy have been selected for modelling.

All selected criteria and sub-criteria are qualitative, so they should be assigned numerical values based on the analysis of the production processes performed in the study. The qualitative characteristic approach, unlike the quantitative results approach, makes the results that were obtained in the approbation part of the methodology more subjective. However, if the accurate quantitative data on the processes were available, the view on the usefulness performance would be limited.

Each sub-criterion will be assessed with a value from -1 to 1, where the strongest link be donated by 1 and it will denote the best, strongest possible link from the point of view of bioeconomy and usefulness. The rating link one that was obtained in the sub-criterion is comparable to the highest implementation efficiency. Whereas the lowest rating -1 indicates the weakest link or result from the point of view on bioeconomy and usefulness.

2.6. Life Cycle Assessment

During research actual, real-life example and models were analysed using Life Cycle Assessment (LCA) methodology, including basic metric for systems, and options on merging of results.

To prove hypothesis and establish major principles, Life Cycle assessment (LCA) approach will be used. The foundations of methodology dates to the 1980s. The overall principles and structure of this methodology were set in ISO 14040 standard in 1997. However other LCA practises exist like the CML, EDIP97 and ILCD guidelines from European Union (EU) Commission.

LCA framework comprises of four distinguished parts: definition of goal and scope, inventory analysis, impact assessment and data interpretation.

A deliberate and well-considered definition of the goal of the study is a key for a successful start of LCA. In this phase the functional unit is defined. It is a quantitative description of the service or function for which the valuation is performed. This phase is the basis that scales the data collection for inventory analysis (next phase) by determining the reference flow of the product. Scope definition includes assessing the product system and determining which processes and activities belong to the life cycle for the subject of the exact study. Geographical and temporal boundaries are set in this phase and the applicable perspective to use in the study is decided. Goal and scope definition subsequently influence when the outcomes of the research are interpreted.

Data about the physical movements is described in the inventory analysis. Input of resources, resources and products are to be considered as well as output of emissions, leftover and valued end products. All the processes that belong to the product system are studied in this part by considering generic cradle-to-gate data (material production, electricity or heat usage, transportation, and waste management). Study is performed by determining and defining process flow within the defined system boundaries, developing data collection methodology, collecting the relevant data, and reporting the results of the study. The life cycle inventory is the outcome of this phase.

Table 2.3

Inventory of cultivational of functional unit

Materials and activity	**Unit**	**quantity**	**kg, diesel**	**l, water**	**kWh**	**Total qnt. in 31 year**	**per 1000 kg frozen berries**
Field preparation - year 0							
Land use	m^2	10000				10000.00	**3377.24**
Ploughing	set	1	24.9			24.90	**8.41**
Disc cultivation	set	1	6.225			6.23	**2.10**
Drag harrowing	set	1	7.055			7.06	**2.38**
Green manure sewing	set	1	6.64			6.64	**2.242**
Green manure harrowing	set	1	7.055			7.06	**2.383**
Field establishment - year 1 to 3							
Fertilizer: NPK 15:8:15	set	1	70				
N			10.5			31.50	**10.638**
P			5.6			16.80	**5.674**

K			10.5			31.50	**10.638**
Fertilizer: ammonium nitrate	set	1	20			60.00	**20.263**
Irrigation energy	set	5			1.5	22.50	**7.599**
Irrigation water	set	5		6250		93750.00	**31661.60**
Mowing between lines	set	2	6.225			37.35	**12.61**
Geotextile	m^2	2500				2500.00	**844.309**
Irrigation system (pipes, PVC, d16)	m	2500				2500.00	**844.309**
Maintenance: year 4 to 30							
Fertilizer: NPK 8:11:23	set	1	250				
N			20			540.00	**182.371**
P			27.5			742.50	**250.760**
K			57.5			1552.50	**524.316**
Fertilizer: ammonium nitrate	set	1	20			540.00	**182.371**
Mowing between lines	set	2	6.225			336.15	**113.526**
Irrigation energy	set	5			1.5	202.50	**68.389**
Irrigation water	set	5		6250		843750.00	**284954.407**
Harvesting: year 4 to 30							
Tractor as support on field	set	1	12.45			336.15	**3.66**

Impact assessment evaluates the product system impact on the environment by using environmental science models. The use of LCA is essential to evaluate the overall impact avoiding environmental burden shift and the effect of energy efficiency measures across the entire cold chain.

Particular attention is given to evaluation of the effect of potential energy efficiency measure within the specific case study of locally produced sea-buckthorn berries. The study followed the ISO 14040 and ISO 14044 guidelines. The LCA software SimaPro 9.0 by Pré Consultants and EcoInvent v.3.5 were used to generate the LCA model and undertake the impact assessment calculations. SimaPro is the world’s leading LCA software package with experience and history of 30 years. It is mainly used by industry and academics in more than 80 countries. SimaPro was established to crate tool to apply LCA principles using proper methodology and to provide the facts needed to create justifiable value using simulations.

2.7. Life Cycle Cost Analysis

The concept of a Life Cycle Cost Analysis (LCCA) is widely used to analyse and evaluate various project alternatives. Main task of LCC is to find out project profitability over the its life span, including obtaining of project assets and ending with disposal. LCC is used as tool to support decision-making process. Life Cycle Costing approach was born few decades ago, at 1965 in USA when the United States Logistics Management Institute used the name of life cycle costing while seeking lower costs in military logistics as a result of economic stagnation [43].

From that time period US departments and agencies were starting to apply this approach in government procurement procedures. Being part of military expenditure calculations created added interest, and of a lot of practices and publications on theory of Life Cycle Costing developed. Now LCC methodology became common worldwide and is used not only by government organizations but also businesses widely have introduced LCC in their procurement and development strategies. Nowadays the approach is commonly adopted in scientific research and engineering fields. The current literature and publications on LCC are filled with examples of application of this approach in various aspects of investments – starting from construction projects and ending with analysis of investment in environmental activities [44].

In addition, LCC is accepted also in European Union (EU) legislative process, for example, public procurement under EU law. Directive 2014/24/EU promotes use of Life Cycle Costing approach in public procurement to detect the most economically advantageous tender in order to support sustainable growth. Life Cycle Costing Analysis approach is widely used due to many advantages while comprising some disadvantages or constraints.

LCC is a purely based on cost efficiency approach and is data driven, therefore it requires a detailed estimation or inventory of the overall costs and benefits of a project studied. Any project comprises countless cost positions. In general, any project has four life cycle phases (see Fig. 2.3).

According to theory, first is development phase, which includes all costs related to research, planning, obtaining of property and design. The second is the construction phase, which comprises all costs associated with establishing of facilities. Next is operation phase, where operational, maintenance and repair costs are to be identified.

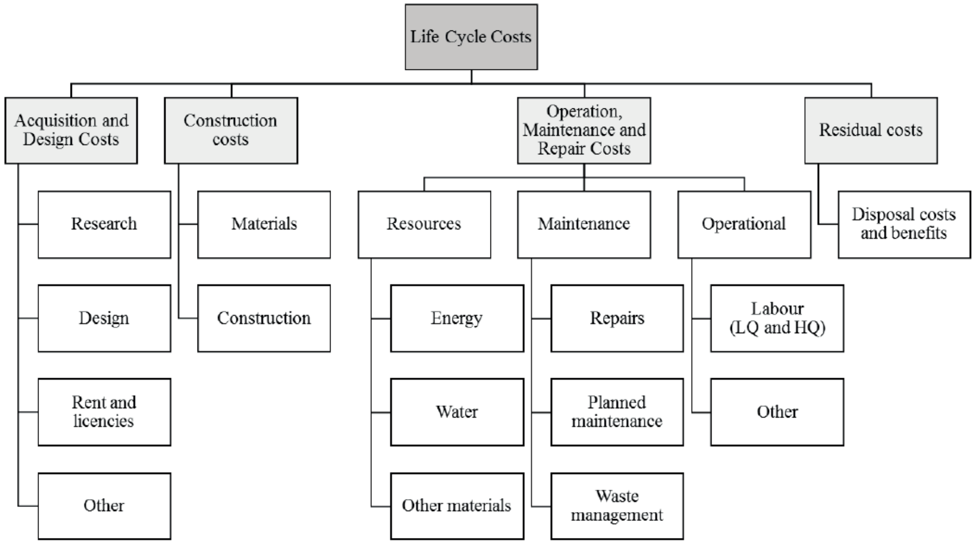


Fig. 2.3 Common Life Cycle Cost structure of a project [45]

A final phase includes all the costs related to maintenance values of the project, which can be positive or negative values. Nevertheless, LCC approach distinguishes three life cycle cost positions, for which an inventory should be done, because commonly acquisition, design and construction costs are considered as initial costs. LCC inventory should be carried out for investment costs, both initial and capital replacement, operating, maintenance and repair costs, and residual costs.

The basic metric of LCC is Net Present Value (NPV). The NPV method is the present value of the total income, created by the project during its expected lifetime. In essence that is a comparison of the present value of all income and expenses within project.

The NPV method is based on discounting of cash flow. In order to discount or convert money flows taking place over time to comparable values, at a given point in time, parameters as discount rate, discount factor, number of cost periods and base year are used. Discount rate is "the rate of interest, reflecting the investor's time value of money (or opportunity cost), that is used in discount formula or to select discount factors which in turn are used to convert (discount) cash flows to a common time" [46].

Discounted net income is an indicator calculated by discounting all expected cash expenditures and revenues from the project to the present value. Discounted net income is the difference between discounted cash income and expenses.

In the NPV calculation, each cash flow element is discounted based on the cost of capital in the given project. The discounted cash flow elements are aggregated so that they can be calculated, and NPV must be greater than zero for successful project. The NPV is then compared with an alternative project.

Discount rate is used in Eq. (2.9) to express discount factor, which in turn is used as discounting multiplicator.

$$DF = \frac{1}{(1+r)^n}, \tag{2.9}$$

where *DF* – discount factor

r – discount rate

n – number of years ahead

Discount factor is a multiplicative value used to convert cash flow (inflow less outflow) over time to comparable values, at a chosen point in time [46].

Cash flows are discounted, or present values are obtained by multiplying discount factor and the value of money in a given year. All calculations obtained over the years are summed up which represent as discounted cash flow amount, or NPV.

In practice, it is usually assumed that discount rate is constant over time ($r_1 = r_2 = r_n$). With a time-invariant discount rate NPV value of cash flows (including initial investment) can be obtained by using general Eq. (2.10).

$$NPV = -K + \frac{CF_1}{(1+r)} + \frac{CF_2}{(1+r)^2} + \frac{CF_3}{(1+r)^3} + \cdots + \frac{CF_n}{(1+r)^n}, \tag{2.10}$$

Where NPV – net present value

K – initial investment at the base year

r – discount rate

CF – cash flow

n – number of years ahead

Cash flow discounting commonly is conducted in terms of "constant dollars" or constant value of money [46].

It means, that in assumptions there is no specific rules for future inflation or deflation. Constant value of money has uniform purchasing power which is linked to the base year. Thus, it is assumed that goods and services will change their value in constant and uniform pace.

The size of the NPV of a project depends on the distribution of negative and positive cash flows at a time. Also, the NPV of a project varies depending on the discount rate. Usually the higher the rate, the lower NPV. The project is acceptable with the given discount rate if the NPV is positive. However, it should be noted that the chosen discount rate may be subjective, thus also the result of NPV calculation may be subjective. These financial aspects should be taken into account in discounted cash flow analysis and well documented.

Valuation of investment projects using Internal Rate of Return (IRR) is based on the discount rate setting a ceiling at which projects remain profitable. IRR - this is it discount rate at which NPV = 0. At the same time, it also shows the maximum return on the project an investor can get. This method assumes that the investor already knows the interest rate. Using different interest rates, one can find a rate that is acceptable in the way of exclusion given investment project. The interest rate (internal rate of return) found in this way is compared with the rate set by the investor and a conclusion is made about the investment project profitability. Investment projects with a higher internal rate of return are more profitable.

The discount rate is freely investigated, and cash flows are calculated on the basis of it total present value. Project investment costs are compared with those obtained the amount of current cash flows. If the first freely chosen discount rate does not give a net zero value of the current cash flow, the second discount rate is selected. If NPV> 0, then the new discount rate must be higher than the one initially selected. If NPV <0, then the new discount the rate must be lower than the one initially selected. The second discount rate is sought if the total present value of the income will be both higher and lower than the project costs.

When choosing a discount rate, it is advisable to increase the interval as much as possible. Accurate IRR calculation is only possible with the help of a computer.

The purpose of the Life Cycle Cost Analysis (LCCA) methodology is to provide basis of economic study to evaluate discounted cash flows of a main scenario and proposed deviations from main scenario over its life span. The Life Cycle Costing (LCC) is an economic analysis and considered as the basic element of LCCA [43] defines a life cycle costing approach as "the process of economic analysis to assess the life cycle cost of a product, service or system over its proposed lifetime or a portion of thereof". In other words, LCCA is a procedure for evaluating and analysis of total costs of a project (or a part of the project) and benefits over its expected life span, while taking into account different alternatives and the time value of money in order to select the most cost-effective solution of the project (Fig. 2.4).

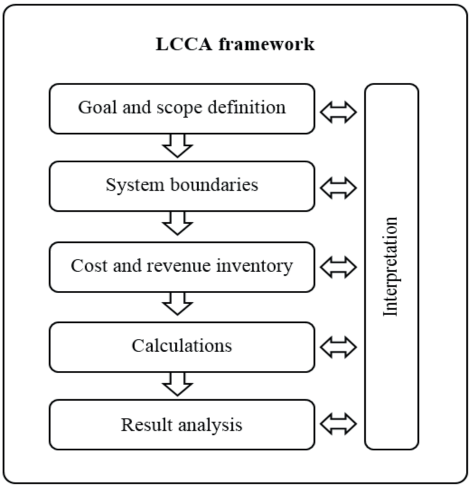


Fig. 2.4 LCCA framework [46]

To be able merge both LCA and LCC, there are some crucial aspects to be taken in account.

In the phase of establishing main targets and definition of a merged LCA and LCC, functional units and system boundaries must be the same. Choosing same functional unit is not a challenge and is rather intuitive step, because systems main product is the same.

Most challenging is to draw system boundaries so that both systems can be inter-compared. It is related to fact, that LCA is not considering, for example, labour intensity and activities in its costs, however it is important in total project cost side, analysed by LCC. Change in labour costs due to fact, that LCC is affected by values like profit, work created costs etc., which do not have impact on LCA model. It is recommended to use the same functional unit when combining LCA and LCC, and also the same system boundaries.

Table 2.4.

Inventory of life cycle costs

Acquisition		
Overgrown land	20000	purchase price 2000 EUR/ha
Construction		
Seedlings	12500	1250 EUR/ha, two-year-old, four varieties, developed from cuttings
Labour	2000	salaries for workers to plant seedlings
Geotextile	8000	800 EUR/ha, 110 g/m^2, 105 cm wide, rolls
Irrigation system	15000	1500 EUR/ha, delivery and assembly included
Land improvement	1500	services for land improvement
Operation and maintenance		
Labour	5000	seasonal workers to pick up berries
Annual debt payment	1536	fixed total costs for bank loan
Transportation of raw material	500	seasons total for ten days rent, 50 EUR/day
Processing	2000	total for freezing, cleaning and packaging
Cold storing	816	12 EUR/ton per month
Cold logistics	1300	seasons total for twenty days rent, 65 EUR/day
Fuels	500	fuels for tractors and rented vehicles
Fertilizers	2430	fertilizers for plants according to schedule
Operational costs	1000	various costs, including accounting, banking fees, electricity etc.

Meanwhile, each separate model system boundaries can present some differences when performing analysis accordingly [47].

There are items that can be distinct within LCA or LCC, based on their relevance to whole inventory. Specifically, while some activities are environmentally relevant (fuel usage, waste management) they could not be so important for LCC analysis. From other side, LCC include crucial parameters without any environmental impact, like salaries, interest rates and profit margins.

According to [47], suggestion is to define cut-off assumptions for both systems, to correctly address them while defining goals and scope.

In merging both LCA and LCC systems most crucial and complex part is combining results and interpretation. There are several suggested methods, how to merge both methodologies.

When outputs from both inventories are collected as described previously, joint LCA and LCC result collection must be put together in equivalent way.

By applying LCA and LCC methodology various indicators were obtained. To properly assess them, it is necessary to use multicriteria analysis. For research purposes Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used.

3. RESULTS

The research subject has many levels, differing in scope and approach. During research several specific dimensions f sustainability in products were chosen for analysis.

3.1. Logistics and processing

Modern economy cannot be imagined without logistics, and it is impacting every level of entrepreneurship. During research cold chain logistics were analysed from perspective of logistics impact on whole chain through LCA (Publication 1).

In Publication 1, to perform analysis of logistics in case study – sea buckthorn supply chain – all the relevant data was collected and LCA model was created. Data collection itself do not let to understanding of characteristics of whole system. Therefore, LCA software SimaPro and impact assessment methodology of Impact 2002+ was used. The main contributors of base scenario to the total aggregated environmental impacts of sea-buckthorn project with mass allocation logistic stage is depicted in Fig. 3.1.

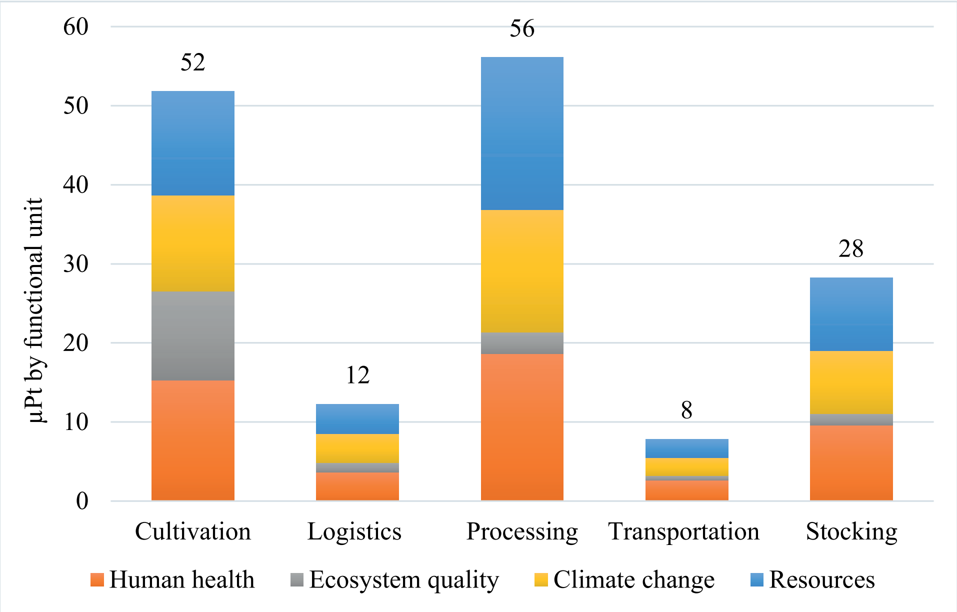


Fig. 3.1 Impact aggregation by SimaPro of base scenario

Processing, as can be seen, has main impact. Data makes sense, because sea-buckthorn berries must be cleaned, and packed, but mostly impact is generated by flash-freezing of all the yield. Logistics and transportation are creating less impact than cultivation and stocking due to rather short delivery distance and energy intense processing.

During research, base model was compared energy efficiency improvement options - warehouse insulation and change of engine of transportation vehicle from EURO 4 to EURO 6 standard without another changes in inventory. The rest of assumptions are the same as in base scenario.

Results of simulations show that total environmental impact per functional unit varies in less than 1%.

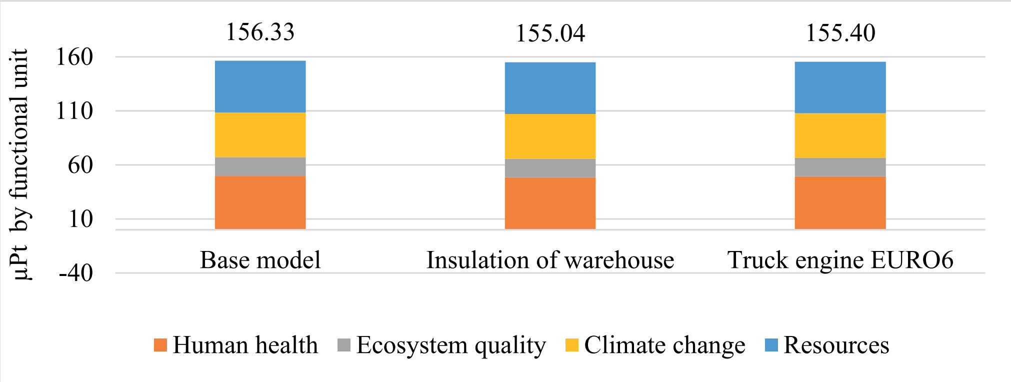


Fig. 3.2 Scenario comparison, total endpoints

Accordingly, midpoint analysis also shows, that differences in each results of simulation vary little. It, nevertheless, should be considered, that for each subprocess of whole model differences can reach bigger proportions (Fig. 3.3).

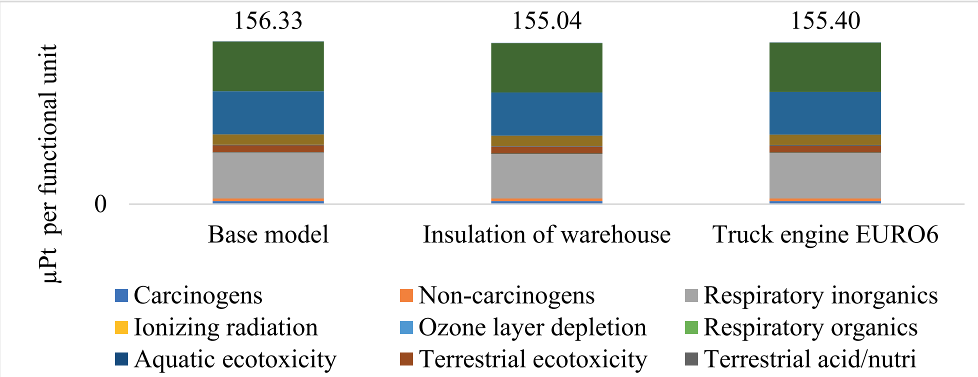


Fig. 3.3 Midpoint analysis of three scenarios

Midpoint analysis permits to see main categories of environmental impact from modelled situation. Impacts are mostly related to non-renewable energy sources used, mainly fuels. Also, electricity contributes to impacts.

3.2. Renewable energy sources

Energy is bloodstream of every economic activity. Publication 2 evaluates renewable energy technologies (RES) using a combination of AHP and TOPSIS methods using technical, economic, environmental, and social criteria. To indicate the needs, potential barriers, and position of enterprises on renewable energy, an enterprise survey is conducted.

The survey results from 146 enterprises were compiled and analysed only in aggregate form. 42 % of respondents already use renewable energy technologies in their enterprises, while the majority or 58 % do not. As main key constraints for the broader use of renewable energy technologies, 33 % of respondents mention other investment priorities, 26% of respondents – long payback periods, that have primary reference to costs, and 20% of respondents – constraints of existing infrastructure, which are connected with technical aspects as well as economic aspects. Grant/subsidy is indicated as the main incentive to promote RES technologies (59% of respondents). Apart from the availability of grants/subsidies, awareness-raising as a better understanding of technology is the second most frequently mentioned option to help increase the use of RES technologies (17% of respondents).

22 % of respondents could not specify their electricity consumption in terms of quantity or cost, while most of the respondents could indicate both consumption and costs or at least one of them. Nevertheless, only 29 % of respondents indicate that energy consumption is among the top three cost positions in their enterprise, while for 63% of respondents, energy costs are not among the top three cost positions, and 8% of respondents cannot indicate if it is or not.

72% of respondents are interested in receiving the results of the survey and obtaining additional information regarding RES technologies, while a relatively large proportion (28%) answered in the negative.

Aggregated results show that according to the respondents' answers, the top three RES technologies for which they see the highest potential in enterprises are solar energy for electricity, solar energy for heat energy, and biomass technologies. Fig. 3.4 shows the rankings of all RES technologies.

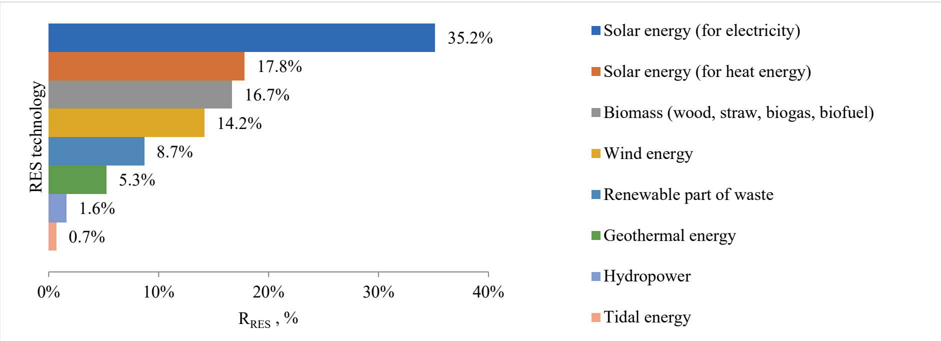


Fig. 3.4 Ranking of RES technologies according to enterprise survey results

In the authors' view, the result which ranks these three technologies as the technologies with the highest potential in view of enterprises can be linked to a better understanding of technologies. These three technologies are already the most widely used (known) among the enterprises surveyed, and some experience has been gained in their utilization. For this reason, it is possible that preference is not given to the most appropriate RES technology but in favour of the technology for which the enterprise has a sufficient amount of information.

In TOPSIS analysis six RES technologies were evaluated using a scale from 2 to 5, where 2 correspond to the lowest score and 5 – to the highest score and potential of the use of renewable energy in the industrial enterprises. Table 3.1 compiles the evaluation values in a decision-making matrix.

Table 3.1

TOPSIS decision-making matrix

RES technology	Aspect			
	Technical	Economic	Social	Environmental
Biomass	4	3	4	5
Solar PV panels	5	4	5	4
Solar thermal	4	3	5	4
Waste	3	4	4	4
Wind	3	3	5	4
Geothermal	3	3	4	4

The result of the TOPSIS analysis is shown in Fig. 3.5. For the best solution, the closest alternative is solar electricity (0.94), which is due to the high valuation of this alternative, not only for the economic criterion which has the highest weight of all criteria (0.4859), but also good performance in the technical criterion which has the second-highest impact on results. Technologies that use renewable part of waste as an energy source ranks second (0.48), however, its performance significantly lags behind solar PV. These technologies are followed by solar thermal energy (0.34) and biomass technologies (0.31) with relatively similar results. The furthest score from the best solution is for wind and geothermal energy technologies (0.16).

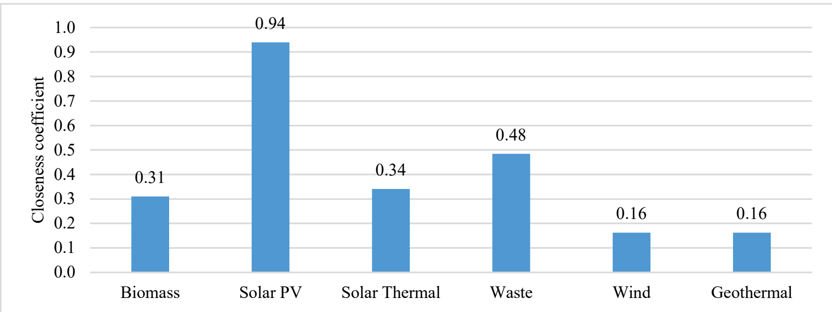


Fig. 3.5 TOPSIS analysis results – the ranking of RES technologies

3.3. Greenhouse gas emissions

During research of cold supply chain (Publication 1) environmental impact of different supply chain length was analysed. Starting model with rather short cold supply chain was used, only 60 km long. For research purposes distance of 120 km and 240 km was analysed. Distances are practically used in Latvia, and represent, for example, delivery from Riga to Liepaja.

Analysis of impact and its relation to distance was carried out. As seen in Fig. 3.6, relation is linear. In Figure starting point is base model, because there was decision not to analyse system with even shorter path than 60 km.

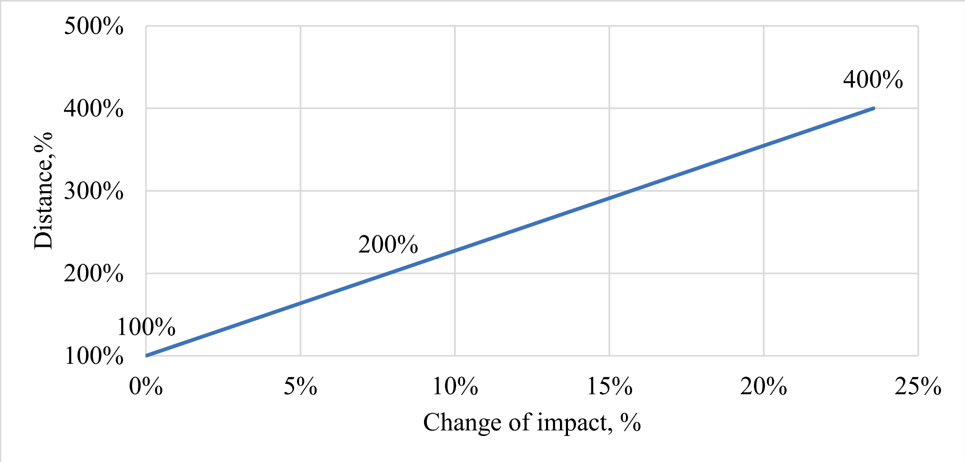


Fig. 3.6 Impact and distance correlation

Fig. 3.6 also lets to understand dynamics of distance impact for international cold supply chain. Even within EU, where distances are not so great, compared with world, delivery of couple of thousand kilometres significantly increase role of cold supply. As seen in Fig. 3.7, even with delivery of 240 km, cold chain transportation impact reaches major impact.

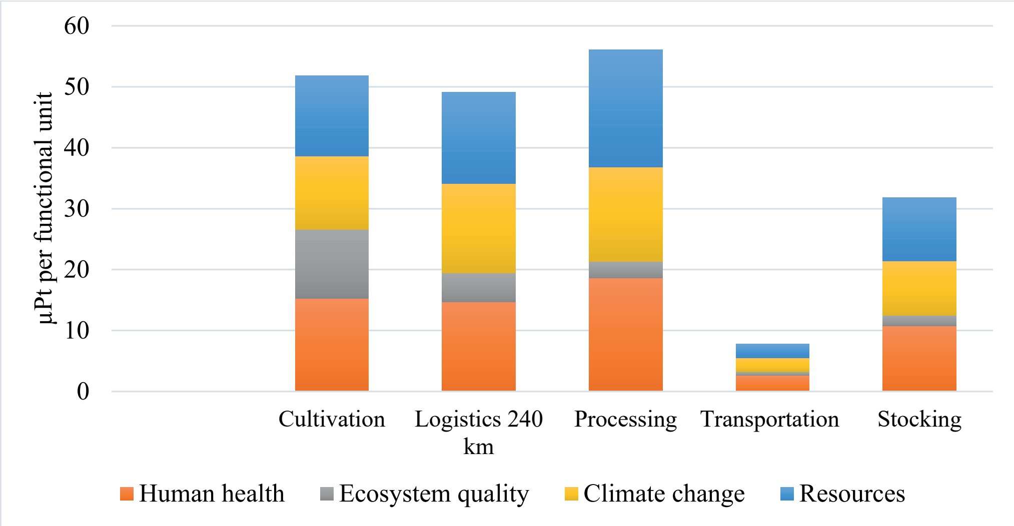


Fig. 3.7 Impact aggregation for 240 km cold chain

This data should be considered when various national or EU level policies are developed. Subsidies for local usage of resources and production, or harsher regulation for long distance deliveries could greatly impact total aggregated environmental impact.

During the research in Publication 5, a systematic review and bibliographic analysis were conducted, and different Decision Support Tools, including calculators used for an impact assessment of the agricultural sector, were investigated. GHG calculators play an essential role in the promotion of sustainable practices in agriculture and help to raise awareness about the need for a shift of agriculture practices towards climate neutrality. The need to access and monitor the environmental impacts of agriculture practices and services has resulted in the development of numerous GHG calculators.

The results of the TOPSIS analysis allowed the identification of the three most advisable decision-making tools for use by horticultural farmers. The results of the TOPSIS analysis are shown in Fig. 3.8.

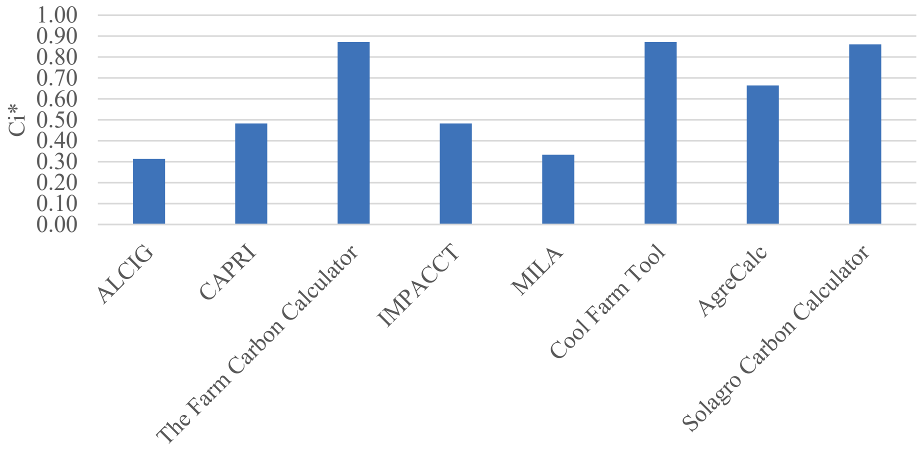


Fig. 3.8 Comparison of ratings of GHG emission calculators

All calculators were analysed from technical, economic, social and environmental dimensions, using five indicators. The results show that the Solagro Carbon Calculator, The Farm Carbon Calculator, and Cool Farm have a higher rating and are recommended in the first place as GHG calculators for farmers. At the same time, it should be noted that all selected GHG calculators are applicable to approach, measure, and evaluate horticulture farming for small and medium-sized companies.

3.4. Materials and added value

Creation and usage of new, sustainable resources and materials is one of main trends for decades to come.

In Publication 3 bio-based thermal packaging is analysed. 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 [48].

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 [49].

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 [50].

During stakeholder interviews the most important criteria of material was determined. Data was used for 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. 3.9.

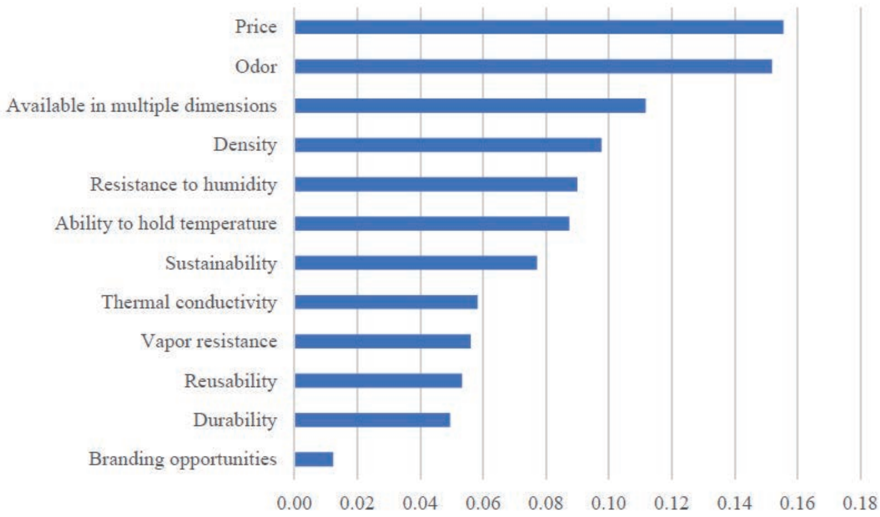


Fig. 3.9 Weighed criteria in ascending order regarding their importance

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. 3.10).

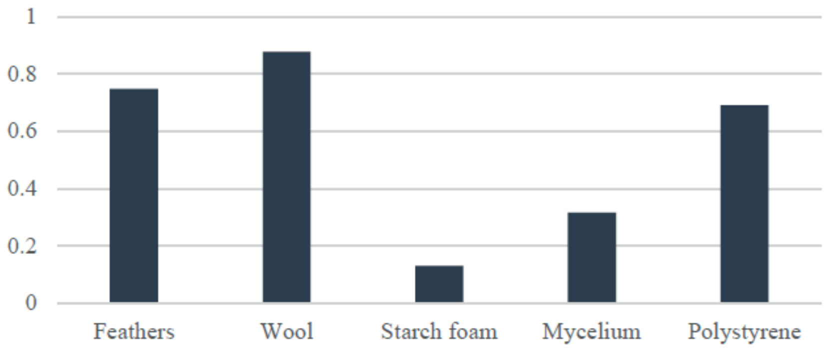


Fig. 3.10 Technique for Order of Preference by Similarity to Ideal Solution ranking of thermal packaging materials. Y axis represents the proximity to ideal solution 1

Among the thermal packaging options, the closest proximity to ideal solution (represented by 1 on Y axis in Fig. 3.10) 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.

Publication 6 also look into added value in bioresources. This research delves into the potential transformation of wood chipboard into a 100% bio-based product. Previous research has shown the possibility of the partial replacement of petrochemical-based adhesives with bio-based adhesives. Hence, previous results do not reach the policy ambitions of the Green Deal of making the Green Transition to a bio-based economy. For chipboard production, logging residues from Latvian State Forests were systematically gathered within two months post-logging, comprising primarily Picea abies and Pinus sylvestris biomass, including branches, needles, bark, and various particles. This study demonstrates the feasibility of creating bio-based chipboards using logging residues and bio-based adhesives.

Analysing 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 Fig. 3.11. 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 were 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).

Calculated standard deviations are depicted in graphs, confidence value of 95% (P-value<0.05) was used in the analysis.

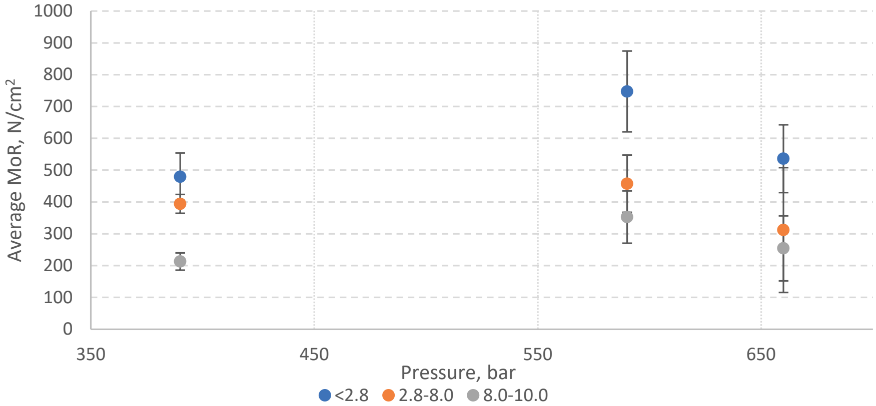


Fig. 3.11 Modulus of Rupture depending on pressure and particle size

There was no significant impact of the chosen pressure extremes on 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.

3.5. Innovations and investments

In Publication 4 added value of bioeconomy products are analysed. Bioeconomy is not only considered to be a bio-resource economy, but it also means the sustainable consumption of bioresources, which creates added value for society. Although it is established in European Union Directive 2008/98/ EK (European Parliament and Council, 2008) that production by-products are not classified as waste, but in establishments they are often considered as one and sent to waste streams or low-value streams, such as, production of biogas or solid fuels [51].

Development of a bioeconomy, based on skills on innovation and investment in knowledge, is inevitably required in turn to achieve a large part of set goals [52].

Bioeconomy is based on three principles of sustainable development – economics, society, and nature. These three pillars – fundamental principles must form a closed cycle, where the by-product of the process (waste product) is the raw material of another process [51].

This kind of approach to bioeconomy raises and enhances the added value of products and replaces fossil fuels in energy production and reduces greenhouse gas emissions.

The aim of the research was to create and offer bioeconomy opportunities, by demonstrating, analysing, and describing possible solution with the help of various examples. This is an illustrative and demonstrative research on how to create possible bioeconomy solutions that would promote the achievement of the goals of the Green Deal and would be suitable for implementation in Latvia.

The study presents a way to select production processes, improve and optimize them, categorize, and classify them according to the principle of sustainability. Analyse the improvement of production processes with different methods and compare them to crystallize the best and most suitable processes from the point of view of bioeconomy and sustainability. A total of 16 different production processes have been selected, based on a significant improvement of an existing production process: process optimization, reduction of residues, full use of added value of emissions or other production process residues, or reduction of electricity consumption and progress towards cleaner production.

In total 16 production processes were analysed using Fuzzy Cognitive Mapping. It was concluded that eleven of the described sixteen production processes have reached very high values in the range of 0.9 to 1 and all eleven production processes correspond to high bioeconomy efficiency towards the goals of the Green Deal, consequently these production processes are very valuable and should be primarily implemented in the economy by investing in production facilities.

Table 3.2

Usefulness of production process

Citric acid production	**0.97**
Synthesis of silver nanoparticles	0.96
Manufacture of composite materials	0.98
Nanocellulose production	0.92
Manufacture of toiletry from whey	0.97
Xylan production	0.92
Polykactide production	0.97
Manufacture of natural nettle fibres	0.29
Biodiesel production	0.73
Production of Dendrolight cellular material	0.98
Pellet production	0.83
Bioethylene production	0.68
Cellulose production	0.94
Tannin-based foam production	0.90
Coniferous extract production	0.96
Lignin production	0.83

Considering the objectives of the study, the obtained results are reliable and objectively reflect the validity of the FCM method, and the use of this type of integrated analysis is appropriate to compare the various alternative production processes considered in the work for obtaining best added value for bioresources.

CONCLUSIONS

Each sustainability dimension, according to the research framework, unlocks new bioresource usage criteria and opportunities. Conclusions are arranged according to the research framework.

It can be concluded that implementation of sustainable practices in the usage of bioresources can significantly reduce environmental impact and enhance economic benefits.

Logistics and processing

Tailored life cycle inventory for both economic and environmental feasibility assessment using primary data sources from actual agricultural practices used in Latvian context (and extendable to Northern European) together with in-depth data inventory from each actor involved in cold supply chain of frozen sea-buckthorn berries was made. This ensures a specific and accurate data collection for the definition of the proposed supply chain. Within the methodology developed merging LCC and LCA it is possible to evaluate the overall feasibility of the cold chain. The results show the main environmental hot spot have been identified in connection to climate change and use of resources in the processing and stocking of production, providing important suggestion about potential improving scenarios.

Renewable energy sources

Considering that the total installed solar energy capacity currently installed in Latvia is growing, but still insignificant in comparison with other RES technologies, the result, which both after multi-criteria decision analysis and in the opinion of enterprises, puts solar PV as a priority technology, is favourable for support policy development. RES can and will pay significant role in sustainable usage of bioresources.

Greenhouse gas emissions

With increased focus on the sustainable agriculture and sustainable development of a sector, farm-level evaluation of GHG emissions is essential to ensure sustainable usage of bioresources. Specific GHG tools make it possible to perform calculations without specific background on subject.

Innovations and investments

The production usefulness of 16 chosen bioproducts show that the most efficient and effective production process is the production of composite materials. This result is justified by the availability of raw materials for composite materials, which are mainly by-products of other production processes: low-quality wood residues and recycled plastics. As well as the demand for such composite materials on the market is growing rapidly due to its physical properties, production technologies are relatively simple and available without excessive investment.

For sustainable development bioresources must substitute or completely exclude fossil-based solutions. With today's climate objectives, it is crucial to completely rethink construction and housing approaches by completely excluding fossil carbon from the market. Therefore, the scientific community and industry need to find working alternatives. The findings are intended to contribute to the development of strategies and policies that promote the sustainable use of bioresources starting from farm level and providing tools for more general policy making.

Materials and added value

Despite polystyrene's popularity, 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 bioproducts – 'Woolcool' and 'Pluumo' outperformed polystyrene packaging when compared in price, density, ability to hold temperature, environmental impact, and thermal conductivity. 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 solution.

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Article

Environmental Impact Decision Support Tools for Horticulture Farming: Evaluation of GHG Calculators

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Abstract: Horticulture is essential in the European agricultural sector and fundamental for many EU member states. Decision Support Systems and Tools can play an essential role in a shift to result-based agriculture and evidence-based decision making, improving productivity and environmental performance of farming practices. Investigations have been conducted on horticulture crop and farming impact on the environment and Green House Gas emissions. Despite the availability of a broad spectrum of tools, the use of Decision Support Tools in agriculture in Europe could be much higher. This research aims to analyze and recommend environmental impact Decision Support Tools for small and medium-sized companies to approach, measure, and evaluate horticulture farming. The research methodology includes a systematic review, bibliometric analysis, Multicriteria Decision analysis, and a case study analysis. During the research, multiple tools, including calculators used for an impact assessment of the agricultural sector, were selected. After applying eligibility criteria, an in-depth analysis of eight of the most suitable calculators was performed. The results of the Multicriteria Decision analysis show that the Solagro Carbon Calculator, The Farm Carbon Calculator, and the Cool Farm Tool are recommended in the first place as Green House Gas calculators for farmers.

Keywords: agri-food systems; common agricultural policy; simplified environmental impact tools; climate neutrality; farm-scale; GHG calculator; horticulture

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1. Introduction

The New European Union (EU) Common Agricultural Policy 2023–2027 is shaping the transition of the Agricultural sector to climate neutrality and sustainability. The future of agriculture is linked to modern, precise farming, leading to a fairer distribution of funding, depending on farming and emission reduction capacity. Decision Support Systems and Tools can play an essential role in a shift to result-based agriculture and evidence-based decision making, improving productivity and environmental performance of farming practices [1]. Different Decision Support Systems have been used in agriculture to help decision makers make optimal decisions regarding developing and managing a farm or a whole sector. Decision Support Systems have been used for decision making regarding water management [2,3], land use changes [4], overall farm management [5], better allocation of resources [6], and mitigation of climate change [7]. Ara et al., 2021 [8] analyzed different Decision Support Systems in irrigated agriculture, and Wong-Parodi et al., 2020 [9] described the role of Decision Support Tools in sustainability assessment.

Decision Support Tools allow for farmers, policymakers, and industry to make effective decisions, illustrating various outcomes from different practices. Rose et al., 2016 [1] listed 395 Decision Support Tools for United Kingdom farmers: software-based, paper-based, and apps.

Simplified sustainability Decision Support Tools have been delimited by Denef et al., 2012 [10] in Arulnathan et al., 2020 [11] as calculators, protocols, guidelines, and models.

Bibliometric analysis of Decision Support Tools in agriculture was used to explore a scientific interest field. Bibliometric analysis aims to show the state of the industry structure and emerging trends, is applied to the broad scope and large datasets, and is quantitative and qualitative [12]. Figure 1 illustrates the result of the bibliometric analysis. Bibliometric analysis was used to analyze open-access articles from the Scopus and the Web of Science databases and resulted in visualization by VOSviewer software (VOSviewer version 1.6.19).

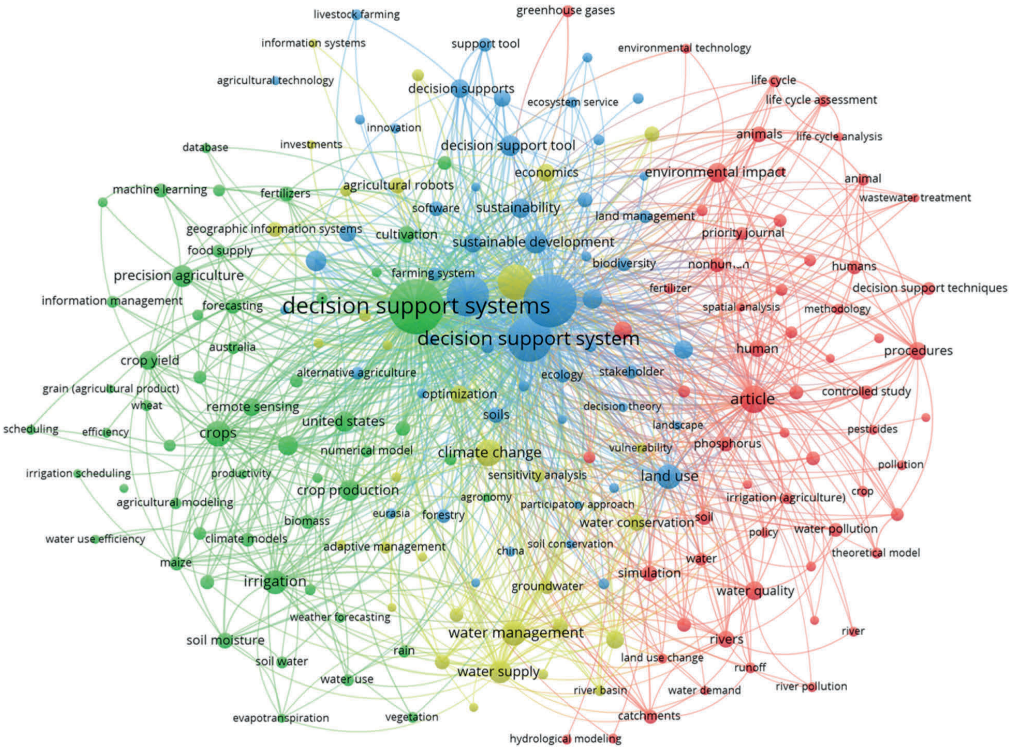


Figure 1. Keyword co-occurrence network for keywords "Decision Support Tools" and "Agriculture".

Articles from Scopus and Web or science databases were used for bibliometric analysis of open-access articles. Keywords "Decision Support Tools" and "Agriculture" were used as topics (search title, abstract, author keywords). When the used keywords appeared in the title, abstract, and author keywords, there were a total of 630 publications in Scopus and 1141 publications in Web of Science collected. Co-occurrences for all keywords equal to ten were used, and 198 of 5645 keywords met the threshold. All keywords were divided into four clusters (clusters are shown with different colors: blue, red, green, and yellow) with a more extensive cluster–Decision Support System. The results of a bibliometric analysis prove the topicality of the topic.

As shown in the bibliometric analysis, Decision Support Systems play an essential role in the sustainability assessment of the agriculture sector, and a broad range of applications and tools are used to analyze and improve the environmental performance of agricultural activities. A range of Decision Support Tools used in agriculture are described in the scientific literature. Olde et al., 2016 [13] focused on sustainability assessment tools at a farm level. As reported in Table 1 of the relevant publications, Whittaker et al., 2013 [14] evaluated carbon accounting tools for arable crops, and Colomb et al., 2013 [15] inspected greenhouse gas assessment (GHG) calculators for agriculture and forestry. In an article by Peter et al., 2017 [16], GHG emission calculators suitable for assessing energy crops were investigated. MacSween and Feliciano 2018 [17] summarized online GHG accounting tools for Tropical climates. Renouf et al., 2018 [18] evaluated customized life cycle assessment tools for agriculture. Decision Support Tools can be analyzed depending on the scope of application, geographic scope, type of modeling, and level of assessment [11]; for example, Farm-level Decision Support Tools [11] or farm-level accounting models for a specific field—dairy cattle systems [19]. Thumba et al., 2022 focused on analyzing Decision Support Tools used to assess livestock farming [20] There are articles in the scientific literature about using specific tools for a particular agri-food sector, like wine [21]. Casson et al., 2023 [22], on an example of 79 simplified environmental impact tools used in the agri-food sector, categorized available solutions to support stakeholders in a distinction of the most convenient tool considering specific elements to consider.

Table 1. Decision Support Tool review studies.

Publication	Field of Application	Tools Reviewed	References
Whittaker et al., 2013	Arable crops in the United Kingdom	11	[14]
Colomb et al., 2013	Landscape GHG assessment for agriculture and forestry	18	[15]
Arzoumanidis et al., 2014	Application of simplified LCA in the wine sector	4	[21]
Olde et al., 2016	Arable and livestock farm assessment in Denmark	4	[13]
Peter et al., 2017	Carbon footprint calculators for energy crop cultivation	18	[16]
MacSween and Feliciano, 2018	GHG Accounting Tools for Tropical Climate	6	[17]
Renouf et al., 2018	Customized agricultural life cycle assessment tools	14	[18]
Arulnathan et al., 2020	Farm-level Decision Support Tools	19	[11]
Vibart et al., 2021	GHG emission models for dairy cattle systems	14	[19]
Thumba et al., 2022	Decision Support Tools in livestock farming	11	[19]
Casson et al., 2023	Simplified environmental impact tools for agri-food system	79	[22]

Horticulture is essential in the European agricultural sector and is fundamental for many EU member states. Sector output comprises twenty-five percent of the total crop value in the EU and more than fourteen percent of the overall agricultural output value [23]. Horticulture contributes to the development of rural areas, encouraging sustainable food production and ensuring the achievement of the EU From Farm to Fork Strategy's targets [24,25]. European Plant Science Organization points to the need of the horticultural industry, dominated by small and medium-sized enterprises, for research-based Decision Support Tools available for farmers [25]. Carbon sequestration and developing "carbon farming" solutions suitable for horticulture is an actual topic in agriculture policy in the EU [26,27]. Carbon farming aims to mitigate climate change and shift to a green business model, like horticulture; therefore, a standard monitoring, reporting, and verification system is needed.

The calculations of GHG emissions from different horticulture practices using standardized tools is one of the possible solutions for monitoring agricultural activities and improving the ecological performance of a sector on the farm level. Multiple researches have been conducted about different horticulture crop and farming impact on the environment and GHG emissions. Soode et al., 2015 [28] measured the cradle-to-grave carbon footprints of strawberries. Schafer and Blanke, 2012 [29] analyzed the environmental impact of pumpkins in Germany. The authors refer to the limited information available about European horticultural product impact assessment and Decision Support Tools and, according to the results of bibliographic analysis, the United States of America, Australia, and Canada are the most analyzed countries.

Articles about perennial crops' carbon sequestration and the environmental performance of these cropping systems in Sweden [30], Spain [31], and Italy [32] analyze the effective strategies to combat climate change and refer to future investigation needs. GHG emission calculations using Decision Support Tools in Iran [33–36] and Japan [37] are found in the scientific literature.

The availability and accessibility of such sustainability assessment tools have extended from only scientists to a broader range of stakeholders, including farmers, managers, and environmental officers [21]. While it is beneficial to account for more viewpoints, several challenges also arise, like data mismatching, performance, easiness of use, availability, and relevance.

Despite the availability of a broad spectrum of tools, using Decision Support Tools suitable for a farm level and focused on GHG emission estimation of the horticulture sector can be broader and more methodical. Although different Decision Support Tools for subcategories of agriculture have been evaluated, the contemplated literature review highlights the need for more guidelines for horticulture farmers on using sustainability assessment Decision Support Tools to estimate GHG emissions. The GHG calculator is an easy-to-use tool available for farmers, allowing the calculation and evaluation of the environmental performance of horticulture practices in Europe. A broad range of GHG calculators can be applied to different fields, including agriculture activities. A roadmap to choosing GHG calculators intended as a Decision Support Tool for European farmers in horticulture is needed.

Considering the previous conclusions discussed in the literature review, this research aims to analyze and recommend environmental impact Decision Support Tools—GHG calculators to approach, measure, and evaluate horticulture farming for small and medium-sized companies.

2. Methodology

The overall research methodology combines different scientific methods: systematic literature review, bibliometric analysis, Multicriteria Aecision analysis, and a case study analysis.

2.1. A Systematic Literature Review on Environmental Impact Decision Support Tools for Horticulture

A systematic review and meta-analysis were used to present the results of data from existing studies conducted on existing Decision Support Tools suitable for a farm level and focused on GHG emission estimation of the horticulture sector. Existing studies were evaluated during the systematic review process, which followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis PRISMA 2020 guidelines [38], and a statistical meta-analysis of results was conducted.

Bibliographic research to find literature matching the topic of the review was performed to contrive an introductory selection based on singular criteria to execute the selection process.

A systematic review aimed to review existing literature on agricultural Decision Support Tools. After the initial selection process, only the most relevant articles were used for review.

Inclusion criteria focused on simplified online environmental impact calculators for small and medium-sized horticulture farmers as a Decision Support Tool. Scopus and Web of Science databases were selected for review. Only open-access articles were included in the database search: 630 articles indexed in Scopus and 1141 articles indexed in Web of Science databases. In addition, the identification of new studies via other methods using the Google search engine was conducted. The first two hundred results proposed by the search engine were analyzed.

The keywords used were "Agriculture" and "Decision Support Tools". Eligibility criteria using five aspects were used to define tools for in-depth analysis: availability, scale, geographical scope, assessment unit, and status. The systematic review highlighted eight environmental impact Decision Support Tools—GHG calculators to approach, measure, and evaluate horticulture farming for small and medium-sized companies.

Before the screening, 560 articles were removed: duplicated records, records marked as ineligible by automation, and records removed for other reasons. In total, 611 articles were screened, and 500 articles were sought for retrieval. The eligibility criteria were selected for a review of Decision Support Tools—GHG calculators to approach, measure, and evaluate horticulture farming for small and medium-sized companies. Thirty-two articles were included in a systematic review of GHG calculators. The methodological framework of a systematic review is shown in Figure 2.

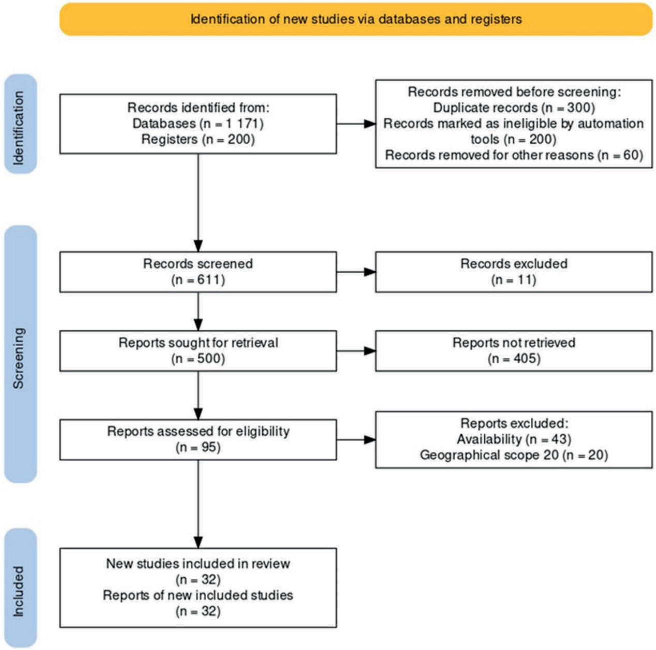


Figure 2. Flow diagram of systematic review.

2.2. Selection of Decision Support Tools—GHG Calculators

Based on the systematic literature review analysis results and the eligibility criteria selected for a review of Decision Support Tools—GHG calculators to approach, measure, and evaluate horticulture farming for small and medium-sized companies, eight GHG calculators were selected. To create a list of the most relevant tools, eligibility criteria were applied. Criteria considered in preliminary eligibility were (a) availability—free access, available after registration and available after purchase; (b) scale—farm-level, regional or global; (c) geographical scope—Europe, World, USA, Canada, and Australia; (d) assessment unit—crops, dairy, livestock, food, and beverage; (e) status—up to date, not updated, not working.

Considering the aim of the research and the needs of farmers, only calculators available for free or after registration were selected. Only the farm-level calculators were analyzed. Considering the need and overall scope, Europe as a primary scope and the world as a secondary scope were selected. Calculators for other regions, like the UK, Canada, Australia, and the USA, were excluded. After analysing the literature and applying eligibility analysis, eight calculators were selected as appropriate for an application on the farm level for horticulture practice analysis and evaluation: Agricultural Life Cycle Inventory Generator (ALCIG) [18,22], Common Agricultural Policy Regionalized Impact analysis (CAPRI) [39,40], The Farm Carbon Calculator [41], Integrated Management oPtions for Agricultural Climate Change miTigation (IMPACCT) [42], Model for integrative Life Cycle

Assessment in Agriculture (MILA) [43], Cool Farm Tool [44,45], Agricultural Resource Efficiency Calculator (AgreCalc) [20,46], and Solagro Carbon Calculator [47].

2.2.1. Bibliographic Analysis of Selected Indicators

Bibliometric analysis can be divided into two types: performance analysis, which shows the contribution of research, and scientific mapping, which shows the interrelationships, or linkages, of science. However, in addition to performance analysis and scientific mapping, network analysis complements bibliometric analysis: metrics, clustering, and visualization methods. The boundaries of the study were determined by the defined keywords used in the Web of Science comprehensive database, where publications were selected based on whether these keywords appear in the title, abstract, and author keywords.

In this bibliometric analysis, publication-related metrics were used because they show the topicality of the topic and the co-word analysis shows the relationships between words that frequently appear in publications and form clusters. VOSviewer software was used to visualize a biometric analysis network result. A Web of Science database was used for bibliometric analysis of the selected GHG calculators.

The folowing keywords were used: "Agricultural Life Cycle Inventory Generator" or "Common Agricultural Policy Regionalized Impact Analysis" or "The Farm Carbon Calculator" or "Integrated Management oPtions for Agricultural Climate Change miTigation" or "Model for Integrative Life Cycle Assessment in Agriculture" or "Cool Farm Tool" or "Agricultural Resource Efficiency Calculator" or "Solagro Carbon Calculator". When the used keywords appeared in the title, abstract, and author keywords, there were a total of 235 publications on the Web of Science. The results are illustrated in Figure 3 and show increased publications in recent years, commonly used in agriculture (29%) and environmental science research areas (24%).

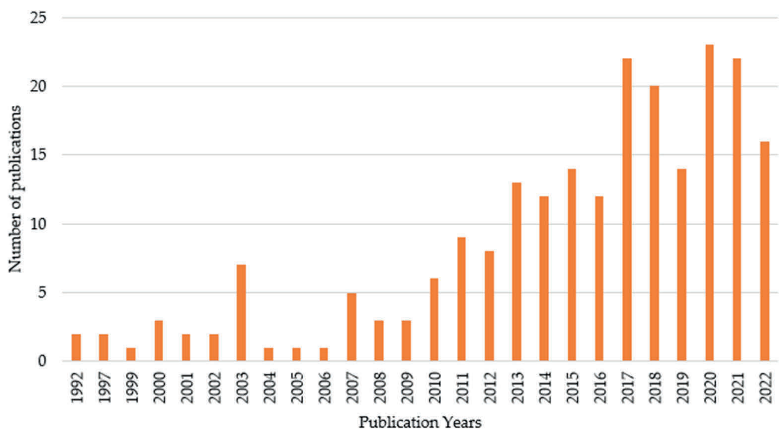


Figure 3. Bibliometric analysis of selected GHG calculators: publications.

In Figure 4, the keyword co-occurrence network is illustrated. Co-occurrence for all keywords equal to five was used. All keywords were divided into five clusters (clusters are shown with different colors: blue, red, green, yellow, and violet), with a more extensive cluster of agriculture (occurrence, 38; links, 61 and the second largest cluster—management (occurrence, 34; links, 61).

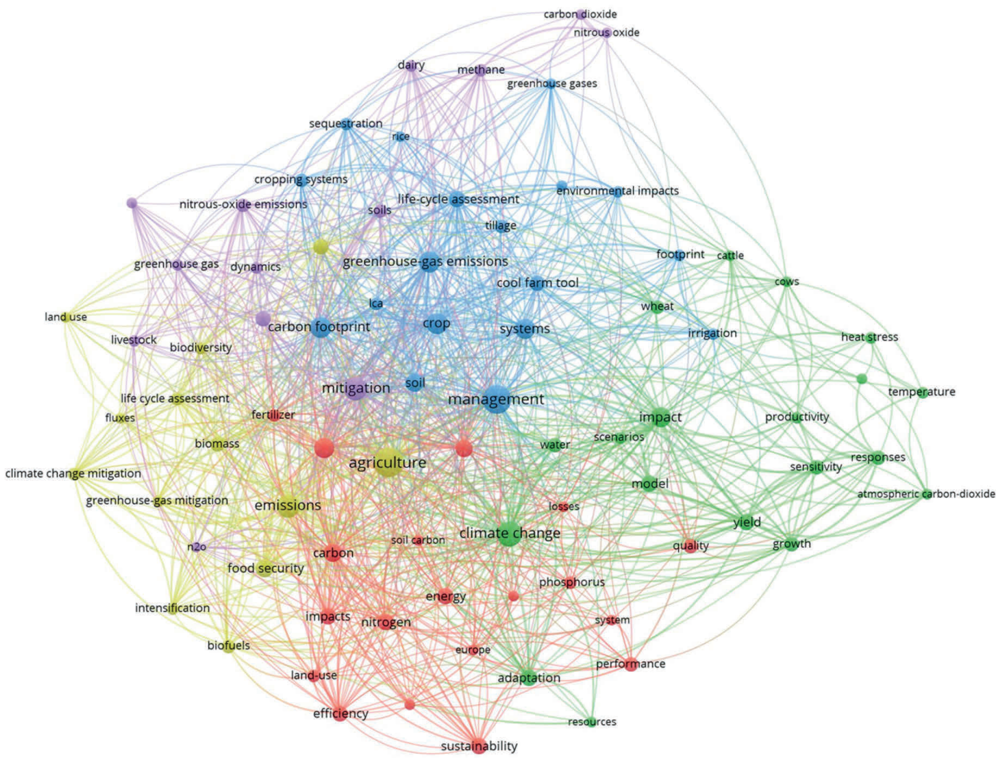


Figure 4. Keyword co-occurrence network of selected GHG calculators.

The results of bibliometric analysis prove the topicality and suitable application of selected Decision Support Tools—GHG indicators in horticulture farming for small and medium-sized companies.

2.2.2. In-Depth Analysis: Multicriteria Decision Analysis

During this stage, the in-depth analysis of eight calculators selected in the previous stages of methodology was conducted. Multicriteria Decision analysis is a process of sequent steps and processes to structure and formalize the decision-making process and allows the rank and prioritization of various selected options and, based on results, the making of recommendations on optimal options. According to the scientific literature, Multicriteria Decision analysis has been used in a sustainability assessment of agriculture [48] for the selection of mechanization patterns on farm levels [49] and crop production evaluation [50].

Selected indicators were used for an in-depth analysis and ranked. For the ranking, the Multicriteria Decision analysis, The Technique For Order of Preference by Similarity to Ideal Solution (TOPSIS), was used for the ranking of calculators for horticulture. This method evaluates the distance of alternatives to the ideal and anti-ideal point, and an option with the shortest distance to the ideal point is the best alternative.

The basic element of the TOPSIS analysis is a data matrix, where evaluation criteria are represented by $x_1, x_2, \ldots, x_j, \ldots, x_n$ (see Figure 5).

$$
\begin{array}{c}
 \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_n
\end{array}
\begin{array}{c}
\begin{matrix} x_1 & x_2 & \cdots & x_j & \cdots & x_n \end{matrix} \\
\begin{bmatrix}
x_{11}^k & x_{12}^k & \cdots & x_{1j}^k & \cdots & x_{1n}^k \\
x_{21}^k & x_{22}^k & \cdots & x_{2j}^k & \cdots & x_{2n}^k \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
x_{i1}^k & x_{i2}^k & \cdots & x_{ij}^k & \cdots & x_{im}^k \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
x_{n1}^k & x_{n2}^k & \cdots & x_{nj}^k & \cdots & x_{nm}^k
\end{bmatrix}
\end{array}
$$

Figure 5. TOPSIS decision-making matrix.

Different criteria used in the analysis have different dimensions. Value normalization is carried out to make these data comparable and, afterward, to rank alternatives in accordance with how closely they resemble the Positive Ideal solution. In this case, normalized values (b_{ij}) were obtained using linear normalization method [51].

$$b_{ij} = \frac{maxx_{ij} - x_{ij}}{maxx_{ij} - minx_{ij}}, \text{ if max } xij \text{ is preferable;} \tag{1}$$

$$b_{ij} = \frac{x_{ij} - minx_{ij}}{maxx_{ij} - minx_{ij}}, \text{ if min } xij \text{ is preferable.} \tag{2}$$

Normalized data were also arranged in a matrix and then weighted by multiplying them with the weights given to each of the criteria (w_j) (see Figure 6). There, $\{A_1, A_2, \ldots, A_i, \ldots, A_m\}$ represents alternatives.

$$
\begin{array}{c}
 \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_n
\end{array}
\begin{array}{c}
\begin{matrix} w_1b_1 & w_2b_2 & \cdots & w_jb_j & \cdots & w_nb_n \end{matrix} \\
\begin{bmatrix}
w_1b_{11}^k & w_2b_{12}^k & \cdots & w_jb_{1j}^k & \cdots & w_nb_{1n}^k \\
w_1b_{21}^k & w_2b_{22}^k & \cdots & w_jb_{2j}^k & \cdots & w_nb_{2n}^k \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
w_1b_{i1}^k & w_2b_{i2}^k & \cdots & w_jb_{ij}^k & \cdots & w_nb_{im}^k \\
\vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
w_1b_{n1}^k & w_2b_{n2}^k & \cdots & w_jb_{nj}^k & \cdots & w_nb_{nm}^k
\end{bmatrix}
\end{array}
$$

Figure 6. Normalized and weighted data matrix.

The next step of the TOPSIS analysis is to determine the Positive and Negative Ideal solutions.

The Positive Ideal solution:

$$A^+ = \text{Max}_\text{i} w_j b_{ij} \tag{3}$$

The Negative Ideal solution:

$$A^{-} = \min_{i} w_j b_{ij} \quad (4)$$

Separation from the Positive Ideal solution (S^{+}) is calculated by following formula:

$$S^{+} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{+}\right)^2},\ i = 1, 2, \ldots, m. \quad (5)$$

Separation from the Negative Ideal solution:

$$S^{-} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{-}\right)^2},\ i = 1, 2, \ldots, m. \quad (6)$$

The final step is calculating alternatives of Relative Closeness to the Ideal Solution:

$$C_i^{*} = \frac{\boldsymbol{S_i^{-}}}{\left(\boldsymbol{S_i^{+}} + \boldsymbol{S_i^{-}}\right)},\ i = 1, 2, \ldots, m. \quad (7)$$

The number obtained is in the range of [0;1] and shows the alternative rating. If $Ci^{*} = 1$, the alternative is equal to the Ideal Solution; if $C^{*}_{i} = 0$, it is the opposite of the Ideal Solution. The closer the rating is to 1, the better the alternative.

2.3. Case Study Analysis

Data from a horticulture farm in Latvia were used as a case study. The company has been engaged in sea buckthorn and quince cultivation since 2020. Data used to calculate GHG emissions are summarized in Table 2.

Table 2. Data used for calculations.

Unit	Data
Total area Area of planted sea buckthorn	12.5 ha 10 ha
Area of planted quinces	0.5 ha
Unmanaged territory area	2 ha
Number of sea buckthorn plants	12,500
Number of quinces plants	1500
Total yield	31.5 t
Total sea buckthorn yield	30 t
Total quinces yield	1.5 t
Soil texture	loam
Soil drainage	very good
Soil management	no tillage
Plant residue management	removed from the field
pH	5.7
Amount of fertilizer—Kristalon Lilac (NPK 19-6-6+micro) [41]	1400 kg; 140 kg per ha
Nitrogen (N)	19%; 27 kg per ha
N (as ammonium N)	16%

Table 2. *Cont.*

Unit	Data
N (as nitrate N)	3%
Potassium oxide (K_2O)	6%; 8.4 kg per ha
Phosphorus oxide (P_2O_5)	6%; 8.4 kg per ha
Amount of fertilizer—Monopotassium phosphate [42]	1000 kg; 100 kg per ha
Phosphorus pentoxide (P_2O_5)	52%; 52 kg per ha
Potassium oxide (K_2O)	34%; 34 kg per ha
Fuel consumption (tractor, mower, distribution truck)	1200 L
Consumed electricity (drip irrigation system)	3000 kWh
Irrigation amount	2400 m^3
Water source	farm storage pond

3. Results: Prioritization of GHG Emissions Calculators for the Horticulture Sector

In total, eight calculators were selected for an in-depth analysis. All selected and analyzed environmental impact Decision Support Tools—GHG calculators are applicable for horticulture farming for small and medium-sized companies. The main characteristics of selected GHG calculators are summarized in Table 3.

Table 3. Farm-level GHG calculators suitable for the horticulture sector.

Calculator	The Base of the Tool	Functional Unit	Sustainability Assessment	References
ALCIG	Excel, version 2310	Surface, time	Single indicator	[18,22]
CAPRI	Software	Mass	Single indicator	[39,40]
The Farm Carbon Calculator	Web-based	Mass, surface	Single indicator	[41]
IMPACCT	Software	Mass, surface	Single indicator	[42]
MILA	Excel, version 2310	Mass, surface, energy	Multi indicators	[43]
Cool Farm Tool	Web-based	Mass, surface	Multi indicators	[44,45]
AgreCalc	Web-based	Mass, surface	Single indicator	[20,46]
Solagro Carbon Calculator	Web-based	Mass	Single indicator	[47]

As concluded from the literature review, a roadmap to choosing GHG calculators as a Decision Support Tool for European farmers in horticulture is needed. Considering the aim of this research—to analyze and recommend environmental impact Decision Support Tools—GHG calculators—prioritization of selected GHG calculators was conducted.

Indicators for prioritizing GHG emission calculators for evaluating the horticulture sector on the farm level were developed. Indicators were selected after examining the literature. The selected indicators are summarized in Table 4.

Table 4. Indicators used for a preference of GHG emission calculators.

Dimension	Indicator	Designation of Indicator	Preferable Outcome
Technical	The base of the tool	I_1	Max
Economic	Costs to farmers	I_2	Min
Social	Convenience of use	I_3	Max
	Recognition by farmers	I_4	Max
Environmental	Transparency of methodology	I_5	Max

Values for technical, economic, and environmental dimensions were taken from the literature. Values for a social dimension were based on the authors' expertise and opinions. The equal weights of indicators were used in the analysis. Each indicator's weight was 0.2. The normalized and weighted matrix used for a TOPSIS analysis is shown in Table 5.

Table 5. Normalized and weighted TOPSIS matrix.

Calculator	I_1	I_2	I_3	I_4	I_5
ALCIG	0.0295	0.0743	0.0645	0.0588	0.0555
CAPRI	0.0590	0.0743	0.0645	0.0294	0.0555
The Farm Carbon Calculator	0.0885	0.0743	0.0806	0.0882	0.0832
IMPACCT	0.0590	0.0743	0.0645	0.0588	0.0555
MILA	0.0295	0.0743	0.0322	0.0588	0.0555
Cool Farm Tool	0.0885	0.0743	0.0806	0.0882	0.0832
AgreCalc	0.0885	0.0371	0.0645	0.0882	0.0832
Solagro Carbon Calculator	0.0885	0.0743	0.0967	0.0735	0.0832

The results of the TOPSIS analysis allowed the identification of the three most advisable decision-making tools for use by horticultural farmers. The results of the TOPSIS analysis are shown in Figure 7.

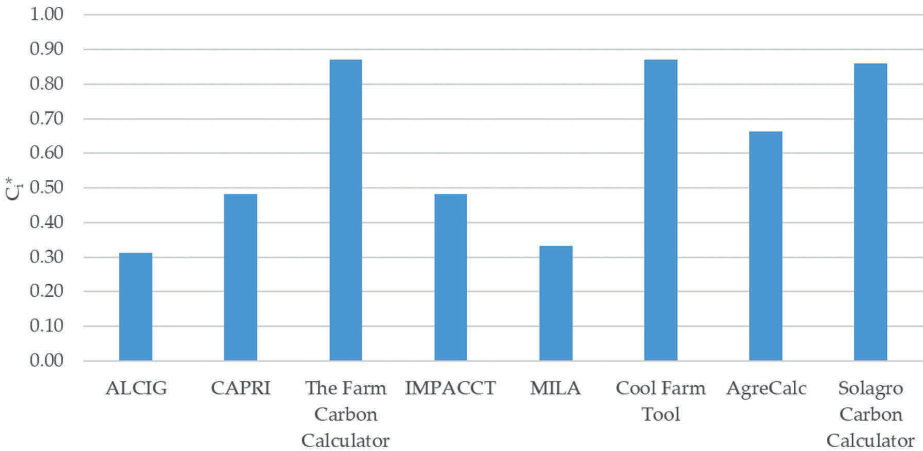
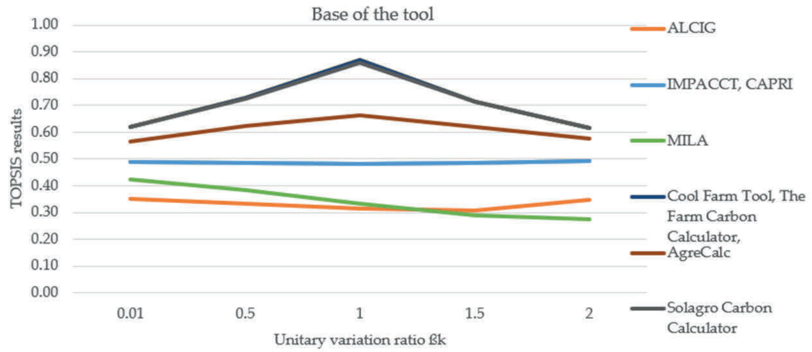


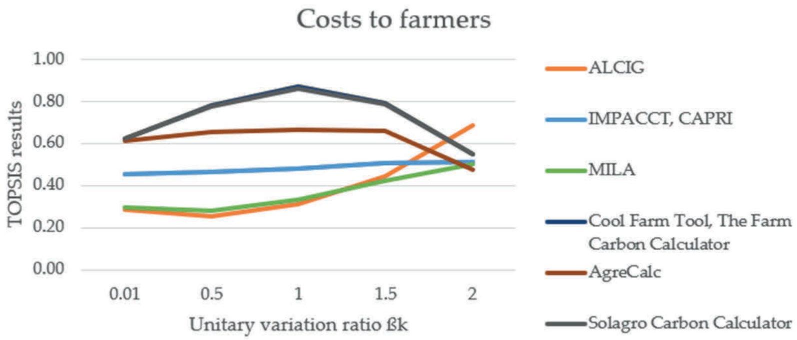
Figure 7. Comparison of ratings of GHG emission calculators.

All calculators were analyzed from technical, economic, social and environmental dimensions, using five indicators. The results show that the Solagro Carbon Calculator, The Farm Carbon Calculator, and Cool Farm have a higher rating and are recommended in the first place as GHG calculators for farmers. At the same time, it should be noted that all selected GHG calculators are applicable to approach, measure, and evaluate horticulture farming for small and medium-sized companies. For the rating of GHG emission calculators, equal weights of indicators were used. The equal weights were selected to minimize the subjectivity in the assessment. Therefore, sensitivity analysis was performed for transparency of a used approach, highlighting the dependence of relative closeness to the ideal solution on the weight (or importance) of criteria.

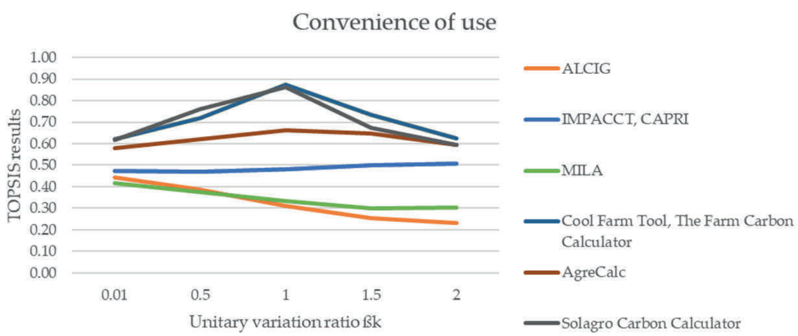
In this study, the weights of the criteria were equal to each other, and then each weight was changed separately to see how the overall results would be affected. According to the sensitivity graphs, Figure 8a–e criteria most depend on their weight in the case of cost to farmers, as variations in these criteria impact the ranking of final results. The results show that the equal division of criteria weights is optimal, less subjective, and objectively compares calculators.



(**a**)

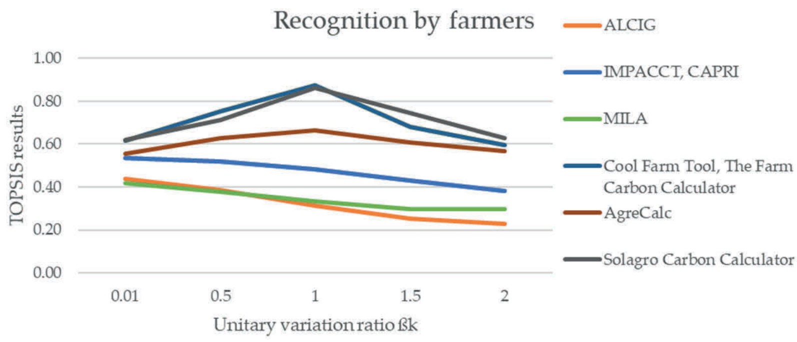


(**b**)

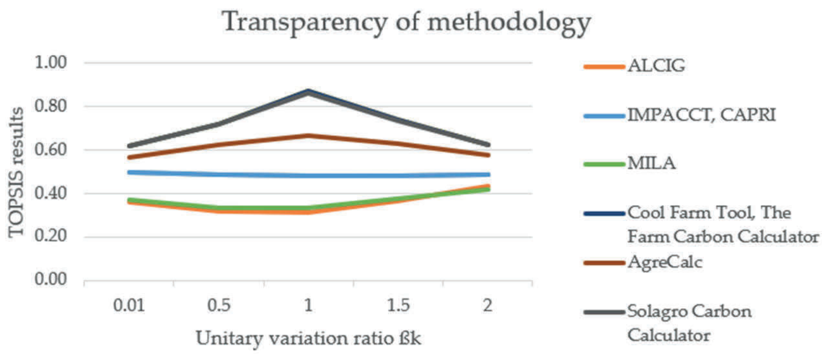


(**c**)

Figure 8. *Cont*.



(**d**)



(**e**)

Figure 8. (**a**). Sensitivity analysis of the Base of the tool indicator. (**b**). Sensitivity analysis of the Cost to farmers indicator. (**c**). Sensitivity analysis of the Convenience of use indicator. (**d**). Sensitivity analysis of the Recognition by farmers indicator. (**e**). Sensitivity analysis of the Transparency of methodology indicator.

In future studies, a set of extended criteria should be brought forward to evaluate the effect on outcomes with respect to the first set of indicators selected.

As part of the review, GHG emission calculations were performed with three modeling tools with higher ratings (The Cool Farm Tool, The Farm Carbon Calculator, and Solagro Carbon Calculator) to examine these tools further and draw conclusions. The estimates were performed using information from the farm. For all three calculators, the same input data were used. Data used to calculate GHG emissions are summarized in Table 2.

Sea buckthorns have a drip irrigation system that delivers water and fertilizers, while quinces grow without watering. Information about the amount of fertilizers (Kristalon Lilac and Monopotassium phosphate) used on sea buckthorns was given in the unit of measure of kg. For The Cool Farm Tool and Solagro Carbon Calculator, it was necessary to convert the measurement units to kg per ha. The following equation for conversions was used:

$$a = \frac{b}{c}, \tag{8}$$

where

a—amount of fertilizer used, kg per ha;
b—amount of fertilizer used, kg;
c—total area of plants, ha.

The percentage distribution of fertilizer components is indicated on the product (Kristalon Lilac and Monopotassium phosphate) homepages, respectively [52,53]. Although the fertilizers contain additional nutrients, only N, K_2O, and P_2O_5 were considered in the work because adding additional nutrients to the NPK compound in the tools was impossible.

In The Cool Farm Tool and The Farm Carbon Calculator, fertilizer components were added in percentages. However, in the Solagro Carbon Calculator, it was necessary to calculate the amount (kg per ha) of each component. Equation (2) was used for calculation.

$$d = \frac{e}{100} \times a, \quad (9)$$

where

d—amount of fertilizer component, kg per ha;
e—amount of fertilizer component, %;
a—amount of fertilizer used, kg per ha.

The total fuel consumption of the tractor, mower, and distribution truck was given. The amount of cargo changed during each distribution time, so when calculating fuel consumption from distribution separately, the data were inaccurate; therefore, the consumption from distribution was included with the field operation machines and not calculated separately.

As an example, the total GHG emissions of the case study farm, according to calculations by the Solagro Carbon Calculator, are illustrated in Figure 9. The result chart created with the use of the Solagro Carbon Calculator shows the total emissions (tCO_2e) of the case study company, divided by sources (blue—machines and equipment, orange—process emissions, green—GHG emissions of energy used on the farm and purchased by thirds, purple—GHG emissions for other purchased inputs).

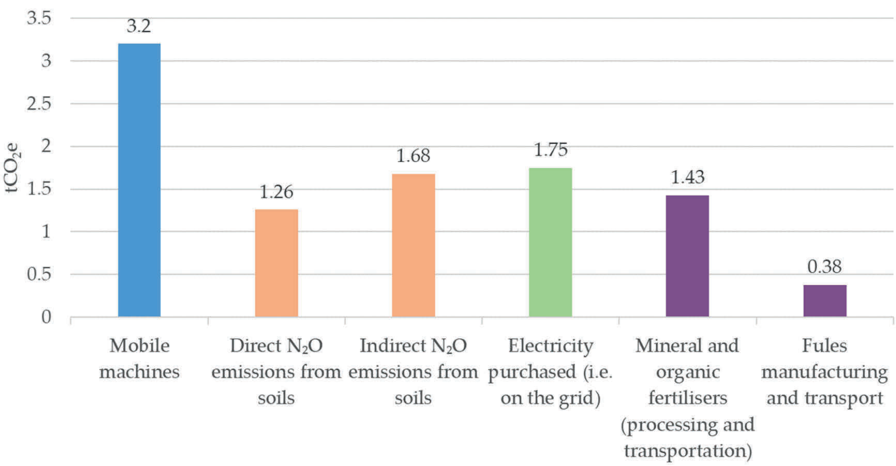


Figure 9. Results obtained by The Solagro Carbon Calculator.

All tools used data about crop area, harvest amount, soil type, fertilizer and fertilizer composition amounts, electricity consumed from irrigation and fuel by tractors and machines, and distribution. However, in The Cool Farm Tool and Solagro Carbon Calculator, it was also possible to enter data about crop residue management and pH concentration in the soil. As a result, emissions from fertilizer production were also considered; therefore, the results in The Cool Farm Tool appear higher.

4. Discussion and Conclusions

With increased focus on the result agriculture and sustainable development of a sector, farm-level evaluation is essential to support farmers in managing farms in a sustainable and competitive manner. Various applications and tools are used to analyze and improve the environmental performance of agricultural activities. Farmers widely use farm-level Decision Support Tools due to their characteristics: ease of use, ability to simplify the complexity of sustainability assessment, accessibility to farmers, and recognition by farmers and stakeholders. There is not and cannot be one universal Decision Support Tool. These tools vary due to focus, objectives, methods, and application differences. Therefore, a framework is needed to analyze and recommend environmental impact Decision Support Tools to approach, measure, and evaluate agriculture practices for small and medium-sized companies, including in horticulture.

During the research, a systematic review and bibliographic analysis were conducted, and different Decision Support Tools, including calculators used for an impact assessment of the agricultural sector, were investigated. GHG calculators play an essential role in the promotion of sustainable practices in agriculture and help to raise awareness about the need for a shift of agriculture practices towards climate neutrality. The need to access and monitor the environmental impacts of agriculture practices and services has resulted in the development of numerous GHG calculators.

From a broad range of simplified online environmental impact calculators for small and medium-sized horticulture farmers as a Decision Support Tool, only eight GHG calculators complied with the set of selection criteria: ALCIG; CAPRI, The Farm Carbon Calculator, IMPACCT, MILA, Cool Farm Tool, AgreCalcand, Solagro Carbon Calculator. Although all selected calculators are based on the IPCC guidelines, this does not provide a uniform approach or guarantee the same accuracy of results across all calculators. Each calculator addresses a different goal and varies in scoring, time investment, and data requirements. The IPCC guidelines provide a general framework, and models are built from a combination of methodology, and the level of detail differs; therefore, the results provided by different calculators may differ. Each calculator represents a different perspective on how the emissions are calculated; therefore, selecting the most suitable GHG calculator is essential: if carefully selected, it can result in correct findings and conclusions and provide sufficient information to assess environmental impacts. All selected and analyzed GHG calculators can be used to approach, measure, and evaluate horticulture farming for small and medium-sized companies. Farmers should work out the balance between efficiency and accuracy when deciding which calculator to use. To make the task easier for horticulture farmers, select GHG calculators were prioritized.

The most suitable GHG calculator tools should include a user-friendly platform for use, provide a comprehensive account of GHG emissions occurring on a farm level, be available in the public domain and free to use. Solagro Carbon Calculator, The Farm Carbon Calculator, and the Cool Farm Tool have a higher rating and are recommended in the first place as GHG calculators for horticulture farmers. These tools were acknowledged as the most relevant tools to gain insight into the sustainability performance of a horticulture farm.

This research is mainly addressed to European farmers in horticulture and can be used as a roadmap to (1) measure and compare horticulture farming, (2) evaluate Decision Support Tools available for horticulture, and (3) find an optimal GHG calculator on a farm-scale level. In future studies, the connection between the use of GHG calculators and subsequent changes in management practices should be investigated. Future effort in education and support of farmers is needed in using the outcomes of the calculations in decision making and improvement of farming practices to mitigate climate change and shift to a green business model.

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Are Industries Open for Renewable Energy?

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Abstract **– The progress towards climate neutrality and sustainable development of the national economy is increasingly challenging. At the European Union level, the target for renewable energy set by Directive 2018/2001 is at least 32 %. Industry is not only an essential part of the national economy but also a field of opportunity for increasing the share of renewable energy in the total final energy consumption balance of the country. The paper evaluates renewable energy technologies using a combination of AHP and TOPSIS methods using technical, economic, environmental, and social criteria. In order to indicate the needs, potential barriers, and position of enterprises on renewable energy, an enterprise survey is conducted. Both the survey and multi-criteria decision analysis ranks solar PV as the technology with the highest potential. The results of the survey overall show that enterprises are open to renewable energy technologies, especially if incentives such as financial support are available, for example, in the form of a grant.**

Keywords **– Analytic hierarchy process (AHP); enterprise survey; multi-criteria decision analysis (MCDA); renewable energy sources (RES); technique for order of preference by similarity to ideal solution (TOPSIS)**

1. INTRODUCTION

One of the most critical sectors of the economy is the energy sector. Its main tasks are the extraction of energy resources, their processing into energy, and supply to consumers. Without energy, no other economic sector can develop. Despite the growing share of renewable energy in recent years, fossil fuels (coal, natural gas, and oil) still dominate the world's energy consumption [1].

Greenhouse gases in the industrial sector have increased rapidly in recent decades with a negative impact on climate. As the environmental, economic, and social requirements rise, the progress towards climate neutrality and sustainable development of the national economy is increasingly challenging.

In order to reduce negative impact on climate, as well as to reduce the use of fossil energy resources, European Union (EU) member states have set mandatory targets for increasing the use of RES. At the EU level, the RES target set by Directive 2009/28/EC for 2020 is 20 % [2]. Based on the starting position and circumstances of each Member State, individual targets have been set, which in the case of Latvia the target is 40 % by 2020. As regards the year 2030, the target for renewable energy set by Directive 2018/2001 is at least 32 % at the EU level [3], which in the case of Latvia is 50 % by 2030. In addition, at the end of 2019, the European Commission presented a new, ambitious package known as the European Green Deal, which sets a target to become the first carbon-neutral continent by 2050 [4]. Carbon-

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neutrality is a state where economic activity and consumption do not have a negative impact on the climate. Achieving climate neutrality is characterized by greenhouse gas balance – reducing all emissions and offsetting non-reducible emissions by capturing them in plants and forests or receiving and storing emissions underground.

Climate change has become a significant issue in recent years, not only because of its environmental, but also economic and social implications. According to survey results presented in the World Economic Forum's Global Risks Report [5], climate change is shown as the number one risk by impact and number two by likelihood. However, transition to carbon-neutrality must be evaluated comprehensively (holistically) to avoid exacerbation of influences because of disordered actions. This comprehensive approach should also apply to decision-making, which is discussed in this paper in relation to the promotion of RES technologies in enterprises.

Aim of research is to identify which RES are most viable when mutually compared and determine which RES has highest potential among Latvian companies.

In Latvia, a high share of renewable energy is provided by hydropower, with a total installed capacity of 1565 MW in 2018, and it accounts for a vast majority of the total installed capacity of renewable energy technologies for electricity generation [6].

Compared to other EU countries, the share of RES in final energy consumption in Latvia is relatively high [7]. According to 2017 data, it reached 39.01 % [8]. This is mainly due to the installed hydropower plant capacity and the fact that, in Latvia, historically biomass (wood) is used as a fuel, and it is widely available [9].

Given the high share of renewable energy in Latvia, finding new opportunities to increase it is a challenge. Nevertheless, there still is potential to increase the share of RES in many sectors, including the industrial sector.

Solar energy is a RES that is available free of charge. Solar energy technologies can generally be divided into two groups: technologies for electricity generation and technologies for thermal energy generation. The conversion of solar energy into electricity takes place through PV systems. Polycrystalline modules are the most common on the market. In 2017, polycrystalline modules accounted for 60.8 % of the total PV production in the world, leaving second place for monocrystalline modules with 32.2 % and third place for thin-film modules with a relatively small share of 4.5 % [10]. The global installed PV power capacity in 2018 was 505 GW, which makes it the third most widely used renewable energy technology [11].

Solar energy in Latvia is currently being used at a minimum. At the end of 2019, the total installed capacity of solar technologies for electricity generation was only 3 MW [6]. In Latvia, the average global horizontal irradiation is up to 1100 kW/m^2 [12]. The most considerable amount of radiation is observed in the coastal zone, where the duration of sunshine reaches 1840 h to 1940 h per year [13]. As for the amount of electricity produced, one kWp of installed capacity in Latvia theoretically is capable of generating an average of 1022 to 1095 kWh of electricity per year [14]. However, in order to obtain the most accurate information, each PV installation should be considered separately.

The conversion of solar energy into useful heat is realized by a solar thermal collector. Solar energy is absorbed into the solar collector, where the heat generated can be transferred to the final consumer through a heat carrier. Solar thermal collectors are divided into two groups – non-concentrating and concentrating. Non-concentrating solar thermal collectors are mainly used for space and domestic hot water heating in buildings while concentrating collectors – for process heat applications and electricity generation using steam turbines.

Wind energy is converted into useful energy using wind turbines. Wind turbines are divided into horizontal and vertical axis turbines. Another simple division of wind turbines includes their location – onshore and offshore wind turbines. Onshore wind turbines are located on land. The best locations to install this type of turbine include hill-tops, gaps in mountain ranges, and coastal areas. Offshore wind turbines are installed in sea and ocean areas where the wind is stronger and more constant in comparison with locations onshore. Onshore wind turbines usually are smaller than offshore wind turbines but are less expensive to establish than offshore wind turbines [15].

Wind energy potential depends on wind speed at the particular location. The average annual wind speed in Latvia is about 5 m/s on the coast of the Baltic Sea and about 3–4 m/s on the mainland [12]. At the end of 2019, the installed capacity for wind energy in Latvia accounted for 78 MW (145 wind turbines with different capacities), which is the third-largest RES technology after hydropower and biomass cogeneration and power plants. The theoretical potential of onshore wind energy in Latvia could be up to 1000 MW of installed capacity, but due to various barriers, the currently estimated amount is significantly smaller [16].

Geothermal energy is thermal energy found in the depths of the Earth that can be used for heating, as well as electricity generation in tectonically active areas where higher temperatures are available. One of the advantages of geothermal energy is its independence from the weather, unlike wind and sun energy. Geothermal energy can be used in a variety of technologies, one of which is heat pumps [17].

In Latvia, the intensity of the internal heat flow of the Earth is very different in different regions. The highest groundwater temperature is in south-western Kurzeme (the Cambrian sediment temperature in this region reaches 38–62 °C at a depth of 1192–1714 m, the Devonian sediment at a depth of 600–775 m; 20–30 °C) and in Jelgava (Eleja) (the Cambrian sediment temperature in this region at a depth of 1100–1436 m reaches 33–55 °C, the Devonian sediment at a depth of 400–584 m; 20–30 °C). In Latvia, the perspective area of using geothermal energy is around 15–20 thousand km^2, but it significantly increases with the use of lower-temperature Devonian sediment-water for heat and hot water production by heat pumps [18]. Although geothermal energy can be used in a variety of technologies, given the situation in Latvia described above, ground source heat pump technologies that use geothermal energy for heat and hot water are the most suitable in Latvia.

Bio-energy is energy produced from biological resources (trees, shrubs, grass, animal waste, etc.). Compared to other RES, biomass is the most geographically available resource, relatively inexpensive, and can be processed into a liquid, solid, and gaseous fuel, which can further be used for the production of electricity, heat energy, and as fuel for vehicles. Biomass can be divided into traditional use and modern use, where with traditional use we understand combustion processes of wood and other forms of biomass and with modern – use of biofuel and biogas produced in biochemical and thermochemical processes [20]. In Latvia, the most widely used bio-resource is wood fuel justified by the aspect that forests cover 52 % of the total land area in Latvia [9]. In 2019 the total installed capacity for biomass cogeneration and power plants, and biogas cogeneration plants was 97 MW and 61 MW, respectively [6].

Although historically, the use of biomass has a significant place in Latvia's energy balance, in the long run, it is necessary to slowly move away or at least not increase the direct use of biomass for energy production and better to use it for higher value-added products.

2. METHODOLOGY

Methodology to reach aim of research is most crucial part and has significant impact on results.

There is not one universal approach to determine relevance of RES in industries, and more than 20 research are done on subject in USA [19]. As [19] conclude in research on industries relations with RES, there are trends of stagnation in growth speed of RES in manufacturing industries in USA, and it is advised to consider type of RES used to obtain more precise results. One of the first steps of the methodology used in research is to conduct an enterprise survey. This is important given that enterprises are the ones that ultimately decide in favour of introducing RES technologies. The survey will indicate the needs, potential barriers, and position of the enterprise on the renewable energy issue as such. There are many aspects to consider when it comes to the decision-making process – for example, if a decision-maker lacks knowledge about technology, he/she may select the technology based on the most obvious aspects such as price [21]. In certain decision-making cases where a decision is based only on economic considerations (for example, lower costs) the environmental dimension (for example, lower CO_2 emissions) or the social dimension (for example, jobs created) is excluded, but in order to ensure sustainable choices, all dimensions of impact must be considered [22]. In view of the above, AHP and TOPSIS methods are used to evaluate renewable energy technologies considering the multi-criteria approach. The results will allow comparing ranking by enterprises surveyed and multi-criteria decision analysis results regarding the best RES technologies.

2.1. Enterprise Survey

The target group of the survey is manufacturing enterprises. The survey was prepared using the online software "Typeform" and sent out to 2000 manufacturing enterprises consuming 500 MWh or more of electricity annually. As only criteria was energy consumption, companies represent various industries. The survey is based on the following questions:

1. Are renewable energy technologies used in your company;
2. Specify which RES is/are used;
3. What limits the use of RES;
4. What would facilitate the use of RES;
5. Which three RES technologies could have the most potential in your company;
6. What is the approximate monthly electricity consumption of your company;
7. Is energy consumption one of the top three cost positions in your company;
8. Would you be interested in the results of this survey and learning more about RES technologies.

When summarizing the result of question No. 5, in order to take into account whether the technology is indicated as the first, second or third priority, coefficients have been selected that are multiplied by the number of respondents who have indicated the specific RES technology at the respective priority level. This coefficient for first priority is 3, for second priority – 2 and for third priority – 1. The incidence of each RES technology is calculated using Eq. (1):

$$R_{RES} = \frac{p_1 \cdot 3 + p_2 \cdot 2 + p_3 \cdot 1}{\sum_{n=1}^{n} p_1 \cdot 3 + p_2 \cdot 2 + p_3 \cdot 1} \cdot 100 \quad (1)$$

where

R_{RES}	incidence of specific RES technology among respondents, %;
p_1, p_2, p_3	number of respondents who indicated RES technology as first priority (p_1), second priority (p_2) and third priority (p_3);
n	number of total RES technologies considered.

2.2. Application of AHP

MCDA basically includes the following steps: target definition, definition of alternatives, selection of criteria, determination of their weight, and evaluation of alternatives. In this paper, AHP is used to determine the weight of the criteria and TOPSIS – for all other steps.

Four main criteria are used for alternative evaluation: technical criteria, economic criteria, environmental criteria, and social criteria – these are the criteria that characterize a decision based on the principles of sustainable development.

The first step for the calculation of criteria weights is the pairwise comparison. For this comparison, the nine-integer value scale is used as presented in Table 1. The nine-integer value scale was initially suggested by Saaty [24].

TABLE 1. SCALE FOR PAIRWISE COMPARISON [23]

Scale	Definition
1	Equal importance
3	Moderate importance of one over the other
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Extreme or absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

Each criterion is compared to all other criteria forming the comparison matrix. In order to determine the ranks of criteria, the next step is solving the eigenvector problem. There are three methods for solving the eigenvector problem – Saaty's method, the power method, and the geometric mean method. In this case, Saaty's method is chosen, given its simplicity compared to the other two methods. The first step is a normalization of the comparison matrix – the sum of each column of the pairwise comparison matrix is calculated, and the values in the corresponding column are divided by it. The next step is the calculation of eigenvectors of each matrix row – values in each row are summed and divided by the number of criteria. The eigenvectors give the ranking (weight) of the criteria [25]. However, so that these weight values can be used with some certainty for further evaluation, it is necessary to calculate the consistency index (*CI*) and consistency ratio (*CR*).

2.3. Application of TOPSIS

TOPSIS has been used in different fields, including the evaluation of different energy generation technologies [26]. TOPSIS main benefits are the choice of an unlimited number of criteria and alternatives, a relatively simple calculation process and no need for a specific software or special programming skills. TOPSIS results allow comparing alternatives in a convenient and easily understandable way.

The target of TOPSIS analysis is to compare RES technologies in order to find technology that performs the best in terms of the criteria set. For the evaluation, six alternatives were selected: biomass technologies, solar PV panels, solar thermal technologies, technologies that use renewable part of waste as an energy source, wind technologies, and geothermal technologies.

Technologies were assessed based on four criteria: technical, economic, social, and environmental. The technical aspect includes the level of technological development, also known as technology maturity, which characterizes how advanced the technology is, i.e., whether there is potential for efficiency gains or whether the theoretical maximum level of technological productivity has already been reached [27]. The technical aspect also includes the feasibility of innovation, process efficiency, and energy quality, which often is expressed as reliability, which describes the ability of technology to work continuously and independently – without unforeseen damage, interruptions, and additional monitoring. Reliability is one of the most commonly used criteria in the multi-criteria analysis and has always been a topical issue in the energy sector [28]. Reliability is affected by conditions such as the quality of technical equipment, required maintenance, the type of energy source used, etc. The economic aspect includes capital investments and operational costs, as well as costs related to additional costs of replacing equipment from an occasional source of energy at a time when energy is not available. Investment costs consist of several parts (equipment costs, installation costs, other system element costs, etc.). Operation and maintenance costs are regular costs associated with the maintenance and optimal operation of technological systems. These may include, for example, regular (scheduled) maintenance, system repairs, etc. These costs are often expressed as a percentage of the total investment costs. The social aspect covers issues of increased or declining employment as well as the impact of imports. The environmental aspect is linked to increasing or reducing impact on environmental pollution and climate change, also considering the production of technological equipment. This is expressed as life cycle emissions that consider the impact at all stages of the technology, which is essential in sustainable decision making. For each criterion, its individual weight representing the importance of the criterion shall be determined. The sum of all the criteria weights shall be equal to 1. For the TOPSIS analysis, the weight values from the AHP results were taken.

The first step using the TOPSIS method is the normalization of the decision-matrix, followed by the calculation of normalized decision-matrix and determination of the best and worst solution. The best solution corresponds to a theoretical option of the most desirable level of each criterion, while the worst solution corresponds to a theoretical option of the least desirable level of each criterion [29]. After that, the distance of each alternative from the best and worst solution is calculated in order to obtain the closeness coefficient, which is used for the ranking of alternatives.

3. Results

3.1. Enterprise Survey Results

The survey results from 146 enterprises were compiled and analysed only in aggregate form. 42 % of respondents already use renewable energy technologies in their enterprises, while the majority or 58 % do not.

As main key constraints for the broader use of renewable energy technologies, 33 % of respondents mention other investment priorities, 26 % of respondents – long payback periods, that have primary reference to costs, and 20 % of respondents – constraints of existing infrastructure, which are connected with technical aspects as well as economic aspects.

Grant/subsidy is indicated as the main incentive to promote RES technologies (59 % of respondents). Apart from the availability of grants/subsidies, awareness-raising as a better understanding of technology is the second most frequently mentioned option to help increase the use of RES technologies (17 % of respondents).

22 % of respondents could not specify their electricity consumption in terms of quantity or cost, while most of the respondents could indicate both consumption and costs or at least one

of them. The average electricity consumption in the enterprises surveyed is 312 MWh per month, and the average electricity bill is 16 075 euros per month. Nevertheless, only 29 % of respondents indicate that energy consumption is among the top three cost positions in their enterprise, while for 63 % of respondents, energy costs are not among the top three cost positions, and 8 % of respondents cannot indicate if it is or not.

72 % of respondents are interested in receiving the results of the survey and obtaining additional information regarding RES technologies, while a relatively large proportion (28 %) answered in the negative.

Aggregated results calculated by Eq. (1) show that according to the respondents' answers, the top three RES technologies for which they see the highest potential in enterprises are solar energy for electricity, solar energy for heat energy, and biomass technologies. Figure 1 shows the rankings of all RES technologies, as proposed in the survey.

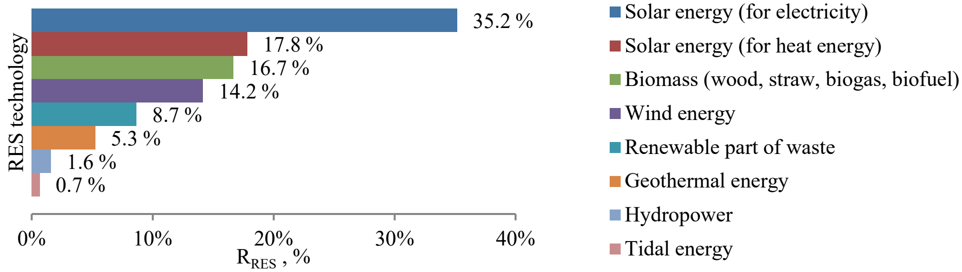

Fig. 1. Ranking of RES technologies according to enterprise survey results.

In the authors' view, the result which ranks these three technologies as the technologies with the highest potential in view of enterprises can be linked to a better understanding of technologies. These three technologies are already the most widely used (known) among the enterprises surveyed, and some experience has been gained in their utilization. For this reason, it is possible that preference is not given to the most appropriate RES technology but in favour of the technology for which the enterprise has a sufficient amount of information.

3.2. AHP Results

Technical, economic, environmental, and social criteria were compared pairwise based on the author's assessment. The pairwise comparison results are shown in Table 2.

TABLE 2. AHP PAIRWISE COMPARISON MATRIX OF CRITERIA

Criteria	**Technical**	**Economic**	**Environmental**	**Social**
Technical	1	0.3333	2	7
Economic	3	1	3	5
Environmental	0.5	0.3333	1	5
Social	0.1429	0.2	0.2	1

After normalization of the matrix, criteria weights were calculated. Results show that economic criteria are of the utmost importance with the weight of 0.4859; technical criteria rank second with the weight of 0.2764, third – environmental criteria with 0.1813, and the fourth – social criteria with the weight of 0.0564.

The calculated consistency ratio value is CR = 0.09351, which conforms to the condition that CR must be ≤ 0.1. It can be concluded that the comparisons are consistent and used in further calculations.

3.3. TOPSIS Results

Six RES technologies were evaluated using a scale from 2 to 5, where 2 correspond to the lowest score and 5 – to the highest score and potential of the use of renewable energy in the industrial enterprises. Table 3 compiles the evaluation values in a decision-making matrix.

TABLE 3. TOPSIS DECISION-MAKING MATRIX

RES technology	**Aspects**			
	Technical	Economic	Social	Environmental
Biomass	4	3	4	5
Solar PV panels	5	4	5	4
Solar thermal	4	3	5	4
Waste	3	4	4	4
Wind	3	3	5	4
Geothermal	3	3	4	4

The final result of the TOPSIS analysis is shown in Fig. 2. For the best solution, the closest alternative is solar electricity (0.94), which is due to the high valuation of this alternative, not only for the economic criterion which has the highest weight of all criteria (0.4859), but also good performance in the technical criterion which has the second-highest impact on final results. Technologies that use renewable part of waste as an energy source ranks second (0.48), however, its performance significantly lags behind solar PV. These technologies are followed by solar thermal energy (0.34) and biomass technologies (0.31) with relatively similar results. The furthest score from the best solution is for wind and geothermal energy technologies (0.16).

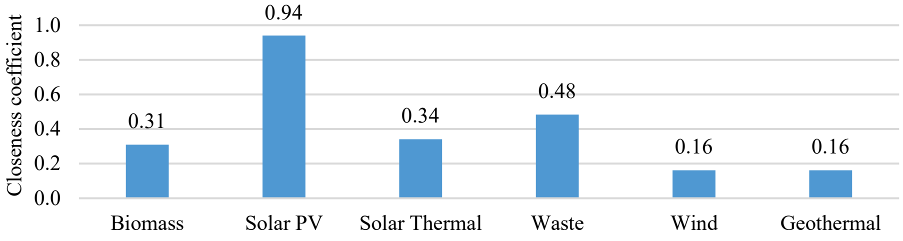

Fig. 2. TOPSIS analysis results – the ranking of RES technologies.

4. CONCLUSION

In this paper, six RES technologies were evaluated using a combination of AHP and TOPSIS methods. The biggest impact on the final result has an economic criterion as it is directly related to the total costs and payback period, which justifies the economic viability of the project. The multi-criteria decision analysis at the selected criteria ranks solar PV as the best performing technology for enterprises. Also, according to the survey, solar PV received the highest rank as the technology with the greatest potential in the opinion of enterprises.

Considering that the total installed solar energy capacity currently installed in Latvia is insignificant in comparison with other RES technologies, the result, which both after multi-criteria decision analysis and in the opinion of enterprises, puts solar PV as a priority technology, is favourable for policy development support. Given the barriers identified in the survey that limit the use of RES in enterprises (other investment priorities, long payback periods, constraints of existing infrastructure), it is necessary to develop appropriate policy measures to overcome these barriers. It is important that enterprises have access to complete information on RES technologies and financial instruments, as well as opportunities to receive in-depth expertise and advice. The results of the survey overall show that enterprises are open to renewable energy technologies, especially if incentives as financial support are available, for example, in the form of a grant. However, there are also a large number of respondents who are not interested in the possibilities of introducing such technologies in their enterprise.

As pointed out in [30], ideally, if more than one method can be used, since often a method change causes a bigger difference in the results obtained than the change of the user of the method, so further work on this issue could involve evaluation of RES technologies using another multi-criteria decision analysis method as well as selecting the most appropriate and the most important evaluation criteria for the decision-maker as Strantzali and Aravossis [30] emphasize that the evaluation criteria should be selected based on the specifics and objectives of the project/case being evaluated.

Another direction for further work includes the development and evaluation of policy measures to facilitate the realization of the industry’s potential for greater use of RES.

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Particle Boards from Forest Residues and Bio-Based Adhesive

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Abstract: Wood chipboard, common in interior spaces for applications ranging from furniture to decorative panelling, often falls short due to the presence of toxic adhesives, posing risks to both human health and the environment. This research delves into the potential transformation of wood chipboard into a 100% bio-based product. Previous research has shown the possibility of the partial replacement of petrochemical-based adhesives with bio-based adhesives. Hence, previous results do not reach the policy ambitions of the Green Deal of making the Green Transition to a bio-based economy. For chipboard production, logging residues from Latvian State Forests were systematically gathered within two months post-logging, comprising primarily *Picea abies* and *Pinus sylvestris* biomass, including branches, needles, bark, and various particles. A custom chipper and Vibrotehnik PM-120 hammer mill were employed for particle size separation into three fractions via sieving: <2.8 mm, 2.8–8 mm, and 8.0–10.0 mm, and combined with binders and hot-pressed into board samples. As a result, particle boards containing 100% bio-based carbon were achieved, demonstrating the possibility of excluding petroleum adhesives from chipboard production, paving the way for new research exploring bio-based binders and conifer bark.

Keywords: chipboards; conifer bark; carbon neutral; transition; resource efficiency; non-conventional building materials; bioadhesives

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1. Introduction

Replacing conventional building materials with wood alternatives can greatly reduce atmospheric carbon [1,2]. In turn, the release of less carbon into the atmosphere reduces its negative impact on the global temperature-change potential [3]. Building with wood has experienced a renaissance [4], and chipboard is one of the leading wood products in international trade used for construction and furniture [5]. The current process of wood particle board production has been getting modernized for a long time, and there are comprehensive reviews emphasizing the importance of information technologies and automatization in increasing production efficiency [6,7]. Nevertheless, the production of chipboard still involves the use of fossil additives [8] and toxic binders or their components [9], as well as the use of quality wood [10]. Production efficiency has been improved, and solutions have been sought to reduce the environmental impact over the entire product life cycle [11]. Nevertheless, the recycling of resin-based materials is challenging, as the resin particles left attached to the wood reduce the bond strength of the second resin and in the recycled product [12].

Particle boards can consist of many layers, and each layer adds functionality. 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 the particle board [13]. Fine particles usually do not add to material integrity but are very important for the final material lamination process, as a smooth surface is crucial for efficient coverage [14]. It is well established that fine particles even reduce the overall strength of the material and absorb more adhesive; therefore, the smallest wood fraction is usually limited to the particleboard surface only [13].

Although low-quality wood can be integrated into chipboards, it is not the preference of the industry but rather the necessity of using cheaper raw materials [10]. Compared to 2000, the global timber production intensity has increased by about 24%. The upward trends in timber production go against the European Union's Green Deal commitment to decouple economic growth from resource consumption [15]. Necessary steps should be taken to increase productivity by using raw materials more efficiently or exploring new and alternative raw materials to replace timber with raw material side streams [16].

Pędzik et al. have reported the potential of chipboard production using residues from forest management, tackling the need for sustainable raw materials. Although the team concluded that the produced boards are applicable to P2 functionality (suitable for the dry environment), the adhesive used in this research is the conventional urea-formaldehyde-based adhesive [16]. Mirski et al. have recently explored pine bark as an additive for chipboards using urea-formaldehyde and melamine-urea-formaldehyde resins [17]; both of these adhesives are fossil-based. With the European Union's goals of a clean circular economy and decarbonization by 2050, it is important to exclude petrochemicals from the economy. Formaldehyde compounds are most often used in adhesives. One of the most essential areas of their production is for urea-formaldehyde resin. Additionally, formaldehyde is classified as a compound that can cause cancer (a class 3 carcinogen), and is poisonous, corrosive, and allergenic [18–24]. In addition, a relatively recent problem observed in the manufacturing process is the detection of and reduction in volatile organic compound (VOC) emissions. Several developed studies on the analysis of the life cycle of wood chipboard (life-cycle assessment), replacing synthetic resins with bioadhesives such as soy protein, lignin, tannin, etc. [18], show a reduction in their impact on the environment [11,19–22]. Nevertheless, a portion of these bio-based compounds have been used in combination with petrochemical adhesives [23,24].

Research on lignin fractionation shows that in the presence of organic acids, steam lignin depolymerizes; nevertheless, when the fractionation conditions continue for a longer period of time, the lignin starts to polymerize back to its original state [25]. This could be an advantage when developing new adhesives for chipboard or other wood-based panels. As 15% of bark consists of lignin [26], this mechanism of depolymerizing and repolymerizing could be significant for ensuring the rigidity of particleboards from bark and other logging residues.

Although lignin is a byproduct from the pulp and paper industry, its market price can be quite high when extra purification steps are undertaken [27]. This might be a hint that using bark without mechanical or chemical treatment could be a feasible way of utilizing lignin polymerization for binding wood particles. In addition to health and environmental benefits [28], there might be economic benefits in replacing fossil-based resins. The cost of the raw materials used—namely, adhesive and wood chips—make up the most significant part of the cost of the finished chipboard. Total material costs account for 40–60% of total production costs; according to various authors in the scientific literature, material costs account for approximately 66% of total production costs. Consequently, replacing wood chips with alternative raw materials other than high-quality wood could lead to significant cost savings [29].

This study explores a new approach to the production of 100% bio-based chipboard, perhaps for a completely new use class. Our proposed hypothesis is that conifer bark will improve the strength of bio-based chipboards from logging residues. This hypothesis is based on the unique properties of conifer bark. Such natural binders could revolutionize the particleboard manufacturing process, leading the wood-based panel industry's Green Transition to completely bio-based industries. By particle size separation using multiple methods, we aim to uncover the potential of renewable resources and pave the way for bio-based chipboard materials, potentially contributing to the sustainability of the bio-based materials industry.

2. Materials and Methods

Logging biomass was sourced from Latvian State Forest logging sites, and the collection took place within two months following the conclusion of logging operations. The biomass was systematically gathered in polyethene bags, ranging from 50 to 100 L in capacity. These bags contained wood chips obtained from forest areas where branches, complete with needles, had undergone chipping. The biomass comprised logging residues primarily derived from *Picea abies* and *Pinus sylvestris*, including small branches and needles. It is important to note that the composition of wood chips varied based on factors such as the specific location, the environmental conditions during the chipping process, and the relative proportions of wood biomass.

Upon visual inspection, the assessment indicated that the wood chips predominantly consisted of heartwood and sapwood, bark, needles, fresh and decomposed biomass particles, and mineral particles.

The following equipment and materials were used for board preparation: (1) Analog pressure gauge (Hansa Flex—600 bar, ±50 bar), (2) Digital manometer (Hansa Flex—1000 bar, ±1 bar), (3) Custom-made hot press, consisting of Cylindrical heating elements (alternating currents); Temperature sensors; Heating metal blocks/surfaces; a Plate drying stand; Metal frames: one frame without perforations for biomass retention and another with perforations for steam discharge; Metal lining for steam removal; and Teflon fabric.

Xanthan powder acquired by glucose fermentation was produced by Fluid Science Ltd., Liverpool, UK and added to the biomass in the form of powder or solution during its preparation.

2.1. Biomass Moisture Content Determination

Chips delivered from forest fellings contained varying but significant amounts of moisture. The different amounts of moisture in the wood chips were observed under different weather conditions during the chipping and delivery of logging residues. Therefore, first, the wood chips were removed from polyethene 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 this 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.

2.2. Size Separation

Two methods were used to obtain the desired particle size; the workflow is depicted in Figure 1. 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 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.

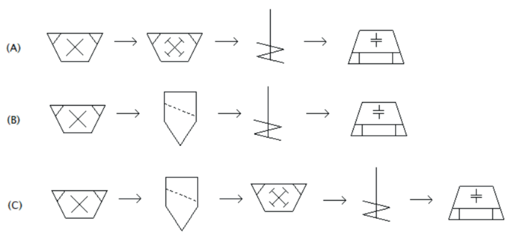

Figure 1. Workflow for particle separation: (**A**) horizontal 2-axis mill followed by hammer mill, particle mixing with binder and pressing; (**B**) horizontal 2-axis mill followed by sieving for particle separation, mixing, and pressing; (**C**) horizontal 2-axis mill followed by sieving for particle separation, particle > 1 mm milling with hammer mill, mixing, and pressing.

The separation approach allowed us to assess the bark and other fine particle impact on the board strength. Particle 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 the boards' mechanical properties.

2.3. 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, before being added to the biomass. In both variants, the binder was added to the logging residue particles no longer than 48 h prior to biomass-pressing to prevent mould formation, moisture changes, and other aspects that would potentially cause unwanted additional effects on the investigated parameters.

2.4. Board Preparation

The production of the boards was carried out using previously prepared logging residue biomass with the required particle size (mm) and moisture mass fraction (%). The board formation process was carried out in the following stages: (1) The digital pressure gauge was turned on and reset. In the case of using an analogue 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 of 140 °C or 160 °C (±5 °C) had been reached, a metal frame was placed on the lower heating surface, and the Teflon cloth was inserted into it. After this, 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 (Table 1) was displayed on the manometer (±10 bar for the digital manometer and ±50 bar for the analogue manometer). (5) The countdown was started, and the pressure was 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.

Table 1. Overview of the strength and density of produced samples with corresponding standard deviations. Particle size achieved by HC-horizontal 2-axis chipping and sifting, HM—Hammer-milling with a screen on the particle outlet.

Pressure, Bar	Temperature, °C	Particle Size, mm	MoR, N/cm^2	Standard Deviation, $\pm N/cm^2$	Density, kg/m^3	Standard Deviation, $\pm kg/m^3$
HC						
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

Table 1. *Cont.*

Pressure, Bar	Temperature, °C	Particle Size, mm	MoR, N/cm^2	Standard Deviation, ±N/cm^2	Density, kg/m^3	Standard Deviation, ±kg/m^3
HM						
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
Sieved 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

2.5. Density Determination

The density of the wooden boards was calculated according to the European standard EN 323:1996 [30] guidelines. The density was determined by dividing the mass of each sample by its volume. The dimensions of the boards were measured using a calliper with an accuracy of ±1 mm. Mass determination was conducted using laboratory scales with an accuracy of ±0.01 g.

2.6. Mechanical Properties Testing

For determining the bending strength of the wooden boards, the standard EN 310:1993 [31] was used. This standard defines a method for testing the modulus of rupture (MoR) and bending strength of horizontally placed boards in the bending of timber boards with a nominal thickness of ≥3 mm. The MoR were determined by applying a load to the centre of the test specimen supported at two external points. 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.

The following steps were taken to determine the strength of plates according to the EN 310:1993 standard [31]: (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 was carried out 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 loading tube on the plate was placed at its longitudinal midpoint, perpendicular to the longitudinal direction of the sheet; (6) A predetermined load was applied to the sheet in certain time intervals (kg/min), depending on the deformation of the sheet at the initially applied load.

2.7. Data Analysis

Each composition and parameter were replicated at least two 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; a confidence value of 95% (p-Value < 0.05) was used in the analysis.

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 [32,33]. An 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. 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.

The ANOVA allowed for the testing of three simultaneous hypotheses: H1: there is no significant difference in 1st variable results, H2: there is no significant difference in 2nd variable results, and H3: there are no significant interactions between both factors.

The Post Hoc test *t*-test was chosen for the pairwise comparison of the disproven null hypothesis. Calculated standard deviations are depicted in graphs; a p value of 5% was used in the analysis [34].

3. Results

Analysing 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 strength results for the same manufacturing parameters. Initial strength results for the three particle-size boards are depicted in Figure 2. 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 were generally less durable than the rest, but as seen from the statistical analysis, the difference between the MoR of the 2.8–8.0 and 8.0–10.0 particle size boards under 660 bar pressure was not significant ($p = 0.27$).

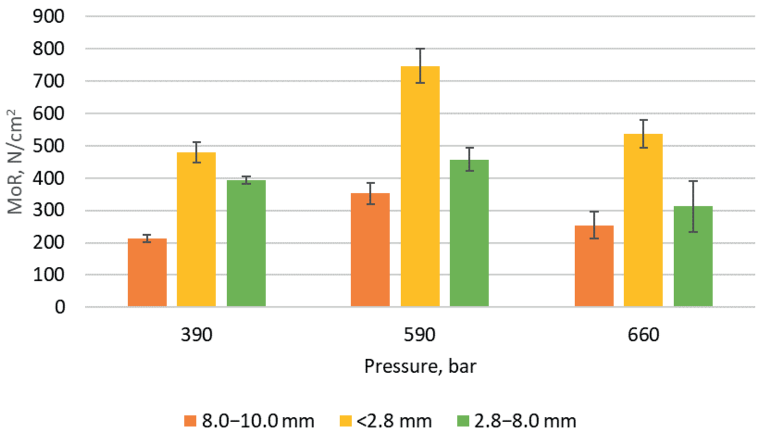

Figure 2. Modulus of Rupture depending on pressure and particle size for <2.8 mm particle size boards; 2.8–8.0 mm particle size boards; 10.0 mm particle size boards. Pressing temperature 140 °C. MoR—Modulus of Rupture; error bars represent standard deviation. An analysis of variance (ANOVA) revealed a significant main effect of particle size $F(2,45) = 41.7$, $p < 0.05$ and pressure $F(2,45) = 13.1$, $p < 0.05$, but no significant interactions within $F(4,45) = 1.80$ $p > 0.05$.

There was no significant impact of the chosen pressure extremes on board strength ($p = 0.43$) for the <2.8 mm particle boards. The boards produced by applying 590 bar pressure showed significantly higher strength compared to 390 bar ($p = 0.002$) and 660 bar

(p = 0.01) pressures. For the further tests, a 600-bar setting was chosen. According to biomass tests conducted in the external laboratory, some supplied biomass had a high sand content in the ash (ashing at 550 °C), showing up to 26% and an around 2% sand content in the raw biomass. Therefore, further tests were carried out by using the hammer mill approach by milling the previously chipped and sieved > 1 mm fractions. Larger particles were combined to prepare boards in the range of a 2.8 mm to 10 mm particle size, as initial tests did not show a significant difference between these two fractions in the chosen pressure range. Boards were prepared using 140 °C and 160 °C temperature regimes to assess the impact of temperature and particle size on the board's mechanical properties. Initial temperature tests were performed before 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 the 140 °C and 160 °C temperature tests are depicted in Figure 3.

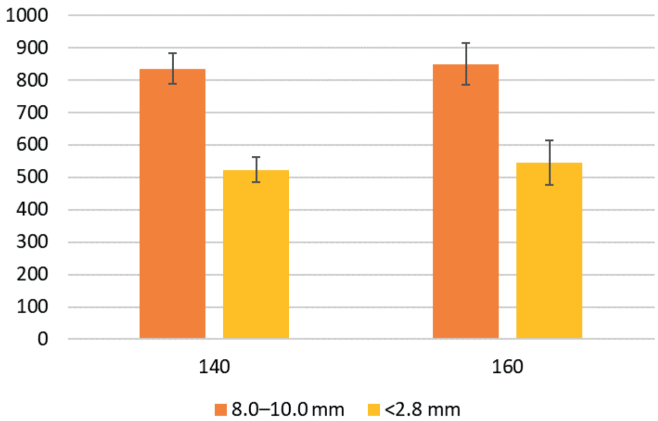

Figure 3. Modulus of Rupture of <2.8 mm particle size boards (yellow), and for 2.8–10.0 particle size boards (orange), depending on hot press temperature. Pressure 600 bar. Error bars represent standard deviation. An analysis of variance (ANOVA) revealed a significant main effect of particle size $F(1,20) = 30.1$, $p < 0.05$, but no significant effect of temperatures $F(1,20) = 0.11$, $p > 0.05$, nor interactions between particle size and temperature $F(1,20) = 0.004$, $p > 0.05$.

The results from combining the 2.8–8.0 and 8.0–10.0 fractions showed a great increase in board strength, showing better results than obtained prior. Nevertheless, smaller fraction boards showed a decrease in strength; this might be explained by bark removal from the biomass. By separating sand from the biomass, other smaller particles were removed from the raw material—including finer bark and needle particles. Temperatures were further tested by combining the hammer-milled biomass with chipped and sieved particles. The results depicted in Figure 4 show that although the larger particle size boards showed roughly the same results as the standard deviations in the same areas on the graph, smaller particle size boards show increased values, with one outlier even reaching the minimum MoR threshold determined by the European standard for wood chip materials EN 312-2:1997 [35].

The ANOVA results elucidated significant interactions between temperature and particle size in samples where the finest particles were present.

Smaller particles pressed together to make the final product denser, resulting in the lower desirability of such woodchip boards. Nevertheless, there was no correlation between overall density increase and increased strength when boards from all particle sizes were compared. The density and mechanical strength of the prepared samples are depicted in Table 1.

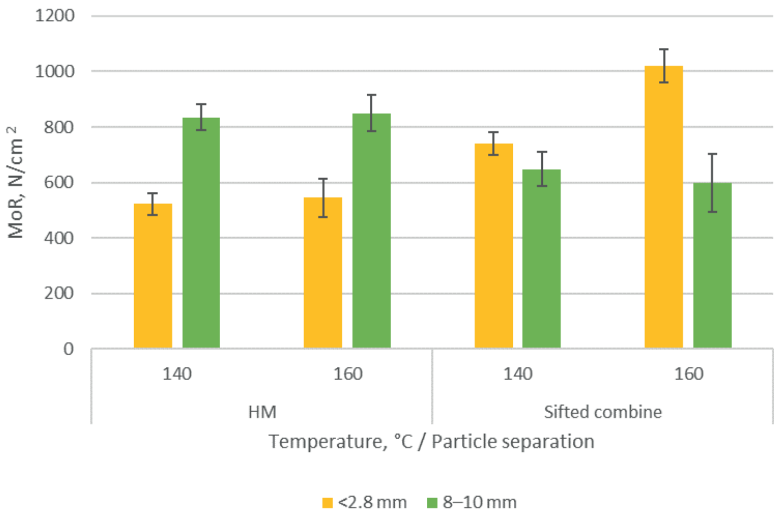

Figure 4. Modulus of Rupture of <2.8 mm particle size boards (yellow), and for 2.8–10.0 particle size boards (green), depending on hot press temperature for combined particles. Pressure 600 bar. Error bars represent standard deviation. An analysis of variance (ANOVA) revealed a significant main effect of particle size, and temperature for the HM (hammer mill) particle separation approach $F(1,20) = 30.1$, $p < 0.05$, but there was no significant effect of temperature $F(1,20) = 0.11$, $p > 0.05$, nor significant interactions between temperature and particle size $F(1,20) = 0.004$, $p > 0.05$. For the Sifted combined particle separation approach there was an effect of particle size $F(1,20) = 13.3$, $p < 0.05$, but no significant effect of the temperature $F(1,20) = 2.6$, $p > 0.05$, on the Modulus of Rupture. There were significant interactions between temperature and particle size $F(1,20) = 0.029$, $p < 0.05$.

4. Discussion

Although other research groups have been testing logging residue and pine bark applications for chipboard production, the possibility of completely excluding fossil-based adhesives has not been investigated [16,17]. 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, the scientific community and industries need to find working alternatives. This research provided insights on the logging residue potential of 100% bio-based chipboard production and provides a few useful takeaways confirming previous work on logging residue potential applications in chipboard production without the use of fossil-based adhesives or highly modified bio-based adhesives. The hypothesis that samples with a bark fraction will show higher strength was confirmed, showing the potential of further bark research in the context of bio-based chipboards. Although recyclability was not tested during this work, due to the nature of the used binder and potential lignin repolymerization, we speculate that recycling could be easier as there is no resin particle formation.

Assuming that the residues are derived from sustainable forestry practices, these residues represent a renewable resource that contributes to waste reduction while potentially aiding in carbon storage [36].

Bio-based carbohydrate adhesive was used in this research, as in previous tests without any adhesive, materials showed low strength and other unwanted effects such as bulging and burning of the material; adding the adhesive allowed for the reduction of these flaws and the production of materials for strength tests. However, moving forward with the technological development of such bio-based chipboard, comprehensive sustainability assessments need to be conducted—particularly concerning xanthan gum, as this component is not available on the Life Cycle Assessment database [37]. Despite the fact that xanthan is a biodegradable polysaccharide and its production methods are renewable [38], the absence of xanthan gum in existing life cycle assessment databases necessitates dedicated research to evaluate its complete environmental impact throughout its life cycle—particularly in the context of chipboard manufacturing.

In essence, while our study presents a significant step towards exploring 100% bio-based alternatives for chipboard production, the quest for a bio-based fossil raw material replacement remains an essential avenue for further research, facilitating the advancement of sustainable practices in the field of composite materials. Particle combinations allowed us to pinpoint the interaction of particle size and temperature using ANOVA. Interestingly, pressure and particle size did not show any significant interactions. Interactions between temperature and particle size could be further analysed by testing not only board strength, but also internal bonds.

This laboratory-scale research was carried out 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 [19] 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 strength, and that methods for mineral separation from bark material could be explored, perhaps by using flotation. Conversely to board rigidity, density increased with particle size reduction. This is a well-known correlation [10]; therefore, the next steps for this research would be to pinpoint the exact fraction mix that would lead to better mechanical properties and a lower density. There already is research on creating adhesives from bark extractables along with other bio-based adhesives [18], and this research confirms the potential of a chipboard transition away from fossil resources and towards completely bio-based materials. However, it is important to recognise the downsides of using logging residues, as they come from the logging sites—the inconsistency in their production means that automation is impossible or more challenging; therefore, the mass, energy, and resource balance should be assessed together.

5. Conclusions

This study demonstrates the feasibility of creating bio-based chipboards using logging residues and bio-based adhesives. The chosen adhesive showed promising results, but the search for a more efficient adhesive is still open. A previously performed literature review on adhesives elucidated multiple bio-based options—even potential adhesives from other industry residues. Successful research in this direction could potentially result in chipboard made from mostly residue-based raw materials—biomass and adhesive—leading to more sustainable products and contributions to the EU Green Deal. The early-stage nature of the research limited extensive testing, primarily focusing on showcasing possibilities only.

The examination of particle size, temperature, and pressure revealed their potential impacts on completely bio-based chipboard properties, suggesting avenues for further exploration and optimization. Future research directions might explore gravimetric separation methods, mineral separation approaches, and adhesive research to enhance chipboard properties while emphasizing sustainability and industry applicability. The transition towards predominantly residue-based chipboards holds promise for sustainable product development, aligning with EU Green Deal objectives.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author (arnis.dzalbs@rtu.lv). Upon request purpose of the data use should be stated.

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

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Criteria for Choosing Thermal Packaging for Temperature Sensitive Goods Transportation

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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

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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.

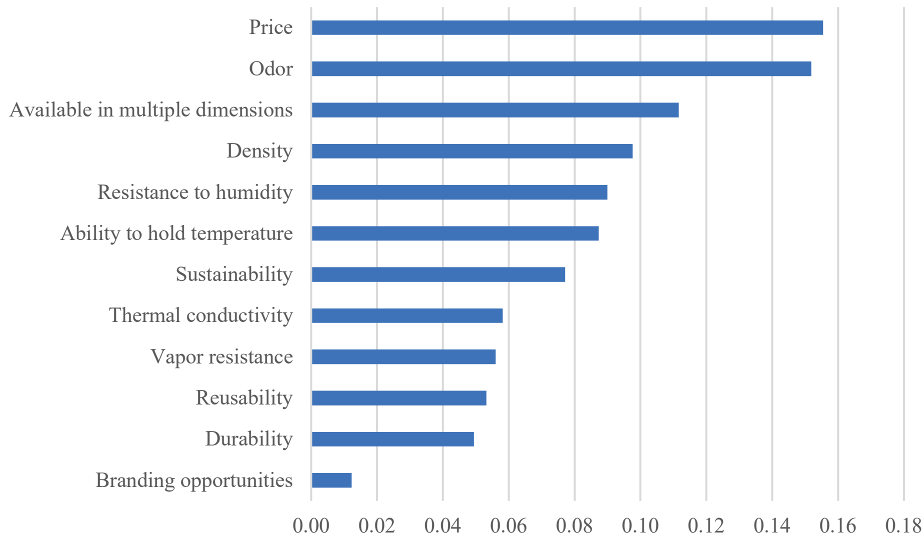

Fig. 1. Weighed criteria in ascending order regarding their importance.

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.

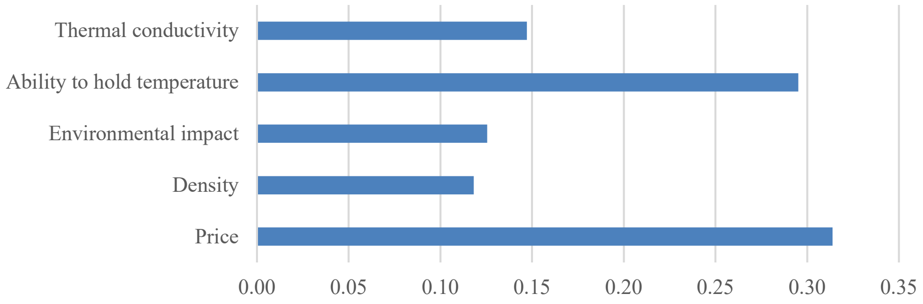

Fig. 2. Chosen quantitative criteria and their weights showing the importance of each criterion in the final decision making.

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).

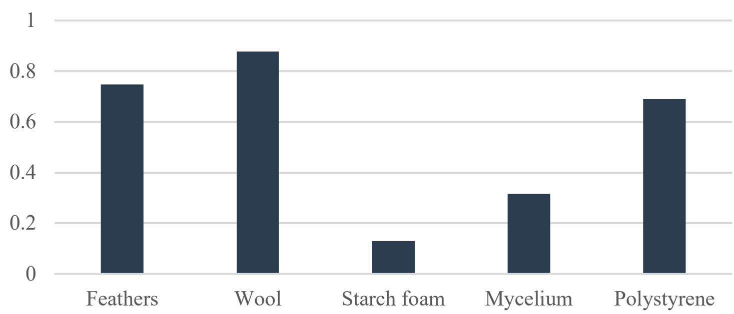

Fig. 3. Technique for Order of Preference by Similarity to Ideal Solution ranking of thermal packaging materials. Y axis represents the proximity to ideal solution 1.

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.

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Bioeconomy Towards Green Deal. Case Study of Citric Acid Production through Fuzzy Cognitive Maps

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Abstract **– The rapid consumption of resources, as well as the increase in the number of people, has raised awareness of the urgent need to change Europe's existing methods and attitudes towards the consumption of biological resources in production, processing, storage, reuse and disposal. One of the key principles of the European Green Deal is to make the EU economy sustainable. Achieving this goal requires promoting resource efficiency through the transition to a clean circular economy, restoring biodiversity and, above all, reducing pollution in order to mitigate climate change. The aim of the research is to create and offer bioeconomy opportunities, by demonstrating, analysing, and describing possible solution with the help of various examples. In order to compare different production process methods, which helps to understand which of them best meets the set sustainability criteria, fuzzy cognitive maps (FCM) modelling method was used. Alternatives to 16 bio-products are evaluated using the FCM (fuzzy cognitive maps) method using the Mental Modeller tool, according to four criteria – environmental, economic, social and technological aspects. Obtained results are reliable and objectively reflect the validity of the FCM method, and the use of this type of integrated analysis is appropriate to compare the various alternative production processes considered in the work.**

Keywords **– Bioproducts; fuzzy cognitive maps (FCM); resources; sustainability**

1. INTRODUCTION

Mankind continues to consume natural resources and services unsustainably, exceeding the rate at which these resources can multiply, regenerate, and renew, in that way increasing pressure on climate, ecosystems, habitats and biodiversity [1]. The aim of The Green deal is to tackle problems of the climate change by striving to change a block of 27 countries into a fair and prosperous society with a modern, resource-efficient, competitive, low-carbon economy, and protect and strengthen the European Union's (EU) natural capital and improve the quality of life for present and future generations [2]–[4].

Overall goals that were set by the European Union are [3], [4]:

- To achieve climate neutrality by 2050;
- To protect human lives, animals, and plants by reducing pollution;
- To help companies become world leaders in the field of clean products and technologies;

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– To help ensure fair and inclusive adjustment.

The European Union's growth strategy points to the necessity to rapidly change the current situation, invest financial resources in research, promote innovation, ensure clean energy, stimulate industry's transition to a clean economy, act energy-efficiently and resource-efficiently, find solutions for food safety and natural resources management, reduce climate changes and dependence on fossil resources, increase European competitiveness, create new jobs, and encourage the bioeconomy [1], [5], [6].

Today, the bioeconomy is not only considered to be a bio-resource economy, but it also means the sustainable consumption of bio-resources, which creates added value for society. Although it is established in European Union Directive 2008/98/ EK (European Parliament and Council, 2008) that production by-products are not classified as waste, but in establishments they are often considered as one and sent to waste streams or low-value streams, such as, production of biogas or solid fuels [7]. Development of a bioeconomy, based on skills on innovation and investment in knowledge, is inevitably required in turn to achieve a large part of set goals [8].

Bioeconomy is based on three principles of sustainable development – economics, society, and nature. These three pillars – fundamental principles must form a closed cycle, where the by-product of the process (waste product) is the raw material of another process [7].

This kind of approach to bioeconomy raises and enhances the added value of products and replaces fossil fuels in energy production and reduces greenhouse gas emissions.

The aim of the research is to create and offer bioeconomy opportunities, by demonstrating, analysing, and describing possible solution with the help of various examples. This is an illustrative and demonstrative research on how to create possible bioeconomy solutions that would promote the achievement of the goals of the Green Deal and would be suitable for implementation in Latvia.

The study presents a way to select production processes, improve and optimize them, categorize, and classify them according to the principle of sustainability. Analyse the improvement of production processes with different methods and compare them to crystallize the best and most suitable processes from the point of view of bioeconomy and sustainability. A total of 16 different production processes have been selected, based on a significant improvement of an existing production process: process optimization, reduction of residues, full use of added value of emissions or other production process residues, or reduction of electricity consumption and progress towards cleaner production.

In relation to the principles of bioeconomy and the Green Deal, the study provides research into the processes to produce citric acid using the FCM method. Biosynthesis of citric acid is a potential method for creating a new production process using the principles of the best available technology – using waste products processed from apples as the raw material.

Of course, most of the change involves less or more investment, a variety of potential of risk factors and required knowledge, but development is a logical, vital, and inevitable phenomenon in today's world.

2. METHODOLOGY FOR EVALUATION OF BIOPRODUCTS

2.1. Description of the General Method

System dynamics is a computerized approach to comprehend activity and behaviour of complex systems, such as, cities, climate, and ecosystems, for policy analysis and development, which was originally developed by Jay W. Forester. System dynamics is related to how things change over time [9]. It embraces most of what seems important to some people.

System dynamics include the interpretation of real-life systems in computer simulation models. This allows us to see how the system's structure and decision-making policy shape its behaviour. Complex systems are any system with many mutually interacting components (agents, processes, etc.) that are often difficult to understand and solve and that require the development or use of new scientific tools, non-linear models, out-of-balance descriptions, and computer simulations. Complex social systems involve human behaviour and may have concepts that interact in a way that is quantitative (final) and/or qualitative (abstract), and the latter is particularly difficult to include into modelling tools due to their qualitative nature and the consequential challenges. The exclusion of such abstract qualitative concepts may call into question the conclusions that were reached and the relation of the models to reality. In order to be able to explain, predict and understand complexity, it is argued that qualitative phenomenon that can play a significant role in systems must be included. Therefore, analysis of qualitative systems or qualitative modelling is increasingly used to analyse the dynamics of complex systems. Kosko introduced fuzzy cognitive maps (FCM) as a tool for dynamic qualitative system behaviour perception and explanation. FCM is increasingly being used to model and analyse the behaviour of qualitative systems. Over the past 30 years, this fuzzy cognitive mapping (FCM) approach has become increasingly popular due to the simplicity of design and low computing requirements. In order to model the dynamics of the social system, two types of application are mainly used – deductive approach and inductive approach. The deductive approach uses the knowledge acquired by interviewing experts in the field of application, while the inductive approach is an automated and semi-automated approach designed to learn FCM rules based on historical data [10]–[13].

In general, it is considered that FCM has several advantages over traditional quantitative modelling approaches. The advantages of FCM include, for example, the ability to model data in limited environments using natural language, expressing knowledge, perception, experience or beliefs, as formulated by an expert or stakeholder, usually characterized by ambiguous information. Besides, the results of FCM are easy to interpret for the layperson and the public. However, if they're used to model qualitative SD behaviour, traditional FCM also has several drawbacks. These shortcomings are largely due to incomplete:

1. Semantics of causation and thus the limited causation dynamics perception, depiction, and simulation;
2. Inclusion of time relations;
3. Diffusion detection, depiction, and simulation;
4. Dynamics simulation using single-layer perceptron mechanisms.

Several FCM extensions have been developed to overcome these shortcomings, but most of the developed extensions are trying to solve specific problems with traditional FCM and do not try to solve the problems related to modelling FCM dynamics [14]–[16].

FCM consists of concepts (linguistic terms) that are expressed by nodes. Directed arrows with scales explain the relations between concepts. These weights describe the strength of causality with $\{-1.0\}$ and $\{0.1\}$, which, respectively, denotes the decrease and increase of causality. Concepts and their reciprocity are depicted by nodes and directed arrows with their weights explain the layout of a particular system. It is depicted in a matrix that allows to perform standard algebraic operations to find relations between nodes. The FCMs that were introduced by Kosko [10] are simulated using a mathematical formula expressed in the Eq. (1).

$$C_j(t+1) = f\left(\sum_{i=1,\, i\neq j}^{n} w_{ij} \cdot C_i(t)\right), \tag{1}$$

where

n Number of concepts;

$C_j(t+1)$ Value of the concept in the next iteration;

$C_i(t)$ Value of the concept during the iteration;

w_{ij} Weight of the reciprocity between cause and effect.

Then it is mapped on a predetermined universe in discourse using transformation functions. It is then mapped to a predetermined universe in discourse using transformational functions, the most common are the achievements of the sigmoid and hyperbolic transformation function FCM in relation to modelling and simulation.

Ideally, when modelling a complex qualitative SD, it should have FCM and be able to capture and model causal dynamics, as experts believe. This includes integration and capture of certain causative dynamics properties, which may include, but are not limited to, the following:

- The cause can manifest itself in different conditions or in different ways;
- The cause cannot be two states or an example of strength in time (two states are possible only in quantum superposition);
- The cause is before the consequences, so time dependence is a characteristic;
- The influence of the cause must either increase or decrease;
- The cause in a certain condition can create consequences, which result because of the dynamic time lag, time delay or time reduction;
- The cause can create consequences that are dynamic as a result of changes in position or strength (i.e., they can be nonlinear, non-monotonic, and asymmetric);
- The effect is felt only when there is a change in the state or the strength of the process;
- Influence may be the result of relative causes.

In addition, ordinary FCMs and several achievements of single-layer perceptron are used to model and explain the dynamics of the quality system as a universal event. However, SD, causation can be conditional, probable or possible in terms. Lastly, in the best-case scenario FCM also reflects the uncertainty and indetermination of excerpt knowledge. They can be represented and simulated by using fuzzy systems and FCM, as it was foreseen by Kosko [17]; his approach is suggested and intended as a combination of fuzzy logic and artificial neural networks.

2.2. Description of the Application of the Method for the Evaluation of Bioproducts

The FCM modelling method described will be used in the study to compare different production processes methods. It will help to understand which of them best meets the sustainability criteria set out in the, and to identify potential barriers to obtaining reliable and objective results, while using the FCM method. And whether the use of this type of integrated analysis is appropriate to compare the different production process alternatives that were looked at in the study. FCM modelling requires a sequential set of activities that will ensure that the research objective is achieved in a transparent and understandable way to analyse 16 manufacturing processes.

In order to compare all the production processes described, it is necessary to define the most important criteria. Several criteria are used in this process, making choices more efficient, rational, and clear. The aim of the analysis is to structure the processes to define the objectives, evaluate the possible alternatives and compare them from different perspectives. The following criteria were selected when evaluating the priority criteria:

1. Environment aspects;
2. Technological aspects;
3. Economic aspects;
4. Social aspects.

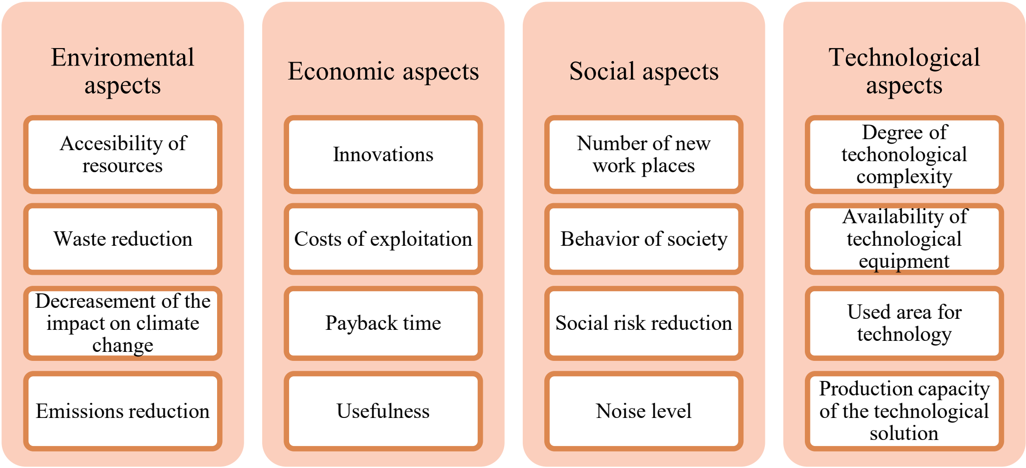


Fig. 1. Aspects of evaluation criteria.

Considering the limitations of the information availability, sustainability, and usefulness indicators from the point of view of bioeconomy have been selected for modelling.

All selected criteria and sub-criteria are qualitative, so they should be assigned numerical values based on the analysis of the production processes performed in the study. The qualitative characteristic approach, unlike the quantitative results approach, makes the results that were obtained in the approbation part of the methodology more subjective. However, if accurate quantitative data on the processes were available, the view on the usefulness performance would be limited.

Each sub-criterion will be assessed with a value from −1 to 1, where the strongest link is donated by 1 and it will denote the best, strongest possible link from the point of view of bioeconomy and usefulness. The rating link one that was obtained in the sub-criterion is comparable to the highest implementation efficiency. Whereas the lowest rating −1 indicates the weakest link or result from the point of view on bioeconomy and usefulness.

3. Approbation of the Methodology

Alternatives of the study result are 16 bioproducts. These alternatives are evaluated by the FCM (fuzzy cognitive maps) method, using the *Mental Modeler* tool according to four criteria – environmental, economic, social, and technological aspects. These core criteria are consolidated into 16 sub-criteria and each alternative is assessed on a scale of −1 to 1, with −1 being the weakest link (worst) and 1 being the strongest (best).

3.1. Reciprocity of Criteria and Sub-Criteria

Figure 2 sums up the assessments of the environmental, technological, economic, and social aspects that must be analysed. Environmental aspects illustrate the interactions between resource availability, waste reduction, the decreasement of the impact on climate change and emission reduction. For example, the reduction of waste and emissions has a negative effect on the availability of resources because a part of the waste (by-products) and emissions can be used as a raw material for another production process. But a reduction in waste with a strong positive link has a direct positive effect on the environment, as it reduces pollution and therefore less or no waste is generated in production processes. From this point of view, the interactions of all sub-aspects have been looked at, which together result in one of the four aspects. Visually, a blue link that have a positive value from 1 to 0 and brown link whose value is 0 to −1 can be seen. The thicker the colour is the link, the greater is its positive or negative value.

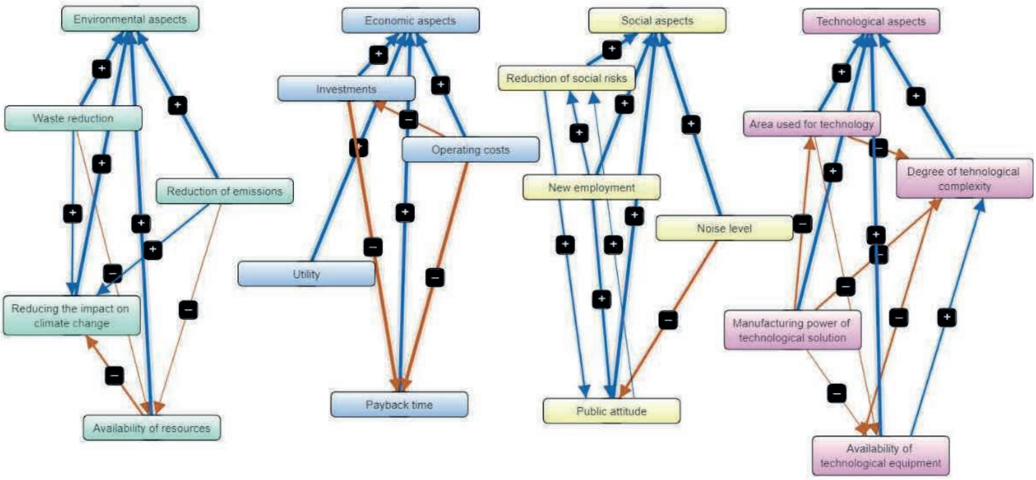


Fig. 2. Links between the interactions of all four aspects and their sub-criteria.

To keep on building the model further, the aspect link described above are used and supplemented with each of the 16 production process name blocks and the same production process usefulness block, which is required for the modelling tool to be able to calculate the total result for a particular production process.

3.2. Approbation of the Methodology for the Citric Acid Production Process

All 16 production processes have been analysed and modelled in the study, however, one of the production processes will be shown in detail in this study, but the results for the other 15 production processes will also be evaluated in the results and discussion section, as the structure and approach are analogous to all production process models.

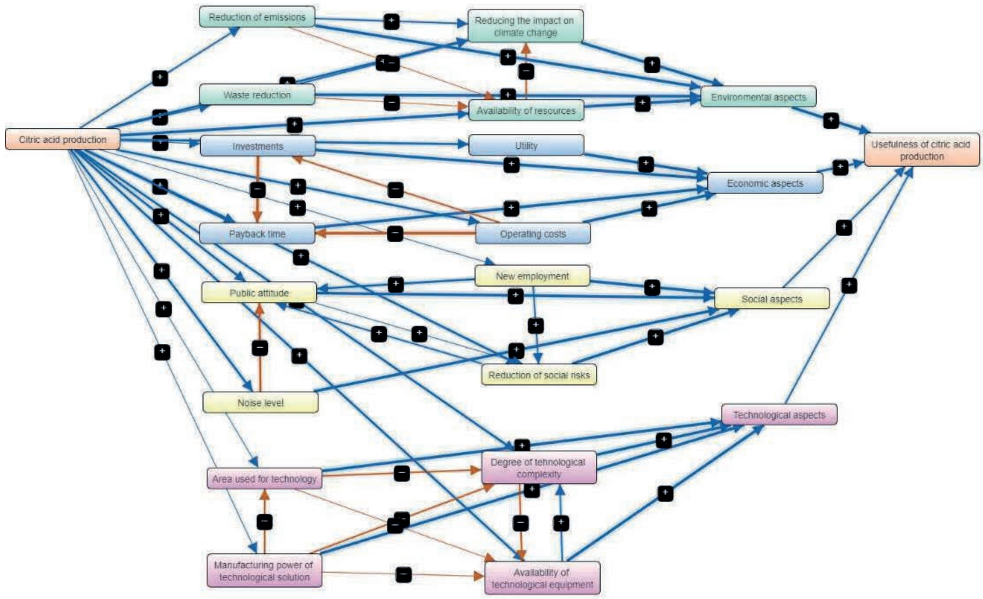


Fig. 3. Advanced visualization model of citric acid production processes.

To make the visualization of the model easier to understand, the group of environmental aspects are coloured green, economic aspects are coloured blue, social aspects – in yellow, and technological aspects are coloured in purple. Whereas the name of the specific variable production process and its usefulness block are coloured orange.

For each production process, links are created for each of the sub-criteria, indicating the strength of the link in the range from −1 to 1, based on expert judgement. For example, Table 1 shows that the payback time for citric acid production is relatively short, so this link has a positive value of 0.7. Meanwhile, the area used for the technology requires about 1 ha, which is estimated at 0.1 positive value.

After completing the visualization part of the model, a quantitative result can be obtained for each of the model positions. The obtained values are shown in Table 1.

TABLE 1. QUANTITATIVE VALUES OF THE CITRIC ACID PRODUCTION PROCESS

Component	Indegree	Outdegree	Centrality
Citric acid	0	6.949	6.949
Environmental aspects	4	1	5
Technological aspects	4	0.48	4,48
Social aspects	4	0.2	4.2
Economic aspects	4	0.81	4.810
Waste reduction	0.47	1.400	1.87
Accessibility of natural resources	1.23	1.19	2.42
Reduction of the impact on climate change	1.21	1	2.21
Emission reduction	0.48	1.339	1.819
Payback time	2.5	1	3.5

Usefulness	0.52	1	3.5
Costs of exploitation	0.5	2.31	2.81
Investments	0.42	2	2.42
Reduction of social risks	1.02	1.25	2.27
Noise level	0.52	1.58	2.1
Public attitude	2.08	1.16	3.24
Number of new jobs	0.09	2,09	2.179
Production capacity of technological solution	0.09	1.680	1.770
Degree of complexity of the technology	1.44	1.28	2.7199
The area used for the technology	0.42	1.28	1.7
Availability of technological equipment	0.960	1.44	2.4
Usefulness of citric acid production	2.49	0	2.49

The table of aspects and sub-criteria of the obtained values is sorted by the central size, it is, the total number of positive and negative links, which shows the most influential aspects and sub-criteria. From the values obtained in the table, it can be concluded that from the point of view of bioeconomy, the most influential aspect of the citric acid production process is the environmental aspect, followed by the economic aspect. In this way, each production process can be reviewed, and the feasible production process can be selected according to any of the proposed aspects. Of course, when working with the model, it is possible to change and view the obtained results by prioritizing social aspect, or any other necessary priority.

Once the quantitative values for each of the sub-criteria have been obtained, the *Mental Modeler* tool has the option to switch to the results section. The main result of the goal is to obtain the efficient results of the production process, which will be in the range from 0 to 1.

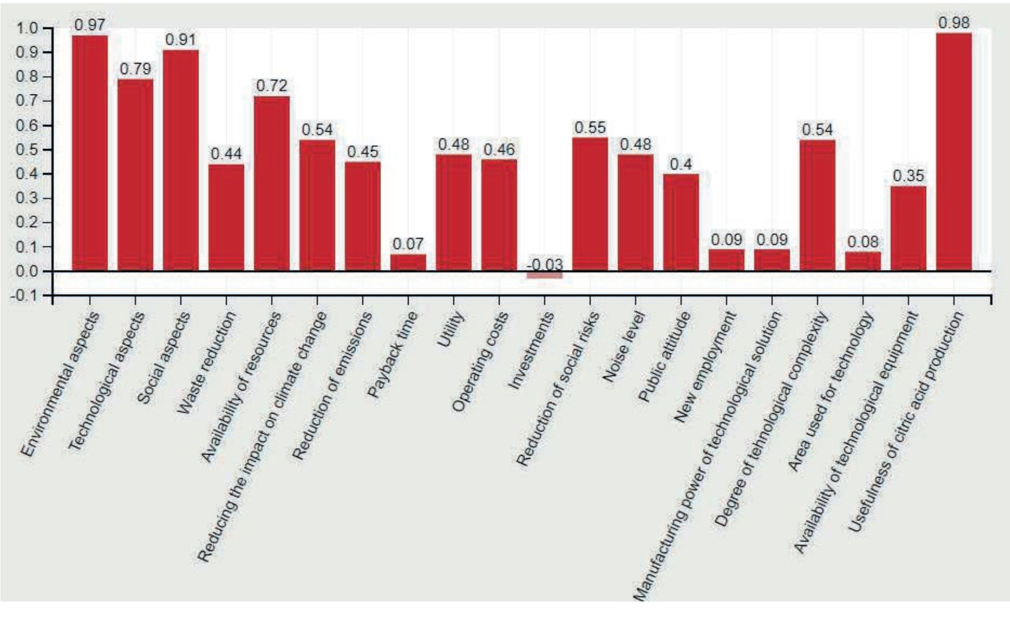
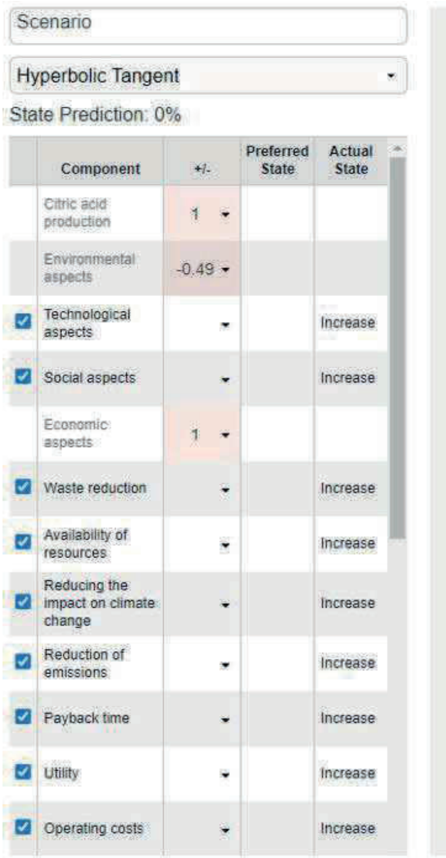


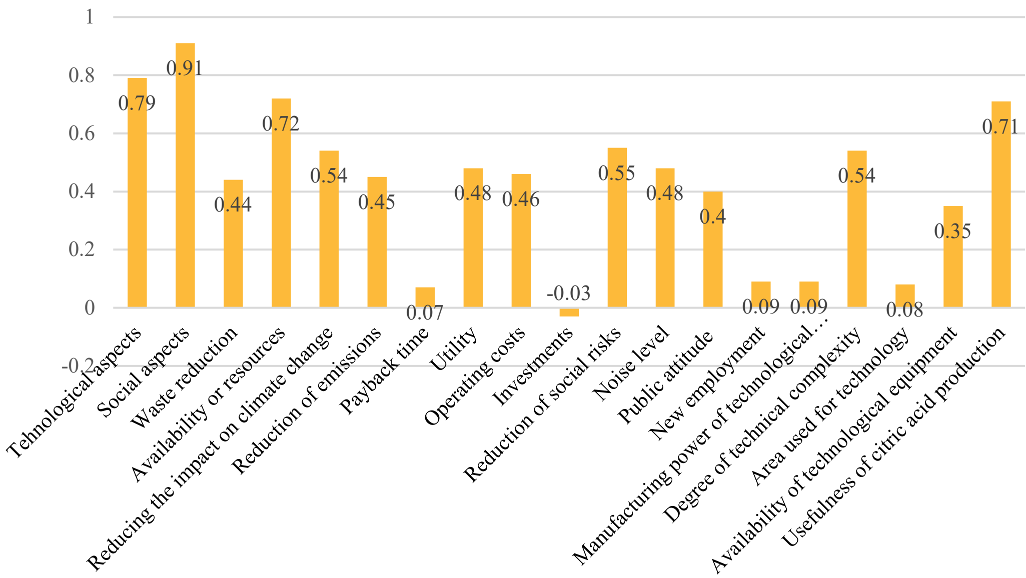
Fig. 4. Results of the citric acid production process.

Fig. 4 shows the main conclusion about the citric acid production process, that is, the citric acid production efficiency is worth 0.97. All production processes described in the work will be compared with this endpoint. As can be seen from the graph, the citric acid production process makes the largest contribution in terms of environmental and social aspects, but the weakest issues in setting up such a plant would be in terms of investment and payback. This is due to the installation of a large amount of necessary industrial equipment and technologies, obtaining relatively small production capacity. Given that the study is prone to sustainability in terms of achieving the objectives of the EU Green Deal, the usefulness of the citric acid production process is very high – 0.97. If the modelling focus was only on the economic aspects, it was thought that the result of this production process would be less positive. Therefore, the author looked for a way to model also changes in priorities.

When designing a model, the *Mental Modeler* tool also provides the ability of influencing and altering priorities at the result and block of scenarios section. Fig. 5 shows the results when the environmental aspects are reduced to −0.49 and the economic aspects are increased to 1. Thus, this simulates the situation where a potential investor wants to assess whether the citric acid production process is economically viable, but the environmental aspects seem less important. In such a situation, the scenario under consideration shows a usefulness value of 0.71, which is also a significant positive value and would be comparable to other alternatives.



(a)



(b)

Fig. 5 (a) and (b). Results of the citric acid production process with increased economic value.

Therefore, such a project is not only environmentally efficient, but also economically viable, and the investor or potential developer can evaluate alternative production processes from different perspectives and compare them with similar criteria.

4. Results and Discussion

In the previous section an example of a citric acid production process model and the obtained results were described. In the same way, all the 16 production processes were analysed by applying an analogous modelling type and identical criteria. However, as it was mentioned above, the main aim of the study is to obtain data to select from the described production processes the primarily established ones, and to rank them, thus determining, which of the proposed solutions is the most efficient and proves added value from the bioeconomy view towards the Green deal goal achievement. To obtain such an outcome, the result obtained for each production process in the section 'efficiency of the production process' is compared with each other according to the obtained quantitative result on a scale up to 1 (Table 2). Listed results are shown in a bar graph in Fig. 6.

The graph (Fig. 6) shows the obtained quantitative results of 16 production processes in the usefulness comparison. The obtained results show that the most efficient and effective production process is the production of composite materials. This result is justified by the availability of raw materials for composite materials, which are mainly by-products of other production processes: low-quality wood residues and recycled plastics. As well as the demand for such composite materials on the market growing rapidly due to their physical properties, production technologies are relatively simple and available without excessive investment.

Without taking a further look into the positive features of each production process, which have brought the described production process closer to the high result obtained, we conclude that eleven of the described sixteen production processes have reached very high values in the range of 0.9 to 1 and all eleven production processes correspond to high bioeconomy efficiency towards the goals of the Green deal, consequently these production processes are very valuable and should be primarily implemented in the economy by investing in production facilities.

TABLE 2. USEFULNESS OF PRODUCTION PROCESS

Citric acid production	0.97
Synthesis of silver nanoparticles	0.96
Manufacture of composite materials	0.98
Nanocellulose production	0.92
Manufacture of toiletry from whey	0.97
Xylan production	0.92
Polykactide production	0.97
Manufacture of natural nettle fibres	0.29
Biodiesel production	0.73
Production of Dendrolight cellular material	0.98
Pellet production	0.83
Bioethylene production	0.68
Cellulose production	0.94
Tannin-based foam production	0.9
Coniferous extract production	0.96
Lignin production	0.83

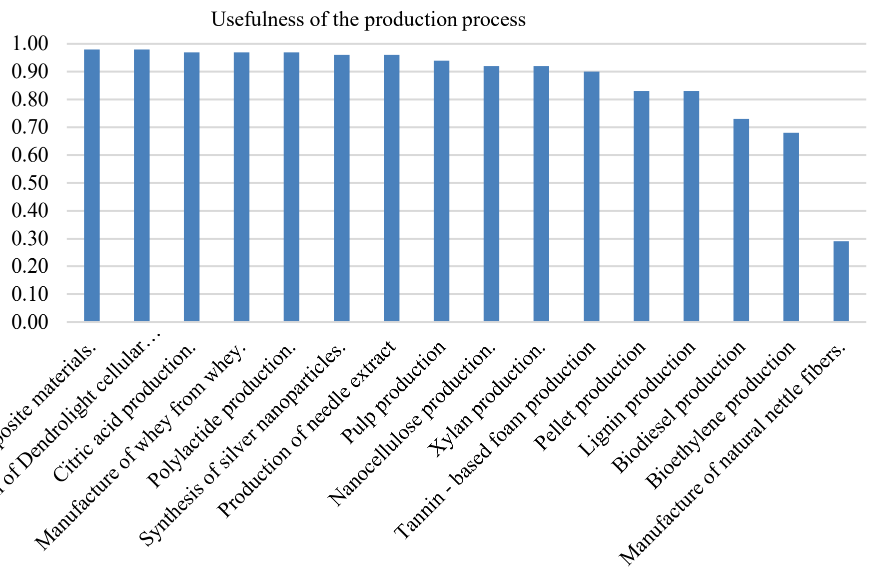


Fig. 6. Summary of efficiency of production processes.

Conversely, the production processes of biodiesel and bioethylene, although very valuable for replacing fossil fuels and increasing the independence of non-oil-producing countries from fossil resources, are still very technologically complex and require huge investments in their production and are currently reducing their production economic viability. However, the rapid development of science and technology will inevitably bring the production of biodiesel and bioethylene closer in the next decade.

The weakest result (0.29 out of 1) was obtained in the production of natural nettle fibres. This result is due to the competition of this production process for agricultural land with the food industry and the low competitiveness of the resulting product in the textile industry, as it would be very difficult to justify the production of nettles in large areas and processing them into textile products from the environmental aspect and economics aspect point of view.

Considering the objectives of the study, the obtained results are reliable and objectively reflect the validity of the FCM method, and the use of this type of integrated analysis is appropriate to compare the various alternative production processes considered in the work.

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