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SUSTAINABILITY ASSESSMENT OF BIORESOURCES. LATVIAN CASES

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Natural Sciences and Technology
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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council at on June 13, 2024, at 14:30 at the Faculty of Natural Sciences and Technology of Riga Technical University, Āzenes iela 12/1, Room 116.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Arnis Dzalbs ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written as a collection of articles. It consists of an introduction, three chapters, conclusions, 18 images, 4 tables, and five appendices. The total number of pages is 51, not including appendices. The Bibliography contains 52 titles.

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.

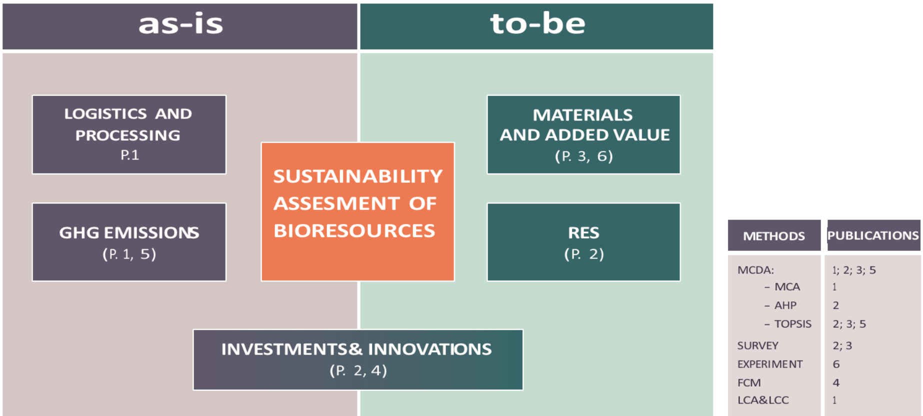

Fig. 1. Research framework.

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.

Approbation

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Participation in conferences: Connect 2023.

1. LITERATURE REVIEW

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

The agricultural cold supply chain plays a pivotal role in ensuring the quality, safety, and shelf-life extension of perishable agricultural products. With 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 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.

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. In [6], a study on USA egg production is conducted, revealing a decrease in GHG emissions over the years, emphasizing the importance of considering local conditions. In [7], a comparative analysis of GHG calculators is conducted, highlighting variations in emissions estimates due to differences in calculation methods and input parameters. Case studies and the performance of GHG calculators emphasize the role of uncertainty in emission estimates and recommend improved data collection and model validation. Furthermore, in [8], four alternative low carbon scenarios for Nigeria are developed, identifying expected future trends of GHG emission in the 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.

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. In [9], a cost-benefit analysis of renewable energy adoption on farms is conducted, highlighting significant long-term savings despite initial investment costs. The authors emphasize the importance of government incentives and financing options in facilitating adoption.

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

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

In recent years, there has been growing interest in utilizing bioresource materials in agriculture to enhance productivity, sustainability, and economic viability. The 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. In [13], the use of biochar, a carbon-rich material derived from biomass, in soil amendment is examined. The study demonstrated the ability of biochar to improve soil fertility, water retention, and crop productivity, thereby enhancing agricultural sustainability.

Similarly, in [14], the utilization of agricultural residues, such as crop residues and animal manure, for biogas production is explored. The authors highlight the dual benefits of bioenergy generation and waste management, emphasizing the potential for renewable energy integration in agricultural operations. Furthermore, in [15], the application of agricultural by-products, such as crop residues and agro-industrial wastes, in the production of bio-based materials is investigated. The study showcases the potential of bio-based materials for diverse applications, including the manufacturing of biofuels, enzymes, vitamins, antioxidants, animal feed, and antibiotics, thereby promoting circular economy principles in agriculture. Moreover, the authors of [16] examin the use of biofertilizers derived from microbial inoculants in agricultural practices. They demonstrate 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.

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. In [17], the authors emphasize the importance of participatory approaches that involve stakeholders at various levels to ensure the relevance and acceptance of sustainable agricultural practices. The study underscores the role of farmer knowledge, local contexts, and socio-economic factors in shaping decision-making processes.

Furthermore, the authors of [18] highlight the need for holistic assessments that consider multiple dimensions of sustainability, including environmental, economic, and social aspects. They advocate for integrated decision-making frameworks that prioritize synergies and trade-offs among different sustainability goals. Moreover, the authors of [19] examine the role of technology adoption and innovation in driving sustainability transitions in agriculture. The study emphasizes 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, in [20], the authors investigate 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 increasing 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, a survey was conducted to identify which RES are most viable when mutually compared and determine the RES with the 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 the 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 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 the first priority is 3, for the second priority – 2 and for the 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 per priority 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 open questions like "How is thermal packaging chosen?", criteria and their indicators were elucidated. In many cases, it became clear that the industry is not using numerical indicators for each criterion. The analysed product data sheets contained information based on performance, for example, hours held in temperatures below +8 °C [23], [24], [25].

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

2.2. Pairwise comparison

After survey the importance of 12 criteria was compared in pairwise fashion. As it is nearly impossible for humans to the reciprocal relationships of 12 criteria simultaneously, 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. The comparison was done verbally, as suggested by Saaty *et al.* 2010 [29].

Further, it was determined whether one criterion is 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 signifyied very high importance, 6 strong to very strong importance, 3 moderate importance, and 1 equal importance [30].

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 they were unsuitable for multi-criteria analysis and criteria comparison. The chosen companies assigned the questionnaire to logistics team experts within the company.
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 criterion – 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 a new biomaterial, an experiment was conducted to make a bio-based chipboard. 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.

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. The crushed particles were sieved using a Retsch AS-400 sieve shaker and metal sieves with different mesh opening sizes.

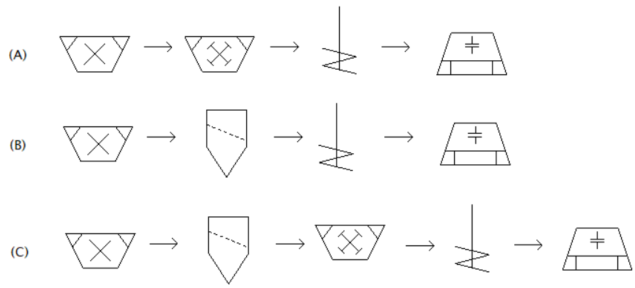

Fig. 2.1. Workflow for particle separation.

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 a sieve for particle separation, mixing, and pressing;

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

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

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 in calculating the of criteria weights is the pairwise comparison. The nine-integer value scale was initially suggested by Saaty [33].

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. 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].

TOPSIS methodology

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

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

TOPSIS methodology is based on five calculation steps. The first step gathers a data set of indicators for each scenario. In the second step, normalization of indicators is performed. In the next step, normalized values are weighted, and their proximity to desirable and avoidable results is calculated. The final step calculates the proximity by ratio of these distances [36].

The mathematical description of the steps is described further. Step one gathers data from n alternatives a with chosen m criteria i in decision matrix X, where $i = 1,\dots, m$ and $a = 1,\dots n$. The data is being normalized so that various units used are comparable. Distributive normalization, used for the Thesis uses Eq. (2.2) [36].

$$r_{ia} = \frac{x_{ia}}{\sqrt{\sum_{a=1}^{n} x_{ia}^2}}, \text{ for } a = 1, \ldots, n \text{ and } i = 1, \ldots, m \quad (2.2)$$

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

$$V_{ai} = w_i \cdot r_{ai} \quad (2.3)$$

In the next step, the results from the 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 the comparison, Eqs. (2.4) and (2.5) are used for zenith and nadir options.

$$A^+ = (v_1^+, \ldots., v_m^+), \quad (2.4)$$

$$A^- = (v_1^-, \ldots., v_m^-), \quad (2.5)$$

From the 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 the performer to determine which are have positive value and which have negative value.

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

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

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

$$C_a = \frac{d_a^-}{d_a^+ + d_a^-}. \quad (2.7)$$

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

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

The aim of the TOPSIS analysis in Publication 2 is to compare RES technologies in order to find the 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 parts 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 criterion in the multi-criteria analysis and has always been a topical issue in the energy sector [39].

The first step using the TOPSIS method is normalizing the decision matrix, followed by calculating the normalized decision matrix and determining 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 comprehending the 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].

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 general, it is considered that FCM has several advantages over traditional quantitative modelling approaches. These advantages 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.

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, denote the decrease and increase of causality. Concepts and their reciprocity are depicted by nodes and directed arrows with their weights explaining 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 Eq. (2.8).

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

where n is the number of concepts, and $C_j(t+1)$ is the value of the concept in the next iteration. $C_i(t)$ is the value of the concept during the iteration t, and w_{ij} is the 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.

The methodology was used for the evaluation of bioproducts. FCM modelling method was used in the study to compare different production process methods, 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. The following criteria were selected when evaluating the priority criteria:

1) environment aspects;
2) technological aspects;
3) economic aspects;
4) social aspects.

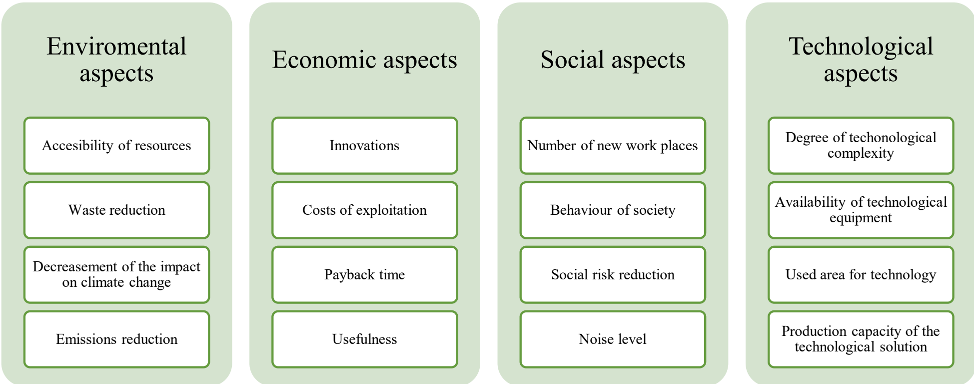

Fig. 2.2. Aspects of evaluation criteria.

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.

Each sub-criterion will be assessed with a value from –1 to 1, where the strongest link will 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 “1”,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 the research, actual, real-life examples and models were analysed using the Life Cycle Assessment (LCA) methodology, including basic metrics for systems and options on merging of results.

To prove the 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 the European Union (EU) Commission.

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

The study is performed by determining and defining process flow within the defined system boundaries, developing data collection methodology, collecting relevant data, and reporting the results. The life cycle inventory is the outcome of this phase.

Table 2.1

Inventory of Cultivation of Functional Unit

Materials and activity	Unit	Quantity	diesel, kg	water, L	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							
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: years 4 to 30							
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
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: years 4 to 30							
Tractor	set	1	12.45			336.15	3.66

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

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 30 years of experience and history. It is mainly used by industry and academics in more than 80 countries.

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. The main task of LCC is to find out project profitability over its life span, including obtaining project assets and ending with disposal. LCC is used as a tool to support the decision-making process. The Life Cycle Costing approach was born a few decades ago, in 1965 in the USA, when the United States Logistics Management Institute used the term of "life cycle costing" while seeking lower costs in military logistics as a result of economic stagnation [43].

The current literature and publications on LCC are filled with examples of application of this approach in various aspects of investments, starting with construction projects and ending with an analysis of investment in environmental activities [44].

In addition, LCC is also accepted in the 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 purely based on a 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, the first is the development phase, which includes all costs related to research, planning, obtaining property, and design. The second is the construction phase, which comprises all costs associated with establishing facilities. Next is the operation phase, where operational, maintenance, and repair costs are to be identified.

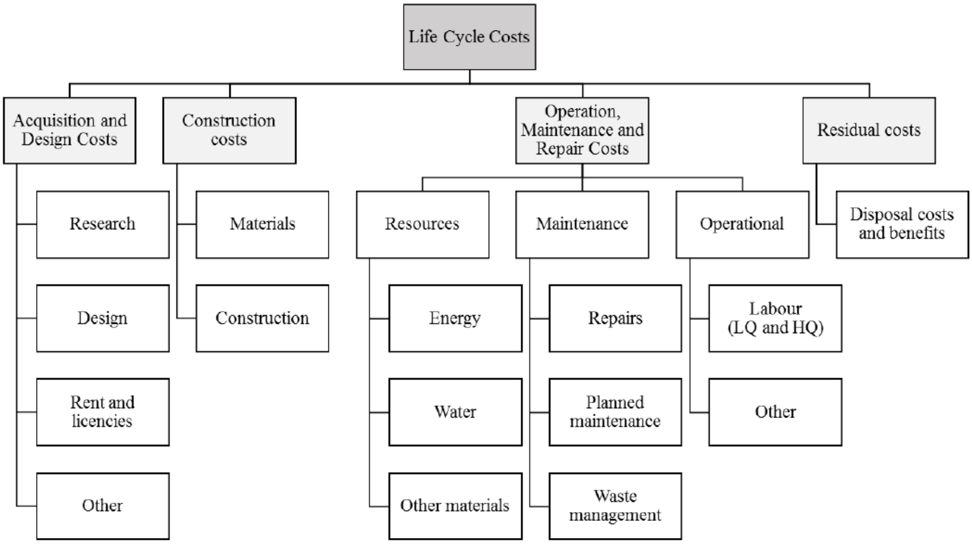

Fig. 2.3. Common Life Cycle Cost structure of a project [45].

The final phase includes all the costs related to the maintenance values of the project, which can be positive or negative. 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 the discounting of cash flow. The discount rate is "the rate of interest, reflecting the investor's time value of money (or opportunity cost), that is used in a discount formula or to select discount factors which in turn are used to convert (discount) cash flows to a common time" [46].

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 a successful project. The NPV is then compared with an alternative project.

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

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

where *DF* is a discount factor, *r* is the discount rate, and *n* is the number of years ahead.

The 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].

In practice, it is usually assumed that the 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).

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

where *NPV* is the net present value, *K* is an initial investment in the base year, *r* is the discount rate, *CF* is cash flow, and *n* is the number of years ahead.

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

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.

Life Cycle Costing (LCC) is an economic analysis and is considered the basic element of LCCA. In [43], it is defined 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" 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).

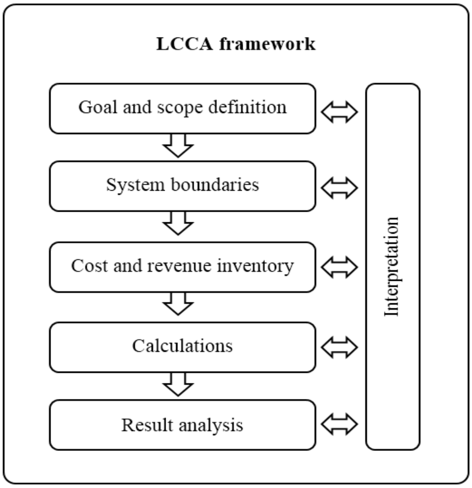

Fig. 2.4. LCCA framework [46].

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

Table 2.2

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 a 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 of rent, 65 EUR/day
Fuels	500	fuels for tractors and rented vehicles
Fertilizers	2430	fertilizers for plants according to the schedule
Operational costs	1000	various costs, including accounting, banking fees, electricity, etc.

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

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

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

3. RESULTS

The research subject has many levels, differing in scope and approach. During the research, several specific dimensions of 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 the perspective of logistics impact on the whole chain through LCA (Publication 1).

In Publication 1, all the relevant data was collected to perform an analysis of logistics in the case study – the sea buckthorn supply chain – and the LCA model was created. The main contributors of the base scenario to the total aggregated environmental impacts of the sea-buckthorn project with mass allocation logistic stage are depicted in Fig. 3.1.

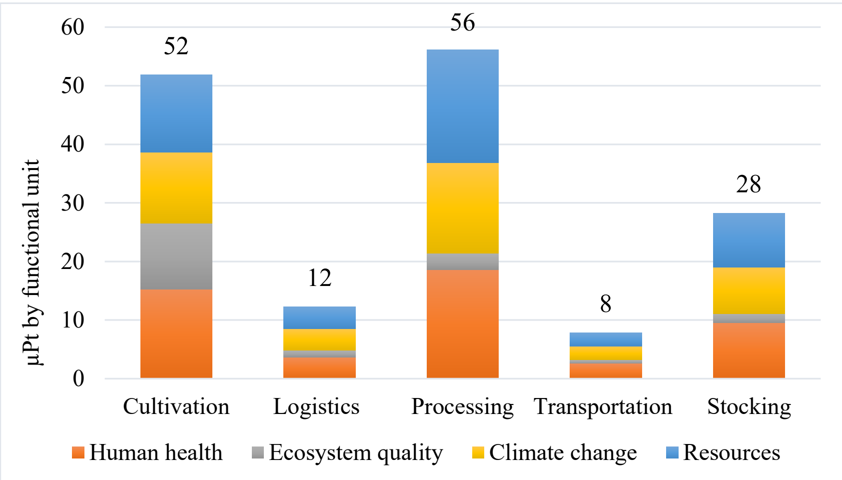

Fig. 3.1. Impact aggregation by SimaPro of the base scenario.

Processing, as can be seen, has the main impact. Logistics and transportation create less impact than cultivation and stocking due to rather short delivery distance and energy-intense processing. During research, the base model was compared to energy efficiency improvement options – warehouse insulation and change of engine of transportation vehicle from EURO 4 to EURO 6 standard without other changes in inventory. Results of simulations show that total environmental impact per functional unit varies by less than 1 %.

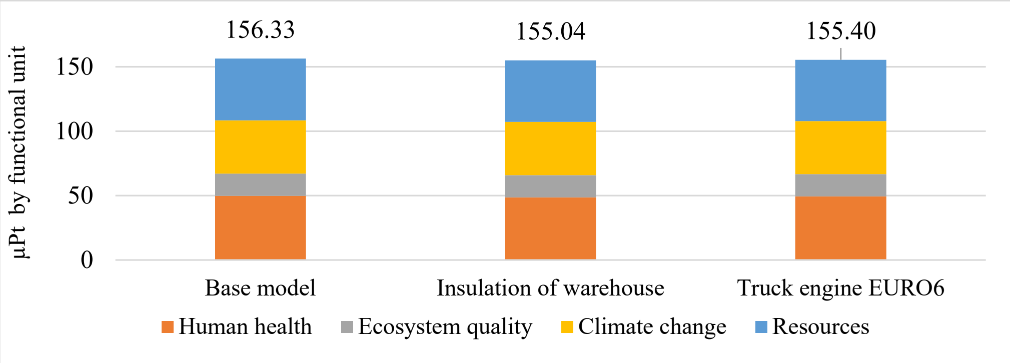

Fig. 3.2. Scenario comparison, total endpoints.

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

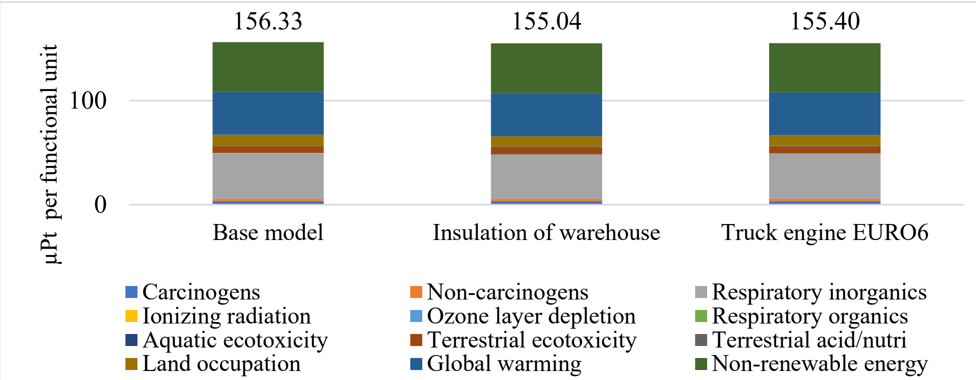

Fig. 3.3. Midpoint analysis of three scenarios

Midpoint analysis permits to see the main categories of environmental impact from the modelled situation.

3.2. Renewable energy sources

Publication 2 evaluates renewable energy technologies (RES) using a combination of AHP and TOPSIS methods and technical, economic, environmental, and social criteria. To indicate the needs, potential barriers, and position of enterprises on renewable energy, an enterprise survey was conducted. The survey results from 146 enterprises were compiled and analysed only in aggregate form.

Aggregated results show that according to 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 3.4 shows the rankings of all RES technologies.

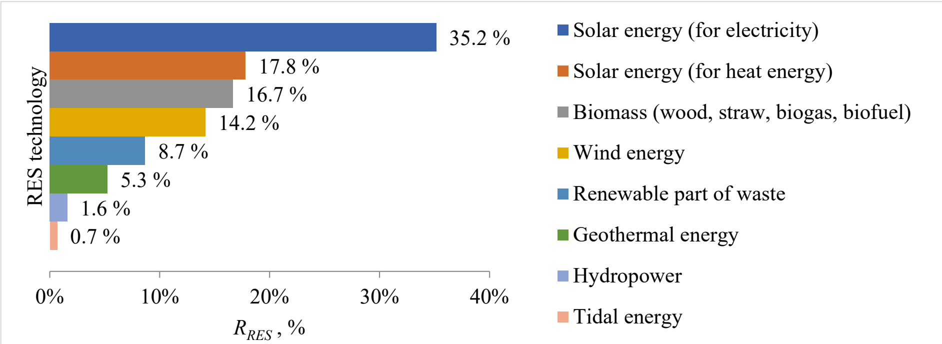

Fig. 3.4. Ranking of RES technologies according to enterprise survey results.

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.

In the TOPSIS analysis, six RES technologies were evaluated using a scale from 2 to 5, where 2 corresponds to the lowest score and 5 to the highest score and the potential of the use of renewable energy in 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.

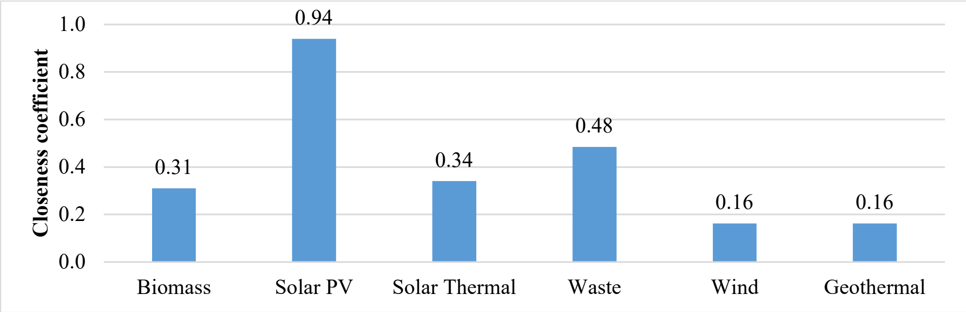

Fig. 3.5. TOPSIS analysis results – the ranking of RES technologies.

3.3. Greenhouse gas emissions

During the research on cold supply chain (Publication 1), the environmental impact of different supply chain lengths was analysed. A starting model with a rather short cold supply chain was used, only 60 km long. For research purposes, the 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, the relation is linear. In the Figure, the starting point is the base model because there was a decision not to analyse a system with an even shorter path than 60 km.

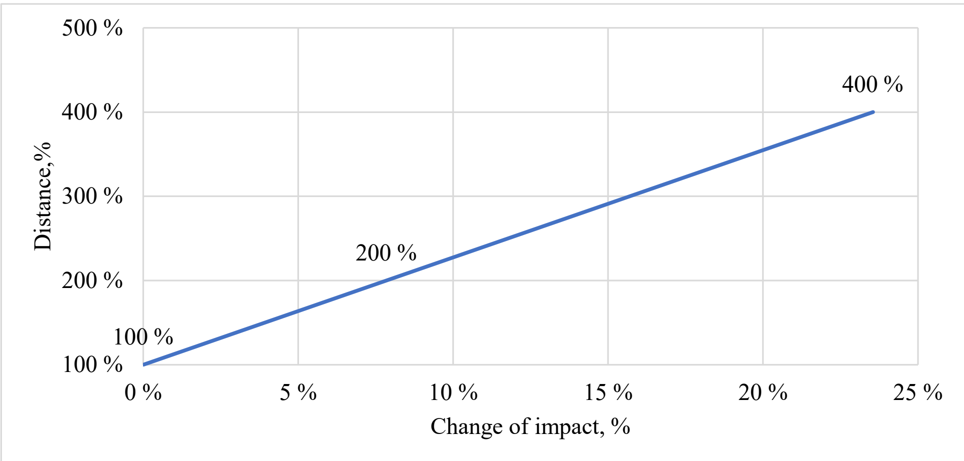

Fig. 3.6. Impact and distance correlation.

Figure 3.6 also helps to understand the dynamics of distance impact on the international cold supply chain. Even within the EU, where distances are not so great compared with the world, delivery of a couple of thousand kilometres significantly increases the role of cold supply. As seen in Fig. 3.7, even with the delivery of 240 km, cold chain transportation has a major impact.

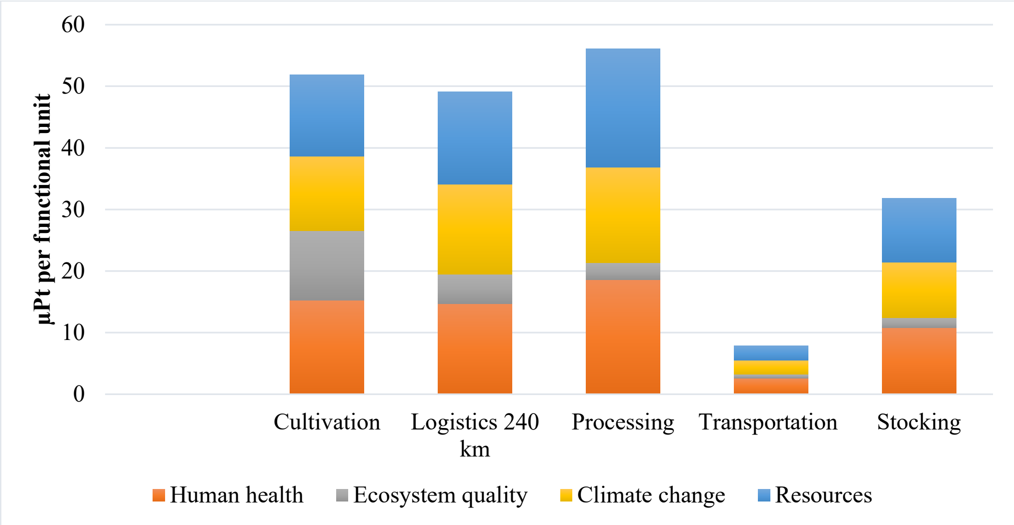

Fig. 3.7. Impact aggregation for a 240 km cold chain.

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. 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 horticultural farmers. The results of the TOPSIS analysis are shown in Fig. 3.8.

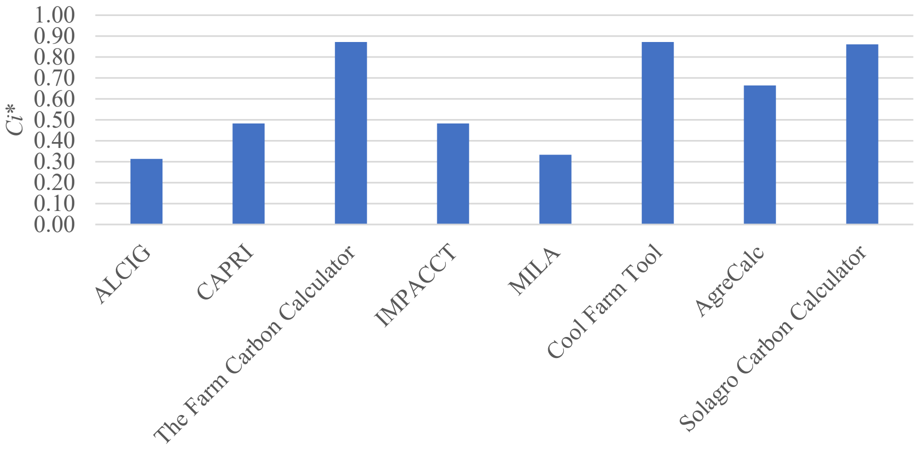

Fig. 3.8. Comparison of ratings of GHG emission calculators.

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.

3.4. Materials and added value

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 reducing 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, around 70 % of companies claim that the environmental aspect is important when outsourcing the transportation service for their goods [50].

The results of weighing are shown in Fig. 3.9.

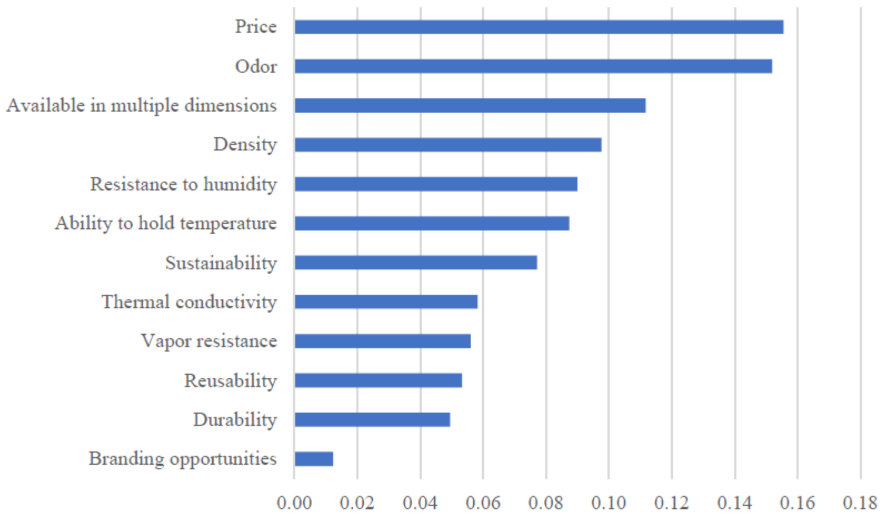

Fig. 3.9. Weighed criteria in ascending order regarding their importance.

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).

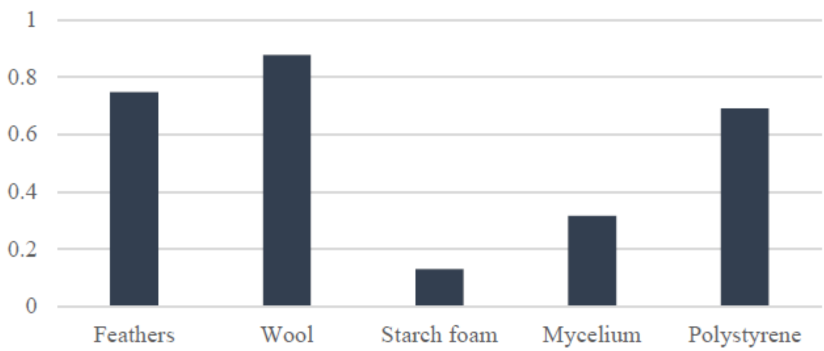

Fig. 3.10. Technique for order of preference by similarity to ideal solution ranking of thermal packaging materials. Y-axis represents the proximity to ideal solution 1.

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 looks 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.

The strength results of the boards whose wood particles were obtained were analysed. Initial durability results for three particle-size boards are depicted in Fig. 3.11. The highest strength was obtained for the 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. The 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).

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

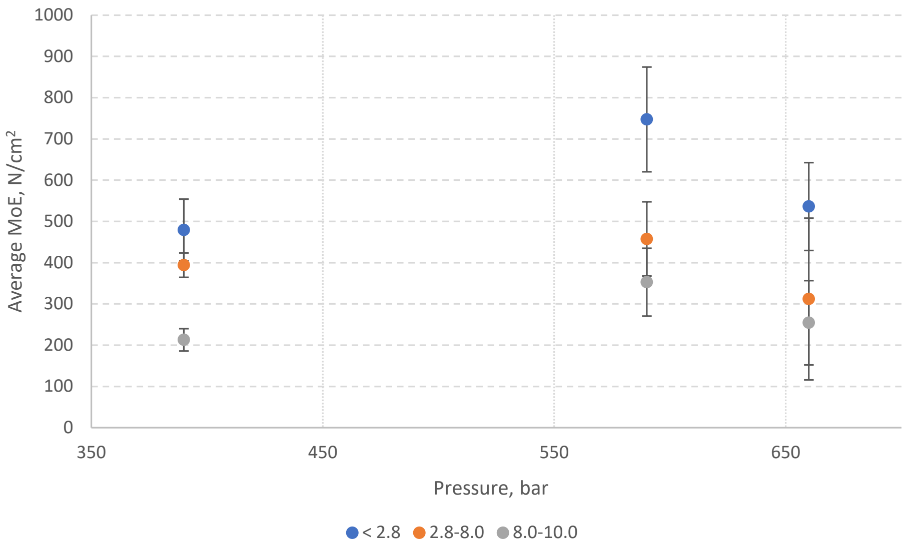

Fig. 3.11. Modulus of rupture depending on pressure and the particle size.

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, the added value of bioeconomy products is analysed. 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, 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, innovation, and investment in knowledge is inevitably required to achieve a large part of the set goals [52].

A total of 16 different production processes have been selected based on significant improvements to 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, sixteen production processes were analysed using Fuzzy Cognitive Mapping. It was concluded that all sixteen production processes correspond to high bioeconomy efficiency towards the goals of the Green Deal.

Table 3.2

Usefulness of the 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. This type of integrated analysis is appropriate to compare the various alternative production processes considered in the work for obtaining the 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.

Tailored life cycle inventory for both economic and environmental feasibility assessment using primary data sources from actual agricultural practices used in the Latvian context (and extendable to Northern Europe) together with in-depth data inventory from each actor involved in the 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 by merging LCC and LCA, it is possible to evaluate the overall feasibility of the cold chain. The results show that the main environmental hot spots have been identified in connection to climate change and the use of resources in the processing and stocking of production, providing important suggestions about potential improving scenarios.

Considering that the total installed solar energy capacity currently installed in Latvia is growing, 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 play a significant role in the sustainable usage of bioresources.

With increased focus on sustainable agriculture and sustainable development in 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 a specific background on the subject.

The production usefulness of 16 chosen bioproducts shows 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.

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.

Research shows that thermal packaging made from expanded polystyrene is not the most preferable choice compared to some environmentally sustainable thermal packaging options. Two bioproducts outperformed polystyrene packaging in price, density, ability to hold temperature, environmental impact, and thermal conductivity. The research elucidates the discrepancy between theoretically preferable and actual choices made by logistics managers.

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