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Nidhiben Arvindbhai Patel

VALORIZATION SOLUTIONS FOR AGRICULTURAL WASTE

Summary of the Doctoral Thesis

RTU Press
Riga 2024

RIGA TECHNICAL UNIVERSITY
Faculty of Natural Sciences and Technology
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Summary of the Doctoral Thesis

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Patel, N. A. Valorization Solutions for Agricultural Waste. Doctoral Thesis. Riga: RTU Press, 2024. 50 p.

Published in accordance with the decision of the Promotion Council "RTU P-19" of 2 February 2024, Minutes No. 186.

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

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https://doi.org/10.7250/9789934370502
ISBN 978-9934-37-050-2 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE 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 on May 9, 2024 at 14:00, at the Faculty of Natural Sciences and Technology of Riga Technical University, 12/1 Azenes Street, Auditorium 116.

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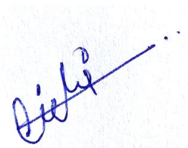
DECLARATION OF ACADEMIC INTEGRITY

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.

Nidhiben Arvindbhai Patel (signature)



Date: 17.04.2024

The Doctoral Thesis has been written in English. It consists of an introduction, 3 chapters, conclusions and recommendations, 50 figures, 21 tables, and 37 mathematical formulas; the total number of pages is 217. The bibliography contains 231 titles.

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INTRODUCTION

Topicality of the Doctoral Thesis

Global transition towards sustainable development has been one of the primary goals in recent years, including developing national and regional bioeconomy strategies. Several national and regional policies show increasing interest in bioeconomy as a solution for sustainable development. Even greenhouse gas emission reduction is one of the critical parts of sustainable development, representing a vital objective of the European Union's sustainable development. The existing regulatory framework clearly shows the development and intensification of carbon footprint trends. The European Parliament committed to reducing greenhouse gas emissions by at least 55 % by 2030 and achieving carbon neutrality by 2050.

Moreover, the 2008 global economic crisis prompted national governments to take more proactive measures to implement a cut-off scenario in costs for research and development, which hinders innovations and, therefore, has an impact on the bioeconomy. The use of agricultural wastes is a worldwide phenomenon that influences the decisions and actions of policy makers, stakeholders, scientists, and society. The initially set objectives of a sustainable bioeconomy in Europe were mainly directed toward bioenergy production. Over time, the already existing regulatory framework and modifications framework show the development and intensification of the bioeconomy. In 2018, the European Commission [1] updated the bioeconomy strategy, stating that the bioeconomy encompasses all systems and industries that depend on biological resources and the principles and functions they provide. It encompasses and connects all economic and industrial sectors that use natural resources and processes to create food, feed, bio-based products, energy, and services, as well as all primary production sectors that use natural resources, such as forestry, fisheries, aquaculture, and agriculture.

The starting point advancing the bioeconomy is the value pyramid that illustrates valorization of biomass. Regarding product value, pharmaceuticals add a lot to the product but in small volumes. In contrast, energy adds little to the product value but in large quantities. Agriculture, horticulture, and stock farming produce the entire value pyramid's worth of products and feedstock. Numerous biobased innovations can be recognized in each tier of the pyramid. However, there is still no standard and consistent framework that aligns with sustainability, bioeconomy, and agricultural waste valorization. Also, it prioritizes products based on critical discourse about sustainable waste utilization and the necessity to deal with plastic waste, which has the potential to boost sustainable bioeconomy development and contribute to the climate neutrality goal.

Therefore, the Thesis contributes to evaluating a diverse array of bioeconomy product levels by sustainably valorizing agricultural wastes and responding to the growing demand for eco-friendly alternatives across various industries. It provides a unique strategy to prioritize biopolymer products to the advanced level. Also, it contributes to reducing the carbon footprint of biopolymer packaging materials. It develops a market opportunity for decision-making in commercializing biopolymer packaging materials. The research provides the knowledge and practical base for topical agricultural waste valorization pathways for energy, biopolymers, food additives, and pharmaceutical products. It also contributes to developing an integrative methodology based on sustainability indicators and criteria for each level of products. The carbon footprint calculator tool would be a game changer for the packaging businesses to sustain and compete in the market and comply with the sustainable development and climate targets. This multidimensional framework is promptly in light of global efforts to achieve sustainable development.

The Aim and Tasks of the Doctoral Thesis

The Doctoral Thesis aims to develop an integrated methodology intended to provide an innovative strategy to prioritize biopolymer packaging material to the advanced level by valorizing agricultural waste. The Thesis contributes to exploring distinct levels of bioeconomy product value under a unified framework with a specific emphasis on promoting biopolymer production. It provides a unique pathway to prioritize biopolymer products to the advanced level by introducing system and market innovation pillars.

In order to reach the aim of the Thesis, the following tasks were set:

1. To investigate the general trends in sustainable bioeconomy considering agricultural waste valorization.
2. To assess the bioeconomy modeling tools within the sustainability framework.
3. To evaluate the valorization pathways for value-added products, including sustainable bioenergy production, and identify the most potential techniques to produce value-added products from agricultural waste.
4. To identify the trends and create a sustainability framework for biopolymers.
5. To provide strategic innovative transfer with market analysis to determine if biopolymer products would have the potential to assess the market.
6. To create an innovative methodology to promote sustainable online marketplace businesses and to develop a carbon footprint tool for packaging materials as a valuable input for prioritization.

Hypothesis

The development of an integrated methodology that emphasizes substantial innovation pillars will lead to the prioritization of biopolymer packaging materials and sustainable valorization of agricultural waste.

Scientific Novelty

The research promotes the sustainable development of the bioeconomy, including the agriculture sector, resulting in higher-value products, socio-economic benefits, and environmental benefits. The Thesis is of high scientific novelty in the European and international context since investigating and analyzing agricultural waste valorization is a topical research area of bioeconomy and sustainable development. It shows that a persistent, sustainable bioeconomy can be developed by implementing three innovation pillars. The sustainability innovation pillar provides a unique approach to agricultural waste valorization in value-added products. The products differ by quality, value, and volume. Market and system innovation pillars prioritize the biopolymer packaging materials in the bioeconomy to the advanced level. In the Thesis, innovative and integrated methods are developed for the sustainable development of the bioeconomy. It considers the agricultural waste valorization approach, which is significant in ensuring the long-term sustainability and integrated profitability of any agricultural waste valorization. Considering the holistic analysis approach, the Thesis data can be used for further scientific studies on agricultural waste assessment.

Practical Significance

The proposed integrated approach has numerous practical applications, providing tangible benefits across various domains. It has high practical significance in the European context. The EU has been actively promoting the transition to a circular economy, focusing on reducing plastic waste and promoting bio-based alternatives. The practical significance of prioritizing biopolymer packaging materials is consistent with initiatives such as the EU Plastics Strategy, which focuses on the transition to carbon neutrality and the circular economy to reduce greenhouse gas emissions and establish more sustainable and safer plastic consumption and production patterns by 2030 aligning with the sustainable development goal. The research results offer a novel approach that can significantly contribute to advancing bioeconomy as part of the Circular Economy Action Plan and the European Green Deal and promote sustainable resource utilization by fostering innovations in bio-based industries. Considering the environmental impact, the findings would be essential for the decision-makers to decide which biopolymer would be sustainable for production and consumption. Market opportunities for biopolymer packaging material and a carbon footprint calculator would be assets for companies in making decisions about packaging materials.

Research Structure

The proposed integrated approach assesses the different levels of bioeconomy by valorizing agricultural wastes. It provides an innovative prioritization of biopolymer products (packaging materials) by developing a sustainability framework, strategic scheme for the market, and carbon footprint tool for the online marketplace. Several methods have been used to analyze each level of bioproducts and prioritize the biopolymer products at the top level in the bioeconomy, including multi-criteria analysis, life cycle analysis, bibliometric analysis, and market analysis (see Fig. 1).

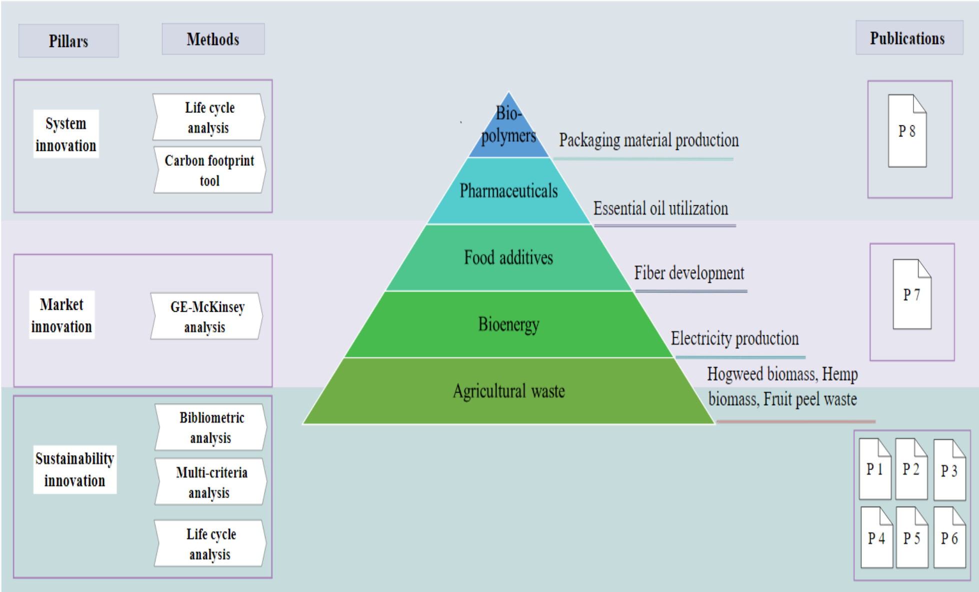

Fig. 1. Research structure.

The research structure is described by implementing three innovation pillars:

a) The sustainability innovation pillar includes valorizing agricultural waste into distinct levels of bioeconomy products, considering electricity production, fiber development, essential oil utilization, and packaging material production from low to high value. Here, multi-criteria decision-making analysis (MCDA), life cycle analysis (LCA), and bibliometric analysis methodologies are applied (See approbation Publications 1–6).
b) Market innovation pillar determines the market potential for biopolymer products (packaging materials) to provide innovative transfer by implementing the GE-McKinsey analysis (See approbation Publication 7).
c) System innovation pillar is developed to promote the sustainable use of packaging materials by developing a carbon footprint tool implementing the life cycle analysis methodology (See approbation Publication 8).

This structured framework integrates sustainability considerations, market analysis and system-level prioritization tools to create a comprehensive and innovative methodology for advancing biopolymer packaging materials in bioeconomy.

Approbation of the Doctoral Thesis

The results of the Doctoral Thesis have been presented at four conferences, in seven scientific publications, and in one submitted manuscript.

Participation in conferences

1. International scientific conference "Biosystems Engineering 2021", paper "Evaluation of bioresource validation", 2021, Tartu, Estonia.
2. International scientific conference "Conference of Environmental and Climate Technologies 2021", paper "An analysis of the extraction technologies: fruit peel waste", 2021, Riga, Latvia.
3. International scientific conference "Conference of Environmental and Climate Technologies 2022", paper "Agro biopolymer: A sustainable future of agriculture – state of art review", 2022, Riga, Latvia.
4. International scientific conference "Conference of Environmental and Climate Technologies 2023", papers "Carbon footprint evaluation tool for packaging marketplace" and "Insights of bioeconomy: biopolymer evaluation based on sustainability criteria", 2023, Riga, Latvia

Publications in journals

1. **N. Patel**., M. Feofilovs., D. Blumberga. (2022), "Agro biopolymer: A sustainable future of agriculture – state of art review", *Environmental and Climate Technologies,* Volume 26, Issue 1, pp. 499–511, https://doi.org/10.2478/rtuect-2022-0038.
2. **N. Patel**., M. Feofilovs., D. Blumberga. (2022), "Evaluation of bioresource value models: sustainable development in the agriculture biorefinery sector", *Journal of Agriculture and Food Research,* Volume 10, 100367, https://doi.org/10.1016/j.jafr.2022.100367.
3. E. Teirumnieka., **N. Patel**., K. Laktuka., K. Dolge., I. Veidenbergs., D. Blumberga. (2023), "Sustainability dilemma of hemp utilization for energy production", *Energy Nexus,* Volume 11, 100213, https://doi.org/10.1016/j.nexus.2023.100213.
4. **N. Patel**., L. Zihare., D. Blumerga. (2021), "Evaluation of bioresource validation", *Agronomy Research*, Volume 19, Special Issue 2, pp. 1099–1111, https://doi.org/10.15159/ar.21.066.
5. **N. Patel**., A. Kalnbalkite., D. Blumberga. (2021), "An analysis of the extraction technologies: fruit peel waste", *Environmental and Climate Technologies,* Volume 25, Issue 1, pp. 666–675, https://doi.org/10.2478/rtuect-2021-0050 (Scopus, WoS).
6. **N. Patel**., D. Blumberga. (2023), "Insights of bioeconomy: biopolymer evaluation based on sustainability criteria", *Environmental and Climate Technologies,* Volume 27, Issue 1, pp. 323–338, https://doi.org/10.2478/rtuect-2023-0025.
7. **N. Patel**., D. Blumberga. "Assessing Biopolymer Packaging in the EU Market for Sustainable Bioeconomy Development", *Environmental and Climate Technologies,* (Manuscript under review).
8. **N. Patel**., M. Feofilovs., F. Romangnoli. (2023), "Carbon footprint evaluation tool for packaging marketplace", *Environmental and Climate Technologies,* Volume 27, Issue 1, pp. 368–378, https://doi.org/10.2478/rtuect-2023-0027 (Scopus, WoS).

Other publications

1. L. Zihare., Z. Indzere., **N. Patel**., M. Feofilovs., D. Blumberga. (2021), "Bioresource value model. case of fisheries", *Environmental and Climate Technologies,* Volume 25, Issue 1, pp. 1179–1192, https://doi.org/10.2478/rtuect-2021-0089 (Scopus, WoS).

1. METHODOLOGY

This chapter describes the integrated approach that assesses the different levels of the bioeconomy value pyramid for valorizing agricultural waste and provides an innovative prioritization of biopolymer packaging materials using the corresponding methodologies. The integrated methodology includes the value pyramid as a core concept and three innovation pillars. Several methods have been used, including multi-criteria decision-making (MCDA), life cycle (LCA), bibliometric, GE-McKinsey analysis, and carbon footprint tool.

1.1. Sustainability innovation

The sustainability innovation pillar consists of five steps. Fig. 1.1 briefly describes the sustainability innovation scheme for valorizing agricultural waste. A vast scientific literature analysis has been performed using Scopus, Web of Science, ScienceDirect, and other reliable scientific sources to assess the sustainability innovation for each step. Here, four different agricultural wastes are selected, i.e., hogweed, fruit peel waste, hemp biomass, and brewers' spent grain. The wastes are selected based on their topicality and wide availability in Europe. Agricultural waste could be unused for society or industry. There must be a potential to use the waste for further assessment and to produce value-added products. The principal methodologies used to assess the sustainability innovation pillar are MCDA, LCA, and bibliometric analysis.

Step 1: First, the trends for the biopolymer products produced from agricultural waste could be identified to know what is lacking for biopolymers to sustainably increase their value in the bioeconomy.

Step 2: To develop a better bioeconomy strategy concerning its sustainability within the agriculture sector, it is crucial to analyze the different bioeconomy modeling tools under one sustainability frame and specific criteria. The most suitable bioeconomy modeling tool is used in the following assessment to analyze the distinct levels of the bioeconomy value pyramid.

Step 3: Next, evaluate the lowest value-added product. Bioenergy produced from hemp biomass must be analyzed using the MCDA and LCA methodologies.

Step 4: Next, evaluate the pretreatment methods for the fiber development produced from hogweed biomass as a food additive and the extraction methods for essential oil from fruit peel waste as a pharmaceutical product using the MCDA method.

Step 5: Develop a sustainability framework for the high-value product biopolymer. Considering the packaging segment, a sustainability framework is developed for the four alternative biopolymer packaging materials. After assessing these value levels, a biopolymer product is transferred to the next stage to validate the product potential for market and system innovations. This enhances the value of biopolymers and sustainability in the bioeconomy.

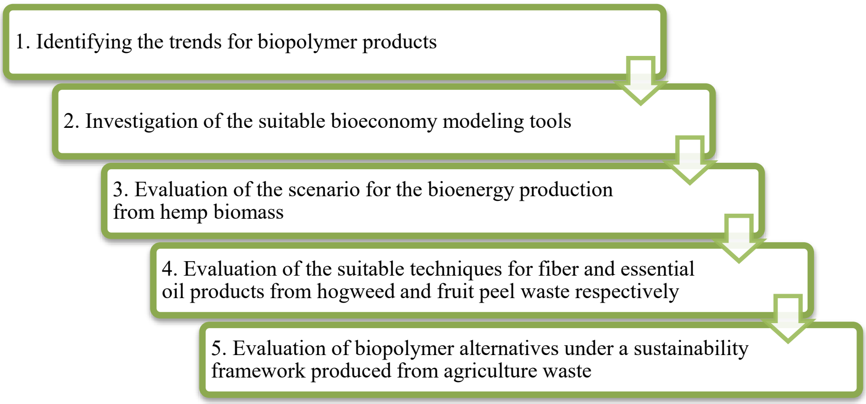

Fig. 1.1. Sustainability innovation scheme (Author's illustration).

Identifying the trends for biopolymers

Bibliometric analysis is performed using the Scopus database to identify the mid-value-added product trends. This method reviews agricultural waste and biopolymer production, considering the sustainable development goals. The overall structure of the bibliometric analysis method is briefly described in Fig. 1.2.

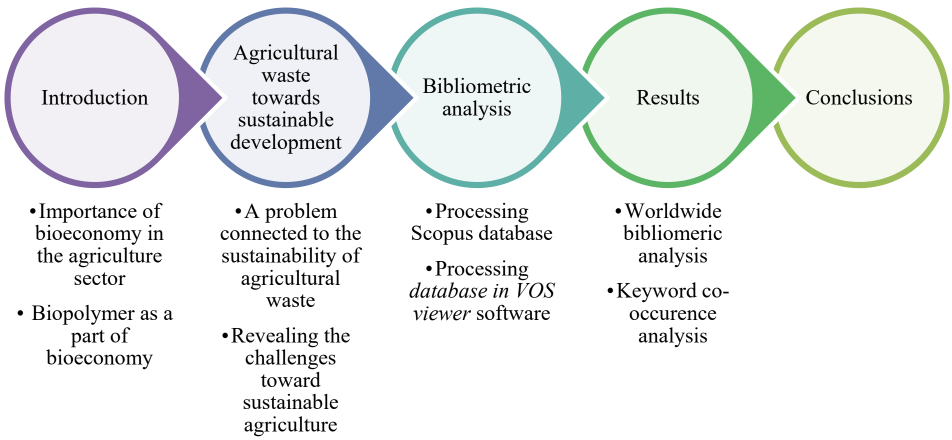

Fig. 1.2. Bibliometric analysis structure (Author's illustration).

Scopus is the largest abstract database and provides exhaustive coverage of scientific journals. Moreover, Scopus provides high-quality assurance of a database highly recommended for research assessment, scientific evaluation, and research studies [2]. Bibliometric analysis by using the keyword co-occurrence is performed by using the following key messages and a combination of key messages: −

- ‘Bioplastic’;
- ‘Bioplastic’ AND ‘Sustainability’;
- ‘Agriculture’ AND ‘Waste’ AND ‘Biopolymer’.

A keyword co-occurrence analysis shows the co-occurrence network of keywords and displays it on a two-dimensional map. The VOS viewer provides a clustering function, which shows the keywords in clusters based on their co-occurrence [3]. All references are downloaded and transferred to the VOS viewer software to identify the occurrences between keywords and abstracts. VOS viewer provides bibliometric maps in a more straightforward form and visualizes the co-occurrence network of terms [4]. The period for the bibliometric analysis is considered with no time limitation. However, the studies included in the analysis are published no later than December 2021.

Investigation of the bioeconomy modeling tools

The MCDA was performed by integrating the criteria and sub-criteria, interpreting the results, and drawing conclusions. Here, semi-quantitative analysis has been used for each modeling tool because of the versatility and diversity of the bioeconomy modeling tools. Semi-quantitative analysis is one of the ideal analyses [5], which defines the values that can be used for modulation and calculation. The evaluations can be identified according to the experts [6], for example, the Likert’s Scale, which shows the preferences for results derived from qualitative and quantitative sub-criteria. In addition, a decision-maker can use the Likert Scale to evaluate and compare the different project’s results. This scale ranges from 1 to 3, where 1 represents deficient performance, 2 represents average performance, and 3 represents good performance. This scale represents the ‘swing weighting’, which means that criteria 1, 2, and 3 can be defined as unimportant, moderately important, and very important, respectively. Similarly, this study uses the Likert scale to evaluate bioeconomy modeling tools from 1 to 4, where scales 1, 2, 3, and 4 represent the very high, high, moderate, and low values, respectively.

The documentation aspects have been determined based on the material provided for modeling tools, such as tutorials, demo models, and library documents. If 100 % data is provided for the model, the considered score is one; if no data is provided, the score is considered four. The flexibility has been determined by analyzing the data adaptability by the modeling tool, i.e., if the data has very high adaptability, then the score is very high (1), and if there is low data adaptability, then the score is low (4).

The compatibility of the bioeconomy modeling tool has been determined based on the possibility of exchanging the input database, where if the model has a very high possibility of exchanging the input data, then the score is one. However, if the model has a low possibility of exchanging the input data, the score is four. The diversity of the modeling tools has been considered by analyzing the model’s applicability, i.e., if the model can be applied for more than 80 % of sectors, then the score is one, but if the model has less than 30 % applicability, then the considered score is four.

The data quality determines the validity, with 90 %, 70 %, and 50 % adequate data ranked 1, 2, and 3, respectively. If the data has no adequacy, then the considered rank is four. The efficiency represents the quality of the data used by the modeling tool; if the model uses very high qualitative verified data, then the given rank is one; if the model uses non-qualified data (low quality), then the given rank is four. The last quality factor is user-friendliness, which is determined by analyzing the ease of understanding of the model. If the interface data and overall model are non-complex to learn, then the rank is one. However, if the interface data and overall model are very complex to learn, then the rank is four.

Moreover, the economic, social, and environmental sub-criteria are evaluated for each criterion, showing the sustainability adequacy of each modeling tool. Simultaneously sustainability can be examined for bioeconomy modeling tools by implementing this approach. Further evaluation was done using the MCDA analysis. A technique for order of preference by similarity to ideal solution (TOPSIS) is one of the standard methods for MCDA. The TOPSIS method justifies results by considering positive and negative ideal solutions [7]. There are several benefits to performing TOPSIS, such as this method providing attribute information, providing the ranking of different alternatives, and giving accurate results.

Evaluation of scenarios for bioenergy from hemp biomass

The application of MCDA allowed the sustainability of eight different hemp products (thermal insulation in the building sector; textile in different sectors; composite materials in different sectors; construction materials in different sectors; paper in the industrial sector; technical materials in different sectors; food in the agriculture sector; energy in the energy sector) to be assessed under crisis and non-crisis conditions, considering six different criteria (resource availability; technological aspects; economic aspects; environmental aspects; climate change aspects; and circular economy aspects). The identified hemp products and the criteria provide the opportunity to use MCDA to evaluate the most sustainable option for using hemp as a raw material. In addition, an LCA to evaluate hemp as a biomass for energy production is compared to three other biomass energy options.

The MCDA was carried out for two different situations in a country: a normal scenario under non-crisis conditions and under energy or economic crisis conditions. TOPSIS is a method used for normalization of MCDA. For this study, ‘a normal scenario under non-crisis conditions’ is defined by the authors as a situation in a country where natural self-regulatory mechanisms exist within a market economy and inflation is within the normal range of 1.5 % to 4 %. ‘Under energy or economic crisis conditions’, on the other hand, refers to a situation in a country where inflation is above the normal range and prices for a particular group of goods, such as necessities or a particular (or all) energy resource, are rising rapidly.

The results were aggregated to assess the use of hemp as a bioresource and biomass for energy production and determine which of these alternatives would be the most sustainable. It was also intended to identify other aspects that would limit or facilitate the broader use of hemp. The LCA is a methodology for evaluating a product’s environmental impact by quantifying all associated inputs and outputs, such as materials, energy, waste, and emissions. The life cycle of a product considers all production processes, from raw material extractions to waste disposal, with a ‘cradle to gate’, ‘cradle to grave’, and ‘gate to gate’ perspective. The LCA is performed in line with the ISO 14040/14044. It contains three main steps: goal and scope definition, life cycle inventory and impact assessment, as well as their interpretation. The scope of the study can be defined by outlining the qualitative and quantitative information included in the study, which starts by defining the functional unit (FU), a 100-kWh electricity production. The system boundary of this study is defined from the ‘cradle to gate’ (see Fig. 1.3), which includes two sub-systems: 1) the biomass processing system, which includes cultivation, fertilization, harvesting, sowing, cutting, and transportation, and 2) the electricity generation system, which includes boiling of biomass, turbine generator, heat exchange, and power generation. In addition to the scope of the study, a comparison of alternative biomasses (peat, wood, and sweet sorghum) for power generation was conducted.

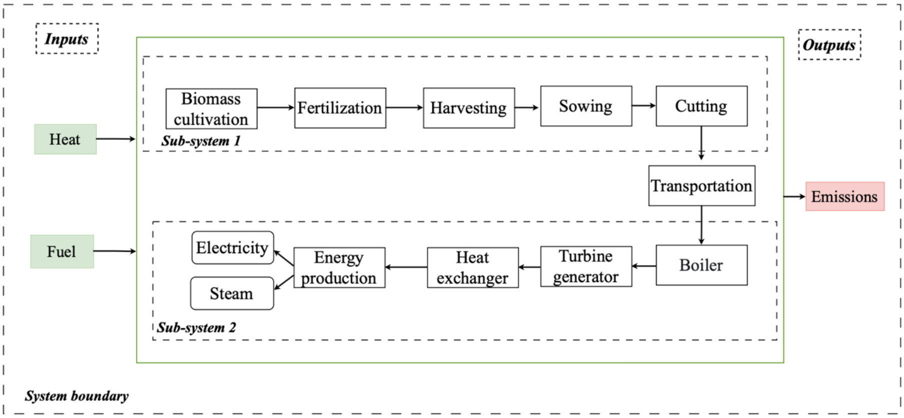

Fig. 1.3. System boundary for biomass for electricity production (Author's illustration).

The life cycle inventory includes material and energy flows, equipment, and infrastructure required for energy generation. As stated in the ISO Standards 14044, data must at least ensure their validity regarding geographic origin, representativeness, technological efficiency, and data sources. The primary data regarding the processing of hemp biomass for electricity production has been presented in Table 1.1 [8][9] for the period 2007–2020. The inventory data of fertilizers, transport, source of energy, and agriculture machinery involved were taken from the *Ecoinvent 3.7.1* database. To generate 100 kWh of electricity, first, the required amount of hemp biomass (22 kg) is calculated (see Equation (1.1)) by normalizing the low heating value of hemp biomass and electric efficiency of the boiler, which is 15.72 kg/MJ [10] and 75 % [11], respectively. The value of the dimensionless factor is 0.75, which is calculated from the boiler’s efficiency.

$$\frac{Kg}{MJ} = D_f, \tag{1.1}$$

where

Kg/MJ – low heating value of hemp biomass;

D_f – dimensionless factor.

The balance of mass for sub-systems 1 and 2 was performed following the reported values for hemp biomass [12][13]. It is assumed that the transport distance from the farm to the incinerator for energy production is 50 km. In addition, the inventory for the alternative raw biomasses of hemp, peat, wood, and sweet sorghum is selected directly from the *Ecoinvent 3.7.1* database [14]. The comparison is made to generate 100 kWh of electricity from 22 kg of biomass, just as for the hemp biomass.

Table 1.1

Inventory Data for Hemp Biomass

Materials	**Amount**	**Unit**
	Sub-system 1: Raw hemp biomass processing	
	Inputs from technosphere	
Ammonium nitrate	0.62	kg N
Triple superphosphate	0.48	kg P_2O_5
Potassium chloride	0.92	kg K_2O
Diesel	0.55	kg
Agricultural machinery	0.12	kg/ha
Energy	2.64	kWh
	Outputs to technosphere	
Hemp biomass	22	kg
Ammonia	0.019	kg/ha
Dinitrogen monoxide	0.022	kg/ha
Nitrogen oxide	0.002	kg/ha
Carbon dioxide	0.011	kg/ha
Transportation of hemp biomass	1.1×10^3	kg·km
	Sub-system 2: Electricity production	
	Inputs from technosphere	
Hemp biomass	22	kg
Energy	2.64	kWh
	Outputs to technosphere	
Heat/electricity	100	kWh
Carbon dioxide	0.00020	kg
Nitrogen dioxide	0.34241	kg
Sulfur dioxide	0.83463	kg
Carbon monoxide	24.52529	kg

The LCA is performed using the *IMPACT 2002*+ V2.15 impact assessment methodology in *Sima Pro 9.4.0.2.* The *IMPACT 2002+* combines four methods: *IMPACT 2002, Eco-indicator, CML*, and *IPCC*. The method proposes a feasible implementation of the combined midpoint and damage-oriented approach [15].

Evaluation of extraction techniques for fiber development and essential oil utilization from hogweed and fruit peel waste

The MCDA method evaluates and finds the best technology for two scenarios. The selected two scenarios are as follows:

1. Evaluation of extraction methods for hogweed biomass to extract fiber as a food additive product (TOPSIS).
2. Evaluation of extraction technologies for fruit peel waste to extract essential oil as a pharmaceutical product (TOPSIS and AHP).

Evaluation of biopolymer alternatives under a sustainability framework from agricultural waste

A multidisciplinary approach is selected to develop sustainability framework for biopolymer alternatives. The methodology starts with scientific literature analysis from Scopus, ScienceDirect, Web of Science, EU bioplastics, and other scientific documents. Then, the framework is having the following steps:

Step 1: Developing the study design, including a selection of the biopolymer alternative, the evaluation criteria, and particular evaluation indicators considering the sustainability indicators.

Step 2: A quantitative data collection was done for selected indicators for each biopolymer type.

Step 3: A worldwide survey analysis conducted to aid a collective policymaking decision from the stakeholder's perspectives,

Step 4: Analytic hierarchy process (AHP) analysis of each survey response to determine the criteria weights.

Step 5: Four different MCDA have been performed to check the method's robustness.

The survey analysis was used to identify the criterion weights for MCDA analysis. The survey was circulated worldwide to stakeholders connected to the biopolymer sector, including value chain actors, consumers, small and medium-sized enterprises, scientists, and organizations (approximately 60 stakeholders). The survey was made to understand and numerically describe the importance of environmental, social, economic, circularity, and technical criteria. The group of questions was divided into five sections. The first section contained general information about the respondent's country and stakeholder group. The second section was devoted to the importance of the circularity criterion over the rest of the four criteria. Other sections were analogously devoted to the importance of environmental, social, and economic criteria over the rest of the four criteria.

The MCDA method is the best choice to assess the sustainability of a product or a system [16]. This study applies four MCDA methods to check the method's robustness and derive comprehensive results. It must be noted that the weights of criteria for each method are considered from the AHP analysis. In sustainability innovation pillar, the AHP method is used for two cases: a) to identify the sustainability criterion weights for essential oil extraction techniques and b) to determine the weights of criteria for survey respondents in the biopolymer case. The AHP method divides and analyzes problems in a hierarchical structure consisting of a goal, a criterion, and a sub-criterion. The AHP methodology was developed in 1980 by Saaty, and experts compared the selected criteria in pairs [5]. Here, semi-quantitative analysis was used to measure the intensity of importance in AHP. Criteria and alternatives were prioritized mainly using the scoring system. Table 1.2 shows the Saaty's scale.

Table 1.2

Saaty's Scale for AHP Analysis

Scale	Definition
1	Equally important
2	Equally to moderately important
3	Moderately important
4	Moderately to strongly important
5	Strongly important
6	Strongly to very strongly important
7	Very strongly important
8	Very to extremely strongly important
9	Extremely important

The comparison matrix comprises criteria, where each criterion is compared with all other criteria. The next step is to solve the problem of eigenvectors by which the criteria will be arranged. The sum of each column of the pairwise comparison matrix is then calculated and used to divide the corresponding column values, thus normalizing the comparison matrix. The values of each row are then summed and divided by the number of criteria to calculate the eigenvector for each row of the matrix. Eigenvectors indicate the ranking (weight) of the criteria. AHP methodology can be implemented in three main steps. Each step must be performed to resolve in a decision-making matrix with AHP, which is described below.

Step 1: Define the objective, selected criteria, and alternatives.

Step 2: Here, elements can be compared to one another, two at a time, concerning their importance to the element above them in the hierarchy, and then the comparison matrix is structured.

Step 3: A pairwise comparison matrix (A) calculates each criterion's significance by taking a geometric mean of pairwise comparison matrices obtained from the survey. Then, the dimension matrix (n × n) formed by using the compared criteria in rows and columns of the matrix is square (see Equation (1.2)).

$$\mathbf{A} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \alpha_{n1} & \alpha_{n2} & \cdots & \alpha_{nn} \end{bmatrix}, \tag{1.2}$$

where

A – comparison matrix;

n – matrix's dimensions.

Step 4: Next, matrix A is normalized to prevent too large or too small values in the comparison matrix. Each value in the comparison matrix is divided by the sum of the column elements. The normalized pairwise comparison matrix is obtained by using Equation (1.3).

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{1.3}$$

Step 5: Next, the maximum eigenvalue ($\lambda_{\max}$) is calculated by Equation (1.4).

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(Aw)_i}{w_i} \tag{1.4}$$

Step 6: Next, the consistency index (*CI*) for acceptance of the consistency ratio of the comparison matrix A is calculated using Equation (1.5).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1.5}$$

CI refers to the mean of the remaining solutions of the characteristic equation for cognizant matrix **A** (see Table 1.3).

Table 1.3

Random Consistency Index

Size of A matrix (*n*)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random average ***CI*** (r)	0	0	0.52	0.89	1.11	1.24	1.35	1.40	1.45	10.49

The comparison matrix's consistency ratio (CR) to eliminate inconsistency is calculated using Equation (1.6).

$$CR = \frac{CI}{RI}, \tag{1.6}$$

where

RI – random index;

CR – measures the judgments of experts.

If $CR \leq 0.1$, the inconsistency is acceptable.

The next step in the methodology is to incorporate AHP weights in MCDA methods, specifically, TOPSIS, MOORA, COPRAS, and VIKOR methods used for the analysis.

1.2. Market innovation

A successful transition toward the sustainability in the agriculture sector would emerge through radical innovations promoted primarily by stakeholders, businesses, or government organizations. Innovation transfer organizations support innovation commercialization by bridging the gap between investors (business thinking) and academics (scientific thinking) through programs supported by domestic or international stakeholders. From one perspective, it is constructive for commercializing invention and uniting two parties with different points of view. However, it also has some needs and obstacles and demands trust from both parties. To prioritize the biopolymer comprehensively in bioeconomy, it is imperative to assess market opportunity for decision-making in commercializing the packaging materials. The market innovation transfer of added-value products produced from agricultural resources is done in four steps:

Step 1: The first stage in fostering agricultural waste valorization is the availability of resources; these resources should be locally sourced and not rely on imports. In this case, the evaluation is based on the availability of resources.

Step 2: Technology must be accessible at a commercial level. Even if a technology is cutting edge, it should be widely accessible. If not, then it goes to the first step.

Step 3: The GE-McKinsey matrix, utilized for market evaluations, is the decision-making matrix in this scenario. Data on the economy, technology, market competitiveness, and products have all been gathered for calculations. The data are entered into the matrix for decision-making when the findings have been obtained. A positive calculation result may not necessarily reflect the actual situation; in most cases, matrix visualization is required. Scientific articles, current plant data, and yearly reports serve as information sources for the matrix. Based on the information gathered, data are analyzed and shown in two dimensions (market attractiveness and product competitive advantage) on the GE-McKinsey matrix. The primary data are gathered from information sources such as scientific research articles.

Step 4: Visualize the results and suggest further investigation into manufacturing new products in the country or place where biopolymers are produced and where local resources are available.

Data collection and evaluation technique

The market analysis is carried out using primary data. The literature analysis is performed to collect the data for each indicator in the GE-McKinsey analysis. The first two steps address the indicators for resource availability and technological advancement, considered under the market competitive advantage. Resources play a central role in the business' environmental performance to establish efficiency in the process, and technology's eco-friendliness significantly addresses the business' sustainable practice. For the market attractiveness, seven key indicators are evaluated: market size, market growth rate, market profit, price sensitivity, access to raw materials, and production cost. For the market competitive advantage, six critical indicators are evaluated, including demand, market share, availability of resources, selling price, environmental ease of technologies, and product quality.

The Likert scale is a commonly used scale that displays the preferences for outcomes derived from quantitative and qualitative indicators. A decision-maker can also use the Likert scale to assess and contrast the outcomes of various projects. A decision-maker can also use the Likert scale to assess and contrast the outcomes of various projects. For market attractiveness, the evaluation is done based on a five-point scale, where 1 represents very unattractive, and 5 – very attractive. Six indicators are selected, including market size, market growth rate, market profitability, price sensitivity, access to raw materials, and production cost. Each indicator is evaluated differently based on the external importance scale, which indicates the position on the scale. Market size is determined based on the potential clients or buyers in a packaging market, where the external importance scale is set from little (1) to great (5) market size. The market growth rate is determined based on the growth of the packaging industry by 2030, where the external importance scale is set from a low (1) to a high (5) growth rate. Market profit is determined based on the economic factors that the business pulls in after accounting for all expenses, and the scale is set from low (1) to high (5). Price sensitivity is determined by the price of a product that affects the consumers' purchasing decisions, which is evaluated on a scale from high (1) to low (5). Access to raw materials indicates the availability of raw materials required for primary production, which is determined based on the scale from difficult (1) to easy (5). Lastly, production cost includes a variety of expenses such as raw materials, labor, manufacturing supplies, and general overhead, which is determined based on the scale from high (1) to low (5).

For market competitive advantage, the evaluation is also done based on five-point ratings. Where 1 represents a very low competitive advantage, and 5 represents a very highly competitive advantage. Each indicator is evaluated individually. Higher demand for the product is weighted as 5, and lower demand is weighted as 1. Market share evaluated as 1 represents 1–20 %, 2 represents 21–40 %, 3 represents 41–60 %, 4 represents 61–80 %, and 5 represents 81–100 %. Regarding the availability of resources, 1 indicates that the resource is difficult to access, and 5 indicates that the resource is easily accessible. The selling price is rated as 1 for lower and 5 for higher selling price. The environmental ease of technology is evaluated based on its impact on the environment during the manufacturing process, where 1 represents a little or no positive environmental impact and 5 represents a very positive environmental impact of technology. Lastly, the quality is evaluated based on the melting point of the biopolymer, where 5 indicates a high melting point of biopolymer with a very highly competitive advantage, and 1 indicates a low melting point with a very low competitive advantage.

GE-McKinsey market analysis

The GE-McKinsey matrix technique includes nine modules or boxes to designate market aspects for possible new bioproducts. The GE-McKinsey matrix approach has been altered to consider factors and limitations, including environmental protection requirements for the manufacturing process and product sustainability. It displays the competitive attractiveness of a specific product rather than the company's competitive standing. After receiving the findings, it is possible to get insight into the product's market prospects. This matrix shows a similar approach to the Boston Consulting Group matrix. For the management of product portfolios and the study of competitive scenarios, the GE-McKinsey matrix is frequently employed. Fig. 1.4 [17] shows the GE-McKinsey matrix, where products that fall in the green boxes are high performers with commercialization potential. Products that fall in the gray boxes must be analyzed and improved upon, at least until they appear in the green boxes.

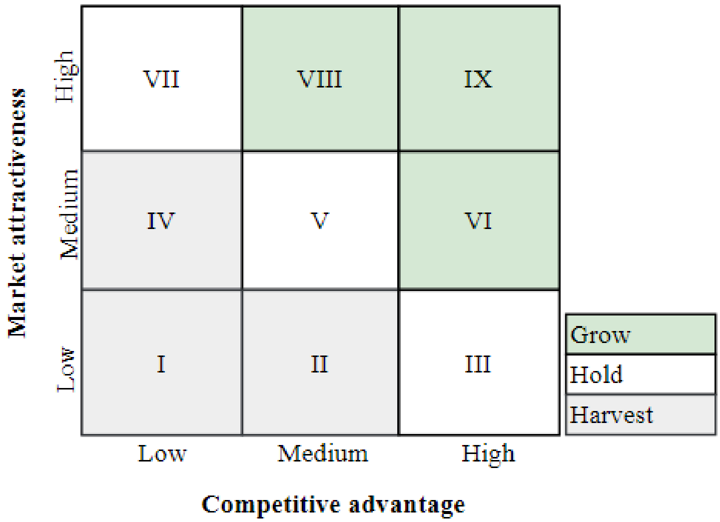

Fig. 1.4. The GE-McKinsey Matrix example [17].

A green box is a growing area, meaning the product has strong competitiveness and attractiveness for the market. If a product is in a holding area, it shows that proper strategies are needed to improve its higher value. If the product is located in the harvest area, it has a low competitive advantage and market attractiveness [18]. This matrix has the benefit of accounting for a greater variety of variables than the Boston Group matrix and being more straightforward to comprehend visually. The nine fields and three times three grids provide the GE-McKinsey matrix with larger dimensions. The Boston Group matrix, in contrast, contains only four fields and a two-by-two grid [19].

Market attractiveness

Market attractiveness replaces market growth as the measurement of industry attractiveness. It refers to the profit possibilities in a product's market or industry. Market attractiveness can be calculated by Equations (1.7) and (1.8).

$$M_a = \frac{(z \cdot k)}{100}, \tag{1.7}$$

where

M_a – market attractiveness total score;

z – estimated rating score.

$$k = \frac{100}{(f \cdot B_{\max})}, \qquad (1.8)$$

where

k – coefficient;

f – number of factors;

$B_{\max}$ – max rating score.

Market competitive advantage

Market competitive advantage refers to a scenario or event that offers a business a competitive or superior position in the marketplace. In this study, a competitive advantage is evaluated for a product. A relative competitive advantage can be calculated by Equation (1.9).

$$R = \left(\frac{B}{B_{comp}} - 1\right) \cdot 100\ \%, \qquad (1.9)$$

where

R – relative indicator of product competitive advantages;

B – new product score estimation;

B_{comp} – strongest competitor score estimation.

1.3. System innovation

To promote the sustainable use of packaging materials and eventually a product, a real case scenario has been developed by implementing a carbon footprint calculator in the packaging industry. A tool for packaging products online marketplace that informs customers about the carbon footprint of packaging products and allows them to evaluate which of the select packaging alternatives is most preferable from an environmental perspective. The online marketplace provides customers with options for selecting different packaging parameters, such as type of material and product, thickness, and size. After that, the comparison of the cost for selected alternative options is provided to the customer, taking into consideration different transport modes and distances from the manufacturer; following the good practice examples found in the literature, the packaging product online marketplace aims to guide customers towards more environmentally friendly decisions by introducing the carbon footprint evaluation tool within their platform.

The study aimed to develop a carbon footprint evaluation tool for packaging materials in the online marketplace. The system boundary used in carbon footprint evaluation is defined from the 'cradle to gate' with transportation to the customer, including the raw materials extraction stage, manufacturing of the packaging, and transportation scenarios to the customer. The system boundaries of the study are shown in Fig. 1.5.

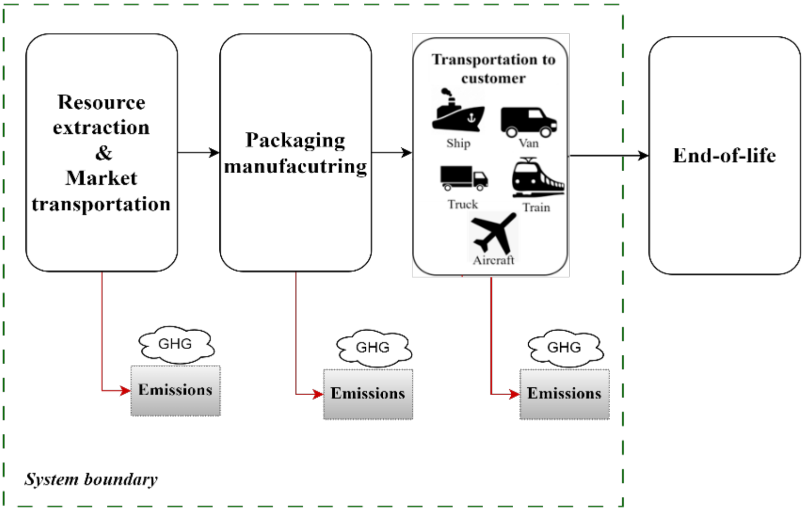

Fig. 1.5. System boundary for carbon footprint evaluation (Author's illustration).

Data for study processes and products used within the defined system boundaries is obtained from the online marketplace company about the different packaging thicknesses and material density. The rest of the data regarding the manufacturing process of specific materials, resource extraction, GHG emissions, and possible transportation modes are obtained from the Ecoinvent database. A total CO_2 footprint is measured from the total GHG emissions associated with all activities. The functional unit (FU) in the study is 1 cm^2 of the packaging, which serves as the reference unit for accounting for the impacts created during the packaging lifecycle in the defined system boundaries.

The life cycle inventory quantifies inflows and outflows of the system, which must be normalized to the FU. Quantitative data for the material variations and parameters are provided by the online packaging marketplace. The inflow of the system includes different materials, their density, and their thickness. For the transportation scenario, different modes of transport are used to distribute packaging materials. Geographically, the global market was selected for all modes of transportation except for trucks. For truck transportation, the market was selected in the geography of Europe. The outflow of the system includes the GHG emissions, where CO_2 emission is considered for the environmental impact assessment. As stated in the ISO standards 14044, the data must ensure at least its validity regarding the geographical origin, representativeness, technological efficiency, and data sources. The carbon footprint is calculated based on the GWP100 using the IPCC 2021 methodology in the SimaPro software 9.4. IPCC 2021 is the successor of the IPCC 2013 method, developed by the IPCC [20]. It contains GWP climate change factors of IPCC with 100 years of timeframe.

2. RESULTS AND DISCUSSION

2.1. Results of sustainability innovation

Results of bibliometric analysis for biopolymers

The keyword co-occurrence analysis has been done by analyzing the different keywords and combinations. This analysis is done of 2723 scientific documents from the Scopus database. The minimum number of co-occurrences of keywords was set at 5. The global co-occurrences at the abstract and keywords level are shown as keywords of each cluster represent its main research area in the domain of biopolymers.

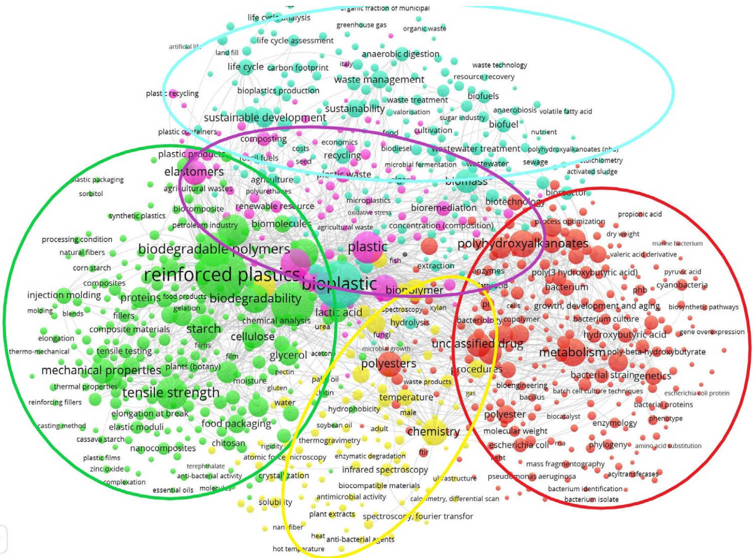

Fig. 2.1. Visualization of co-occurrences for the keyword 'bioplastic'.

The critical research area could be a) biopolymer properties (green cluster), b) sustainable biopolymer production (blue cluster), c) classification of biopolymers (red cluster), d) biopolymer characteristics (pink cluster), and e) plastic degradation (yellow cluster) (see Fig. 2.1). The bibliometric analysis for the keywords 'bioplastic' and 'sustainability' is shown in Fig. 2.2. The key research area from the co-occurrences for keywords 'bioplastic' and 'sustainability' can be framed as a) sustainable development of bioplastic (green cluster), b) bioeconomy concept (red cluster), c) biodegradable plastics (yellow cluster), and d) assessment methodologies (blue cluster).

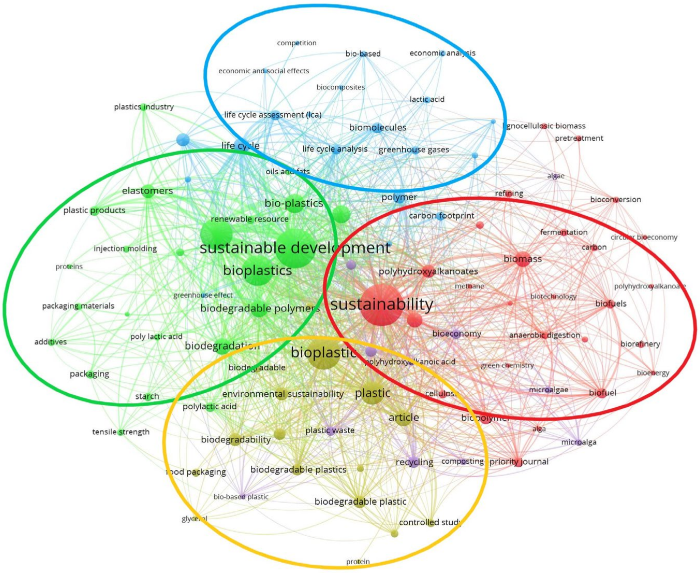

Fig. 2.2. Visualization of co-occurrences for keywords 'bioplastic' and 'sustainability'.

The bibliometric analysis for the keywords 'agriculture' and 'waste' and 'biopolymer' is shown in Fig. 2.3. The red cluster shows the main co-occurrence with agricultural waste, valorization, and biopolymers. It also relates to biodegradable polymers, sustainable development, and biomolecules. The blue cluster includes the terms related to biomass activities (biofuel and biogas), such as the food industry, waste management, sustainability, hydrolysis, and polysaccharides.

The green cluster relates to agricultural activities with agricultural waste, wastewater, and wastewater management with nanotechnology and biocompatibility. The yellow cluster relates to the biological process, including metabolism, fermentation, extraction, biosynthesis, isolation, and purification. Lastly, the purple cluster shows the link between bioplastic (polyhydroxy alkenoates), waste streams (industrial waste and waste disposal), and tissue engineering biomaterials. This cluster relates to the biomedical application of biopolymers. The key research area based on co-occurrences for keywords 'agriculture' and 'waste' and 'biopolymer' could be framed as a) agricultural waste management (green cluster), b) biopolymers (red cluster), c) bioproducts (blue cluster), d) industrial waste (purple cluster), and e) biological processes (yellow cluster).

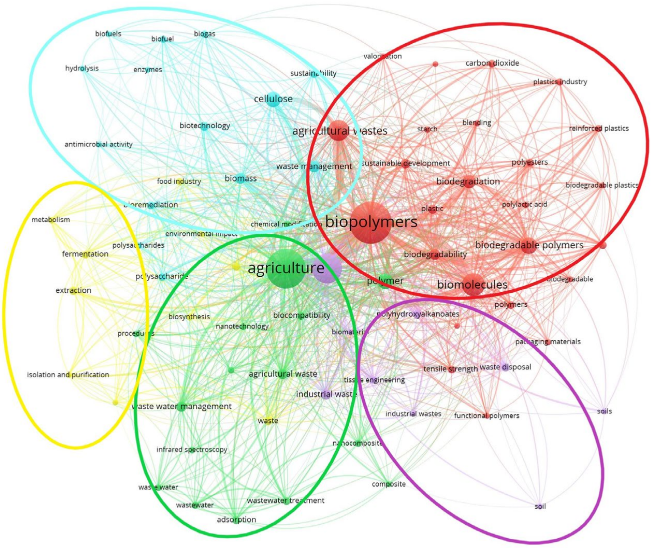

Fig. 2.3. Visualization of co-occurrences for keywords 'agriculture' and 'waste' and 'biopolymer'.

Ranking of bioeconomy modeling tools

The bioeconomy modeling tools have diverse applications for sustainable bioeconomy, such as The Mixed Integer Linear Programming (MILP), Modular Applied GeNeral Equilibrium Tool (MAGNET), The Market Allocation-Energy Flow Optimization Model System (TIMES), Global Biosphere Management Model (GLOBIOM), and Life Cycle Analysis (LCA). The evaluation results are presented for the criteria and three main sustainability sub-criteria. Firstly, the criteria and sub-criteria were evaluated using the semi-quantitative analysis for bioeconomy modeling tools. The semi-quantitative analysis results for selected criteria and sub-criteria for each model have been presented in Table 2.1.

Table 2.1

Semi-quantitative Analysis Results for a Bioeconomy Modeling Tool

Criteria	**Sub-criteria**	**MILP**	**MAGNET**	**TIMES**	**GLOBIOM**	**LCA**
Documentation aspects	Economic	2	3	1	3	1
	Social	2	3	1	4	1
	Environmental	2	3	1	3	1
Flexibility	Economic	1	2	2	2	1
	Social	1	2	2	4	1
	Environmental	1	2	2	3	1
Compatibility	Economic	2	4	2	2	2
	Social	2	4	2	4	3
	Environmental	2	4	2	2	2
Diversity	Economic	2	3	1	2	2
	Social	2	3	2	3	2
	Environmental	2	3	1	2	2
Validity	Economic	2	2	1	3	2
	Social	2	2	2	4	2
	Environmental	2	2	2	3	1
Efficiency	Economic	3	2	2	2	1
	Social	3	2	2	4	1
	Environmental	3	2	2	2	1
User-friendliness	Economic	2	3	1	3	1
	Social	2	3	1	4	1
	Environmental	2	3	1	3	1

The closeness coefficient values for each model present the model's efficacy, and based on that, the models have been ranked. The unitary variation ratio is ideally considered '1', therefore the ranking is based on the distance derived from the unitary variation ratio. For example, the nearest result from the unitary variation ratio is derived for the LCA model, so it is ranked 1. The TIMES, MILP, MAGNET, and GLOBIOM models are ranked 2, 3, 4, and 5, respectively. The graph is plotted based on the closeness coefficient (see Fig. 2.4). The graph shows that the MCDA results are more suitable for the LCA model because it derives the nearest value (0.64) to the unitary variation ratio. The lower values are derived for the GLOBIOM (0.47) and MAGNET (0.53) models compared to other models, which show less efficacy in estimating the bioresources. The derived result for the MILP model is 0.58. Lastly, the TIMES model has high documentation, flexibility, compatibility, and efficiency; therefore, the result is 0.60. Concisely, the MCDA analysis sheds light on the most suitable bioeconomy modeling tool (LCA) to estimate the added value of bioresources within the scope of the agricultural sector.

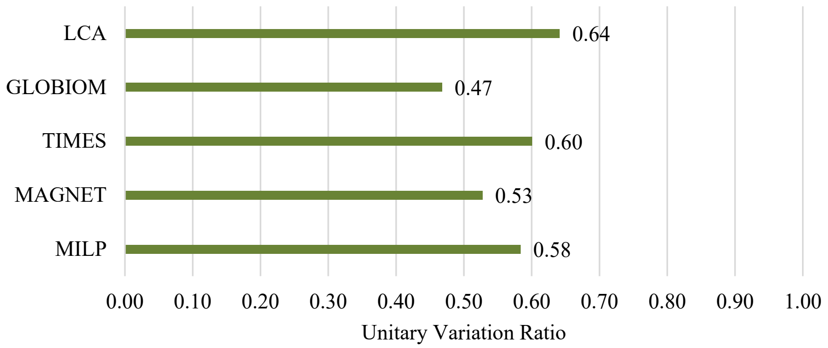

Fig. 2.4. TOPSIS results for modeling tools.

Results of evaluating scenario for bioenergy production from hemp biomass

Aggregating the experts' assessments of the compliance of different groups of hemp products with the six sustainability criteria for a normal scenario under non-crisis conditions, a normalized decision matrix is obtained. In addition, the weights of the criteria from the expert evaluation were added, which aimed to rank the importance of the criteria themselves under the non-crisis scenario. The experts ranked the economic and environmental aspects as the most important criteria with a weight of 0.20, with the other criteria equally weighted at 0.15 (see Table 2.2).

Table 2.2

Normalized Decision Matrix for a Normal Scenario Under Non-crisis Conditions

Criteria	**Thermal insulation**	**Textile**	**Composite materials**	**Construction materials**	**Paper**	**Technical material**	**Agriculture**	**Energy**	**Criteria weights**
Resource availability	0.325	0.217	0.325	0.542	0.325	0.325	0.434	0.217	0.15
Technological aspects	0.435	0.348	0.261	0.435	0.261	0.348	0.348	0.348	0.15
Economical aspects	0.470	0.376	0.376	0.376	0.188	0.188	0.376	0.376	0.20
Environmental aspects	0.408	0.408	0.408	0.327	0.327	0.408	0.245	0.245	0.20
Climate Change aspects	0.399	0.399	0.319	0.319	0.319	0.399	0.239	0.399	0.15
Circular economy aspects	0.328	0.410	0.410	0.410	0.410	0.410	0.164	0.164	0.15
								Total	**1.00**

TOPSIS calculations comparing the eight hemp products under non-crisis conditions were used to determine the product group closest to the ideal positive solution (1.00), the results are shown in Fig. 2.5. The closeness proximity of the selected hemp product groups to the ideal positive solution indicates their more robust compliance with the six sustainability criteria. In contrast, the proximity to the ideal negative solution indicates the opposite. The closest to the ideal positive solution is the production of building materials and thermal insulation, with values of 0.74 and 0.70, respectively. On the other hand, the worst results are for energy and paper production, with 0.39 and 0.38, respectively. All eight products compared are far from the positive ideal solution. The best and second-best performances differ by only 0.04 units. However, the sustainability performance of building materials is almost 50 % better than paper production from hemp. This is a substantial difference, suggesting that the MCDA analysis, driven by the research criteria, concludes that hemp-based building materials are more sustainable than hemp-based paper and energy.

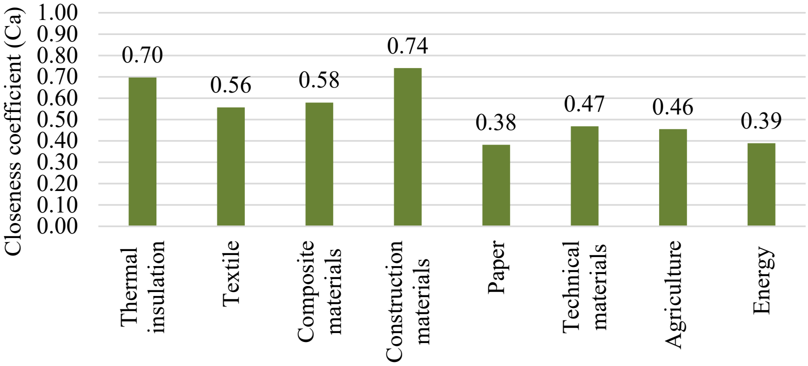

Fig. 2.5. TOPSIS results for hemp products under non-crisis conditions.

When a global and national economic and energy crisis develops, circumstances change. In such a scenario, all potential energy sources must be evaluated differently, as the price of fossil fuels could become much higher. A normalized decision matrix was created by combining experts' scenario assessments for energy or economic crisis conditions (see Table 2.3).

The weighting of the criteria from the expert evaluation was added. The change in the situation is also clearly visible in the experts' evaluation. In a crisis, the experts weigh the criterion economic aspects more heavily with 0.40 points. In contrast, resource availability, technological aspects, and climate change have a weighting of 0.15. The lowest weighting in a crisis is given to environmental aspects – 0.10, and aspects of the circular economy with the lowest weighting of 0.05.

Table 2.3

Normalized Decision Matrix for Energy or Economic Crisis Situation

Criteria	**Thermal insulation**	**Textile**	**Composite materials**	**Construction materials**	**Paper**	**Technical material**	**Food**	**Energy**	**Criteria weights**
Resource availability	0.291	0.194	0.291	0.486	0.291	0.291	0.389	0.486	0.15
Technological aspects	0.435	0.348	0.261	0.435	0.261	0.348	0.348	0.348	0.15
Economical aspects	0.453	0.362	0.362	0.362	0.181	0.181	0.362	0.453	0.40
Environmental aspects	0.408	0.408	0.408	0.327	0.327	0.408	0.245	0.245	0.10
Climate Change aspects	0.399	0.399	0.319	0.319	0.319	0.399	0.239	0.399	0.15
Circular economy aspects	0.307	0.383	0.383	0.383	0.383	0.383	0.153	0.383	0.05
								Total	**1.00**

The TOPSIS calculations comparing the eight hemp products under conditions of energy or economic crisis, using the method of finding the solution closest to the positive ideal solution (1.00), gave the results shown in Fig. 2.6. The generation of energy and thermal insulation comes closest to the positive ideal solution 1.00, with values of 0.85 and 0.80, respectively. On the other hand, technical materials and paper products have the lowest values, 0.25 and 0.17, respectively. Energy generation has moved closer to the ideal. Thermal insulation has also moved closer to the ideal positive solution, as the consequential application of these products in buildings can reduce the energy consumption in dwellings. The best and second-best performances differ by only 0.05 units. The other six products compared are further away from the ideal positive solution. However, the sustainability performance of energy production is 80 % higher than that of paper production from hemp. This is a significant difference, indicating the need for additional analysis and adjustment of priorities for the use of hemp in the context of an economic crisis.

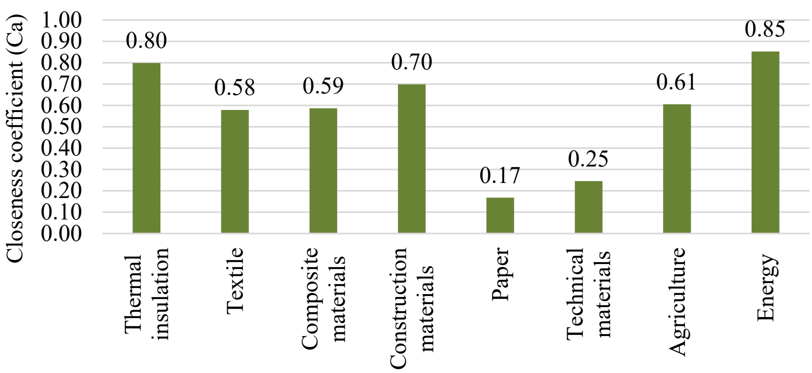

Fig. 2.6. TOPSIS results for hemp products under energy or economic crisis conditions.

Interpretation of LCA results

The results show the contribution of sub-systems to the total potential impacts in each category. The raw hemp biomass processing sub-system shows low environmental impacts in each category. At the same time, the electricity generation sub-system is responsible for most of the environmental toll in all the impact categories. In the global warming category, electricity generation is responsible for 5.31×10^1 kgCO_2 eq per FU. The highest environmental impact share is for the aquatic ecotoxicity 1.4×10^4 kg TEG water per FU.

The environmental impact shares for the electricity generation from raw hemp biomass in the four main damage categories (climate change, ecosystem quality, human health, and resource use) can be seen in Fig. 2.7. The aggregation of midpoint impact categories into damage categories is achieved using a specific set of characterization factors given by the chosen LCA method. As can be seen, electricity generation dramatically impacts human health and ecosystem quality. The *IMPACT 2002+* method enables weighting factors to develop a single score unit for all categories (eco-points Pt). It allows comparisons between the different damage categories. The comparison between categories allows to determine which category is most affected overall and to summarize all categories, as in Fig. 2.8. Overall, the single score for electricity generation from raw hemp biomass is 30 Pt, with the electricity generation sub-system as the most critical hotspot with 26.8 Pt, followed by the raw hemp biomass processing sub-system at 3.28 Pt. The comparison between various biomass sources is presented in Table 2.4. In the global warming impact category, the electricity generation from peat has the highest impact with 1.2×10^2 kg CO_2 eq per FU.

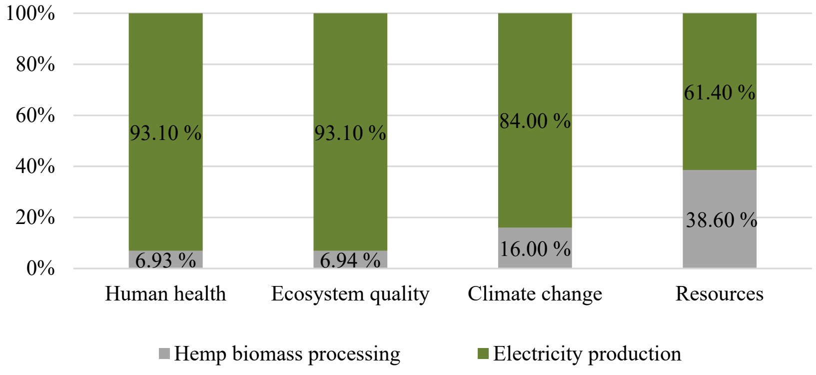

Fig. 2.7. Damage assessment results for hemp biomass for electricity production.

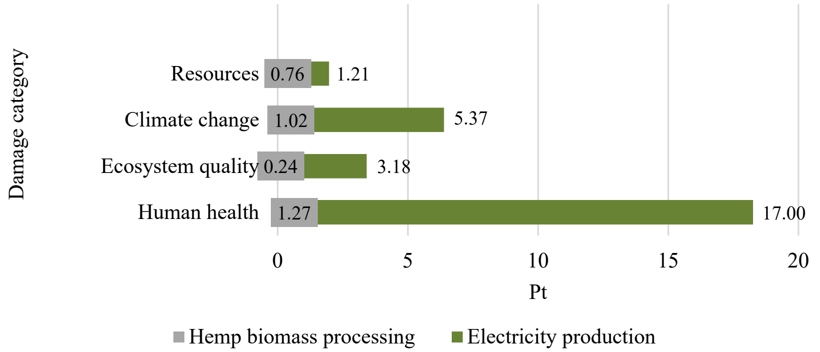

Fig. 2.8. Weighted totalized results for the hemp biomass for electricity production.

In contrast, the least influence has sweet sorghum biomass with 2.3 kg CO_2 eq per FU. The electricity generation from peat shares the highest toll for non-renewable energy impact category, 1.3 × 10^3 MJ primary per FU. Regarding sweet sorghum and wood biomass, the highest toll share is in the category of aquatic ecotoxicity, 3.4 × 10^3 and 1.1 × 10^4 kg TEG water per FU, respectively. Overall, the raw hemp biomass is competitive with other biomasses.

Table 2.4

Comparison of Environmental Impact Assessment to Produce Electricity from Alternate Biomasses

Impact category	**Unit**	**Raw hemp biomass**	**Peat biomass**	**Sweet sorghum biomass**	**Wood biomass**
Carcinogens	kg C_2H_3Cl eq	5.7 × 10^{-1}	8.0 × 10^{-2}	1.0 × 10^{-1}	6.3 × 10^{-1}
Non-carcinogens	kg C_2H_3Cl eq	2.2	2.8 × 10^{-1}	2.7 × 10^{-1}	1.7
Respiratory inorganics	kg PM2.5 eq	1.7 × 10^{-1}	5.8 × 10^{-2}	1.7 × 10^{-2}	2.4 × 10^{-2}
Ionizing radiation	kBq C-14 eq	2.1 × 10^{2}	7.9 × 10^{1}	1.4 × 10^{1}	6.8 × 10^{1}
Ozone layer depletion	kg CFC-11 eq	2.2 × 10^{-6}	6.7 × 10^{-7}	2.4 × 10^{-7}	1.5 × 10^{-6}
Respiratory organics	kg C_2H_4 eq	1.2 × 10^{-2}	2.8 × 10^{-3}	1.3 × 10^{-3}	1.2 × 10^{-2}
Aquatic ecotoxicity	kg TEG water	1.4 × 10^{4}	7.2 × 10^{2}	3.4 × 10^{3}	1.1 × 10^{4}
Terrestrial ecotoxicity	kg TEG soil	5.2 × 10^{3}	2.9 × 10^{2}	5.9 × 10^{2}	4.0 × 10^{3}
Terrestrial acid/nutri	kg SO_2 eq	3.8	1.0	2.8 × 10^{-2}	6.4 × 10^{-1}
Land occupation	m2org.arable	8.8 × 10^{-1}	3.4× 10^{-1}	5.5	3.3 × 10^{1}
Aquatic acidification	kg SO_2 eq	1.4	3.3 × 10^{-1}	4.3 × 10^{-2}	1.4 × 10^{-1}
Aquatic eutrophication	kg PO_4 P-lim	1.4× 10^{-2}	7.8 × 10^{-4}	4.7 × 10^{-3}	7.2 × 10^{-3}
Global warming	kg CO_2 eq	6.3 × 10^{1}	1.2 × 10^{2}	2.3	1.8 × 10^{1}

Table 2.4 continued

Non-renewable energy	MJ primary	3.0×10^{2}	1.3×10^{3}	3.1×10^{1}	2.1×10^{2}
Mineral extraction	MJ surplus	1.2	1.7×10^{-1}	1.1×10^{-1}	9.4×10^{-1}

Note: The datasets for the peat, wood, and sweet sorghum biomasses to produce electricity are taken from *Ecoinvent 3* databases [14].

The MCDA analysis for the everyday situation has shown that the use of hemp in the energy sector performs poorly, which means that it is far from the ideal solution. However, the situation changes in an energy crisis, when the use of hemp in energy production comes first and is the best solution. These results suggest that more research is needed to answer the question: Can a short-term solution also be considered sustainable? The LCA of raw hemp biomass combustion answers this question compared to other biomasses and indigenous fuels (peat) for energy production. Answers were sought on the impacts of different energy sources on human health, climate change, resources, and ecosystem quality. The results confirm that the use of hemp in the energy sector for energy generation is not sustainable. It should be avoided even in times of economic crisis. The developed sustainability assessment methodology has shown that the MCDA method provides only a partial answer to the efficiency and effectiveness of the biobased product. Only if the results obtained with MCDA are further analyzed with LCA will it be possible to have a complete picture of whether the use of hemp in the energy sector is sustainable under all circumstances and could be a future solution to replace fossil energy sources. It is, therefore, expected that the integrated sustainability assessment method will be widely used in the near future.

Results of evaluation of pretreatment methods to extract fiber from hogweed (Heracleum Sosnowski) biomass

A MCDA TOPSIS has been performed to compare and find the most appropriate method for pre-treatment and obtaining fibers from biomass resources. The main goal of applying the pre-treatment method is to break down the cellulose fiber [21]. Pre-treatment accelerates the process and has many advantages, such as:

a) it is creating pores in biomass, which allows the separation of cellulose, hemicellulose, and lignin residues;
b) it also enhances enzyme activity;
c) it is a cost-effective method in terms of low requirement of heat and power;
d) it extracts the valuable component from lignin [22].

A comparison of the performance of seven different chemical pre-treatment methods considering four leading indicators for hogweed biomass was performed. Indicators have been selected based on the literature analysis and availability of technical, environmental, and economic data. After that, the decision-making matrix is compiled. All costs are considered to pre-treat 1 kg of hogweed [23]. However, for KOH, cost assumption is based on the literature [24], the concentration, required amount of time (i.e., considering the total experiment time and chemical reaction between substrate and chemical), and methane generation capacity for each alternate method was assumed based on literature analysis [25]. Methane generation capacity is a positive indicator because generated methane can be used for bioenergy applications at the end of the process. The decision-making matrix indicates the numerical information for each criterion and alternative (see Table 2.5) [23].

Table 2.5

Pre-treatment Method Alternatives and Selected Criteria

		Alternatives						
	Indicators	NaOH Xa1	KOH Xa2	$Ca(OH)_2$ Xa3	H_2SO_4 Xa4	HCL Xa5	H_2O_2 Xa6	CH_3COOH Xa7
i1	Concentration (%)	2	2.5	2.5	2	2	3	4
i2	Time (days)	3	1	1	7	7	7	7
i3	Cost (EUR)	0.54	3	0.59	0.33	0.64	0.47	1.22
i4	CH_4 generation capacity (mL gVS^{-1})	220	295	210.71	175.6	163.4	216.7	145.1

The significant findings of this case study are identifying the best possible method to produce a valuable product, i.e., fiber. The TOPSIS method showed that the $Ca(OH)_2$ chemical pre-treatment method is the most suitable for pre-treatment. The graph is plotted based on the closeness coefficient (see Fig. 2.9). The graph shows the results obtained from TOPSIS and unitary variation ratio, ideally considered '1'. The nearest alternative to the maximum unitary variation ratio is the third alternative, which is $Ca(OH)_2$. The lowest value derived is for alternative 2, which is KOH.

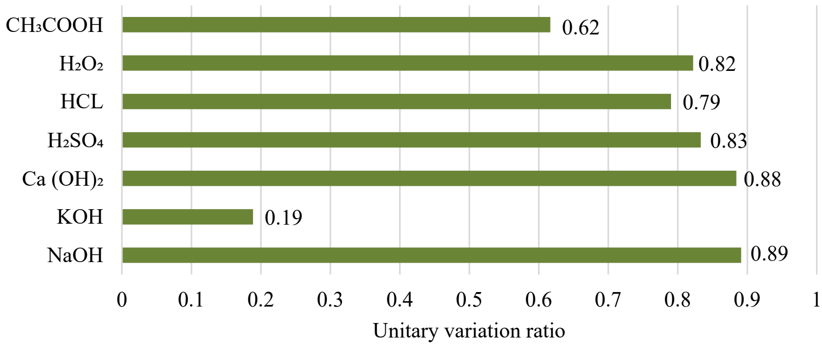

Fig. 2.9. TOPSIS results for pre-treatment methods.

Results of evaluation of extraction techniques to extract essential oil from fruit peel waste

Fruit peels have the best medicinal properties, such as antimicrobial, antioxidant, anti-inflammatory, anti-infectious, anti-mutagenic, and hepatoprotective. The MCDA TOPSIS is used to make decisions, analyze the significance of objectives, and to evaluate problem solutions based on various types of information and data – qualitative and quantitative data, data from the physical and social sciences, and politics and ethics.

The performance of four different green extraction methods were compared: steam distillation, cold-pressing, solvent extraction, and hydro distillation. The selection of the criterion, i.e., technical, environmental, economic, and social acceptability, is based on the vast literature analysis. Table 2.6 shows a detailed overview of the selected criteria and sub-criteria. These techniques are used in the evaluation to extract the essential oil from the fruit waste. Steam distillation is a separation technique that can be applied to separate volatile organic compounds [26]. Earlier studies show that 93 % of the proportion of essential oil can be extracted by steam distillation [27]. The cold-pressing method is the standard technique used to extract essential oil from the seeds of plants and fruits. Also, this process can be done at a low temperature below 60 °C [28]. The solvent extraction method, also known as liquid-liquid extraction, is a method to separate compounds based on the solubility of their parts [29]. Hydro distillation is a traditional method to extract oil or bioactive compounds from plants [30]. Overall, all four methods have different functionalities and apparatuses.

Table 2.6

Sustainability Criteria Selection for Extraction Methods

Essential oil (from fruit waste)				
	Technical aspect	**Environmental aspect**	**Economical aspect**	**Source**
Steam distillation	Pressurized container required	Less fuel & high temperature required	High equipment & operating cost	[31]
Cold pressing	High-quality production possibility	Lack of hazardous organic solvent & environmentally friendly	Low cost & less manpower required	[32]
Solvent extraction	Simple equipment used, low efficiency	High temperature & production of hazardous waste	Low cost	[32]
Hydro distillation	Simple instrumentation	High consumption of energy, no organic solvent	Low cost	[33]

The TOPSIS analysis results are shown in Fig. 2.10. Cold pressing (0.9) is the closest alternative for the best solution not only for the technological criterion with the highest weight of all criteria (0.45) but also for good performance in the economic criterion with the second-highest impact on results. Steam distillation ranks second technology, with an evaluation of 0.6, and as a third possible technological solution, hydro distillation with 0.3 and solvent extraction with 0.1.

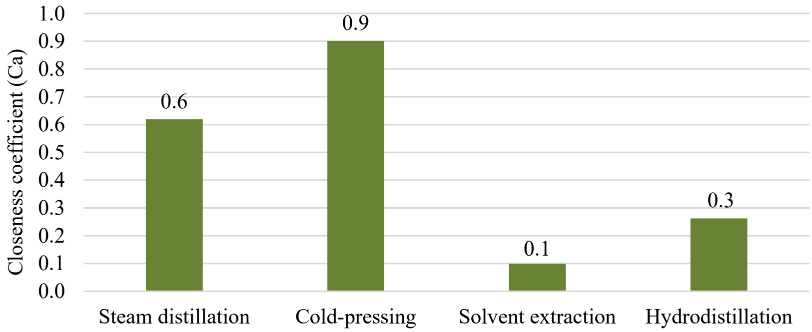

Fig. 2.10. TOPSIS results for extraction technologies.

Results of evaluating biopolymers alternatives under sustainability framework

A set of indicators considers aspects from ‘the cradle to the grave’, ranging from farm areas to the complete life cycle of biopolymers as boundaries. Considering the literature analysis on sustainable development in agriculture, the criteria were chosen for producing biopolymers. The selected criteria and indicators used to evaluate alternative biopolymers are listed in Table 2.7.

Table 2.7

Set of Criteria and Indicators Used to Evaluate Alternative Biopolymers

Criteria	Indicator	Unit of measures
Environmental	Carbon footprint	CO_2eq/kg polymer
	Energy consumption	MJ/kg polymer
	Acidification	SO_2eq/kg
Circularity	Biodegradability	%
	Period of biodegradability	Days
Technical	Melting point	°C
	Density	kg/m3
	Tensile strength	MPa
Social	Human health	kg 1,4-DB_{eq}
Economic	Production cost	USD/kg
	Market price	USD/kg
	Global production capacity	%

Among the survey respondents, 41 % were consumers, 14 % were from society, 7 % were scientists, and the rest, 38 %, were value-chain actors, government policy makers, and academic educators. Moreover, the survey respondents were from different countries, including India, Egypt, Latvia, Spain, and the United Kingdom. The results of the weights of criteria derived from the survey analysis are presented in this section. Based on the score from pairwise comparison from every respondent, the consistency index ranged from 0.00 to 0.09.

The AHP results of 29 respondents are presented in Fig. 2.11. According to the average mean of the five main criteria, the environmental aspect was of the highest priority (0.30), followed by the circularity aspect (0.23), economic aspect (0.18), technical aspect (0.16), and social aspect (0.13). These AHP weights are included in the MCDA methods. Selecting a proper MCDA method is salient for a given decision situation, as various methods can yield different results for the same decision-making problem.

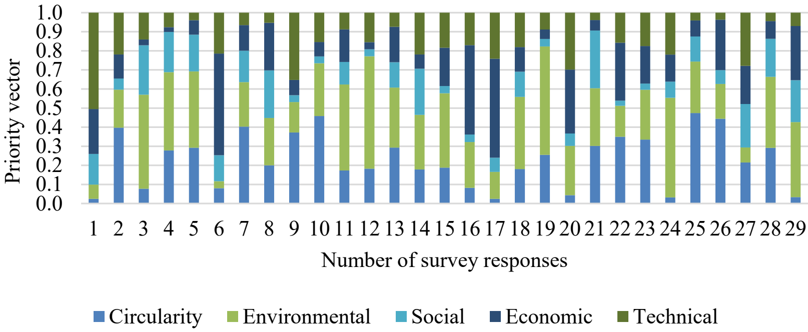

Fig. 2.11. AHP survey results.

Several factors influence the different results when applying various calculating procedures, such as, a) the use of weights in a different way, b) different algorithms to select the best solution, c) many algorithms attempt to scale the objectives, which affect the weights, d) some algorithms include the additional parameters, which affects the results. The results are summarized in Table 2.8 based on the ranking of biopolymers.

Table 2.8

Summary of MCDA Results

Rank	**MCDA methods**			
	TOPSIS	MOORA	COPRAS	VIKOR
1	Cellulose	PLA	Cellulose	Starch
2	Protein	Starch	PLA	Cellulose
3	Starch	Cellulose	Starch	PLA
4	PLA	PHA/PHB	Cellulose	PHA/PHB
5	PHA/PHB	Protein	PHA/PHB	Protein

The results show that the best biopolymer alternative in TOPSIS and COPRAS methods is a cellulose-based biopolymer, as these methods work on the same principle of vector normalization [34]. However, [35] argued that the TOPSIS and VIKOR methods work on the same principle; equally significant similarities can be found between these methods. Also, a key point is mentioned that TOPSIS works on vector normalization, and VIKOR works on linear normalization. In contrast, the MOORA and VIKOR methods show that PLA and starch-based biopolymers are the most suitable option, respectively. In this study, the decision was made considering most of the best results among four different MCDA methods integrating with the AHP. The cellulose-based biopolymer is the most suitable to produce from agricultural waste.

2.2. Results of market innovation

The most available and easy-to-access resource considered is agricultural residues, and the eco-friendliness of the conversion technique is considered according to the type of packaging materials. The market is set for Europe, and the products chosen are biopolymer packaging materials, including PLA, PHA, starch, and cellulose. The evaluation rating for market attractiveness is presented in Table 2.9. Since all market attractiveness indicators are equally important, every indicator was assigned a weight of 16.666 %.

Table 2.9

Evaluation Rating for Market Attractiveness

Indicators	**Weights**	**External importance scale**	**Very unattractive**	**Unattractive**	**Neutral**	**Attractive**	**Very attractive**	**External importance scale**
			1	**2**	**3**	**4**	**5**	
Market size	16.666 %	Little	C	P2	S	P1		Great
Market growth rate	16.666 %	Low		C	S	P2	P1	High
Market profit	16.666 %	Low		C	S	P2	P1	High
Price sensitivity	16.666 %	High		C; P2	S		P1	Low
Access to raw material	16.666 %	Difficult					C; S; P1; P2	Easy
Production cost	16.666 %	High		P2		C; P1	S	Low

Note: C-cellulose; P1 – PLA; P2 – PHA; S – starch.

The evaluation rating for market competitiveness advantage is shown in Table 2.10. The weight was set for the market competitive advantage indicator in percentage, considering the importance of the indicator. The highest weights are 20 % for the availability of resources and environmental ease of the technology. As per our developed methodology, these two indicators are crucial for a strong business portfolio. The rest of the indicators are evaluated for the 15 % of weights.

Table 2.10

Evaluation Rating for Market Competitive Advantage

Indicators	**Weights**	**Very low competitive advantage**	**Low competitive advantage**	**Moderate competitive advantage**	**High competitive advantage**	**Very high competitive advantage**
		Rating scale				
		1	**2**	**3**	**4**	**5**
Demand	15 %		S	P1	P2	C
Market share	15 %		C	S	P2	P1
Availability of resources	20 %					C; S; P1; P2
Selling price	15 %		C; P2	S		P1
Environmental ease	20 %				P1; P2	S; C
Quality (based on melting point)	15 %			P2	P1; S	C

Note: C – cellulose; P1 – PLA; P2 – PHA; S – starch.

The visualization of GE-McKinsey results is shown in Fig. 2.12. The results in the matrix show that PLA has a substantial potential for market attractiveness (4.65) and competitive advantage (4.15) because PLA has the comparatively low market price (1.50–2.09 USD/kg) with the highest production capacity (37.9 %) compared to other packaging materials. PHA packaging material has the weakest position in the market competitive advantage (3.15).

To strengthen the position, PHA should be able to compete better and, if feasible, make the market more appealing. On the other hand, cellulose material shows the least market attractiveness (2.66), which can be improved by increasing the market size, growth rate and potentially giving a better price. The market share for the cellulose is only 1.5 %. Starch packaging materials show an average position for market attractiveness (3.65) and competitive advantage (3.65). However, improving both ratios can lead to a higher position for starch material.

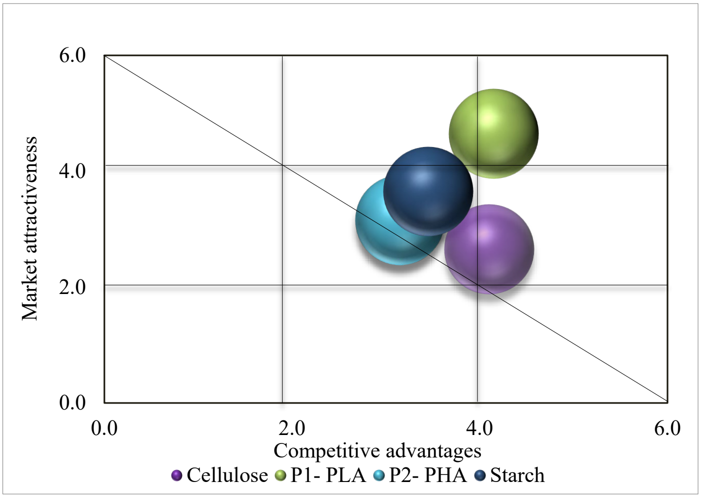

Fig. 2.12. GE-McKinsey matrix results for biopolymer packaging material alternative.

The results of this study strongly favor PLA packaging materials production with both market attractiveness and competitive advantage. Moreover, biopolymer packaging material investment opportunities bring an advantage to acting towards climate neutrality by complying with the global environmental policy to decrease CO_2 emissions by increasing the use of agricultural residues and share of biobased products in the market.

2.2. Results of system innovation

A carbon footprint evaluation tool is developed for packaging products in the online marketplace to help customers to identify and evaluate different packaging alternatives, from the worst to the best scenario, based on their carbon footprint. The created tool foresees carbon footprint evaluation among user-selected alternative packaging materials in five steps. The first step is the selection of packaging material alternatives, among which the online marketplace customer would like to make the carbon footprint evaluation. Once the packaging material has been identified from the list of alternative options, the second step is defining the packaging material's amount based on the size and thickness of the packaging material. Step three defines the transportation scenario, including information on transportation type and traveled distance to transfer the packaging. Step four is the carbon footprint calculation for selected alternative packaging scenarios. In this step, the calculation is made for the created GHG emissions in packaging production and transportation to the client based on the information provided in the previous steps. Finally, in step five, a color indicator is assigned to every alternative, indicating the worst, medium, and best options among the selected alternatives.

For the selection of packaging material, information from the packaging company is obtained for different packaging material parameters, including the density and thickness variation. The amount of material in the packaging area equal to 1 cm^2 is estimated based on density and thickness. The packaging size can differ depending on customer needs. In the marketplace, the customer can select his preferred packaging (p) and such parameters as packaging material (x) and size from the available options. This information will serve as input in carbon footprint evaluation. For packaging p of a specific size with an area A_p (cm^2) and thickness Th (μm), the mass of packaging m_p will be estimated in the tool by Equation (2.1).

$$m_p = A_p \cdot \rho_A, \tag{2.1}$$

where

m_p – the mass (g) of selected packaging;

A_p – area (cm^2) of selected packaging p;

ρ_A – area density ($\mu g/cm^2$) of material x.

To estimate transportation impact, the definition of transportation scenario must include two essential parameters: transport mode and transport distance. The carbon footprint calculations for selected packaging can be performed by Equation (2.2).

$$CF_p = CF_{x_p} + CF_{t_p}, \tag{2.2}$$

where

CF_p – total carbon footprint of packaging *p;*

CF_{xp} – carbon footprint of material x in packaging *p;*

CF_{tp} – carbon footprint of transportation scenario t of packaging *p.*

The variables CF_{x_p}, and CF_{t_p} are estimated according to Equations (2.3) and (2.4).

$$CF_{x_p} = CF_x \cdot A_p, \tag{2.3}$$

where

CF_x – estimated carbon footprint for 1 cm^2 of packaging materials *x;*

A_p – area of packaging *p.*

The carbon footprint for the transportation scenario of packaging p is estimated as the sum of the multiplication of transportation distance, the carbon footprint of transport type used, and the mass of packing transported.

$$CF_{t_p} = \sum_{i=t}^{n} D_t \cdot CF_t \cdot m_p, \tag{2.4}$$

where

D_t – distance by transport type t;

CF_t – carbon footprint coefficient for transport type t;

m_p – mass of packaging *p.*

CF_x and CF_t are the carbon footprint values obtained for a single unit process from Ecoinvent by the IPCC 2021 impact assessment method. The CF_{t_p} is calculated by selecting the global average datasets from Ecoinvent. The transport mode for specific delivery routes must be distinguished among ship, truck, van, train, and aircraft based on information from the shipping company. The carbon footprint coefficient for all transport modes is considering delivering the transportation service of 1 kg of material across a distance of 1 km.

To provide packaging products online marketplace customers with an explicit and simple way to compare carbon footprint values among their selected alternatives, the color indicators are assigned to the obtained carbon footprint values. The color indicator is used for the three carbon footprint levels: low, medium, and high. The different carbon footprint levels can be calculated using Equations (2.5) and (2.6).

$$I = \frac{Max\left(CF_p\right) - Min\left(CF_p\right)}{3}, \tag{2.5}$$

where

I – value that is used for distinguishing carbon footprint levels;

$Max\ (CF_p)$ – maximum value among CF_p of selected alternative options;

$Min\ (CF_p)$ – minimum value among CF_p of selected alternative options.

$$\begin{gathered} If\ \left(CF_p\right) < Min\ (CFp) + (I)\ , then\ (I_{low}); \\ else\ \left(if\ \left(CF_p\right) \geq Min\ (CFp) + (2 \cdot I);\ then\ \left(I_{high}\right);\ else\ (I_{medium})\right), \end{gathered} \tag{2.6}$$

where

I_{low} – low levels of carbon footprint;

I_{medium} – medium levels of carbon footprint;

I_{high} – high levels of carbon footprints.

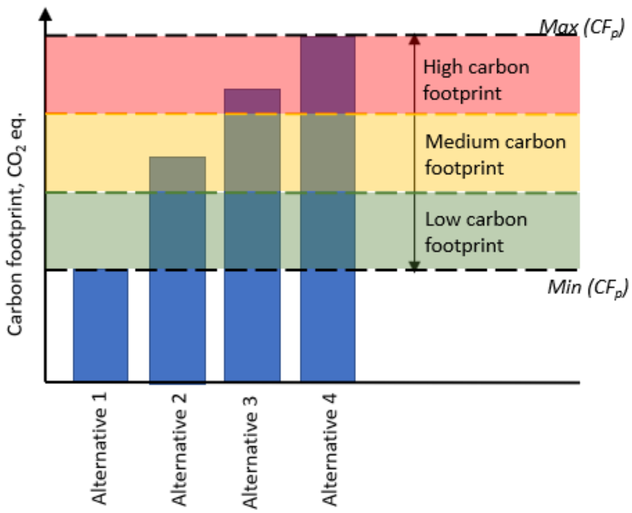

Fig. 2.13. Colour visualization of carbon footrprint calculation for packaging alternatives.

A simple evaluation of packaging alternatives can be performed by indicating three carbon footprint levels for packaging alternatives and their transportation scenarios: low, medium, and high. The carbon footprint calculation results can be presented to the online marketplace client using color indicators to distinguish these levels. As shown in Fig. 2.13, low, medium, and high carbon footprint levels can be visualized in green, yellow, and red color indicators. It is noteworthy that the current tool may be developed further, including surface variation and more materials. The carbon footprint calculation of the packaging, including the transportation scenario not only shows numerical results and educates clients but also allows the different stakeholders to prioritize opportunities to reduce GHG emissions associated with the product supply chain.

Therefore, product policies that promote implementing carbon footprint reduction schemes are worth considering. These policies should be standard and comprehensive, embracing the environmental assessment of products considering their life cycle. In the short term, companies are expected to incorporate carbon footprint schemes as a strategic measure for market competition and decision-making. This goal can be achieved by following well-defined methods. As a long-term goal, policy makers should enforce to implement carbon footprint schemes for companies.

CONCLUSIONS AND RECOMMENDATIONS

The results reveal the key conclusions and provide a set of recommendations, incorporating future advancement in sustainable bioeconomy by valorizing agricultural waste.

Conclusions:

1. The research approach addresses the pressing need for the adoption of biopolymer packaging materials sustainably while simultaneously advocating sustainable agricultural waste valorization practices. Thus, the Thesis hypothesis stands valid – the development of an integrated methodology that emphasizes substantial innovation pillars will lead to the prioritization of biopolymer packaging materials and sustainable valorization of agricultural waste.
2. The developed integrated methodology of the Thesis pinpoints the significance of holistic and innovative approaches in promoting sustainability within the bioeconomy by valorizing agricultural waste. Implementing a robust sustainability innovation pillar can potentially achieve agricultural waste valorization. Integrating market and system innovation pillars can sustainably drive a bioeconomy through unique biopolymer packaging strategies, which enhances the value and usage of biopolymer packaging material, fostering more innovations and sustainability.
3. The study emphasizes that the evaluation of bioeconomy modeling tools encompasses various criteria, including documentation aspects, flexibility, compatibility, diversity, validity, efficiency, and user-friendliness, and sub-criteria, including environmental, social, and economic. These are crucial for researchers and scientists in decision-making processes. For instance, the LCA tool stands out for its sufficient documentation, flexibility, and diversity, making it suitable for evaluating agricultural resources. Similarly, the TIMES model boasts high documentation, while the MILP model excels in flexibility. Each model employs different algorithms, sub-criteria, and protocols for analysis, highlighting their varied utility. Furthermore, modeling tools like MILP, TIMES, and GLOBIOM hold promise for providing optimal outputs, particularly in the agricultural biorefinery sector and land-use scenario analysis.
4. The research underscores that with the escalating global energy demand and ambitious climate objectives, biomass utilization for energy production emerges as increasingly imperative. However, careful selection and targeting of biomass sources are essential. Notably, LCA findings highlight hemp's higher impact than other energy sources like peat, wood, and other biomasses. During economic and energy crises, the immediate solution may involve using hemp for energy generation or producing materials such as thermal insulation to enhance energy efficiency. Nonetheless, this poses a dilemma between short-term relief and long-term value creation. While hemp cultivation for energy generation may offer short-term respite, sustainable and economically viable solutions should prioritize processing hemp into high-value-added products long-term, aligning with economic and environmental sustainability goals.

5. The Thesis underscores the significance of developing an agricultural waste valorization pathway that presents opportunities to leverage hogweed and fruit peel waste to produce food additives and essential oils. Evaluating agricultural resource valorization alongside alternative techniques involves considering various factors. Moreover, establishing multi-level valorization of a single agricultural waste, such as Brewer's Spent Grain (BSG), requires an assessment of the current utilization and valorization practices, laying the groundwork for effective waste management and resource optimization.
6. The study emphasizes that prioritizing biopolymer products involves conducting bibliometric analysis to identify research gaps and trends, particularly in sustainable biopolymer production and agricultural waste management. Key areas such as assessment methodologies and integrating bioconversion processes with sustainable development goals emerge as crucial focus points. Developing a sustainable assessment framework using the four MCDA methods combined with AHP survey analysis emphasizes the importance of quantitative indicators in measuring biopolymer sustainability and promoting the bioeconomy concept. This comprehensive approach aligns intending to elevate sustainability and resource utilization in biopolymer production with cellulose-based biopolymer emerging as the top alternative in TOPSIS and COPRAS methods. Conversely, PLA and starch-based biopolymers are identified as the most suitable options according to MOORA and VIKOR methods, respectively.
7. The research encourages that the introduction of system and market innovation pillars facilitates the development of a concrete pathway to prioritize sustainable packaging materials within the bioeconomy. By increasing the utilization of biopolymer products, particularly in packaging materials, sustainable bioeconomy development can significantly enhance contributing to the overarching goal of climate neutrality. The research findings underscore a novel approach to biopolymers, emphasizing sustainability considerations and advocating for investment in PLA biopolymer packaging material, which presents an exceptional opportunity, with cellulose, starch, and PHA packaging materials also positioned to seize significant market interest. The study stresses the complexity in assessing the full sustainability and market potential of a product. Market analysis indicates that PLA has the most potential despite sustainability assessment favoring cellulose biopolymer. This dilemma illustrates the necessity of identifying synergies between profitability and sustainability in product development with market strategies, underscoring the significance of balancing economic and environmental considerations when making strategic decisions.
8. The methodology proves that achieving sustainable development and climate neutrality targets articulates the implementation of a proposed solid bioeconomy development strategy, prioritizing biopolymer products through the creation of system and market innovation scenarios. The developed integrated methodology serves as a valuable tool for policy makers to navigate more effective bioeconomy development paths. At the same time, municipalities can utilize it at a regional level to inform invasive species management plans and leverage the concept of agricultural waste value. This comprehensive approach facilitates practical solutions to advance sustainable bioeconomy development and address pressing environmental challenges.

9. The research offers data availability, which aids decision-makers in selecting sustainable biopolymers for production. Additionally, market opportunities for biopolymer packaging materials and implementing a carbon footprint calculator are valuable assets for companies when making informed decisions regarding specific packaging materials.

Recommendations:

- Future research developments should focus on agro-biopolymer production and socio-economic aspects of sustainability alongside environmental considerations.
- Attention should be given to developing quantitative sustainability indicators specifically tailored to biopolymer production from agricultural waste.
- The research recommends that more efforts must be made to address the lack of extensive data on the market studies for biopolymers, especially concerning the circularity and sustainability of the biopolymer. Improved data availability will enable a more accurate evaluation of market potential and facilitate strategic decision-making by industry stakeholders.
- It is suggested that further research on refining parameters for carbon footprint tools, such as packaging surfaces and additional materials used in packaging, is necessary to enhance their accuracy and applicability.
- Efforts should be made to improve the data availability on a regional scale to enhance the precision of the carbon footprint tools and support policymakers in making informed sustainability decisions.
- The proposed methodology of the study should undergo further validation and real-case applications to assess its effectiveness and reliability. This could include pilot projects that evaluate sustainable strategies for biopolymer packaging materials from a sustainability perspective.
- The proposed approach is to advance the bioeconomy strategy by elevating the higher-added value products in the bioeconomy, which should be further developed based on the changing conditions of the industrial demand.
- The study aligns with the sustainable development goals, and further research would be worth developing policy frameworks that incentivize and promote sustainable practices in biopolymer packaging material production and utilization.

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