RIGA TECHNICAL UNIVERSITY

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VALORIZATION SOLUTIONS FOR AGRICULTURAL WASTE

Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
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Doctoral Thesis

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ANNOTATION

The “Valorization Solutions for Agricultural Waste” doctoral Thesis is elaborated on by the author Nidhiben Arvindbhai Patel at the Institute of Energy Systems and Environment, Riga Technical University. 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 value products 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 innovation 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.

The study offers several innovative strategies for agricultural waste not previously employed in the bioeconomy. In this Thesis, diverse types of agricultural waste valorization assessment have been presented using multiple approaches. The results of this Thesis add to the body of knowledge already known about bioeconomy by assessing sustainable agricultural waste valorization using three innovative pillar approaches. The results benefit national, local, and international stakeholders and scientists.

The doctoral Thesis consists of an Introduction, 3 Chapters, and a Conclusion. The introduction includes the topicality of the doctoral Thesis, aim, tasks, hypothesis, scientific novelty, practical significance, the structure of the work, and information about the approbation of the work. The first chapter, a literature review, provides an overview of the agricultural sector's unsustainable practices, current trends in sustainable bioeconomy, feasible agricultural wastes, and a substantial framework for a new vision of bioeconomy value chains. The second chapter of the Thesis discusses the research technique based on three innovative pillars. The first pillar is designed to boost agricultural waste into high-value products. The second and third pillars demonstrate product development transferred from the first pillar, needing value enhancement. The third chapter of the Thesis outlines the results and discussions, followed by the conclusion, recommendations, and a reference list. The work has been endorsed by seven scientific publications and one scientific publication manuscript.

ANOTĀCIJA

Promocijas darbu "Lauksaimniecības atkritumu valorizācijas risinājumi" izstrādājis autors Nidhiben Arvindbhai Patel Rīgas Tehniskās universitātes Energosistēmu un vides institūtā.

Promocijas darba mērķis ir izstrādāt integrētu metodiku, lai piedāvātu inovatīvu stratēģiju augstākas prioritātes piešķiršanai biopolimēra iepakojuma materiāliem, valorizējot lauksaimniecības atkritumus. Promocijas darbs palīdz izpētīt noteiktus bioekonomikas produktu vērtības līmeņus vienotā ietvarā, īpašu uzsvaru liekot uz biopolimēru ražošanas veicināšanu. Darbā izmantotā pieeja nodrošina unikālu pieeju biopolimēru produktu prioritātes paaugstināšanai, ieviešot sistēmas un tirgus inovācijas pīlārus.

Lai sasniegtu promocijas darba mērķi, noteikti vairāki darba uzdevumi.

1. Izpētīt ilgtspējīgas bioekonomikas attīstības tendences, ņemot vērā lauksaimniecības atkritumu valorizāciju.
2. Novērtēt bioekonomikas modelēšanas rīkus ilgtspējas ietvarā.
3. Novērtēt pievienotās vērtības produktu valorizācijas pieejas, tostarp ilgtspējīgu bioenerģijas ražošanu, un noteikt iespējamos paņēmienus, kā no lauksaimniecības atkritumiem ražot produktus ar pievienoto vērtību.
4. Identificēt attīstības tendences un izveidot biopolimēru ilgtspējības ietvaru.
5. Lai nodrošinātu stratēģisko inovatīvu pārnesi, izmantojot tirgus analīzi, novērtēt, vai biopolimēru produktiem ir potenciāls iekļūt tirgū.
6. Izveidot inovatīvu metodoloģiju, lai veicinātu tiešsaistes pārdošanas uzņēmumu ilgtspēju un izstrādātu oglekļa pēdas rīku iepakojuma materiāliem kā vērtīgu ieguldījumu tālākai prioritizēšanai.

Pētījums piedāvā vairākas inovatīvas stratēģijas attiecībā uz lauksaimniecības atkritumiem, kas līdz šim bioekonomikā nav izmantotas. Šajā promocijas darbā ir izklāstīti daudzveidīgi lauksaimniecības atkritumu valorizācijas novērtēšanas veidi, izmantojot vairākas pieejas. Šī darba rezultāti papildina jau esošo zināšanu kopumu par bioekonomiku, novērtējot ilgtspējīgu lauksaimniecības atkritumu valorizāciju trīs inovatīvu pīlāru pieejā. Iegūtie rezultāti ir noderīgi valsts, vietējām un starptautiskajām ieinteresētajām pusēm un zinātniekiem.

Promocijas darbs sastāv no ievada, 3 nodaļām un secinājumiem. Ievadā ietverta promocijas darba aktualitāte, mērķis, uzdevumi, hipotēze, zinātniskā novitāte, praktiskā nozīme, darba struktūra un informācija par darba aprobāciju. Pirmajā nodaļā, literatūras apskatā, sniegts pārskats par lauksaimniecības nozares neilgtspējīgu praksi, pašreizējām ilgtspējīgas bioekonomikas tendencēm, lauksaimniecības atkritumiem ar peivienoto vērtību un būtiskss bioekonomikas vērtību ķēžu jauna redzējuma ietvars. Darba otrajā daļā ir aplūkota pētniecības metode, kas balstīta uz trim inovatīviem pīlāriem. Pirmais pīlārs ir paredzēts, lai lauksaimniecības atkritumus pārvērstu par augstvērtīgiem produktiem. Otrais un trešais pīlārs demonstrē produktu izstrādi, kas pārcelta no pirmā pīlāra, kam nepieciešama vērtības palielināšana. Darba trešajā nodaļā ir sniegti rezultāti un diskusijas, kam seko secinājumi, ieteikumi un literatūras saraksts. Darbu apstiprinājušas septiņas zinātniskas publikācijas un viens zinātniskās publikācijas manuskripts.

ACKNOWLEDGMENT

In conveying my deepest gratitude, I want to express my profound appreciation for the immense support, guidance, and encouragement I have received throughout my doctoral journey. I am deeply thankful to everyone who has played a role in helping me reach this milestone.

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I would also like to thank all my co-authors for collaborating with scientific articles and contributing their time to give valuable input to my doctoral Thesis.

This Thesis is more than just an academic achievement; it is a collaborative masterpiece, reflecting the brilliance and support of many people.

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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, impacts the bioeconomy. The use of agricultural waste is a worldwide phenomenon that influences the decisions and actions of policymakers, 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 the 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:

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4. To identify the developing 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 waste. It provides an innovative prioritization of biopolymer products (packaging materials) by developing a sustainability framework, a strategic market scheme, and a 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).

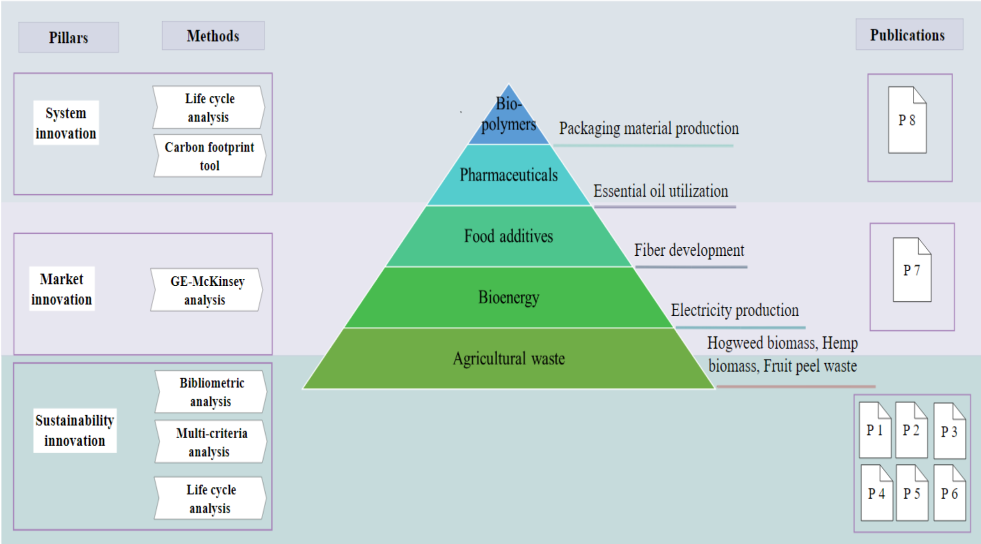


Fig. 1. Research structure.

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, life cycle analysis, and bibliometric analysis methodologies are applied (See approbation Publication 1 to 6).
b) The 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) The 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 the 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. LITERATURE REVIEW

1.1. Trends in sustainable bioeconomy

In practice, bioeconomy involves using existing bioprocesses and a wide range of natural bioresources, such as land, sea, plant, animal, and microbial resources. The modern approach to bioeconomy involves many technological innovations, such as the large-scale application of biotechnology. Modern biotechnology has numerous opportunities to produce new biomaterials and bioproducts from bioresources, ensuring that the use of resources in the bioeconomy is sustainable, efficient, and economical [2]. For example, the conversion of agricultural resources into higher added-value products by using a biotechnological process promotes the bioeconomy in the agriculture sector as the agro-industrial waste generates a vast amount of grain waste, dairy waste, and food waste, in which only a tiny portion of the waste uses as animal feed, manure, and other products. Most of the waste is unutilized, a potential source in producing biopolymers [3][4].

The vision of the bioeconomy is an efficient use of bio-based products and technologies and the development of bioeconomy policies, which includes the development of green growth, innovation, and resource efficiency by implementing bioeconomy activities [5]. The bioeconomy activities are measures to achieve the aim of bioeconomy strategies, and these activities comply with the economic, social, and environmental challenges [6]. The bioeconomy relates to sustainability policies such as climate change mitigation, technological progress, employment, and value creation. The sustainable development goals include economic, social, and environmental development [9]. Sustainability is the fundamental idea behind the bioeconomy in creating long-term value and benefits for these sectors [7]. The sustainable bioeconomy depends on the production and consumption pattern, which can be improved by evolving the fossil fuel-based economy into a bioeconomy by promoting bio-based, recirculated products and renewable energy [8].

The European bioeconomy strategy supports promoting sustainable development goals and fosters innovations, job creation, and escalating the sector's economic growth. Socio-economic indicators are one of the main valuable drivers of bioeconomy performance. Specifically, the indicators determining the socioeconomic dimension of the bioeconomy are the number of persons employed, turnover, and value-added share of the bioeconomy [9]. Fig. 1.1 shows the turnover and number of persons each country employed in the agriculture bioeconomy sector in 2020. The turnover comprises the total value of market sales of goods and services. The number of people employed is the total number of people who work inside and outside the observation unit. The highest turnover is made by France (81,553 million euros), and the lowest is made by Malta (127.2 million euros) in the agriculture bioeconomy sector. However, the highest number of people employed in the sector is 1.8 million in Romania.

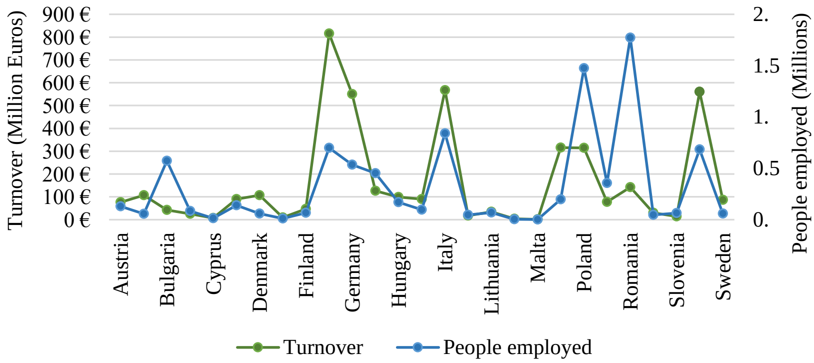


Fig. 1.1. Socio-economic aspect of the agriculture sector in bioeconomy (year 2020) [9].

In contrast, the lowest number of people employed in the sector is in Malta, which is only 1.730. Each European Union (EU) country's economic and social growth fluctuates in the agriculture bioeconomy sector, clearly showing each territory's implementation of different bioeconomy strategies. On the other hand, one uniform and comprehensive bioeconomy strategy needs to be developed for the overall growth of the EU. The value added is an essential indicator for measuring the development of the bioeconomy. After deducting indirect taxes and operating subsidies, the gross income from operations is displayed [9]. Fig. 1.2 shows the total value added generated by the EU 27 from 2008 to 2020 in the agriculture sector. The lowest value added was measured in 2009 at 138,85K; the highest was obtained after the ten years of 2019 at 192K. The value added has been raised by 32.09K in 13 years from 2008 to 2020, showing the benefits of bioeconomy implementation in the agriculture sector.

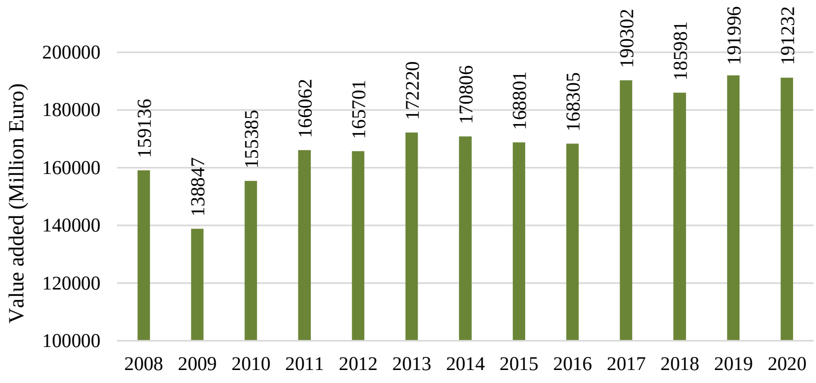


Fig. 1.2. Value added share of bioeconomy in agriculture by year [9].

The value-added share by each European country in 2020 is presented in Fig. 1.3. Latvia has the highest share of about 90 % for the bioeconomy development due to its high potential for producing and processing biomass and its considerable proportion of agricultural land and forests. Additionally, Latvia has a national bioeconomy strategy that runs through 2030 and aims to make its bio-based industries more sustainable and competitive [10]. Germany and

Belgium share the lowest shares, about 58 %, towards developing the bioeconomy in 2020. The strong demand for traditional agricultural products in Germany is one of the factors contributing to the lower rate of bioeconomy, as it reduced the amount of biomass available for bio-based products. By encouraging creativity, sustainability, and circularity, the strategy seeks to accelerate the bioeconomy rate in agriculture [11][12]. In Belgium, several obstacles are observed for the low bioeconomy rate, such as dependency on animal husbandry-based agriculture, low value of some crops, lack of investment, and innovations in bioeconomy related sectors [13].

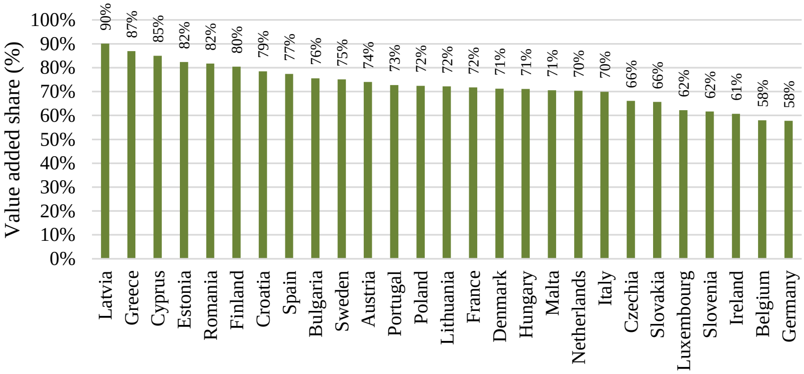


Fig. 1.3. Value added share of bioeconomy by country in the year 2020 [9].

Finland, Romania, Estonia, Cyprus, and Greece show the bioeconomy share between the 80-87 % range. The rest of the EU countries have a bioeconomy share range between 61-79 %. The reason why different European countries have different bioeconomy shares is that they have different approaches and programs in place to grow and assist the bioeconomy industry. A few variables that impact the bioeconomy share are the accessibility of biomass resources, the degree of innovation and investment, the governance and policy framework, and the level of societal awareness and demand for goods and services derived from biobased sources [14][15].

Successful implementation of a sustainable bioeconomy requires a novel policy that includes a) replacement of fossil fuel, b) innovative production techniques, and c) well-established Sustainability in bio-based value chains [16]. The bioeconomy can be developed and improved by including innovative policies, strategies, and legislation in monitoring and measuring the overall framework, as it is the most vital parameter to establishing the bioeconomy [17].

1.2. The unsustainability of the agriculture sector

Modern agricultural practices severely affect the environment, soil, surface, and groundwater, which releases polluting compounds (such as heavy metals, excess fertilizers, and chemical substances). These compounds affect crop productivity, human health, soil, and water quality. In addition, chemical substances can cause human diseases through food and water contamination [18]. Due to unfavorable conditions of the environment, crop productivity can be reduced by 30-70 % [19]. The farmers are the first to be affected by this uncertainty. The depletion in crop production leads to a decline in crop prices, and farmers must face an income crisis.

Moreover, occupational injury, illness, and fatalities can occur to the workers and local communities [20]. In the agriculture sector, crops are long-term investments. Food waste covers the most significant part of agricultural waste, which can cause a loss of economic value for the agriculture business entities. Globally, food loss and waste value are estimated at 1 trillion USD. Food crops are the primary source of income in some regions, and the international market can be affected due to seasonal fluctuations in crop prices. Consequently, a significant loss in the availability of agricultural products and prices arises, which affects the overall income of associated agricultural entities [21].

Many scientific studies have addressed the three pillars of sustainability, i.e., environmental, social, and economic, regarding agricultural waste management. Bhuvaneshwari et al. address the issue of burning agricultural waste in India. A significant environmental problem is burning crop residue worldwide, which can cause human health issues and global warming, leading to climate change. Moreover, burning agricultural residues involves several other sectors, including the environment, agriculture, economy, society, education, and energy. However, the government's efforts toward educational and societal development are insufficient. The burning issue and related impacts can be solved if proper education and awareness are raised among farmers and society [22]. Scarlat et al. addressed environmental and economic concerns associated with removing agricultural crop residues, reducing soil quality, losing organic matter, soil carbon, and nutrient content, and increasing erosion. The inappropriate disposal of agricultural biomass can cause severe effects such as crop farming practices, soil fertility, moisture, and climate conditions (wind and precipitations) [23], leading to a decline in harvested crops and, thus, economic loss. Sabiiti Elly reports concerns regarding the amount of waste the agriculture sector generates. Growing food demand produces substantial agricultural waste at various levels, including farmers, municipalities, and urban areas. This untreated waste can cause human illness and affect the environment [24]. The improper disposal of agricultural waste can impact its quality by emitting odorous substances such as ammonia and greenhouse gas (GHG) emissions that cause climate change issues [25].

Several barriers to implementing sustainability in the agricultural sector are identified by Benyam et al. The continuously growing farm, and demand cause resource scarcity and extreme climate change. Modern farming techniques (such as fertilizer and pesticides) undermine using naturally derived crop nutrients [26]. The significant economic barrier to sustainability includes the complexity in the efficiency of the technology, lack of knowledge of the production technology, and technology cost limits to the socio-economic benefits for small-scale farmers. The barriers to social sustainability are the farmers' lack of expertise in digital technologies, knowledge transfer issues varying the uptake of technologies, and extensive adoption of the technologies driving unemployment [26].

Agricultural biomass is a vast market in which bioproducts can be produced. However, several barriers can affect the development of sustainability, for example, a) access to information on biomass market functions, b) insufficient knowledge about the benefits of energy efficiency, c) financing sources, d) market infrastructure, and e) agricultural, energy, & environmental policy development. Moreover, other significant concerns identified in developing the agricultural biomass market are less possibility of selling biomass profitably, no systematic collection of biomasses, lack of interest in biomass, lack of transportation to supply biomass, and unawareness of the biomass concept [27]. The consequence of agricultural waste production reveals many potential steps that must be taken to prevent environmental impacts and promote sustainable development of the agricultural sector. A tremendous amount of agricultural waste is produced every year. Still, current approaches to waste reduction are comparatively ineffective due to several barriers, such as a lack of farmer's expertise in long-term planning considering sustainability aspects, inconsistent sustainability strategies, and a lack of added-value approaches. With this concern, the next chapter of this study introduces the approaches that can contribute to resolving a global challenge and establishing sustainable agriculture.

1.3. Resolving the sustainability challenges

Bioeconomy is a dynamic and intricate system, and to navigate this intricate system and bring it into compliance, decision-makers require new strategies and tools. The European bioeconomy strategy integrates various sustainable pathways for sustainable development. A strategy for sustainable development goals includes different approaches toward the bioeconomy, such as production patterns, industrialization, consumption of resources, green energy, innovation, and climate change issues. The agricultural biorefinery presents a more sustainable way for bio-based industries to convert agricultural resources into value-added products. The biorefinery concept is suitable for all biomasses (first, second, and third-generation crops) [28]. The decision-making process of selecting a biorefinery system is complicated due to various available options and their advantages and disadvantages. The decision-making process is another existing issue in biorefinery prioritization.

According to the global survey, biomass value chain assessment should consider the bioproduct's whole life cycle, from biomass production to pre-treatment, transport, conversion techniques, and end-of-life. Several opportunities have been identified for the biomass market, considering economic development, job creation, improvement in the production system, sustainable development, and progress in the supply chains [29]. The transformation of the agricultural industry to circular practices has become a challenge for the industrial revolution. A recent study investigated a circular economy conceptual framework as a way forward to sustainability at the industrial level. The framework of sustainability focuses on the circular economy concept. This framework mainly consists of a) pillars of sustainability (economic, social, and environmental), b) key drivers (feedstock, low carbon product, life cycle, zero-emission, reduce, recycle, and reuse), c) tools to evaluate and design circularity (material flow analysis, life cycle analysis (LCA), and eco-design), and d) the conceptual framework (production stages and integrated assessment methods). This strategic framework can establish sustainability at the industrial level [30].

Belaud et al. proposed an integrated approach that integrates big data and sustainability assessment to improve the supply chain design of the agriculture sector. Big data shows the digital and ecological transition for the valorization of agricultural waste. Agricultural by-product valorization is a challenging supply chain, including the operational stages (from biomass to waste disposal), transformation, and upstream and downstream processes. Also, the LCA methodology has been approached to analyze the impact and various sustainability indicators. However, this approach has a limitation that needs to be explored more: a) the addition of specific data sources, methods, and visualization for economic and social areas to improve data inventories and assessment methods, b) the design models for energies, c) development of libraries, sources, and studied for agro-food process engineering, and d) the development of qualitative explanation systems for stakeholders [31].

Barros et al. presented a systematic approach to the input-output methodology for agricultural waste valorization. The input (i.e., fuel, water, energy, raw material, animal food, and seed), output (i.e., wastewater, emissions, grains, and agricultural waste), material, and energy flow in the agriculture sector. The input-output flows vary to the different alternatives, such as rural properties containing animal breeding, and the inputs include water, energy, animal food, and medicine. On farms for wheat, corn, and soybean crops, the inputs include water, fuel, seed, and fertilizers. Also, the techno-economic assessment and LCA have been used to assess the environmental impact of an entire agriculture supply chain, including transportation, processing unknit, and agro-industrial processes. However, the life cycle sustainability assessment method is complex and time-consuming; therefore, limited approaches have been carried out for the sustainability assessment in the agricultural field. Also, new circular business models need to be created considering the diversity of the circular agricultural economy. The tools and indicators for material and energy should also be elaborated to facilitate organizations [32].

A recent study presented an overview of the existing modeling tools to assess the environmental impacts of agricultural waste considering the circular economy concept and industrial ecology, life cycle thinking, and flow analysis. The study finds that life cycle thinking can be a promising tool for assessing several aspects of policies, impact, and circular economy characteristics. Overall, this study encourages scientists to use such strategies to solve waste problems. The study suggests that the circular economy development policies need in-depth investigation. The integrated approach for the circular economy should be studied more to find more strategies, i.e., suitable for all types of waste categories [33].

Amran et al. addressed the issue of agricultural waste valorization to improve economic and environmental sustainability. Also, the sustainable strategy in terms of applying green extraction technology. Agricultural waste valorization by using green extraction techniques can increase productivity, social acceptance, and economic stability. Universal problems such as waste management, environmental impacts on landfills, climate change, fossil fuel reduction, and sustainability issues for farm owners can be solved by implementing such strategies. However, this strategy still requires further development to integrate sustainability into the valorization system at the industrial level [34]. Cho et al. presented the potential use of biochemical processes to produce biochemicals. Biomass waste is inexpensive, readily available, and renewable, accomplishing the fossil fuel demand, manufacturing costs, and environmental concerns. However, this study identified that conversion technologies need further research to produce competitive products [35].

The indicator analysis provides the opportunity to develop a sustainable decision-making process [36]. Also, establishing three main pillars of Sustainability, i.e., environmental, social, and economic, is the most important for developing a sustainable product. The main environmental indicators, including global warming, pollution, acidification, biodiversity, land usage, and water scarcity, should be considered while performing the quantitative or qualitative analysis of the bioproducts. Regarding social indicators, employment, health, human rights, wages, and child labor need more focus. Economic indicators include revenue services, production costs, operational costs, maintenance costs, and other economic activities for sustainability [37].

However, bioeconomy strategies can evolve by implementing a more advanced approach. The challenges and shortcomings of sustainable agriculture are broader than the already established solutions, which require a novel idea to be developed that estimate the added value of a product by comparing different bioeconomy modeling tools within the sustainability framework.

1.4. Agricultural waste as a core of bioeconomy

Agricultural waste is a significant sector of the bioeconomy. In EU-27, almost 70 % of the biomass is of agricultural origin, which makes agriculture the largest source of biomass. Here, diverse types of agricultural waste are researched considering the abundant amount, topicality of the resource, and uniqueness. The Thesis further explores agricultural residues, hemp biomass, hogweed biomass, fruit peel waste, and brewers' spent grain resources for bioeconomy development.

Agricultural residues

The vital use of agricultural waste to produce value-added products is an excellent approach to complying with EU regulations. The "resource, recovery, and recycle" paradigm must be imposed to bring about the industrial revolution in the agricultural sector. The technological, social, economic, and environmental aspects of agricultural waste can all be more harmoniously balanced by the bioeconomy. Additionally, by utilizing waste, fostering economic growth for waste, and striking a balance between production and consumption, the bioeconomy promotes sustainable agricultural sector growth [36]. A more concentrated area is biopolymer production from agricultural waste because it promotes sustainable development. Agricultural crop residues, lignocellulosic feedstocks, and organic wastes are significant biopolymer resources from agricultural byproducts and edible food waste [38][39]. Among these resources, agricultural crop residues are more efficient for biopolymers, as they require the least land to grow and produce high yields. It is crucial to have easy access to agricultural residues to produce biopolymers. The total available agricultural residue in Europe is 72,529 kilotons/year [40].

Country-specific annual available agricultural residues are shown in Fig. 1.4. The production of crops generates copious amounts of agricultural residues. Agricultural practices, crop mix, crop rotation, and crop types affect residue production. The yield and cultivated area determine the amount of residues directly correlated with crop productivity. Remainders are only as available as their competitive use for industrial or agricultural uses and how much can be removed from the land to maintain land fertility [23].

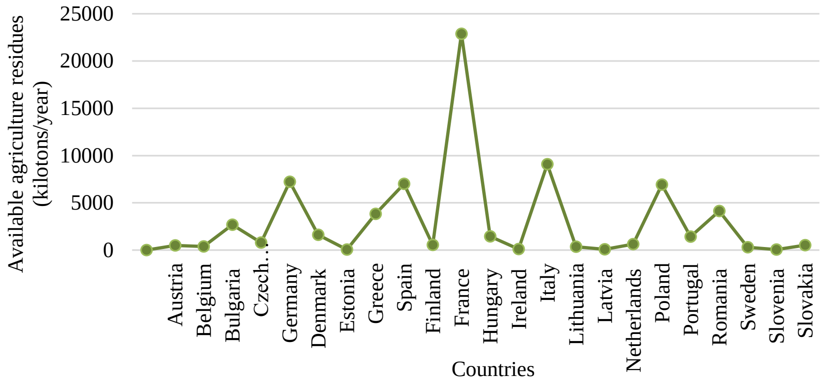


Fig. 1.4. Availability of agricultural residues in EU [40].

Hemp biomass

Industrial hemp (Cannabis sativa L.) has been cultivated for generations and is still grown nowadays all over the world. The fact that it can be processed into more than 25,000 different goods classifies it as a crop with multiple uses [41]. Industrial hemp (hemp) belongs to the Cannabaceae family. It contains psychoactive substances such as the cannabinoids tetrahydrocannabinol (THC) and cannabidiol (CBD) [42]. However, the notable difference between hemp and cannabis is that the amounts of THC found in hemp are quite low - 0.3 % or less. In the EU Member States, the regulation is even stricter, and the THC content may not exceed 0.2 %. Seeds, flowers, leaves, stems, and roots are the primary components of the hemp plant [42]. Although hemp cultivation has regained popularity in the last decade, it is one of the oldest plants used to produce food, textiles, and medicine [43]. Hemp was a widely used crop until the early 1900s when many countries banned hemp cultivation precisely because of the psychoactive substances it contained, which affected the purpose and use of hemp [42]. In addition, synthetic materials became more common due to their higher profitability [43]. With the focus on sustainability in recent decades, hemp production has increased again. The cultivation of hemp is more suitable for temperate climates, but it can also be grown in other conditions. From 2015 to 2019, the total area used to produce hemp in Europe has increased by 75 %. In 2019, it was 34,960 ha, and the total product produced was 152,820 tons. France contributes the most to hemp production in the EU, producing about 70 % of the total EU volume. About 75 hemp varieties are registered in the EU catalog and allowed to be grown. The cultivated hemp is used to produce fibers, seeds, CBD, or for combined purposes. In Latvia, the area under hemp cultivation in 2019 was 868 ha [44].

Hemp's properties make it an excellent raw material to produce products that are useful to society, including oils, food products, construction materials, paper, and biofuels. Compared to other industrial crops, hemp's value increases because it can be processed into various products. Compared to other crops, such as sugar beets or potatoes, hemp production requires fewer resources and has a lower overall environmental impact [45]. Although hemp has a wide range of practical applications, it is currently not economically feasible to substitute hemp fiber for traditional raw materials such as cotton for textiles and wood for papermaking with hemp fiber [46]. Despite subsidies, European hemp producers cannot yet compete with China, where the traditions of hemp cultivation are much older, and labor costs are much lower. The production and commercial potential of hemp is considered low in the North American environment, and the growing emphasis reflects support for cannabis growing, especially for therapeutic purposes. Currently, hemp's most significant advantage is that it can create environmentally safe goods, such as textiles, building materials, and insulation; however, from a commercial perspective, this may not be economically feasible [46]. The EU is hopeful about the market and production capacity for hemp as a raw material and continues to promote the cultivation of hemp, recognizing its enormous potential as an environmentally friendly material [46]. According to a study by Kraszkiewicz et al. [47], the technical and chemical features of hemp biomass are suitable for energy generation. According to the evaluated factors, hemp biomass was among the best biomass sources for energy generation [48][49]. The study by Petlickaite et al. [50] looks at the properties of pressed solid biofuel of multi-crop plants hemp, maize (Zea mays L.), and fava bean (Vicia faba L.) as mono, binary, and trinomial crops. With global energy demand rising and climate change targets becoming more ambitious, biomass for combustion will become even more critical than it already is. As wood supplies become scarce, leading to increased demand for materials and energy, the demand for alternative solid biofuels for energy use is growing.

Hogweed biomass

The most common tall invasive hogweed (*Heracleum Sosnowski*) was initially identified in 1895. Botanical records from several European sources, such as the Netherlands, Norway, and the United Kingdom, indicate that this plant was introduced to Europe earlier. Hogweed is an invasive species in Latvia, Lithuania, Estonia, Belarus, Ukraine, and Germany, whose management methods are mostly connected to control and eradication. The only significant hazard in the spread of hogweed is the risk of damage to human health. There are prevention techniques, too, such as chemical-mechanical treatment. Excessively long times, i.e., 2-7 years, are needed to apply the technique [51]. Nevertheless, in Latvia, hogweed distribution is a significant problem as it covers an area of 10,000 ha. [52] state that using invasive plant species as an underused bioresource is essential for bioeconomy development. They also suggest that further reuse of the by-products from high value-added product production should be used in a cascading or biorefinery approach to producing biofuels or energy [52]. The typical application of hogweed biomass is its use as feed for bovine animals or sheep. However, many added-value products could be made from hogweed, such as bioethanol and biobutanol [51]. [53] have also investigated the production of solid biofuels as pellets from hogweed. Another study [52] identifies that a large share of research on hogweed focuses on its application for food or agricultural feed. Moreover, some studies investigate its application as a fertilizer, antifungal agent, and biofuel in the pharmaceutical industry. Cellulose can be obtained from hogweed plants and used in cardboard production [52]. One of the potential products that can be obtained from hogweed is fiber. However, there is a lack of research on obtaining fiber from hogweed [51]. Therefore, this approach is taken further in developing the Thesis by exploring suitable pretreatment methods for fiber extraction.

Fruit peel waste

With the worldwide increasing population, production and cultivation of fruits and vegetables are also increasing. Besides, food waste has a long-lasting footprint in terms of landfill and socio-economic impacts due to its higher moisture and biodegradability [54]. Therefore, food waste management is becoming a primary concern worldwide. With advanced technology, food waste can be a versatile environmental bioresource converted to biofuel, value-added products, and biomaterial [55]. This research includes fruit waste valorization pathways because fruit peel waste is the most avoidable waste in the EU 50 % of household waste contains fruit and vegetable waste. Enormous studies have been done on converting fruit waste into landfills, anaerobic digestion, and composting [56]. Pfaltzgraff et al. argues that fruit waste is a comprehensive energy source and can produce industrial products such as essential oil, medicines, cosmetics, and organic amendment [57]. Each part of a fruit, for example, peel, pulp, and seed, has a unique residual and chemical composition that can be used to produce various organic products.

Traditionally, fruit peels are the most common waste that can be easily found in the environment. Fruit peels have the best medicinal properties, such as antimicrobial, antioxidant, anti-inflammatory, anti-healing, anti-infectious, anti-mutagenic, and hepatoprotective. Essential oil is one of the crucial extractions from fruit peels. Researchers have discovered after several experiments that essential oil has antimicrobial activity against bacteria, molds, yeasts, pathogenic and phytopathogenic microorganisms. It has been proven that essential oil can be used to confront the microorganisms of antibiotics [58]

One of the essential components that can be derived from fruit peel (apple pomace, citrus, sugar beet pulp) is pectin. Earlier research shows that pectin is an effective component at the industrial level and is also valuable for the medical treatment of cancer, cell apoptosis, and cholesterol [59]. Several studies have discovered that fruit peel waste has a potential application to medicinal products (see Table 1.1). Essential oils are also called volatile oils, ethereal oils, or aethrolea, which contain the essence of a plant fragrance. It is a concentrated hydrophobic liquid naturally derived from plants [60]. A recent systematic review investigated the extensive use of essential oils in the cosmetic industry, daily life due to the fragrance [61], and the pharmaceutical industry [62], which shows the increasing demand for essential oils in the market.

Table 1.1

Fruit Peel Waste into Medicinal Use

Fruit waste	Value-added product	Medicinal use	Methods	Reference
Banana peel	Essential oil	Antioxidant property	Extraction	[58]
Citrus peel	Essential oil	Alleviates pain Relieves inflammation Dissolve's gallstones	Extraction	[63]
Orange peel	Essential oil	Antimicrobial activity Flavoring agent of medicine	Steam distillation Cold pressing Solvent extraction Enfleurage	[58][64]
Mango peel	Pectin	Health benefits	Extraction	[65]
Grapefruit peel	Essential oil	Antibacterial and Antioxidant properties Biopesticide against mosquito larvae	Paper disc diffusion	[66]

Brewers' Spent grain (BSG)

Renewable raw materials called lignocellulosic materials are obtained from natural sources or bio-based chemical and biotechnological processes. There is growing interest in using them as a fossil carbon substitute in producing various products, including high-value chemicals and biomaterials [67]. Currently, they are primarily used directly or indirectly as feed or as a source of bioenergy. Polymers, specifically cellulose, hemicellulose, and lignin, are the primary structural elements of lignocellulosic materials. Although BSG is mainly used in the production of feed and food, recent reviews have shown a trend toward its conversion into goods in the higher reaches of the biobased value pyramid [68][69][70][71][72]. The BIOEAST initiative, based in Central and Eastern Europe, promotes the shift towards a circular and sustainable bioeconomy that includes the sustainable production and utilization of leftover biomass. Since beer production in BIOEAST member nations accounts for roughly 26% of all beer produced in the EU27, BSG is a plentiful resource to consider when developing regional and national bioeconomic strategies [73]. An estimated 11,000 breweries are currently operating in the EU, producing about 400 million hectoliters of beer annually, according to data from the European Beer Association for 2021. As estimated by calculations based on market movements over the previous five years, the EU will produce 8.5 million tons of BSG annually and about 425 million hectoliters of beer in 2030, which makes BSG an intriguing biomass waste for upcoming biorefineries [74].

1.5. Leveraging a novel vision of bioeconomy value chains

Bioeconomy product value level needs to be defined universally as various levels of bioeconomy-added value products are listed in different literature. For example, [75] presented a five product level of the bioeconomy pyramid intending to provide recommendations for continuously maximizing the value of biomass in a bioeconomy and mentioned that relocating down the value pyramid is linked to a decline in the quality of the resource and fewer chances for additional material applications. Whereas [76] presented a bioeconomy pyramid with four product levels indicating the difference in value and market size of products, and [77] presented only three levels of products (energy, chemical/materials, and pharmaceuticals) for bioeconomy development focusing on the value and framing the cascading in a bioeconomy value pyramid.

A focus should be developed on underrated value-added products by classifying the products with diverse levels and labeling numbers. According to the EU bioeconomy strategy, a sustainable bioeconomy is essential to achieving GHG neutrality in Europe. Compared to primary biomass use, using residues and wastes can achieve higher reductions in GHG emissions and lower feedstock costs [78]. It is anticipated that the bioeconomy has substantial potential for biopolymers, pharmaceuticals, and food and feed additives. However, low-value applications like bioenergy, biofuels, and bulk chemicals have a weak potential for bioeconomy development [78]. As per data published by [9], starting from lower value-added products, bioenergy, and bulk chemicals and materials show a fragile line for value-added development from 2008 to 2020. The high value-added products, including food and pharmaceuticals, show enormous value-added development. It is clearly seen that biopolymers seek attention for value-added development even after having a vast potential to drive the bioeconomy sustainably (see Fig. 1.5).

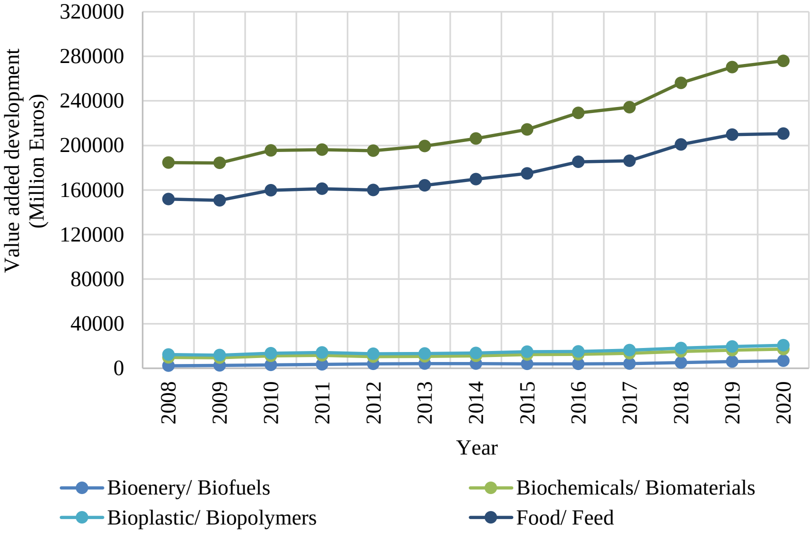


Fig. 1.5. Bioeconomy added value share of distinct levels of products from agriculture waste [9].

The most recent market data gathered by European Bioplastics indicates that worldwide biopolymer production capacity is expected to rise from roughly 2.2 million tons in 2022 to roughly 6.3 million tons in 2027 [79]. The data shows that the industry is progressing toward a sustainable future with less environmental impact, but it also goes beyond that. It is also anticipated that over the next few decades, the emerging biopolymers sector will reveal enormous economic potential [80]. The biopolymer markets are expanding, encompassing consumer electronics, toys, packaging, horticulture/agriculture, consumer electronics, automotive, textiles, and many other industries. Packaging will remain the largest segment in the 48 % global bioplastics market in 2022. Biopolymers are utilized in various products, including keyboards for consumer electronics, beverage bottles in the packaging sector, and interior car parts [81][82].

However, the packaging market significantly contributes to GHG emissions [83]. In 2009, plastic packaging waste generated 29 kg per capita in the EU. In 2010, global plastic waste production was 265 million tonnes [84]. Some packaging manufacturers aspire to measure, develop, and reduce the carbon footprint of their products. Companies have decided to reduce the carbon footprint of their products and educate customers about how their purchasing decisions influence GHG emissions [85]. Direct application of carbon footprint for companies includes several approaches, including [86]:

- assessment of product lifecycle GHG emissions and their significant reduction;
- emission impact on decision-making for suppliers, materials, product design, and manufacturing processes;
- cost-saving opportunities;
- set a benchmark for measuring emission reduction and;
- comparison of GHG emission levels for a product.

Moreover, another concern for the value-added development of biopolymers is to make the right investment choice for biopolymer packaging materials, ensuring their sustainability and profitability in the market. In order to be sustainable, a business model must show society or customers how biopolymers will advance in the future. Companies must establish business models that effectively close the biopolymer life cycle, confront the potential impacts on agricultural production that may surpass those associated with processing and use, and establish industrial standards to guarantee that biopolymer companies promote sustainability throughout the product life cycle [87][88].

2. METHODOLOGY

This chapter describes the integrated approach that assesses the different levels of the bioeconomy value pyramid by 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.

2.1. Sustainability innovation

The sustainability innovation pillar consists of five steps. Fig. 2.1 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 BSG. 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 must be identified to determine 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.

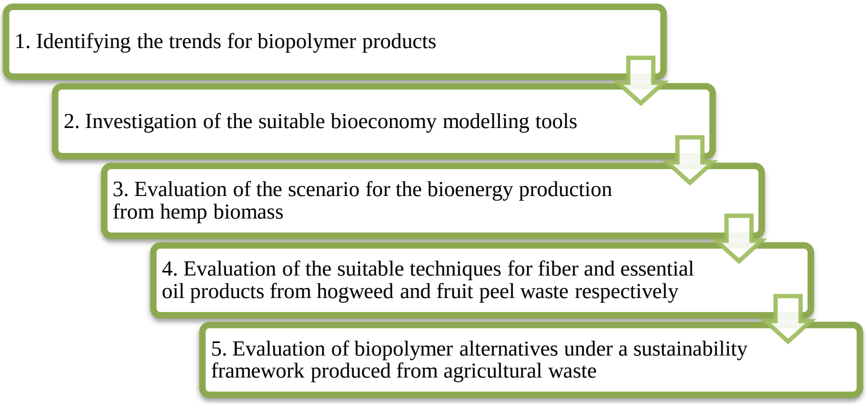


Fig. 2.1. Sustainability innovation scheme (Author's illustration).

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. 2.2.

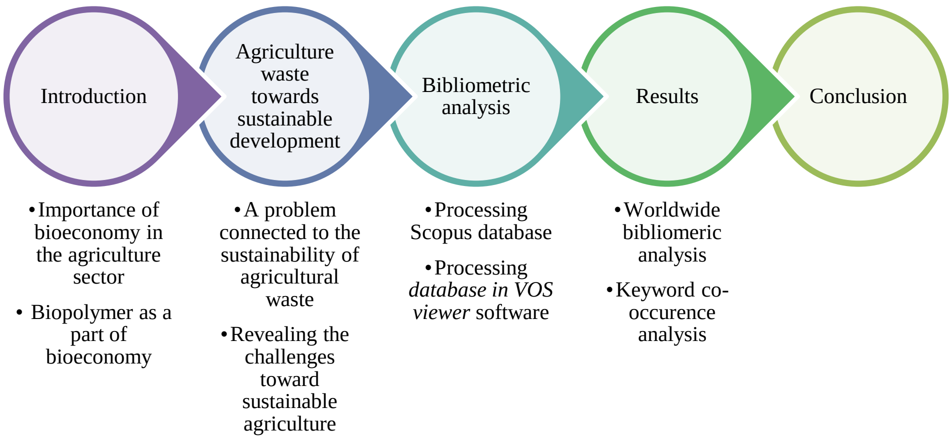


Fig. 2.2. Bibliometric analysis structure (Author's illustration).

Scopus is the largest abstract database and provides exhaustive coverage of scientific journals. Moreover, Scopus provides high-quality assurance of a database that is highly recommended for research assessment, scientific evaluation, and research studies [89]. 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 [90]. 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 [91]. 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 proposed algorithm for the bioeconomy modeling tools is briefly described in Fig. 2.3. Firstly, a vast literature analysis for each modeling tool has been performed using databases (such as ScienceDirect, Google Scholar, and Scopus database). The literature analysis is done by considering more than 160 scientific documents. Secondly, by analyzing the existing studies, suitable criteria and sub-criteria for each criterion have been selected for each modeling tool. Finally, MCDA was performed by integrating the criteria and sub-criteria, interpreting the results, and drawing conclusions.

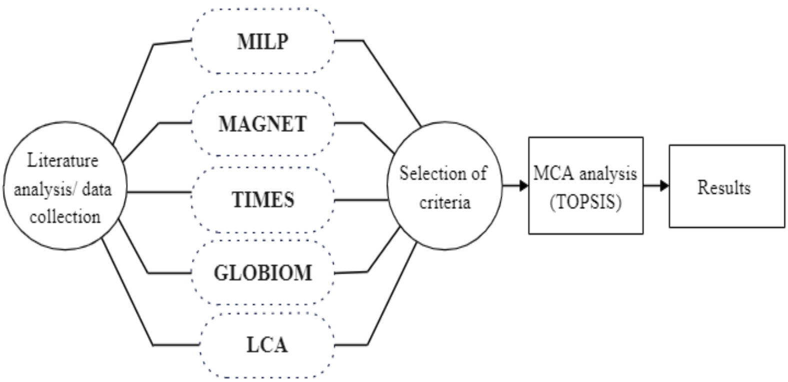


Fig. 2.3. Algorithm for evaluation of bioeconomy modeling tools (Author's illustration).

Here, semi-quantitative analysis has been used for each modeling tool because of the versatility and diversity of the bioeconomy modeling tools. The semi-quantitative analysis is one of the ideal analyses [92], which defines the values that can be used for modulation and calculation. The evaluations can be identified according to the experts [93], 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. Table 2.1 briefly presents the semi-quantitative scores for evaluating the bioeconomy modeling tools.

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 [94]. There are several benefits to performing TOPSIS, such as this method providing attribute information, providing the ranking of different alternatives, and giving accurate results.

Table 2.1

Semi-quantitative Analysis for Selected Criteria for Modeling Tools.

Criteria	**Semi-quantitative scale**			
	1	2	3	4
Documentation aspects	100 % data is provided for a model	70 % of data is provided for a model	50 % data is provided for a model	No data is provided for a model
Flexibility	Very high adaptability of data	High adaptability of data	Moderate adaptability of data	Low adaptability of data
Compatibility	Very high possibility of exchanging the data (>80 %)	High possibility of exchanging the data (<70 %>)	Moderate possibility of exchanging the data (<50 %>)	Low possibility of exchanging the data (<30 %)
Diversity	Very high level of applicability (more than 80 %)	High level of applicability (about 70 %)	Moderate level of applicability (about 50 %)	Low level of applicability (in (less than 30 %)
Validity	Relevant data has a very high (90 %) adequacy	Relevant data has a high (70 %) adequacy	Relevant data has a moderate (50 %) adequacy	Reinvent data has no adequacy
Efficiency	Verified data are highly qualitative	Verified data are partly qualitative	Verified data has a moderate quality	Non-qualified data
User-friendliness	Interface data and models are non-complex to learn	Interface data and models are fewer complexes to learn	Interface data and models are complex to learn	Interface data and models are very complex to learn

Evaluation of scenarios for bioenergy from hemp biomass

The evaluation of bioenergy production is assessed using an integrated set of methods, MCDA and LCA (Fig. 2.4). 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.

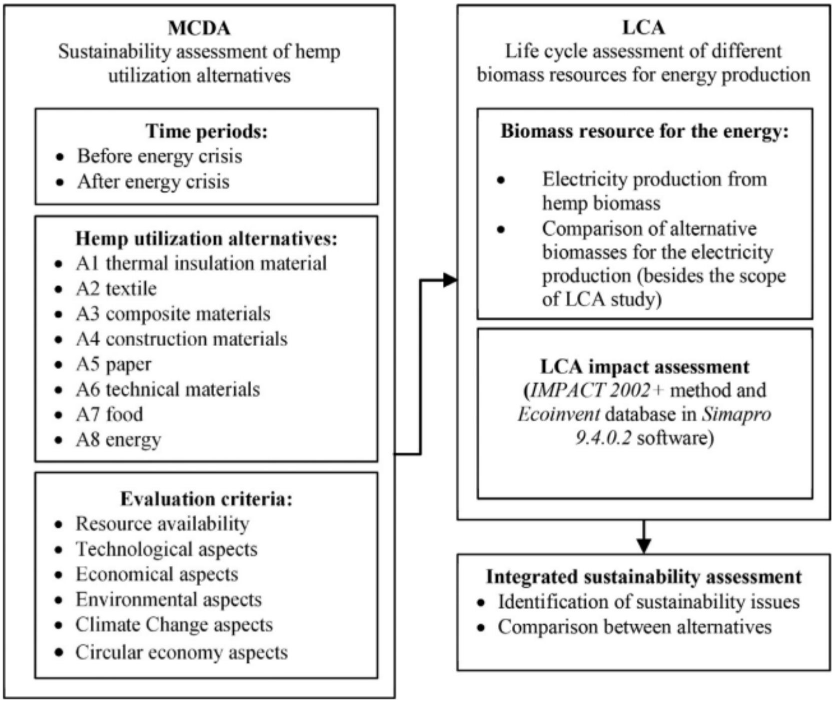


Fig. 2.4. Bioenergy production from hemp biomass (Author's illustration).

The TOPSIS method was selected as the most appropriate method. 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.

LCA was carried out for four biomass energy resources: peat, wood, sweet sorghum, and hemp. 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, and their interpretation.

Goal and scope

The LCA aims to analyze the environmental performance of hemp biomasses. 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. 2.5), 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.

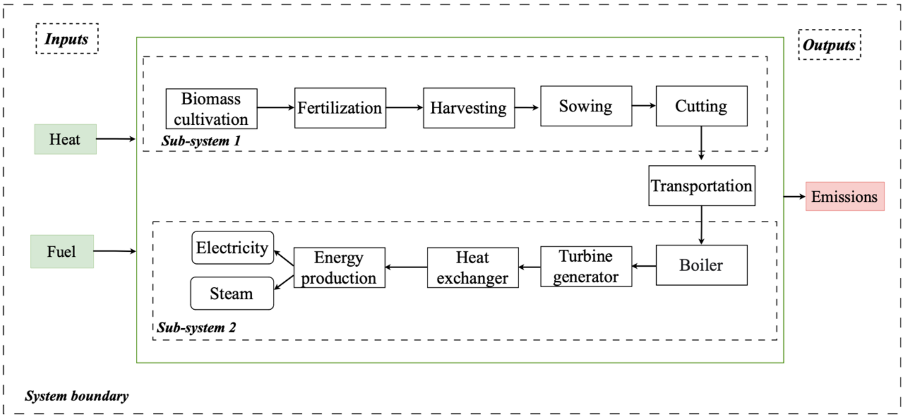


Fig. 2.5. System boundary for biomass for electricity production (Author's illustration).

Life cycle inventory

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. In summary:

- the background is from Ecoinvent 3.7.1 [95], and the weight and specification of materials are as specified by the manufacturer.
- the geographic context of the system refers to the Rest-of-World (RoW).
- the data quality is generic.
- technological characteristics refer to raw biomass processing operations (biomass cultivation, fertilization, harvesting, sowing, and cutting), transportation, and electricity generation (boiling, turbine generation, heat exchange).

The primary data regarding the processing of hemp biomass for electricity production has been presented in Table 2.2 [96][97] 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 (2.1)) by normalizing the low heating value of hemp biomass and electric efficiency of the boiler, which is 15.72 kg/MJ [98] and 75 % [99], respectively. The value of the dimensionless factor is 0.75, which is calculated from the boiler's efficiency.

$$\frac{\mathrm{Kg}}{\mathrm{MJ}} = \mathrm{D_f}, \tag{2.1}$$

where

Kg/MJ – low heating value of hemp biomass;

D_f – dimensionless factor.

Table 2.2

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	1.1E3	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 balance of mass for sub-systems 1 and 2 was performed following the reported values for hemp biomass [100], [101]. 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 [95]. The comparison is made to generate 100 kWh of electricity from 22 kg of biomass, just as for the hemp biomass.

Environmental Impact assessment

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 [102]. It analyses 14 midpoint categories, including human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction. The LCA concerns four damage categories and indicates a significant adverse environmental impact. The damage categories include resources, human health, climate change, and ecosystem quality. A further definition of each damage category is given below [103]:

- resources account for the percentage of consumption of resources.
- climate change indicates potential global warming due to GHG emissions into the air.
- ecosystem quality shows the protection zone, which is related to impacts on the natural environment.
- human health shows the impact of human toxic substances emitted into the environment.

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

The method applied to evaluate the value-added products from the agriculture waste is briefly shown in Fig. 2.6. It starts with the literature analysis, which includes knowledge of potential agriculture waste valorization, existing alternative pathways, and resource cascading to extract the added-value products. Next is to find the most sustainable and suitable technology. Important aspects (i.e., technical, economic, environmental, and social) must be considered. In order to design an accurate scenario, knowledge of evaluation criteria and an alternative is necessary.

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).

Sensitivity analysis is performed for scenario 1 to check the influence of attribute distribution on the results of the TOPSIS method. For scenario 2, AHP weights are used for the analysis. Saltelli defined sensitivity analysis as quantitative data analysis of performances in the output of a chosen system that can be distributed to various performances in the system [104]. In this analysis, different weights are used to determine the performance of the alternatives. Initial weights are considered, as shown in the MCDA method. The weight distribution that will be imposed for the analysis is considered to have two types of values: a) values smaller than one and b) values greater than 1.

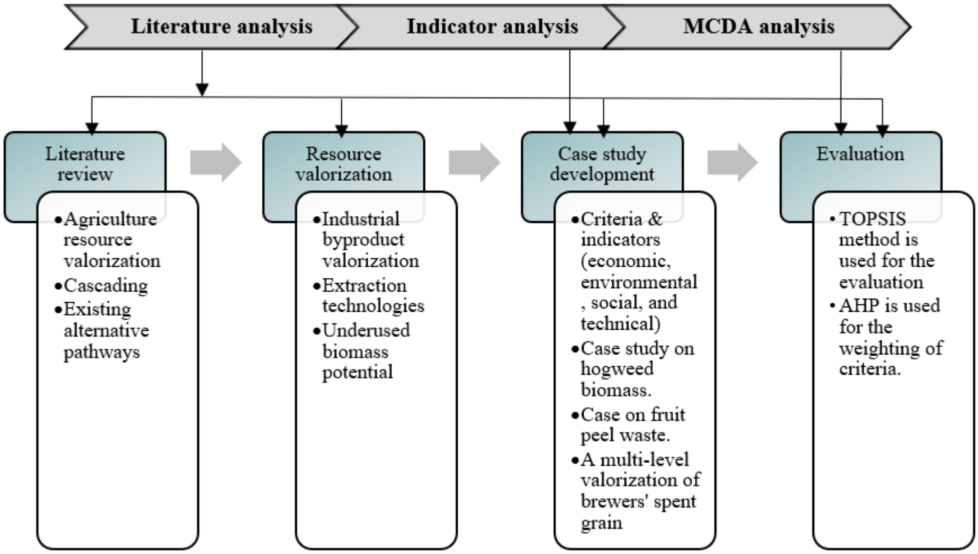


Fig. 2.6. Schematic presentation of case studies evaluation & multi-level assessment (Author's illustration).

A multi-level valorization of a single agricultural waste is also developed by following the scheme presented in Fig. 2.6. To compare the alternative pathways of post-industrial resource valorization, three scenarios were designed for BSG valorization considering low, medium, and high-added value products, a) biogas production, b) animal feed, and c) single-use biodegradable dishes. The TOPSIS method is used for the evaluation. The selected criteria for these alternatives are environmental aspects (CO_2 emissions) and economic aspects (Net present value, capital investments). Due to better data availability, BSG is selected for three scenarios: evaluating valorization alternatives for low, medium, and high-value products.

Evaluation of biopolymer alternatives under a sustainability framework from agricultural waste

A multidisciplinary approach is selected to develop a sustainability framework for biopolymer alternatives. Fig 2.7. shows the overall methodology algorithm. The methodology starts with analyzing scientific literature 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.

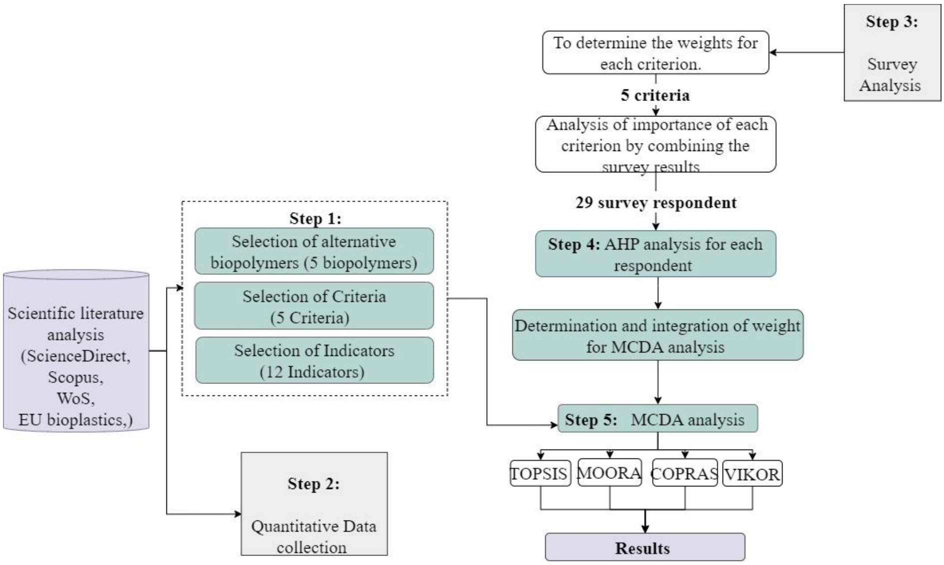


Fig. 2.7. Multidisciplinary approach for evaluating biopolymers (Author's illustration).

Survey analysis

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.

Multi-Criteria Decision Analysis

The MCDA method is the best choice to assess the sustainability of a product or a system [105]. 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.

Analytic hierarchy process (AHP)

The sustainability innovation pillar uses the AHP method 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 [92]. Here, semi-quantitative analysis was used to measure the intensity of importance in AHP. Criteria and alternatives were prioritized mainly using the scoring system [106][107]. Table 2.3 shows the Saaty's scale.

Table 2.3

Saaty's Scale for AHP Analysis

Scale	Definition
1	Equally important
2	Equally to moderate important
3	Moderately important
4	Moderately to strongly the important
5	Strongly important
6	Strongly to very strongly important
7	Very strongly important
8	Very to extremely strongly the 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 ($n \times n$) formed by using the compared criteria in rows and columns of the matrix is square (see Equation (2.2)) [108].

$$\mathbf{A} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \dots & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \dots & \alpha_{2n} \\ \dots & \dots & \dots & \dots \\ \alpha_{n1} & \alpha_{n2} & \dots & \alpha_{nn} \end{bmatrix} \quad (2.2)$$

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 (2.3).

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (2.3)$$

Step 5: Next, the maximum eigenvalue ($\lambda_{\max}$) is calculated as following Equation (2.4).

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(Aw)_i}{w_i} \quad (2.4)$$

Step 6: Next, the consistency index (*CI*) for acceptance of the consistency ratio of the comparison matrix A is calculated using Equation (2.5).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2.5)$$

CI refers to the mean of the remaining solutions of the characteristic equation for cognizant matrix A (see Table 2.4) [109].

Table 2.4

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 (2.6).

$$CR = \frac{CI}{RI} \quad (2.6)$$

where

RI – random index;

CR – measures the judgments of experts.

If CR ≤ 0.1, the inconsistency is acceptable [110]. The next step in the methodology is to use the TOPSIS method. Below is a brief explanation of MOORA, COPRAS, and VIKOR methods.

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

Technically, MCDA has multiple properties that explain its application in this research. The following properties can be considered:

A) It looks to take very precise, multiple, and contrast criteria,

B) It helps to define the problem,

C) The provided model by MCDA gives focus and direction,

D) It gives a justifiable, manageable, and explainable decision [111].

The TOPSIS is one of the classic methods used for MCDA [112]. By using this method, several alternatives can be compared with the chosen criteria. The reason behind using the TOPSIS method over any other method is the clarification and specification of the method. By this method, appropriate and justifiable results can be obtained remarkably straightforwardly. One of the significant advantages of this method is that it does not need any unique program for evaluation [112]. The various steps to perform the TOPSIS have been described in detail here.

Step 1: It is used for two cases: a) to determine the best pre-treatment method for hogweed invasive plant and b) to choose the best value-added product from BSG industrial leftover using the suitable criteria for each scenario.

Step 2: Development of a decision-matrix shows the quantitative or qualitative information for each alternative and criteria. For qualitative data, specifically for the TOPSIS method, it is vital to derive scores. This score is dependent on technically obtainable data. To obtain these comparative scores for qualitative data, one of the standard scales is used, for example, the Likert scale that can take values from 1 to 3 (poor, average, good performance), from 1 to 4 (very poor, poor, good, very good), or other range of scale depending on the requirements for the necessary investigation [113].

Step 3: All values obtained from the decision-matrix (Step 2) need to be normalized by using the following Equation (2.7).

$$r_{ai} = \frac{x_{ai}}{\sum_{a=1}^{n} x_{ai}^2} \tag{2.7}$$

where

a – alternative, $a= 1,..,n$;

i – criteria, $i=1,..,m$;

r_{ai} – normalized criteria value.

Step 4: Equation (2.8) shows the formula to calculate the weight for each criterion.

$$w_i = \frac{1}{n_i} \tag{2.8}$$

where

w_i – weighted value;

n_i – total number of criterions.

Step 5: Normalized matrix value can be derived by multiplication of normalized value (step 3) and weight, which is done by following Equation (2.9).

$$v_{ai} = w_i \times r_{ia} \tag{2.9}$$

where

v_{ai} – weighted value;

w_i – weight, $w_{i1}+w_{i2}+\ldots+w_{im}=1$, $w_i=1\ldots m$;

r_{ia}– normalized criterion value.

Step 6: The distance for each ideal and non-ideal alternative can be calculated by dividing the squares of weighted criterion values (step 5). The distance measure of the ideal solution has been developed by following Equation (2.10).

$$d_a^+ = \sqrt{\sum_{j=1}^{n} (v_i^+ - v_{ai})^2} \tag{2.10}$$

where

d_a^+ – distance for each action to the ideal solution;

v_i^+ – ideal solution;

v_{ai} – weighted value.

The development of distance for each action to the non-ideal solution has been calculated by following Equation (2.11).

$$d_a^- = \sqrt{\sum_{j=1}^{n} (v_i^- - v_{ai})^2} \tag{2.11}$$

where

d_a^- – distance for each action to the non-ideal solution;

v_i^- – non-ideal solution;

v_{ai} – weighted value.

Step 7: The relative closeness coefficient (Ca) is different for each alternative. Ca is between 0 and 1; but 1 is considered the most suitable value. Ca ratio shows the distance to the non-ideal solution, which is determined by the sum of the distance to the non-ideal solution divided by the distance to an ideal and non-ideal solution. Equation (2.12) shows the Equation for the relative closeness coefficient.

$$\text{Ca} = \frac{d_a^-}{d_a^+ + d_a^-} \tag{2.12}$$

It is essential to perform a sensitivity analysis for each criterion. To find out the new weight for each criterion following, Equations (2.13) and (2.14) are used. Different weight distributions are changed based on the weight imposed on the distribution.

$$\beta_k' = \sum_{k=1}^{n} w' = 1 \tag{2.13}$$

$$w_{k1}' = \beta_k \times w', \text{ k = 1,2, 3…. n} \tag{2.14}$$

where

β_k' – unitary variation ratio of w_k after distribution;

w_k – weight being imposed on the distribution.

Multi-Objective Optimization based on Ratio Analysis (MOORA)

MOORA is the multi-attribute optimization method. This method simultaneously processes the optimization of two or more attributes. The MOORA method can be applied to solve various complex decision-making problems. The step-by-step calculation formula for the MOORA method is described below [114].

Step 1: The first step is determining the objective and identifying the pertinent evaluation attributes.

Step 2: The decision-making matrix develops (see Equation (2.15)).

$$X = \begin{bmatrix} X11 & X12 & X1n \\ X21 & X22 & X2n \\ X_{n1} & X_{n1} & X_{nn} \end{bmatrix} \tag{2.15}$$

where

X – decision-making matrix.

Step 3: Normalization of the decision-making matrix

The square root of the sum squared of each alternative per attribute can be calculated to normalize the quantitative values. This ratio can be expressed in Equation (2.16).

$$X_{ij}^* = \frac{X_{ij}}{\sqrt{\left[\sum_{i-1}^{m} x_{ij}^2\right]}} \tag{2.16}$$

where

X^*_{ij} – performance measure;

i – alternatives;

j – attributes.

Step 4: Multi-objective optimization

The normalized matrix will now be added in case of maximization and subtracted in case of minimization (see Equation (2.17)).

$$y_i = \sum_{j=1}^{g} x^*_{ij} - \sum_{j=g+1}^{n} x^*_{ij} \tag{2.17}$$

where

g – number of attributes to be maximized;

n-g – number of attributes to be minimized;

y_i – normalized assessment value of i.

Step 5: Weighted matrix

To give importance to an attribute, it could be multiplied by its corresponding Weight (see Equation (2.18)). Our study considers weights based on AHP analysis of the survey results.

$$y_i = \sum_{j=1}^{g} w_j \, x^*_{ij} - \sum_{j=g+1}^{n} w_j \, x^*_{ij} \tag{2.18}$$

where

j – 1, 2,…, n;

w_j – weight of attributes.

Step 6: The y_i Value can be positive and negative depending on the total of its maximum and minimum in the decision matrix. In MOORA, the best alternative has the highest y_i Value and the worst alternative have the lowest y_i Value.

Complex Proportion Assessment Method (COPRAS)

COPRAS is one of the most common methods in MCDA, which analyses various alternatives based on different criteria and indicators by determining a rank of alternatives. COPRAS is a simple, less time-consuming, and transparent computation process. The step-by-step calculation formula for the COPRAS method will be described below [115].

Step 1: Development and normalization of the decision-making matrix

First, the selection of attributes and alternatives takes place. Then, the decision-making matrix X needs to be developed following Equation (2.19).

$$X = \begin{bmatrix} \mathrm{w}11;\ b11 & w12;\ b12 & w1m;\ b1m \\ w21;\ b21 & w22;\ b22 & w2m;\ b2m \\ w_{n1};\ b_{n1} & w_{n2};\ b_{n2} & w_{nm}; w_{nn} \end{bmatrix} \tag{2.19}$$

where

j – 1, n;

i – 1, m;

X – decision matrix.

Step 2: Weighted normalized decision-making matrix

To give importance to an attribute, it could be multiplied by its corresponding Weight (see Equation (2.20)). Our study considers weights based on AHP analysis of the survey results.

$$X *= \begin{bmatrix} w*11;\ b*11 & w*12;\ b*12 & w*1m;\ b*1m \\ w*21;\ b*21 & w*22;\ b*22 & w*2m;\ b*2m \\ w*_{n1};\ b*_{n1} & w*_{n2};\ b_{*n2} & w*_{nm}; b*_{nn} \end{bmatrix} \tag{2.20}$$

where

w*– w*ij · qj;

b* – b*ij · qj.

Step 3: Calculation the sum of an attribute value whose maximum value is preferable for each alternative; this can be calculated by following Equation (2.21).

$$P_j = \frac{1}{2}\sum_{i=1}^{k}(w*ij + b*ij) \tag{2.21}$$

where

k – number of attributes that must be maximized;

P_j – attribute values.

Step 4: Calculate the sum of an attribute value whose minimum value is preferable for each alternative; this can be calculated by following Equation (2.22).

$$\mathrm{R_j} = \frac{1}{2}\sum_{\mathrm{i=k+1}}^{\mathrm{k}}(\mathrm{w*ij + b*ij}) \tag{2.22}$$

where

R_j – attribute values.

Step 5: Determination of the minimal value of R_j, which is shown in Equation (2.23).

$$R_{min} = \frac{min}{j} R_j \tag{2.23}$$

Step 6: Determination of relative weights of each alternative (see Equation (2.24))

$$Q_j = P_j + \frac{\sum_{j=1}^{n} R_j}{R_j \sum_{j=1}^{n} \frac{R_{min}}{R_j}} \tag{2.24}$$

Step 7: Ranking of alternatives according to the relative significance of each alternative.

Determination of the ranking or priority of the alternatives is done based on the relative weightage of the alternative. That means a higher value of Q_j has the first ranking.

Vlsekriterijumsko kompromisno Rongiranje (VIKOR)

VIKOR method is one of the applicable techniques within MCDA methods. This method solves a discrete decision-making problem with non-commensurable and conflicting criteria. The VIKOR method works based on the ranking system. It selects the best alternative based on the compromise solution for a problem with conflicting criteria. The step-by-step calculation formula for the VIKOR method is described in [116].

Step 1: Formation of decision matrix

The first step is determining the objective and identifying the pertinent evaluation attributes.

Step 2: Identification of ideal best and ideal worst indicators

Determination of the best f_j^* and the worst f_j^- Values of all criterion functions j = 1, 2, …, n, which can be calculated by following Equation (2.25).

$$f_j^* = {}^{max}{}_i f_{ij} \; ; \; f_j^- = {}^{min}{}_i f_{ij} \tag{2.25}$$

Step 3: Weighted normalization

The weighted normalization matrix can be calculated by following Equations (2.26) and (2.27).

$$S_i = \sum_{j=1}^{n} w_j (f_j^* - f_{ij}) / (f_j^* - f_j^-) \tag{2.26}$$

$$R_i = {}^{max}{}_i w_j (f_j^* - f_{ij}) / (f_j^* - f_j^-) \tag{2.27}$$

where

w_j – weight of criteria, expressing their relative importance

S_i – maximum group of utility;

R_i – minimum individual regret of the opponent.

Step 4: Determination of best and worst value

The best and worst values of indicators can be calculated by following Equation (2.28).

$$Q_i = v(S_i - S^*)/(S^- - S^*) + (1 - v))(R_i - R^*)/(R^- - R^*) \quad (2.28)$$

where

S^* – $\min_i S_i$;

S^- – $\max_i S_i$;

R^* – $\min_i R_i$;

R^- – $\max_i R_i$;

v – weight of criteria.

Step 5: Performance score and ranking

The alternative is ranked by sorting the values of S, R, and Q in decreasing order. The results are three ranking lists. The minimum value of Q is ranked as the best alternative.

2.2. Market innovation

A successful transition toward 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 the bioeconomy, assessing the market opportunity for decision-making in commercializing the packaging materials is imperative. Fig. 2.8 shows the strategic scheme for the market innovation transfer of added-value products produced from agricultural resources. This section shows a market analysis for the four different biopolymer packaging materials from agriculture crop residues.

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.

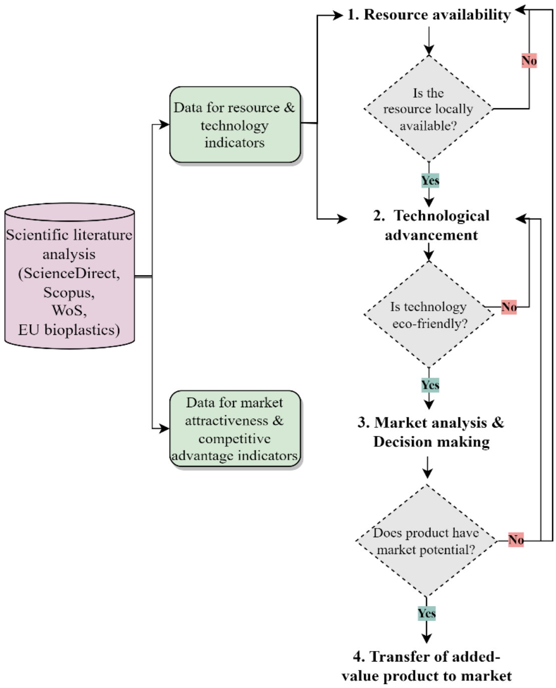


Fig. 2.8. Market innovation transfer scheme (Author's illustration).

GE-McKinsey analysis for the biopolymer packaging materials

Data collection and evaluation technique

The market analysis is carried out using primary qualitative 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, which are considered for the market competitive advantage to provide value-added benefits. Resources play a central role in the business' environmental performance to establish efficiency in the process [117], and the eco-friendliness of technology significantly addresses the business' sustainable practice [118]. For market attractiveness, six key indicators are evaluated: market size, market growth rate, market profit, price sensitivity, access to raw materials, and production cost [119]. The market competitive advantage is evaluated based on the six critical indicators: demand, market share, availability of resources, selling price, environmental ease of technologies, and product quality [119].

The Likert scale is a commonly used scale that displays the preferences for outcomes derived from quantitative indicators [120]. A decision-maker can also use the Likert scale to assess and contrast the outcomes of various projects. The market attractiveness evaluation is based on a five-point scale, where 1 represents very unattractive, and 5 is 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, labour, manufacturing supplies, and general overhead, which is determined based on the scale from high (1) to low (5).

The evaluation is also done based on five-point ratings for market competitive advantage. 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 indicates a very positive environmental impact of technology. Lastly, the quality is evaluated based on the melting point of the biopolymer, where 5 shows 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 [121]. Fig. 2.9 [122] 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.

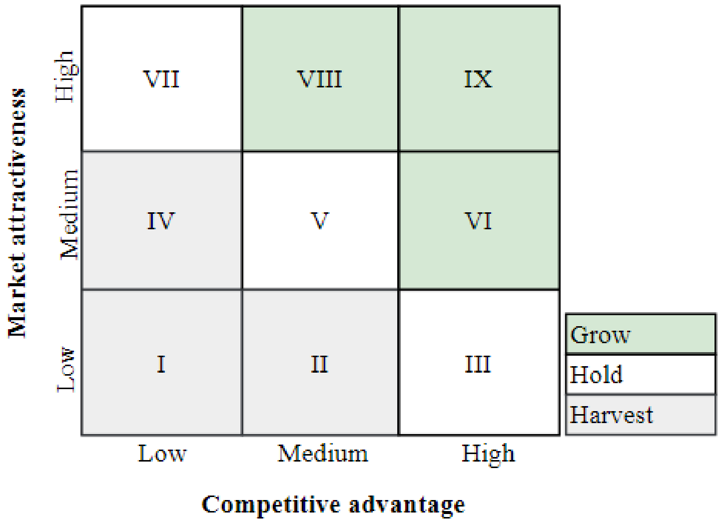


Fig. 2.9. The GE-McKinsey Matrix example [122].

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 [123]. 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 [124].

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 Equation (2.29) and (2.30).

$$M_a = \frac{(z \cdot k)}{100} \tag{2.29}$$

where

M_a – market attractiveness total score;

Z – estimated rating score.

$$k = \frac{100}{(f \cdot B_{max})} \tag{2.30}$$

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 (2.31).

$$R = \left(\frac{B}{B_{comp}} - 1\right) \cdot 100\ \% \tag{2.31}$$

where

R – relative indicator of product competitive advantages;

B – new product score estimation;

B_{comp} – strongest competitor score estimation.

2.3. 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 in the online marketplace that informs customers about the carbon footprint of packaging products and allows them to evaluate which of the selected packaging alternatives is most preferable from an environmental perspective. The schematic diagram for the system change is shown in Fig. 2.10.

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.

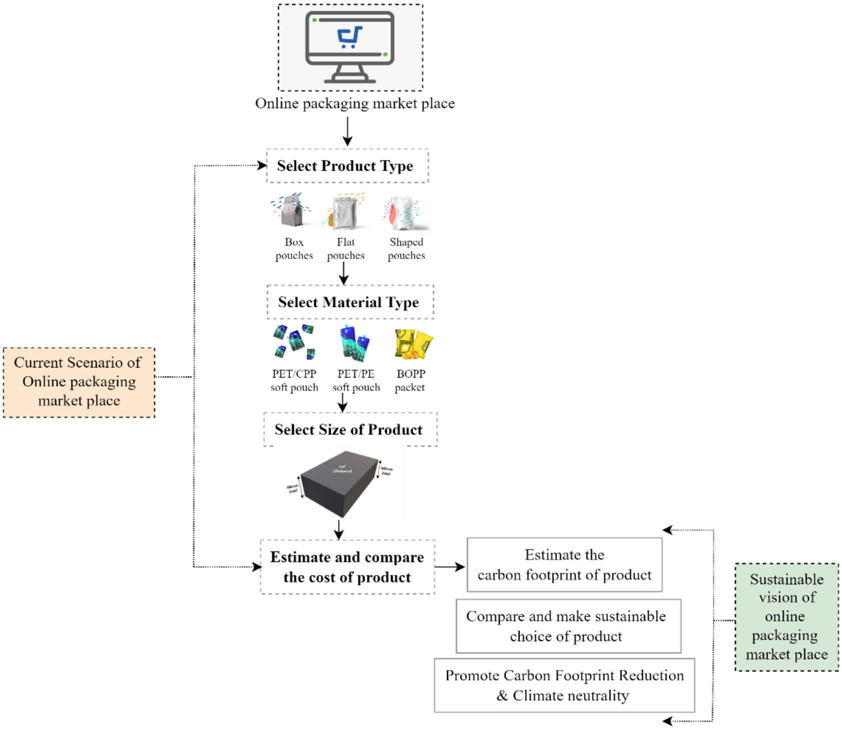


Fig. 2.10. System innovation schematic presentation (Author's illustration).

Life Cycle Analysis for carbon footprint evaluation in the packaging industry

Goal and Scope

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. 2.11.

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.

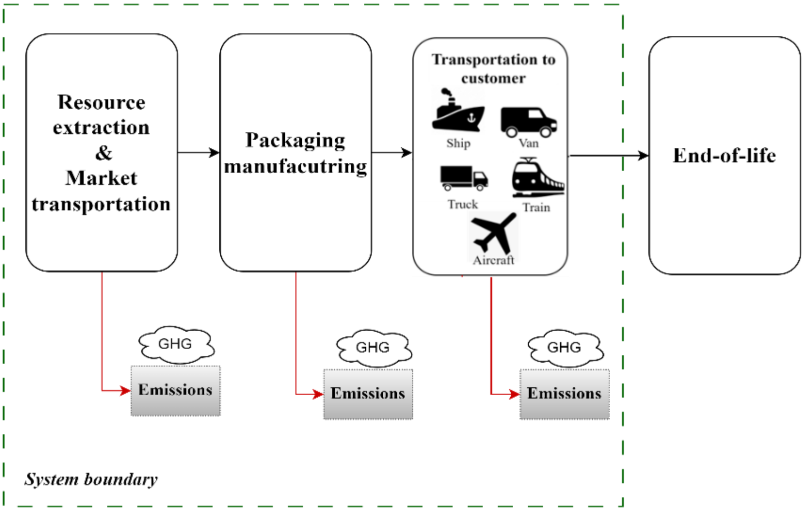


Fig. 2.11. System boundary for carbon footprint evaluation (Author's illustration).

The main limitation of the study is a lack of data on packaging products in different regions. The data used in this study is based on the global average values for the manufacturing process of specific materials and transport modes as given in the Ecoinvent database. Moreover, at the tool's current development level, the impacts related to different packaging surface production and additional materials in the packaging (e.g., zipper, slider, and other additional options) are excluded from the scope of the study.

Life cycle inventory

The life cycle inventory quantifies inflows and outflows of the system, which must be normalized to the FU. The online packaging marketplace provides quantitative data for the material variations and parameters. 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. Summarizing:

- the background is from Ecoinvent 3.7.1, and the weight and specification of materials are according to the manufacturer.
- the geographical context of the system is considered for Europe.
- the data quality is generic.
- the year of data is 2022, and the representativeness per FU is for the year 2021.

- the technological characteristics concern the operations of resource extraction, market transportation, manufacturing, and distribution of packaging materials.

Impact assessment method

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 [125]. It contains GWP climate change factors of IPCC with 100 years of timeframe. According to the method description, IPCC characterization factors for the GWP of air emissions are [126]:

- including carbon cycle response.
- not including the indirect formation of dinitrogen monoxide from nitrogen emissions.
- not including radiative forcing due to nitrogen dioxide emissions, carbon monoxide, voltaic organic compounds, black carbon, organic carbon, and sulfur oxides.
- not including the indirect effects of carbon monoxide emissions.

The results can be calculated cumulatively as GWP100 or per category: GWP100- fossil, GWP100- biogenic, and GWP100- land transformation [126].

3. RESULTS AND DISCUSSION

3.1. Results of sustainability innovation

Results of bibliometric analysis for biopolymers

Worldwide bibliometric analysis

Different database coverage has been used to analyze worldwide research, knowledge, and interest. First, the number of documents published by various countries has been studied using the 'biopolymer' keyword; the first twenty countries with published papers are shown in Fig. 3.1. The United States has the highest number of documents (313) among other countries, followed by Italy.

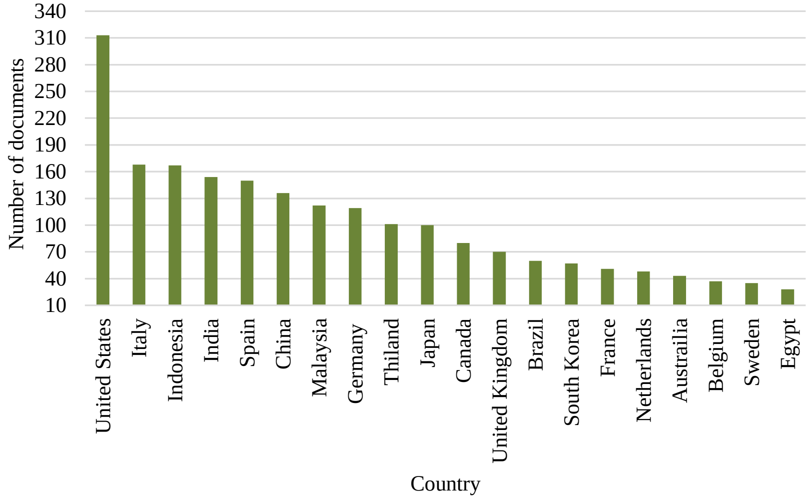


Fig. 3.1. Documents published per country.

Second, documents published by year have been analyzed by choosing the 'biopolymer' keyword. Fig. 3.2 shows that since 2000, interest in biopolymers has grown and continuously increased. In 1947, the first technical biopolymer was introduced [127]. Therefore, with the developing trend and interest in biopolymers, by the end of 2021, the highest number of documents were published.

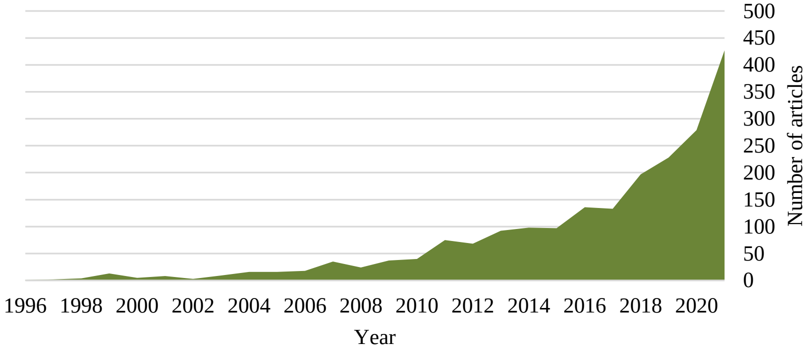


Fig. 3.2. Documents published per year.

Keywords co-occurrence analysis

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. 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. 3.3).

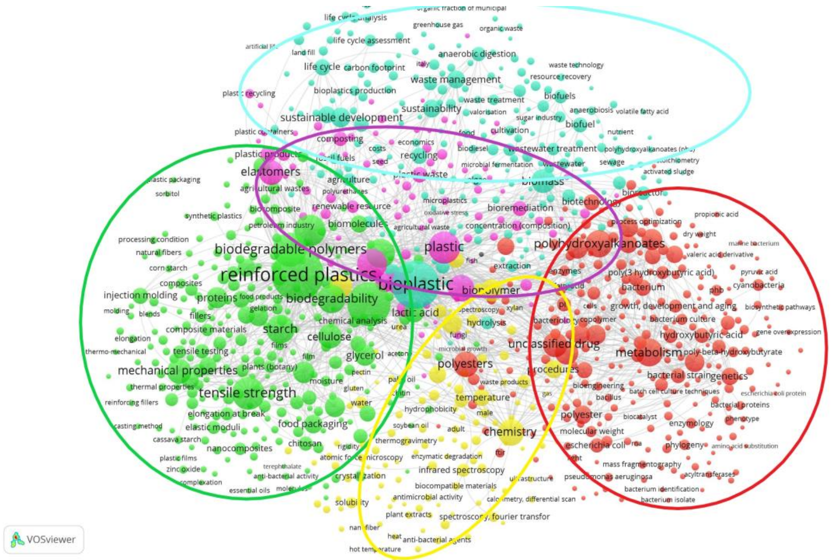


Fig. 3.3. Visualization of co-occurrences for the keyword 'bioplastic'.

The green cluster co-occurrences with mechanical properties, thermal properties, corn starch, biodegradable polymers, and bioplastic components (starch, glucose, glycerol, cellulose, and pectin). The blue cluster co-occurs with biopolymers, LCA, sustainability, waste management, sustainable development, bioplastic production, resource recovery, and valorization. The red cluster is the third largest and has co-occurrence with the classification of bioplastic, which includes polyalkenoates, polyesters, poly (3hydroxybutyric acid), poly-beta hydroxybutyrate, biocatalyst, and enzymology. The fourth cluster shows the co-occurrences between agricultural waste, bioremediation, microplastic, renewable resources, plastic waste, and extraction. The fifth yellow cluster shows the relation between degradation activities, which are enzymatic degradation, antimicrobial activities, anti-bacterial agents, solubility, and biocompatible material.

The bibliometric analysis for the keywords' bioplastic' and 'sustainability' is shown in Fig. 3.4. 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). The green cluster is linked with sustainable development, including biopolymers, biodegradation, packaging materials, renewable sources, and plastic products. The red cluster relates biomass, bioconversion, biopolymer, biorefinery, circular bioeconomy, biotechnology, and sustainability. The yellow cluster shows the link between bioplastic, environmental sustainability, biodegradability, food packaging, and biodegradable plastic. The blue cluster represents the assessment methodologies, including LCA, economic analysis, and economic and social effects. The purple cluster can be found in different areas and describes terms related to other components.

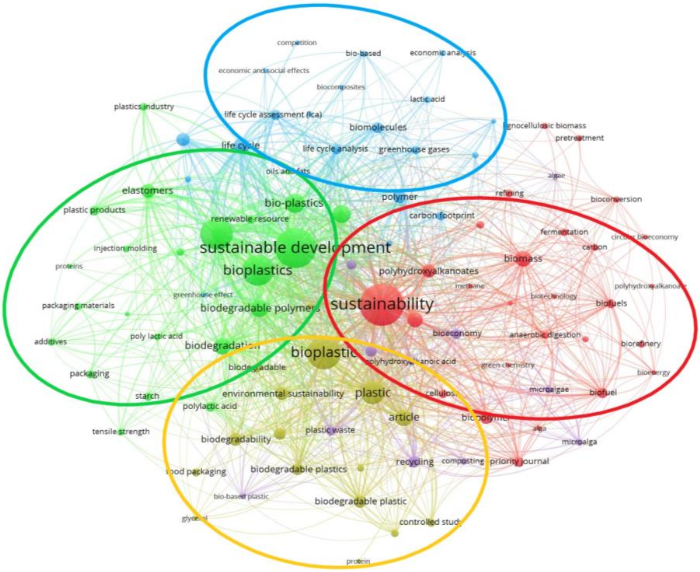


Fig. 3.4. Visualization of co-occurrences for keywords' bioplastic' and 'sustainability'.

The bibliometric analysis for the keywords' agriculture' and 'waste' and 'biopolymer' is shown in Fig. 3.5. 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, such as agriculture 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) agriculture waste management (green cluster), b) biopolymers (red cluster), c) bioproducts (blue cluster), d) industrial waste (purple cluster), and e) biological processes (yellow cluster).

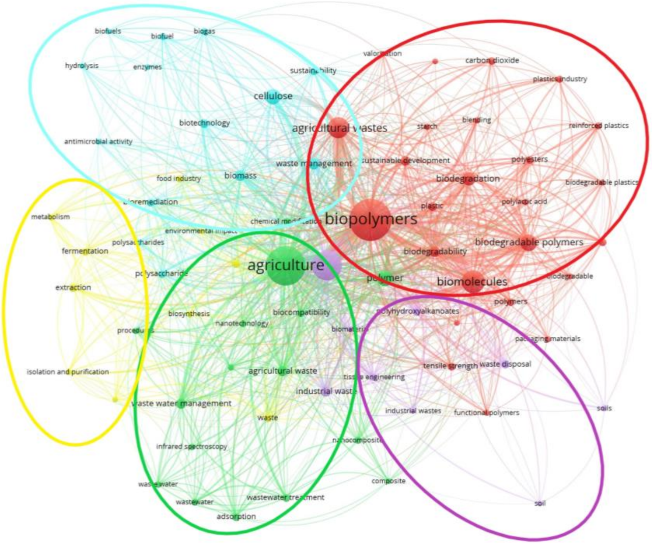


Fig. 3.5. Visualization of co-occurrences for keywords' agriculture' and 'waste' and 'biopolymer'.

Ranking of bioeconomy modeling tools

Bioeconomy modeling tools such as MILP, MAGNET, TIMES, GLOBIOM, and LCA have diverse applications for sustainable bioeconomy. The Mixed Integer Linear Programming (MILP) model is an optimization framework that performs linear and non-linear programming. The MILP model has a vast capacity, flexibility, and rigorousness to detect and solve problems from single-stage multi-products to general multi-purpose processes [128]. The MILP model solves linear programming problems using linear optimization methodology. Integrating the Geographic Information System (GIS) with the MILP model can give the framework to determine the biorefinery production process with specific sub-criteria. A framework to optimize the biorefinery processes using the MILP model and with constraints proposed by [129]. A potential indicator found in this study is an economic indicator (considering several factors such as feedstock, transportation, biorefinery, and optimization variables). The GIS-based approach can be applied to solve land-based problems with MILP integration. [130] presented an analytical framework for evaluating biorefinery using the environmental and economic indicators in the MILP model. The main economic indicators of soil erosion due to cultivation, carbon dioxide emission, and carbon sequestration are the establishment cost, selling price, production cost, transportation cost, and harvesting cost. The results of this study favor profit on biorefinery applications and environmental and economic benefits [131].

Modular Applied GeNeral Equilibrium Tool (MAGNET) is a global general equilibrium model with a modular structure and has several critical benefits for modeling bioeconomy, including in the development of the agricultural market, biomass usage for energy, food sector, land supply, land transfer, feed or fertilizer requirement, agricultural activities, labor market, and non-agricultural sector. This model aims to detect the changes in agro-food demand activities [132]. The MAGNET model works on the principle of the Computable General Equilibrium (CGE) model, which can evaluate the global economy with biofuels, agricultural, and energy sectors. Also, this model can integrate with the Global Trade Analysis Project (GTAP) database and includes all the information on the global economy. This model has a wide application in terms of extending the policies of agricultural, food security, and bio-based economy in a more secure way. The MAGNET model uses the relative indicators in the GTAP or CGE model, including agricultural land, labor, capital, natural resources, energy, and animal components.

Moreover, the leading indicators are capital and labor for agricultural and non-agricultural sectors [133]. One of the studies considered the six drivers as demographics (population growth, education, and human capital), consumer preferences (consumer behavior), economic development, global environmental change, resource availability (land availability), and innovation or technical change. The main impacts are non-renewable resources, GHG emissions, biodiversity, job creation, and food security. So, these drivers can be used to analyze the specific impacts (economic, environmental, or social) for Sustainability [134].

The Market Allocation-Energy Flow Optimization Model System (TIMES) model allows integrated assessment of social, economic, energy, and environmental issues based on partial equilibrium. The TIMES model's main benefit is finding the least-cost options for various technologies through a dynamic simulation. The main scope of the TIMES model is that it addresses the environmental emissions, material, and energy systems [135]. The TIMES model is a bottom-up model used to evaluate energy systems. The model can be applied to long-term horizons, including extraction, transformation, distribution, end-uses, and trade of energy sources. The evaluation uses the TIMES model's techno-economic assessment (cost and efficiency). However, it also analyses GHG emissions, fuel consumption, and related environmental processes. The main indicators that can be used for economic sub-criteria are feedstock cost, feedstock availability, investment cost, operating cost (variable or fixed), annual availability factor, and lifespan. These indicators are used for biofuel, electricity, and heat production by using a variety of agricultural feedstocks such as corn, soybean, fish oil, forest residues, agricultural residues, and industrial wastes [136]. One of the studies shows an interesting way to evaluate the increased value of biomass resources considering the biorefinery scenario [137]. Environmental, economic, and social are the main sub-criteria used for the TIMES model. Environmental indicators include GHG emissions, CO2 emissions, soil carbon changes, and carbon sequestration. The economic indicator includes the production cost, feedstock cost, maintenance cost, operational cost, technical cost, and transportation cost. The social indicators include household demands and population. The indicator analysis can be compared, and the increased value for the biomass resources can be derived [137].

The Global Biosphere Management Model (GLOBIOM) assesses trade-offs among land use and ecosystem services in agricultural, bioenergy, and forestry sectors. The model was developed for impact assessment of climate change mitigations, but over time, it can also be used for agricultural, timber market foresight, and economic analysis of climate change. The

GLOBIOM model represents the land-use scenario and works on the partial equilibrium principle. The model evaluates the agricultural, forestry, cropland, and other land-based activities. This model uses socio-economic and environmental indicators to perform the evaluation. Also, the GLOBIOM model solves the issues related to an international bioenergy system by incorporating the indicators and drivers [138].

LCA is the method used to solve environmental problems within all the life cycle stages of a product, process, or service. This method is based on an inventory of a product, including all the energy and materials used within its life cycle, accounts for respective emissions and impacts on the environment, and analyzes social and economic assessment of a product's life cycle [139]. The LCA analysis assesses the product's performance during the whole life cycle by analyzing environmental, social, and economic aspects [140][141]. The evaluation results are presented for the criteria and three main sustainability sub-criteria (see Table 3.1).

Table 3.1

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 criteria and sub-criteria were evaluated first, using the semi-quantitative analysis for bioeconomy modeling tools. Secondly, 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, and 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. 3.6). 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.

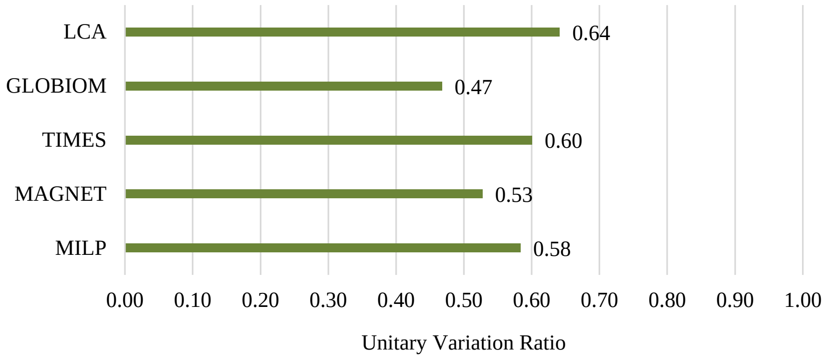


Fig. 3.6. TOPSIS results for modeling tools.

Lastly, the sensitivity analysis results were obtained for documentation aspects, flexibility, compatibility, diversity, validity, efficiency, and under-friendliness Criteria. Fig. 3.7 shows the sensitivity analysis results for the documentation factor. The highest result is obtained for the LCA (0.82) and TIMES model (0.78), and the lowest result is obtained for the GLOBIOM model (0.32) and MAGNET model (0.34) if the weight is three times more than the initial weight (0.25). The derived results for the MILP model are 0.58 for three times higher weights. For weight 0.1, 0.2. Moreover, 0.5 the documentation aspect shows comparable results for all bioeconomy modeling tools. A minor difference in results has been obtained for 1.5- and 2-times higher weights for all bioeconomy modeling tools.

Furthermore, the three times higher weights for the documentation aspect show that the material availability, libraries, and online sources are 100 % available for the LCA and TIMES models. Conversely, for GLOBIOM and MAGNET, sufficient material availability, libraries, and online sources are unavailable in the context of the agriculture biorefinery.

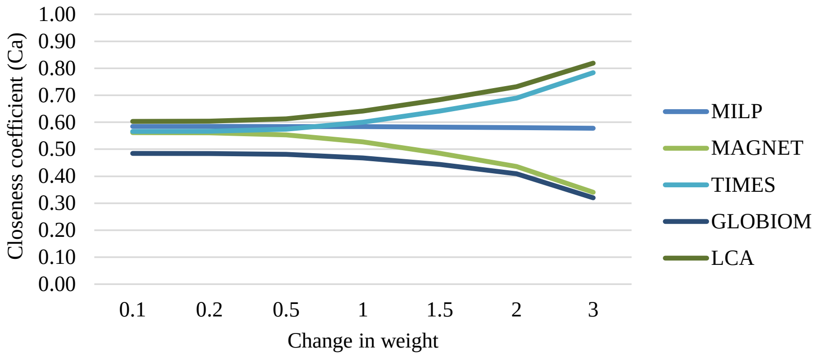


Fig. 3.7. Sensitivity analysis results for documentation aspect.

The sensitivity analysis results for the flexibility are presented in Fig. 3.8. If the weight is three times higher than the initial weight, the MILP and GLOBIOM show the highest (0.83) and lowest (0.40) flexibility, respectively. The MILP and LCA models show drastic changes for lower and higher weights. However, the MAGNET, GLOBIOM, and TIMES models show a minor change for lower and higher weights.

The higher flexibility for MILP and LCA models shows that the models have a remarkably high level of adaptability and standardization towards the sustainability sub-criteria. The MAGNET and GLOBIOM models show low adaptability and standardization towards the sustainability sub-criteria for the agricultural biorefinery sector. The TIMES model has a moderate standardization toward the sustainability sub-criteria.

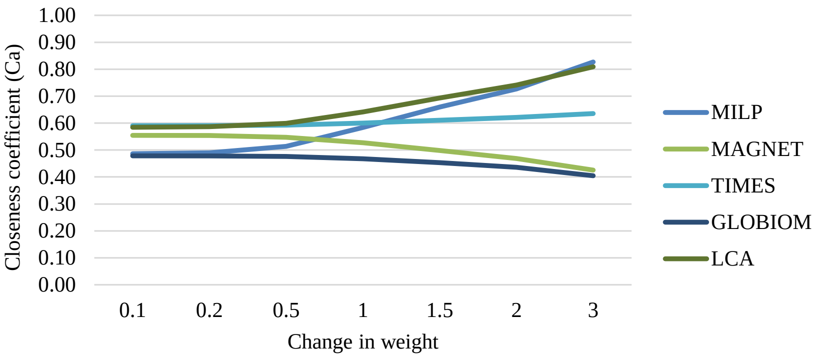


Fig. 3.8. Sensitivity analysis results for flexibility.

Fig. 3.9 shows the sensitivity results for compatibility. The compatibility factor's higher and lower weight changes show the same results as initial weights for all bioeconomy modeling tools. The compatibility indicates the interaction of the model with input data and the possibility of exchanging the data. All five models show the constant possibility of exchanging data. In other words, the interaction of models with their input data, i.e., economic, social, and environmental, is constant for lower and higher weights.

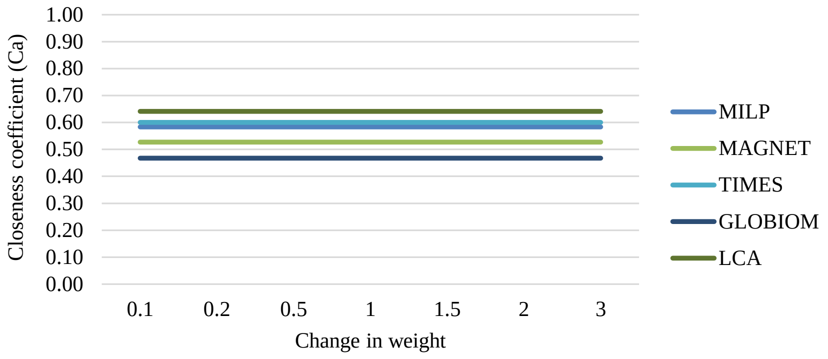


Fig. 3.9. Sensitivity analysis results for compatibility.

Fig. 3.10 shows the sensitivity results for the diversity factor. On one side, for lower weights (0.1, 0.2, and 0.5), the highest diversity is obtained for the LCA model, and the lowest is for the GLOBIOM model. Conversely, no significant difference can be seen for higher weights (1.5, 2, and 3). All modeling tools observe a notable change from lower to higher weights. The diversity indicates the variety of model applications with diverse goals and scope. For lower weights, the LCA model shows the highest applicability, which means the model can be used more than 80 % in the agricultural biorefinery sector with diverse goals and scopes. However, the GLOBIOM and MAGNET models can be used for less than 30 % of the agricultural biorefinery sector. The MILP and TIMES model shows 70 % applicability with diverse goals and scope. For higher weights, all models show moderate (i.e., about 50 %) applicability in the agricultural biorefinery sector, conserving the economic, social, and environmental sub-criteria.

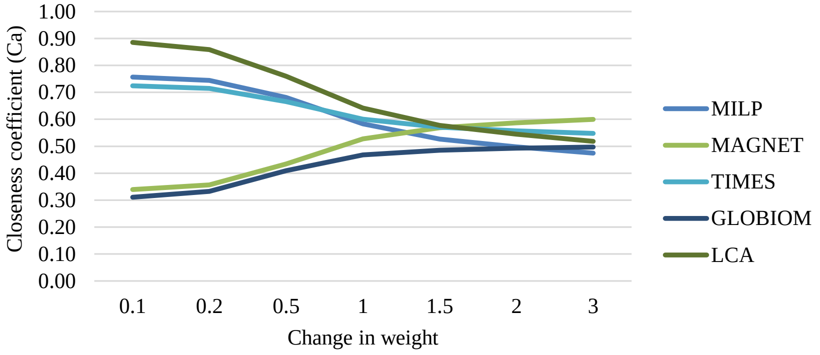


Fig. 3.10. Sensitivity analysis results for diversity.

Fig. 3.11 shows the sensitivity results for validity. The higher and lower weight changes for the validity factor show equivalent results as initial weights for all bioeconomy modeling tools in all scenarios. The validity indicates how the models are adequate for their relevant data. Each model shows equal adequacies for all weights, which means the models can obtain economic, social, and environmental data considering the study's relevance for the agricultural biorefinery sector as they have constant adequacy.

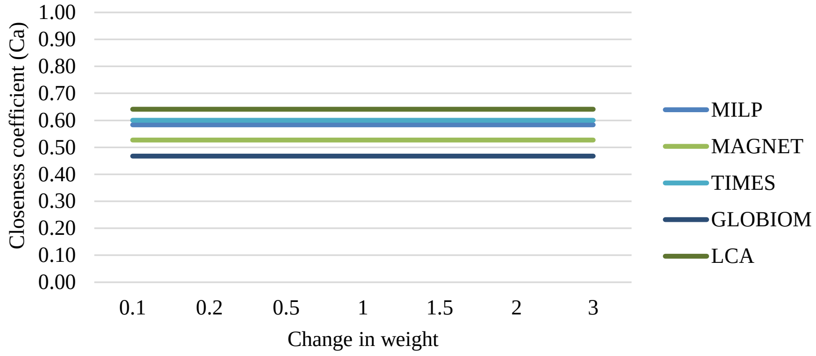


Fig. 3.11. Sensitivity analysis results for validity.

Fig. 3.12 shows the sensitivity results for efficiency. The sensitivity analysis for efficiency criteria for higher and lower weight changes shows consistent results as initial weights for all bioeconomy modeling tools. Efficiency represents the quality of the input data in terms of economic, social, and environmental input data used to perform the modulation. All models show constant values for efficiency, which indicates that all models are qualified to give qualitative input data.

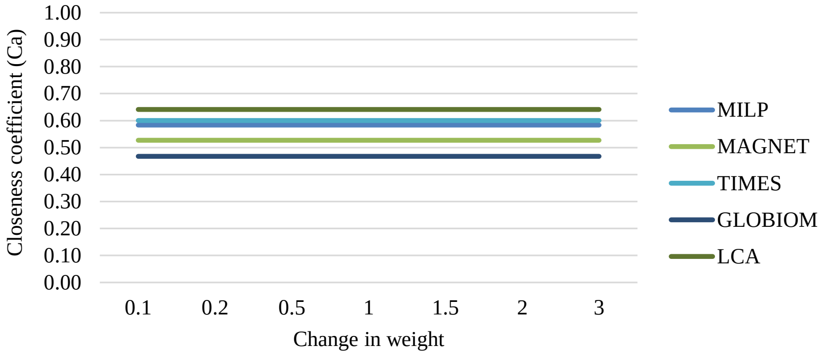


Fig. 3.12. Sensitivity analysis results for efficiency.

Fig. 3.13 shows the sensitivity results for user-friendliness. The user-friendliness for all bioeconomy modeling tools is equal to the initial weights for all higher and lower weight changes. The user-friendliness shows the ease of learning the model and interference data, which indicates the complexity of learning the interference data (i.e., economic, social, and environmental) and model. All models show constant complexity for all types of weighting scenarios.

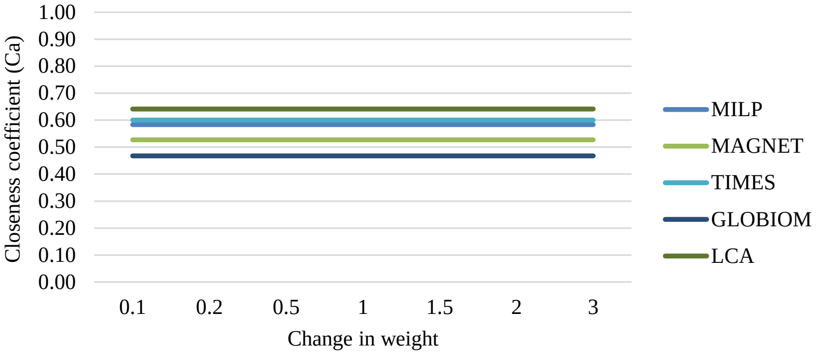


Fig. 3.13. Sensitivity analysis results for user-friendliness.

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. In sensitivity analysis, the three times high weight shows that the documentation aspect, flexibility, and diversity are highest for LCA, MILP [128], and MAGNET [132][133], [135] models. For lower weights (0.1), the documentation aspect and diversity are higher for LCA models. In contrast, the flexibility is higher for the TIMES model. The compatibility, validity, efficiency, and user-friendliness criteria are equal for all scenarios.

The LCA model is adequate for the sustainability sub-criteria (economic, social, and environmental) to discuss the anticipated interpretations. The LCA interpretation for documentation shows the highest pick (see Fig. 3.7), which shows that the learning material, tutorials, and libraries are widely available for the LCA model. The article [142] concluded that the LCA is rapidly advancing. This article presents the bibliometric analysis considering citation, co-citation, and co-occurrences on the 20,153 articles related to LCA studies with increasing research interest and publications every year [142]. Coherently with [143], the research has addressed the fact that the LCA model flexibly integrates the economic, social, and environmental aspects, which assists in developing agricultural sustainability and food security goals. Despite the broad scope of reusability and applications of the LCA model with increasing research interest [144][145], the development of sustainable strategies using the LCA tool in the agriculture sector is minimal. The life cycle inventory database is the gold standard for the LCA tool [41], which bridges the data gaps to provide information for agriculture inputs, outputs, and production processes. However, many authors addressed the concern about the databases due to gaps and not updated data [146]. The reliance on diverse data sources leads to the difficulty of obtaining accurate results for the LCA model [143]. Indirectly, the quality of data might be affected. Overall, this clarifies the consistent interpretation of the LCA model for compatibility, validity, and efficiency criteria.

Results of evaluating scenario for bioenergy production from hemp biomass

MCDA (TOPSIS) results

A normalized decision matrix is obtained by 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. In addition, the weights of the criteria from the expert evaluation were added, which aimed to rank the importance of the criteria under the non-crisis scenario. The experts ranked the economic and environmental aspects as the most essential criteria, with a weight of 0.20, while the other criteria were equally weighted at 0.15 (see Table 3.2).

Table 3.2

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

Criteria	**Thermal insulation**	**Textile**	**Composite materials**	**Construction materials**	**Paper**	**Technical material**	**Food**	**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 shown are in Fig. 3.14. 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 that of 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.

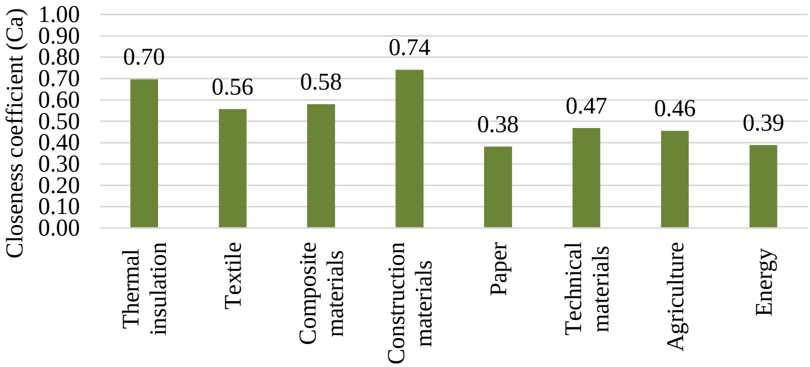


Fig. 3.14. TOPSIS results for hemp products under non-crisis conditions.

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 3.3).

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. 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. 3.15. The energy and thermal insulation generation 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.

Table 3.3

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**

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 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.

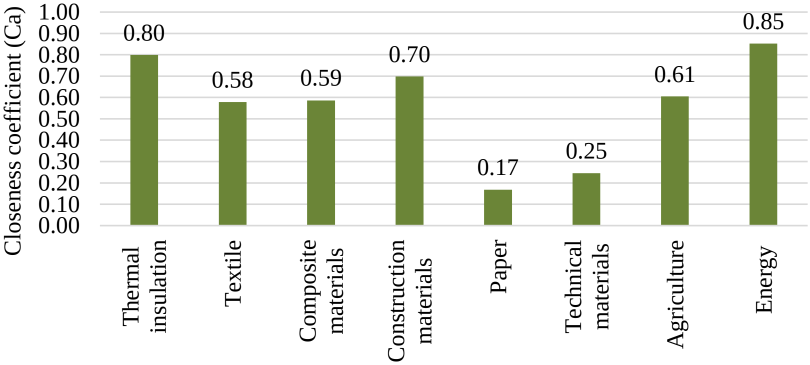
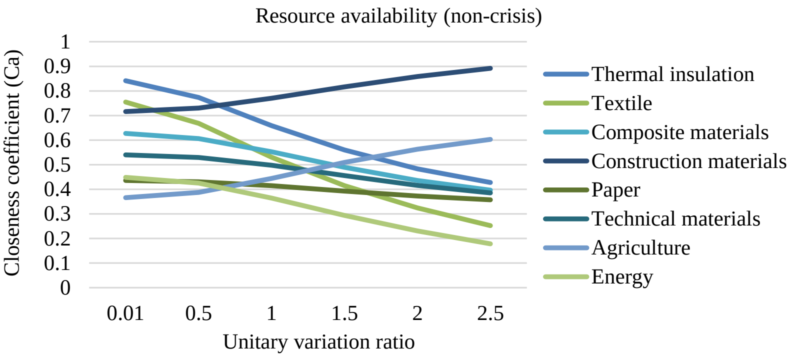
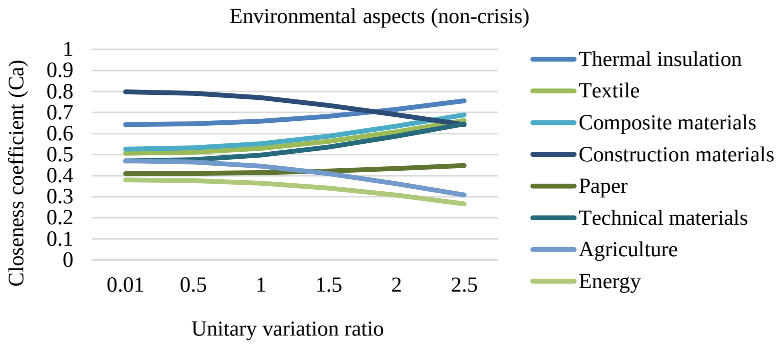


Fig. 3.15. TOPSIS results for hemp products under energy or economic crisis conditions.

A sensitivity analysis was performed for all alternatives to assess the stability of the alternatives under changing conditions. Sensitivity analysis was carried out with unitary variation ratios β_k considering scale 0.1, 0.5, 1, 1.5, 2, 2.5. Sensitivity analyses were performed for all the criteria used in the TOPSIS analysis. However, only the sensitivity analysis graphs showing the most significant changes for the products closer to the positive ideal solution (1.00) are presented.



(a)

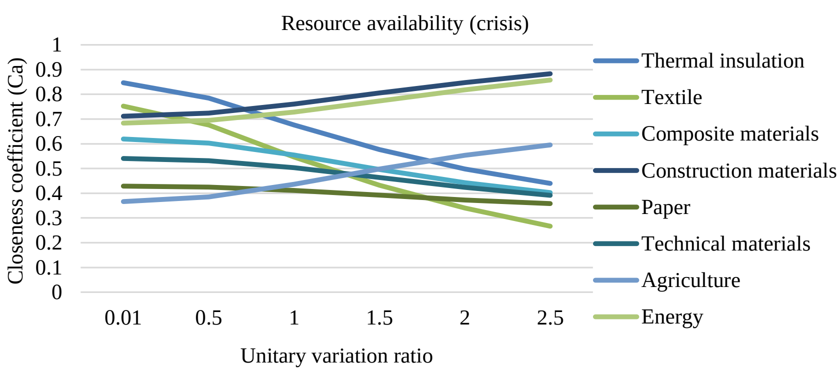


(b)

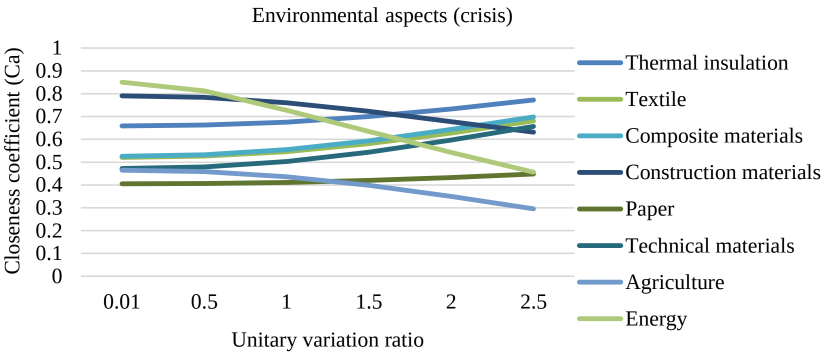
Fig. 3.16. Sensitivity analysis for the criteria (a) “resource availability” and (b) “environmental aspects" under non-crisis conditions.

The sensitivity analysis for the TOPSIS results for an everyday scenario under non-crisis conditions shows that the products closer to the positive ideal solution in the TOPSIS analysis - construction materials, thermal insulation, and composite materials - are affected differently by the change in the unitary variation ratio. Construction materials made from hemp are most positively affected by resource availability. In contrast, the other products, except paper, are negatively affected (see Fig. 3.16 (a) and (b)). On the other hand, environmental aspects negatively impact construction materials of all the aspects discussed. The opposite is almost the case for thermal insulation, which is strongly negatively affected by resource availability. At the same time, environmental aspects have a moderately positive impact on this and other products, such as composite materials and textile products.

The sensitivity analysis for the TOPSIS results under conditions of energy or economic crisis indicates that the products closer to the ideal positive solution in the TOPSIS analysis – energy, thermal insulation, and construction materials experience the most fluctuations in the influence of resource availability and environmental aspects.



(a)



(b)

Fig. 3.17. Sensitivity analysis for the criteria (a) "resource availability" and (b) "environmental aspects" under conditions of energy or economic crisis situation.

Again, changes in the unitary variation ratio affect each of the alternatives. In the TOPSIS analysis, energy production from hemp in a crisis came closest to the positive ideal solution and ranked first. The resource availability positively impacts energy production, construction materials, and agriculture. At the same time, the other products are, on the contrary, negatively affected, as shown by the sensitivity analysis (see Fig. 3.17 (a) and (b)). Sensitivity analysis for the other products, which scored lower overall in the TOPSIS analysis, showed growth trends related to environmental aspects. While the use of hemp for energy production performed the worst among all alternatives in terms of environmental aspects, construction materials and agriculture also showed a downward trend.

Interpretation of LCA results

The results for electricity generation from raw hemp biomass are shown in Table 3.4. 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} kgCO2eq per FU. The highest environmental impact share is for the aquatic ecotoxicity 1.4×10^{4} kg TEG water per FU.

Table 3.4

Characterization Results for the Hemp Biomass for Electricity Production

Impact category	Unit	Total	Hemp biomass processing	Electricity production
Carcinogens	kg C_2H_3Cl eq	5.7×10^{-1}	1.2×10^{-1}	4.4×10^{-1}
Non-carcinogens	kg C_2H_3Cl eq	2.2	2.0×10^{-1}	2.0
Respiratory inorganics	kg PM2.5 eq	1.7×10^{-1}	1.2×10^{-2}	1.6×10^{-1}
Ionizing radiation	kBq C-14 eq	2.1×10^{2}	6.6×10^{1}	1.4×10^{2}
Ozone layer depletion	kg CFC-11 eq	2.2×10^{-6}	7.9×10^{-7}	1.4×10^{-6}
Respiratory organics	kg C_2H_4 eq	1.2×10^{-2}	2.8×10^{-3}	8.9×10^{-3}
Aquatic ecotoxicity	kg TEG water	1.4×10^{4}	7.5×10^{2}	1.3×10^{4}
Terrestrial ecotoxicity	kg TEG soil	5.2×10^{3}	2.9×10^{2}	4.9×10^{3}
Terrestrial acid/nutri	kg SO_2 eq	3.8	4.9×10^{-1}	3.3
Land occupation	m2org.arable	8.8×10^{-1}	3.7×10^{-1}	5.1×10^{-1}
Aquatic acidification	kg SO_2 eq	1.4	1.3×10^{-1}	1.2
Aquatic eutrophication	kg PO_4 P-lim	1.4×10^{-2}	4.2×10^{-3}	1.0×10^{-2}
Global warming	kg CO_2 eq	6.3×10^{1}	1.0×10^{1}	5.3×10^{2}
Non-renewable energy	MJ primary	3.0×10^{2}	1.2×10^{2}	1.8×10^{2}
Mineral extraction	MJ surplus	1.2	3.6×10^{-1}	8.6×10^{-1}

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. 3.18. 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.

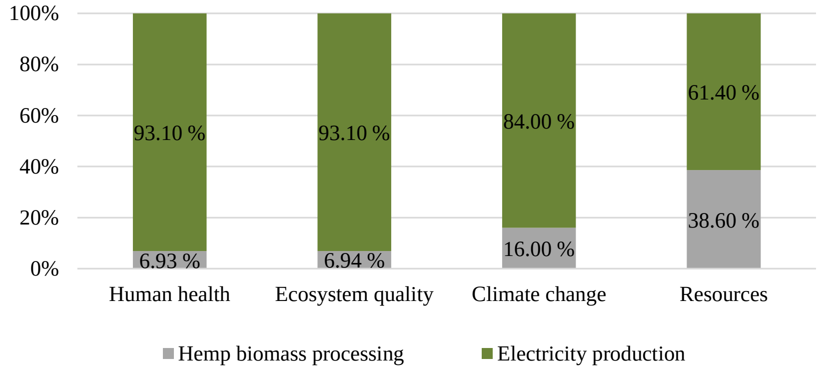


Fig. 3.18. Damage assessment results for hemp biomass for electricity production.

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 for determining which category is most affected overall and summarizing all categories, as in Fig. 3.19. 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 3.5.

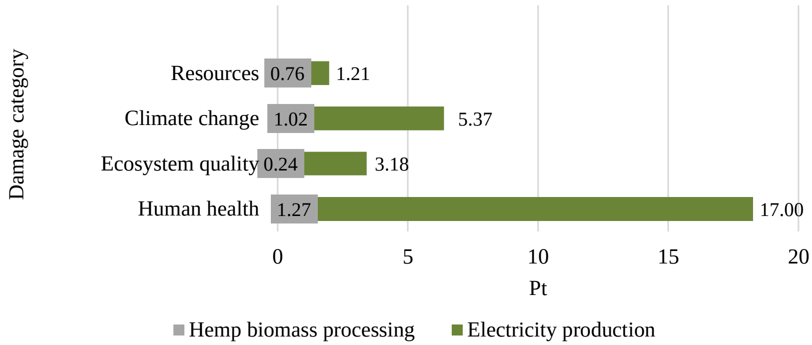


Fig. 3.19. Weighted totalized results for the hemp biomass for electricity production.

Table 3.5

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}
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 [95].

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. In contrast, the least influential is sweet sorghum biomass, which has 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.

If hemp can produce about 25,000 different products [147], it would only be reasonable to produce higher value-added products. However, crises can undermine the importance of the sustainability criterion. It is essential to set priorities because sometimes humanitarian and economic indicators take precedence in the short term. The war in Ukraine has led to adjustments in the energy market. Therefore, it is essential to understand the sustainability challenges in this situation. The multidimensionality of sustainability becomes clear regarding the use of hemp.

On the one hand, it defines the use of hemp resources for combustion and energy production. This type of use is close to the pyramid's base [148], indicating low added value. On the other hand, under certain circumstances, such as economic and energy crises, the sustainability approach may lose priority and become a minor issue. The Russian war in Ukraine created significant problems for many countries, as they had to decide on the long-term development of the energy sector and change their long-term development policies. European countries urgently needed to move away from fossil fuels such as natural gas and find ways to replace these fossil fuels with renewable energy sources. In this case, finding criteria covering the entire sustainability spectrum is crucial.

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

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 [149]. Pre-treatment accelerates the process and has many advantages, such as:

a) 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 [150].

Many pre-treatment methods, such as physical, chemical, physicochemical, and biological, can be applied to the biomass. The physical pre-treatment method requires a vast amount of energy; it also depends on the type of biomass. Due to each biomass's different porosity and particle size, the physical pre-treatment method requires different energy consumption. In contrast, the biological pre-treatment method requires microorganisms like fungi, algae, and bacteria to digest hemicellulose and lignin residues. The biological method also requires certain conditions at a laboratory scale, which are not costly but are time-consuming, such as microbial pre-treatments.

On the other hand, the physical method requires less time and requires a higher amount of energy, which is not environmentally friendly [150]. Chemical pre-treatment can be done by using various solvents. Also, this method is costly but the most promising. Alkali pre-treatment requires a catalyst to access the process, which is expensive. In contrast, acid pre-treatment requires costly acids for recovery and specific standard equipment that can resist corrosion [151]. An organic solvent is also one of the chemical pre-treatment methods with remarkable environmental benefits, such as the requirement of low temperature and pressure, but with a high capital cost [152].

The case study was conducted to evaluate different chemical pre-treatment methods for one biomass source (Hogweed). Three main criteria considered for evaluation are technical, economic, and environmental. In terms of the economic parameter, the cost is considered the most influential criterion because pre-treatment scenarios involve equipment costs, maintenance costs, capital costs, and the costs for catalysts and reactors. Environmental evaluation criteria are aggressive chemicals, percentage of by-products (by mass or weight), amount of wastewater, and hazardous disposals.

The second possibility for pre-treatment assessment is to use three biomass sources which are *Sorbaria sorbifolia* (false spirea), *Heracleum Sosnowski* (hogweed), and *Solidago canadensis* (goldenrod), and compare their properties with one pre-treatment method. The aim is to take three different biomasses and compare the potential of maximum fiber extraction. *Sorbaria sorbifolia* species is extremely useful in the medicinal area. It treats the breakdown of bones, swelling, and pain [153]. However, this area of research is under widespread scrutiny and investigation. At the same time, the *Solidago canadensis* species has been widely observed as a decorative plant. Different parts of this plant have their specialty to produce valuable products such as flowers, leaves, and stems that can produce honey, essential oils, and cellulose.

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 technical, environmental, and economic data availability. After that, the decision-making matrix is compiled. All costs are considered to pre-treat 1kg of hogweed [154]. However, for KOH cost assumption is based on the literature [113], 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 [155]. 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 (Table 3.6) [154].

Table 3.6

Pre-treatment Method Alternatives and Selected Criteria

		Alternatives						
		NaOH	KOH	Ca $(OH)_2$	H_2SO_4	HCL	H_2O_2	CH_3COOH
	Indicators	Xa1	Xa2	Xa3	Xa4	Xa5	Xa6	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 (Fig. 3.20). 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.

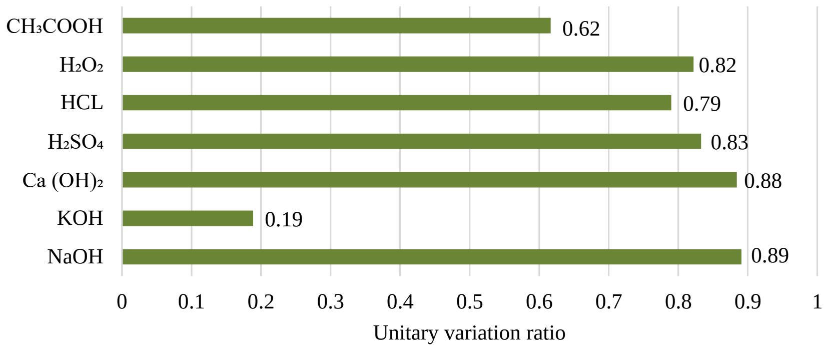


Fig. 3.20. TOPSIS results for pretreatment methods.

The different weights are attributed to each alternative pretreatment method used to perform sensitivity analysis for the concentration indicator. The visualization of the impact of weight change for the concentration indicator is shown in Fig. 3.21. The graph shows the TOPSIS results for concentration over the unitary variation ratio, considering 1 as the initial state. Xa1 shows the highest performance when the weight is three times higher than initially. However, Xa7 shows the opposite result at the same weight. In the case of Xa4 and Xa5, they have increased results at a united variation ratio of 3. The most stable is Xa6, which only slightly decreases at three times the weight for concentration criteria. Decreasing the weight significance minimally impacts the alternative results; for example, weight variation for 0.01 and 0.5 shows similar values for all alternatives as in the initial assessment.

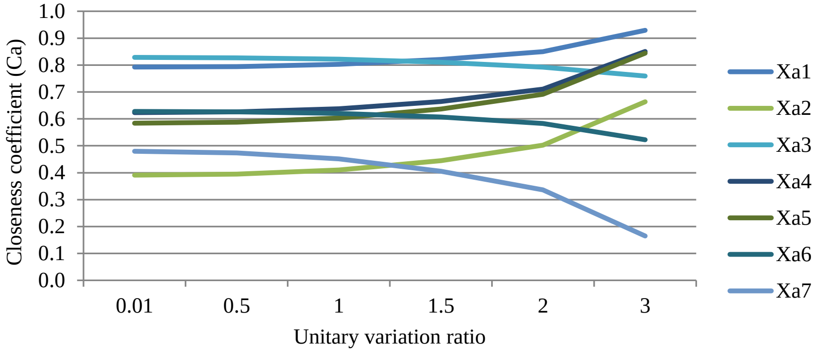


Fig. 3.21. Results of sensitivity analysis for the concentration indicator.

A sensitivity analysis for the Time indicator shows the variation in results due to increased or decreased significance of pre-treatment time criteria (see Fig. 3.22). Xa3 reaches the highest result if the importance of time criteria is increased. At the same time, Xa7 has the lowest results for unitary variation ratio 3. In the case of Xa4, Xa5, and Xa6, there is a similar decreasing tendency due to an increase in the significance of pretreatment time criteria compared to other evaluation criteria. Xa2 is showing an increasing pattern due to weight increase.

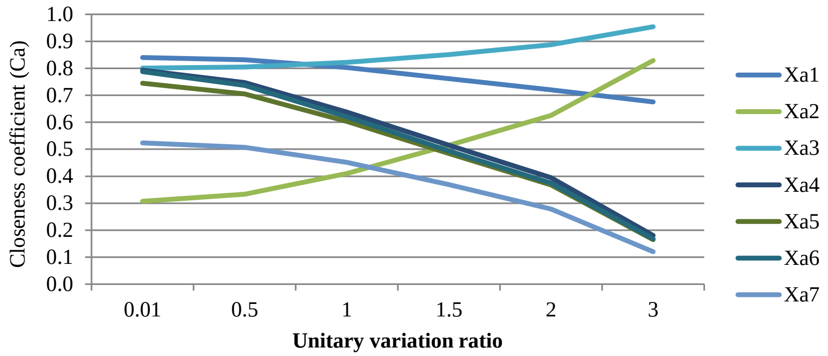


Fig. 3.22. Results of sensitivity analysis for the time indicator.

Fig. 3.23 shows the drastic change in the cost indicator. Xa2 shows the decreasing order from weight variation 0.01 to 3. Xa7 shows the minor slope and crossed with alternative 2 at ideal unitary value 1. Xa3 and Xa1 have equal values for variation weights 1.5, 2, and 3. Xa4, Xa5, and Xa6 steadily increase from a weight variation of 0.01 to 3. Overall, sensitivity analysis for the cost indicator shows the opposite results of the time indicator.

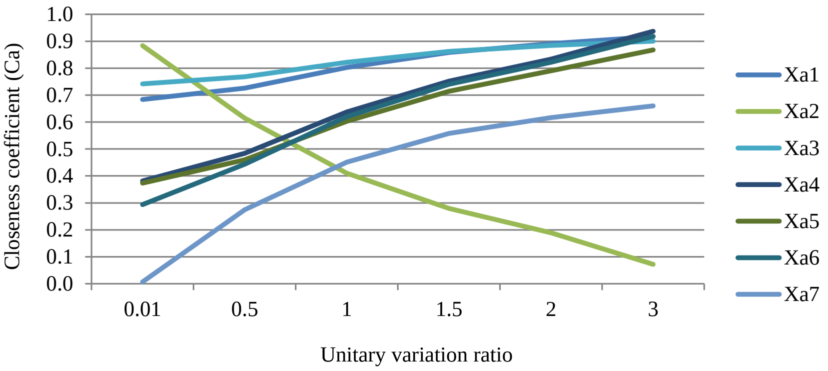


Fig. 3.23. Results of sensitivity analysis for the cost indicator.

The CH_4 generation capacity indicator is considered to have an appositive effect on the pretreatment methods as it benefits the environment. Fig. 3.24 shows the sensitivity analysis results for the CH_4 generation capacity indicator. Xa2 is the only alternative that shows the increase in value if the unitary variation ratio is changed from 0.01 to 3. This is because Xa2 has the highest CH_4 generation capacity. The rest of the alternatives present decreasing results for increased weights of the CH_4 generation criteria, but all alternatives show the same action performance for decreased weight.

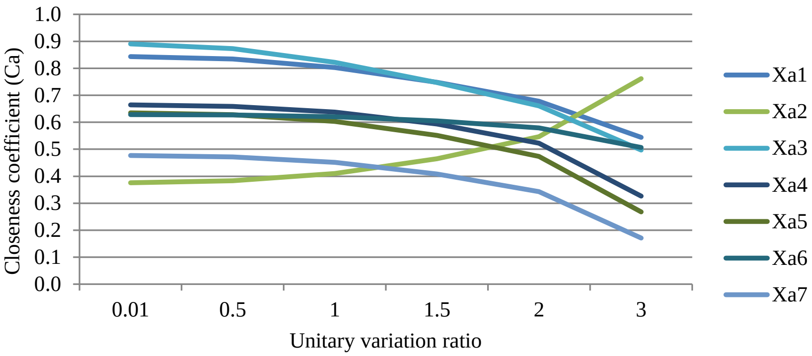


Fig. 3.24. Results of sensitivity analysis for the CH_4 generation capacity indicator.

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. Fig. 3.25 describes the essential oil extraction pathway from fruit peel waste using green extraction methods. The MCDA TOPSIS is used to make decisions, analyze the significance of objectives, and 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.

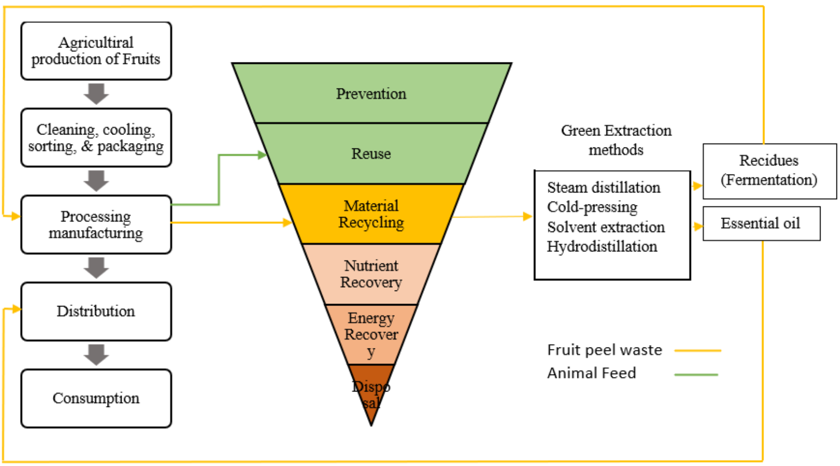


Fig. 3.25. Essential oil extraction pathway (Author's illustration).

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 3.7 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 [156]. Earlier studies show that 93 % of the proportion of essential oil can be extracted by steam distillation [157]. 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^{o}C [158]. The solvent extraction method, also known as liquid-liquid extraction, is a method to separate compounds based on the solubility of their parts [159]. Hydro distillation is a traditional method to extract oil or bioactive compounds from plants [160]. Overall, all four methods have different functionalities and apparatuses.

Table 3.7

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	[161]
Cold pressing	High-quality production possibility	Lack of hazardous organic solvent & environmentally friendly	Low cost & less manpower required	[162]
Solvent extraction	Simple equipment used, Low efficiency	High temperature & production of hazardous waste	Low cost	[162]
Hydro distillation	Simple instrumentation	High consumption of energy, no organic solvent	Low cost	[163]

The pairwise comparison between technological, economic, environmental, and social criteria with the AHP results is shown in Table 3.8. The results show that the weight of the technological criterion is the most important (0.45), the second most crucial weight is economical (0.25), and the third and fourth criteria are environmental and social, which are 0.22 and 0.08, respectively. The comparisons are consistent and used in the following calculations, considering that the value of the consistency rate is CR = 0.079. The discrepancy is acceptable if the CR is less than or equal to 0.1. However, the subjective assessment must be reconsidered if it is higher than 0.1.

Table 3.8

AHP Pairwise Comparison Matrix of Criteria

Criteria	Technological	Economical	Environmental	Social
Technological	1	3	2	4
Economical	0.333333333	1	2	3
Environmental	0.5	0.5	1	4
Social	0.25	0.3333333	0.25	1

The potential for using the four technologies was rated on a scale from 1, which corresponds to the lowest rating, to 5, which corresponds to the highest rating. Table 3.9 shows the evaluation values in a decision-making matrix.

Table 3.9

Decision-making Matrix

Alternative technologies	Criteria			
	Technological	Economical	Environmental	Social
Steam distillation	4	4	3	4
Cold-pressing	4	5	4	3
Solvent extraction	3	3	3	4
Hydro distillation	3	3	4	4

The TOPSIS analysis results are shown in Fig. 3.26. 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.

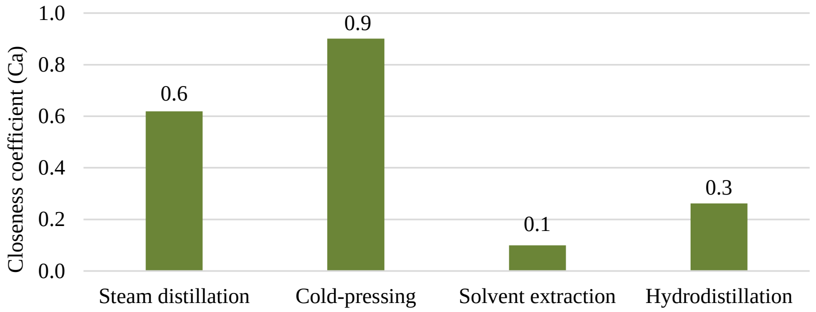


Fig. 3.26. TOPSIS results for extraction technologies.

Results of evaluation multi-level assessment for BSG

The multi-level valorization of single agricultural waste BSG is evaluated by determining the existing situation regarding the utilization and valorization of waste. The following three scenarios are developed to compare the different value levels and determine the best value-added product.

Scenario 1: Biogas production

For scenario one, it is assumed that 1 ton of BSG is used to supplement an existing biogas production plant. No drying of BSG is needed before adding it into the bioreactor. The methane production yield from BSG is 218.89 m^3 CH_4 / ton, and the methane calorific value is 9.97 kWh /m^3; combustion plant efficiency is assumed to be 0.884 [164]. Thus, from 1 ton of BSG, 218.89 m^3 CH_4 can be produced with a maximal calorific value of 2181.9 kWh and an output of obtainable energy of 1928.8 kWh. As BSG is bioresource, the CO_2 emissions from burning bioresource-based biogas are assumed to be 0. For the economic costs of using BSG for biogas production, they are assumed to be given to biogas plants at no cost. In detail, the transportation costs should be accounted for in each potential project separately. However, to calculate the net present value of this scenario, transportation costs were assumed to be similar to in [164].

Scenario 2 –Single-use biodegradable dishes

The scientific literature recently reported the production of single-use dishes from BSG and potato starch by hot-pressing [165]. They report that the share of BSG can be up to 80 % of the final product. However, the best flexural strength compared to expanded polystyrene was obtained at 60 % of BSG share and the addition of chitosan and glyoxal. Examples of single-use plates are produced from a similar material. [165]. The moisture of BSG is 77 % in the sample used. In comparison, 68 % of initial moisture has been reported for a Latvian sample [164]. Therefore, BSG must be dried before hot-pressing single-use dishes. The energy required to dry 680 kg of water is calculated as 490.1 kWh, accounting for 88.21 Euro costs if an electric drying oven is used. From 1 ton of wet BSG, 320 kg may be obtained. Therefore, according to the formulation, 195.73 kg of starch and 17.6 kg of glycerol would be needed, costing 47,0225.6 euros, considering current chemical prices. In the current scenario, it is assumed that the water added to form the mixture is evaporated during the hot-pressing process, and the mass of the end product equals the weight of dry components. If the weight of a ready plate is assumed to be 100 grams (similar to products available in retail stores, then around 5,333 plates can be made from 1 ton of BSG. The hot-pressing temperature may be from 130 °C to 220 °C, and the time required for pressing differs from 2 to 20 minutes. For a cautious assumption, 10 minutes' residence time is assumed, and the equipment power requirements are assumed from listings for an automatic flat heat press.

Scenario 3 –Animal feed

One potential higher-added-value application of BSG is the production of dog biscuits. The price of flour is assumed to be 1 Euro/kg, the price of peanut butter is assumed to be 13.50 Euro/kg, and the price of eggs is assumed to be 0.2 Euro per piece according to retail prices in May 2020. It is assumed that BSG is available at no cost to the brewery. The input mass of the available recipe is approximately 1kg, and the recipe provides that the outcome would be about 100 dog snacks. However, the outcome in weight (weight changes during cooking and drying) is not mentioned. It is cautiously assumed that 100 dog snacks equal one commercial package of dog snacks (200 g), for which a retail price of approximately 9.17 Euro per package was found in the source. Therefore, the cost for raw material for 1 batch would be approximately 2.40 Euro, and the energy cost assuming small-scale production (electric oven) is 1.50 Euro per batch. The labor costs are assumed to be negligible for initial assessment, considering that brewery workers could be able to do small-scale production within their day-to-day duties. CO_2 emissions from production arise due to the electricity use of an oven. As Latvia's electricity CO_2 emission factor is reported to be 0,149 kgCO_2 eq kWh-1 [217], the CO_2 eq emissions for 1 batch of dog biscuits would be 1.3 kgCO_2 eq. From 1 ton of BSG, approximately 1,950 batches of dog biscuits can be produced. Therefore, the economic costs for raw materials and energy would account for 7,632.3 Euro, the CO_2 emissions due to electricity use would account for 2,470 kgCO_2 eq, and the profit could account for 17,881 Euros. It is assumed that the production process and packaging would be manual work. The costs of packaging materials are not considered, assuming that during start-up, simple packaging means could be used, and distribution could be organized through breweries' in-house shops or farmers' markets.

The results for comparing environmental and economic aspects (CO_2 emissions) (Net present value, capital investments) for all three scenarios are discussed below. The functional unit for which the initial scenarios were calculated was 1 ton of BSG, assumed to be the monthly amount that a medium-sized brewery can supply. The Net present value values were calculated for all three scenarios based on the assumptions of capital investments needed, the annual costs, and income. The labor costs were not considered, as it is assumed that a single employee could be employed for each of the scenarios, or in case the breweries themselves develop the production of additional products, existing employees can be involved. The results of the Net present value, annual CO_2 emissions, and profit are shown below (see Fig. 3.27). The highest CO_2 emissions are for dog treat production due to the technological process where wet BSG is used directly in the mixture. However, baking dog treats require longer residence time in the oven, thus more extensive energy use and higher CO_2 emissions. On the other hand, the Net present value for dog treat production is also the highest, partly due to lower necessary capital investments and partly due to the higher price of the end product (as well as a cautious assumption of half of the price found in a foreign example was used for calculations, considering the lower willingness to pay of Latvian consumers).

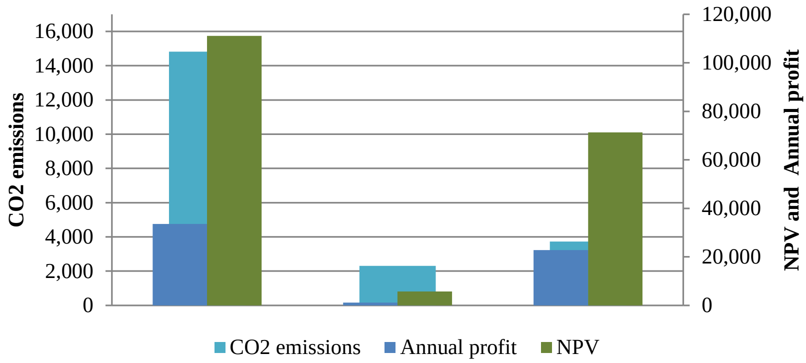


Fig. 3.27. Results of multi-level assessment.

The biogas scenario has the lowest annual CO_2 emissions. No capital costs are needed, but this scenario also has the lowest Net present value and annual profit due to only a small addition of added value during BSG processing into biogas. Besides, to consolidate the effects of various evaluation criteria and provide a single value evaluation for each of the scenarios, a TOPSIS method was applied. The ideal solution is assumed to be minimal in terms of capital costs and CO_2 emissions. In contrast, for the Net present value, the ideal solution is maximum (see Fig. 3.28). Finally, sensitivity analysis is performed to check the influence of attribute distribution on the TOPSIS method results for both case studies.

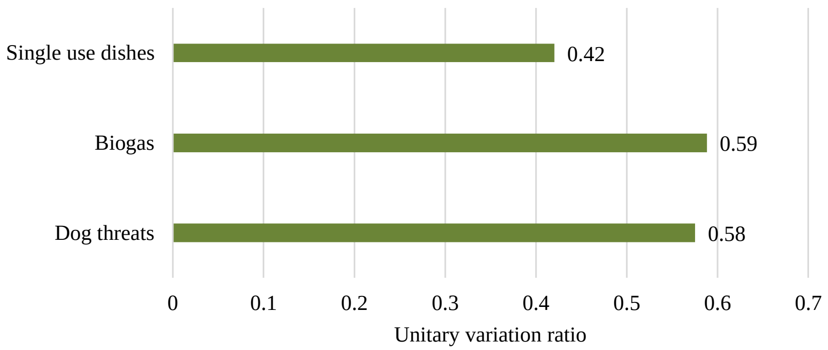


Fig. 3.28. TOPSIS results for multi-level valorization.

Results of evaluating biopolymers alternatives under sustainability framework

Indicator selection

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 for producing biopolymers were chosen. The selected criteria and indicators used to evaluate alternative biopolymers are listed in Table 3.10.

Table 3.10

Set of Criteria and Indicators Used to Evaluate Alternative Biopolymers

Criteria	Indicator	Unit of measures	Source
Environmental	Carbon footprint	CO_2eq/kg polymer	[4][166]
	Energy consumption	MJ/kg polymer	[4][166]
	Acidification	SO_2eq/kg	[4][167]
Circularity	Biodegradability	%	[168]
	Period of biodegradability	Days	[168]
Technical	Melting point	℃	[169]
	Density	kg/m^3	[169]
	Tensile strength	MPa	[169]
Social	Human health	kg 1,4-DB$_{eq}$	[4][170]
Economic	Production cost	USD/kg	[4][171]
	Market price	USD/kg	[4][171]
	Global production capacity	%	[172]

Biopolymer production is an effective way to replace fossil fuel-based biopolymers. However, extensive production and consumption generate several adverse effects, including GHG emissions [173]. The indicators for the environmental aspect are selected to achieve sustainable development. Three leading indicators (carbon footprint, energy consumption, and acidification) are selected to evaluate the environmental feasibility. The circular economy concept shows the minimal waste of materials and energy through extensive reuse, recycling, and recovery in production and consumption [168]. Biodegradability and the period of biodegradability indicators depict the efficiency of using biopolymers during and after the lifespan of the biopolymer [174]. The technical aspects represent the properties of biopolymer. Density is a crucial indicator for producing biopolymers, as the environmental impact can change if the density of the biopolymer alters [169]. Tensile strength is defined as stress, which gives the crystallinity of the biopolymer film [175]. The melting point is one of the significant indicators. The high melting point reduces the viscosity and improves the processability of the biopolymer [169]. The human health indicator is considered for the social aspect, which determines the exposure and effects of toxic substances for biopolymer production [176].

Moreover, the migration of nanomaterial (the particles' size and the biopolymer's consumption rate) affects human health [177]. Three indicators are selected to assess the economic feasibility of the biopolymer: production cost, market price, and global production capacity. The production cost includes product expenses, such as capital, maintenance, and operational costs [178]. Market price shows the economic value of the biopolymer, which is determined by the forces of supply and demand [179]. Global production capacity shows the worldwide production capacities of biopolymers, which are used to determine the growth rate and developing trends in biopolymers [180].

Data collection

Only quantitative values are considered for each indicator to derive solid results. Five types of biopolymers, five criteria, and twelve indicators are analyzed in this study, and all the gathered input data are summarized in Table 3.11. It is a fact that the availability of quantitative data was a significant obstacle to gathering the quantitative input for the indicators.

Table 3.11

Data Collection for Biopolymers

No.	Agricultural resources	Type of biopolymer	Criteria	Indicator	Unit of measures	Output	Source
1	Sugar cane, maize, wheat, sugar beet	Polylactic acid (PLA)	Environmental	CO_2 emission	CO_2eq/kg polymer	1.8	[181]
				Energy consumption	MJ/kg polymer	54.1	[181]
				Acidification potential	SO_2 eq/kg	7.3	[182]
			Circularity	Biodegradability	%	79.7	[183]
				Period of biodegradability	Days	28	[183]
			Technical	Melting point	°C	180	[184]
				Density	kg/m^3	1210	[185]
				Tensile strength	MPa	15.5-150^	[186]
			Social	Human health	kg 1,4-DB eq	1.2	[187]
			Economic	Production cost	USD/kg	1.47	[188]
				Market price	USD/kg	1.50-2.09*^	[189]
				Global production capacity	%	18.9	[190]
2	Spent coffee grounds, waste rapeseed oil, sugarcane bagasse, paddy straw, and molasses (Grain waste)	Polyhydroxy alkenoate (PHA) & Polyhydroxy butyrate (PHB)	Environmental	CO_2 emission	CO_2eq/kg polymer	2.6	[181]
				Energy consumption	MJ/kg polymer	54.1	[181]
				Acidification potential	kg/ SO_2 eq	24.9	[182]
			Circularity	Biodegradability	%	80	[183]
				period of Biodegradability	Days	28	[183]
			Technical	Melting point	°C	175	[191]

				Density	kg/m^3	1180	[192]
				Tensile Strength	MPa	20-40^	[191]
			Social	Human health	kg 1,4-DB eq	0.85	[193]
			Economic	Production cost	USD/kg	2.65	[194]
				Market price	USD/kg	4.09-4.59*^	[189]
				Global production capacity	%	1.8	[190]
3	Maize, potatoes, cassava, barley, rice, sorghum, sweet potato, and wheat (Food and Grain waste)	Starch-based biopolymer	Environmental	CO_2 emission	CO_2eq/kg polymer	1.14	[181]
				Energy consumption	MJ/kg polymer	25.4	[181]
				Acidification potential	SO_2 eq/kg	8.7	[182]
			Circularity	Biodegradability	%	85	[183]
				Period of biodegradability	Days	90	[183]
			Technical	Melting point	℃	180	[195]
				Density	kg/m3	1650	[196]
				Tensile strength	MPa	0.4-25^	[197]
			Social	Human health	kg 1,4-DB eq	0.0112	[198]
			Economic	Production Cost	USD/kg	0.61	[199]
				Market price	USD/kg	2.59-3.39*^	[189]
				Global production capacity	%	16.4	[190]
4	Wheat gluten, egg white, milk whey, and soy protein (Dairy waste and Soy protein)	Protein-based biopolymer	Environmental	CO_2 emission	CO_2eq/kg polymer	0.115	[187]
				Energy consumption	MJ/kg polymer	2.9	[187]
				Acidification potential	SO_2 eq/kg	9.3	[187]
			Circularity	Biodegradability	%	95	[200]
				Period of biodegradability	Days	30	[200]
			Technical	Melting point	℃	140	[201]
				Density	kg/m^3	1090	[202]
				Tensile Strength	MPa	3.4	[203]
			Social	Human health	kg 1,4-DB eq	0.28	[187]
			Economic	Production cost	USD/kg	3.78	[204]
				Market price	USD/kg	2.89-6.88*^	[189]
				Global production capacity	%	1.2	[190]
5	Cotton, bagasse, corn stalk	Cellulose-based biopolymer	Environmental	CO_2 emission	CO_2eq/kg polymer	0.79	[205]
				Energy consumption	MJ/kg polymer	5.4	[206]
				Acidification Potential	SO_2 eq/kg	0.0078	[205]

Table 3.11 continued

	Circularity	Biodegradability	%	35	[183]
		Period of biodegradability	Days	14	[183]
	Technical	Melting point	°C	233	[207]
		Density	kg/m^3	490	[208]
		Tensile strength	MPa	1.81	[208]
	Social	Human health	kg 1,4-DB eq	0.3	[209]
	Economic	Production cost	USD/kg	1.9	[210]
		Market price	USD/kg	3.99*	[211]
		Global production capacity	%	3.2	[190]

Notes: * Market value is considered based on the conversion rate EURO to USD on August 25, 2022.
^ Tensile strength and market price are calculated by calculating a range median.

Survey & AHP results

Among the survey respondents, 41 % were consumers, 14 % were from society, 7 % were scientists, and the rest, 38 %, were value-chain actors, government policymakers, 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. 3.29.

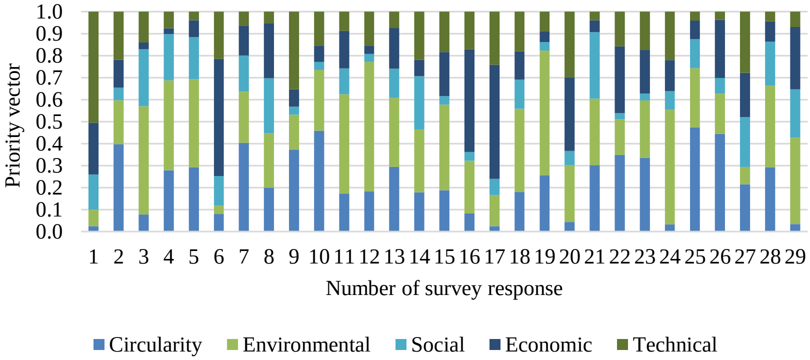
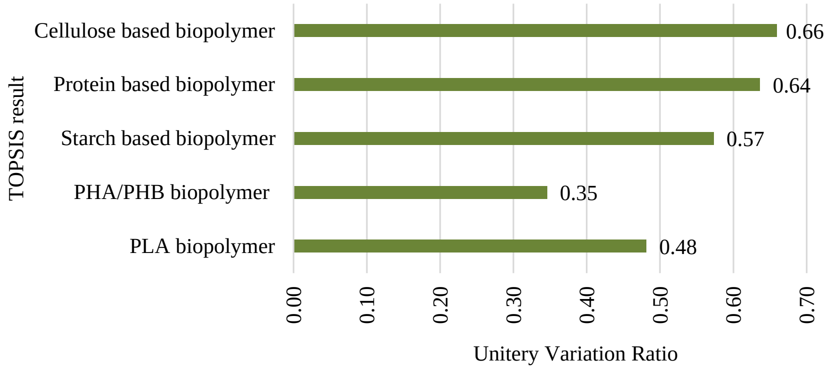


Fig. 3.29. AHP survey results

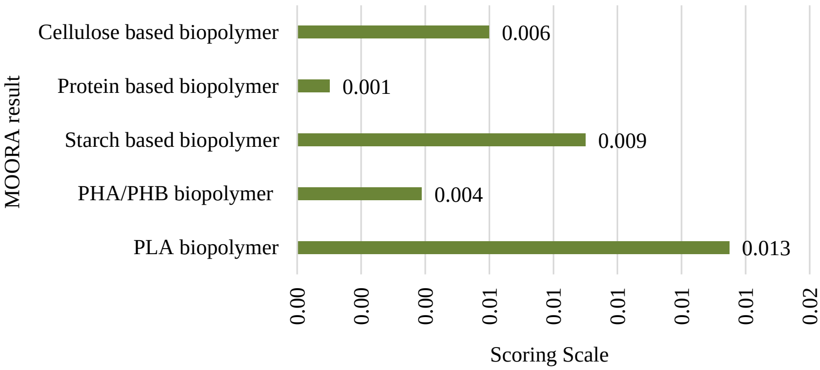
According to the average mean of the five main criteria, the environmental aspect was of the highest priority (0.30), followed by the circularity aspect (0.23), economic aspect (0.18), technical aspect (0.16), and social aspect (0.13). These AHP weights are included in the MCDA methods.

Decision-making results for biopolymer packaging material

The MCDA results for TOPSIS, MOORS, COPRAS, and VIKOR are briefly described in this section (see Fig. 3.30). Integrating the same AHP weights into MCDA methods shows different results for each method. Fig. 3.30(a) shows the interpretation of TOPSIS results. The best biopolymer alternative derived is the cellulose-based biopolymer (0.66) followed by the protein-based biopolymer (0.64), starch-based biopolymer (0.57), PLA biopolymer (0.48), and PHA/PHB biopolymer (0.35). The alternative ranking is based on the unitary variation ratio's high to low value.



(a)



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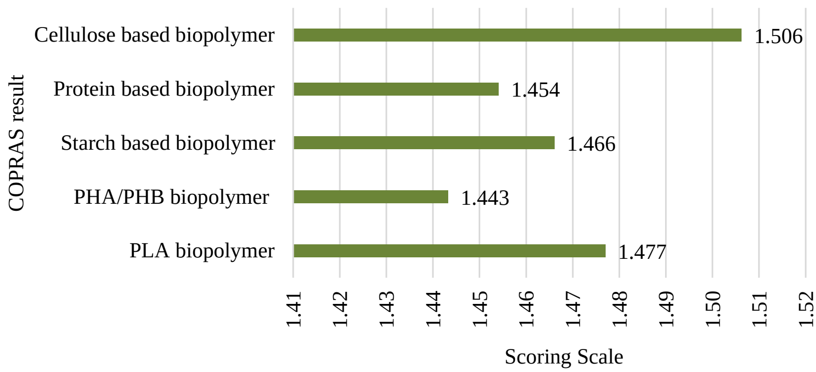

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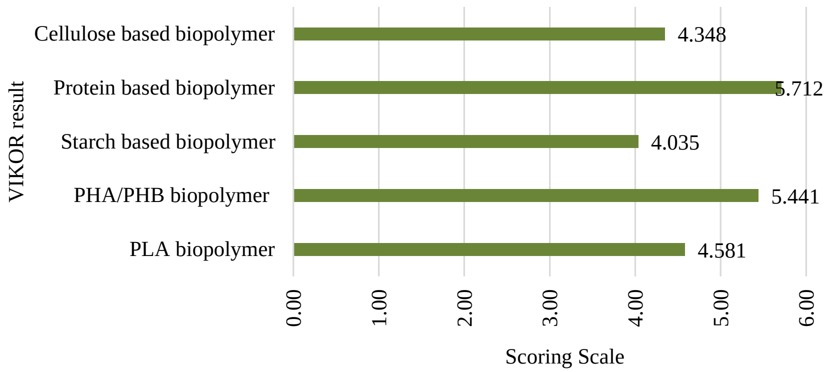

(d)

Fig. 3.30. MCDA results: (a) TOPSIS results, (b) MOORA results, (c) COPRAS results, and (d) VIKOR results.

On the other hand, the MOORA analysis shows that the best biopolymer alternative is the PLA biopolymer (0.013), followed by the starch-based biopolymer (0.009), cellulose-based biopolymer (0.006), PHB/PHA biopolymer (0.004), and protein-based biopolymer (0.001). Fig. 3.30(b) shows the overall results of the MOORA analysis. The ranking in MOOORA analysis is based on alternatives' high to low-scoring values, which means a high-scoring value derives the first rank.

Fig. 3.30(c) shows COPRAS analysis results. The ranking of alternatives for COPRAS analysis is based on the high to low scoring value. The highest scoring value and first rank are derived for the cellulose-based biopolymer (1.51). In contrast, the lowest value and fifth rank are derived for the PHA/PHB biopolymer (1.44). The rest of the alternatives, PLA (1.48), starch-based (1.47), and protein-based (1.45) biopolymers, ranked second, third, and fourth, respectively.

In VIKOR analysis, alternatives are ranked based on low to high scores, meaning the lowest score derives from the first rank. As shown in Fig. 3.30(d), the first rank goes to the starch-based biopolymer with the lowest score (4.03), and the last rank goes to the protein-based biopolymer (5.71) with the highest score. The cellulose-based (4.34), PLA (4.58), and PHA/PHB (5.44) biopolymers derived second, third, and fourth ranking, respectively.

Different MCDA methods were compared by [212], and different results were obtained for each MCDA method. Since 1996, the problem of selecting a proper MCDA method has been a vital discussion topic [213]. 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 [214]. Several factors influence the different results when applying various calculating procedures, such as [215][216], 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 3.12 based on the ranking of biopolymers.

Table 3.12

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 [217]. However, [218] 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 [218]. In contrast, the MOORA and VIKOR methods show that PLA and starch-based biopolymers are the most suitable options, 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 for production from agricultural waste.

3.2. 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 results for market attractiveness are presented in Table 3.13. Since all market attractiveness indicators are equally important, every indicator was assigned a weight of 16.666 %.

The evaluation rating results for market competitiveness advantage are shown in Table 3.14. 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 the methodology developed, these two indicators are crucial for a strong business portfolio. The rest of the indicators are evaluated for the 15 % of weights.

Table 3.13

Evaluation Rating Results for Market Attractiveness

Indicators	Weights	External importance scale	Very unattractive 1	Unattractive 2	Neutral 3	Attractive 4	Very attractive 5	External importance scale	Source
Market size	16.666 %	Little	C	P2	S	P1		Great	[219]
Market growth rate	16.666 %	Low		C	S	P2	P1	High	[220][221][81][222]
Market profit	16.666 %	Low		C	S	P2	P1	High	[219]
Price sensitivity	16.666 %	High		C; P2	S		P1	Low	[189][211]
Access to raw material	16.666 %	Difficult					C; S; P1; P2	Easy	[223][224][225]
Production cost	16.666 %	High		P2		C; P1	S	Low	[210][194][199]

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

Table 3.14

Evaluation Rating Results for Market Competitive Advantage

Indicators	Weights	Very low competitive advantage (Rating scale 1)	Low competitive advantage (Rating scale 2)	Moderate competitive advantage (Rating scale 3)	Highly competitive advantage (Rating scale 4)	Very highly competitive advantage (Rating scale 5)	Source
Demand	15 %		S	P1	P2	C	[220][221][226][222]
Market share	15 %		C	S	P2	P1	[219]
Availability of resources	20 %					C; S; P1; P2	[223][224][225]
Selling price	15 %		C; P2	S		P1	[189][211]
Environmental ease	20 %				P1; P2	S; C	[181][205]
Quality (based on melting point)	15 %			P2	P1; S	C	[192][191][195][207]

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

Table 3.15 demonstrates the weighted scores for the market attractiveness and competitive advantages. The visualization of GE-McKinsey results is shown in Fig. 3.31. 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) [189] with the highest production capacity of 37.9 % [79] compared to other packaging materials. PHA packaging material has the weakest position in the market competitive advantage (3.15).

Table 3.15

Results Overview for Biopolymer Market Attractiveness and Competitive Advantages

Market attractiveness evaluation									
Weights of importance						**Weighted scores**			
	Biopolymer packaging materials								
Indicators	**Cellulose**	**Starch**	**P1- PLA**	**P2- PHA**	**Weights**	**Cellulose**	**Starch**	**P1-PLA**	**P2-PHA**
Market size	1	3	4	2	16.666 %	0.166	0.498	0.664	0.332
Market growth rate	2	3	5	4	16.666 %	0.332	0.498	0.83	0.664
Market profit	2	3	5	4	16.666 %	0.332	0.498	0.83	0.664
Price sensitivity	2	3	5	2	16.666 %	0.332	0.498	0.83	0.332
Access to raw material	5	5	5	5	16.666 %	0.83	0.83	0.83	0.83
Production cost	4	5	4	2	16.666 %	0.664	0.83	0.664	0.332
Total	16	22	28	19	100 %	**2.66**	**3.65**	**4.65**	**3.15**

Market competitive advantage evaluation									
Weights of importance						**Weighted scores**			
	Biopolymer packaging materials								
Indicators	**Cellulose**	**Starch**	**P1- PLA**	**P2- PHA**	**Weights**	**Cellulose**	**Starch**	**P1-PLA**	**P2-PHA**
Demand	5	2	3	4	15 %	0.75	0.3	0.45	0.6
Market share	2	3	5	4	15 %	0.3	0.45	0.75	0.6
Availability of resources	5	5	5	5	20 %	1	1	1	1

Table 3.15 continued

Selling price	2	2	5	2	15 %	0.3	0.3	0.75	0.3
Environmental ease	5	4	3	1	20 %	1	0.8	0.6	0.2
Quality (based on melting point)	5	4	4	3	15 %	0.75	0.6	0.6	0.45
Total	24	20	25	19	100 %	**4.10**	**3.45**	**4.15**	**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, market growth rate and potentially giving a better price. The market share for cellulose is only 1.5 % [79]. Starch packaging materials show an average position for market attractiveness (3.65) and competitive advantage (3.45). However, improving both ratios can lead to a higher position for starch material.

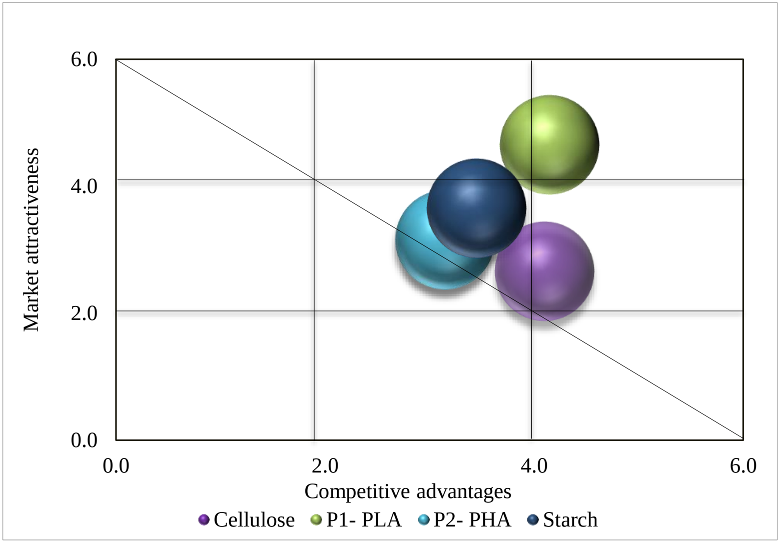

Fig. 3.31. GE-McKinsey matrix results for biopolymer packaging material alternative.

The agriculture industry is a comprehensive source of biomass resources and biomaterial suppliers with significant potential for producing biopolymer packaging materials [227]. Over time, market demand for biopolymer packaging materials should be raised to ensure environmental safety. According to the recent report from European Bioplastics 2022, 48 % of the biopolymer is used as a packaging application in Europe [79]. Despite having a tremendous market opportunity, biopolymer packaging materials seek less cost-effective market strategies to complete the synthetic polymers [228]. Moreover, biopolymers have sensitive characteristics that must be considered when producing mechanical, thermal, and barrier properties. Our previous study [229] shows the evaluation of biopolymer alternatives using different MCDA methods, where cellulose was found to be the best possible alternative in terms of sustainability. The results of this study show that cellulose has the second highest position in terms of market competitive advantage but the weakest market attractiveness. However, it is not always straightforward to determine if the product is fully sustainable and has high market potential. Market potential seeks economic benefit more than environmental benefit [230]. The results of this study strongly favor the production of PLA packaging materials with both market attractiveness and competitive advantage. Moreover, investment opportunities for biopolymer packaging material 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.

3.2. 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, as shown in Fig. 3.32.

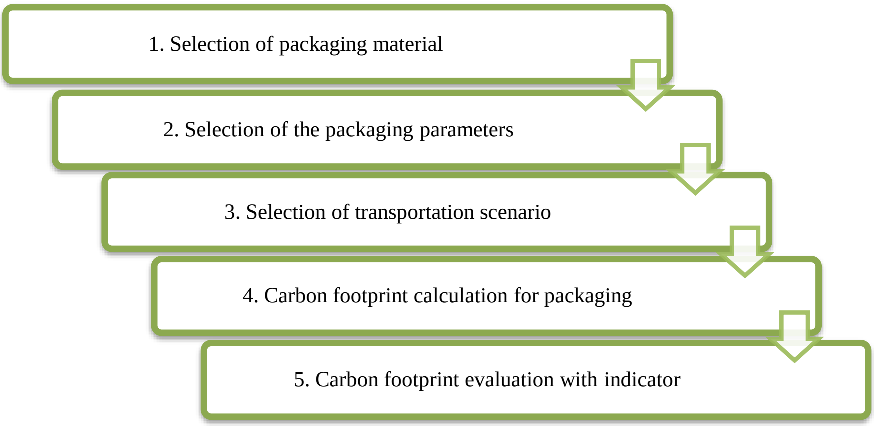

Fig. 3.32. Steps for carbon footprint evaluation.

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 parameters of different packaging materials used for further estimations are given in Table 3.16.

Table 3.16

Parameters of Packaging Materials Included in the Tool

Material, *x*	**Density, ρ (g/cm^3)**	**Thickness variation, *Th* (µm)**	**Material in packaging, σ_A (µg/cm^2)**
Polyethylene Terephthalate (PET)	1.4	12 - 30	1680 - 4200
Low-density polyethylene (LDPE)	0.91	40 -120	3640 - 10920
Polyethylene (PE)	0.95	45 -142	4275 -13490
Recyclable Polyethylene (Recyclable PE)	0.95	25 -142	2375 -13490
Kraft paper	1.201	45 - 80	5405-9608
Brown Kraft Paper	1.201	45 - 90	5405 -10809
Monoaxial-oriented Polyethylene Film (OPE)	0.95	15 - 20	1425 -1900
Polylactic acid (PLA)	1.24	20 - 50	2480 - 6200
Polypropylene (PP)	0.9	15 -70	1350 - 6300
Aluminum (AL)	2.705	7 - 9	1894 - 2435
Polyamide (PA)	1.14	50 - 150	5700 - 17100
Paper	1.201	18	2162
Polyamide nylon (OPA)	1.14	15	1710
Wax (paraffin)	0.9	5	450
Biaxially oriented polypropylene (BOPP)	0.946	15 -70	1419 - 6622
Cast polypropylene (CPP)	0.9	25 - 60	2250 - 5400

Note: The online marketplace provides density ρ, (g/cm3) and Thickness variations Th, (µm).

The packaging size can differ depending on customer needs [231]. In the marketplace, the customer can select the preferred packaging (*p*), 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 (3.1).

$$m_p = A_p \cdot \rho_A \tag{3.1}$$

where

m_p – the mass (g) of selected packaging;

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

ρ_A – area density (µg/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 (3.2).

$$CF_p = CF_{x_p} + CF_{t_p} \tag{3.2}$$

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 (3.3) and (3.4).

$$CF_{x_p} = CF_x * A_p \tag{3.3}$$

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.

$$CF_{t_p} = \sum_{i=t}^{n} D_t \cdot CF_t \cdot m_p \tag{3.4}$$

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 $\mathrm{CF}_{\mathrm{t_p}}$ 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 considers 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 straightforward 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 (3.5) and (3.6).

$$I = \frac{Max\left(CF_p\right) - Min\left(CF_p\right)}{3} \tag{3.5}$$

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.

$$If\ (CF_p) < Min\ (CFp) + (I)\ , then\ (I_{low}); \quad (3.6)$$
$$else\ (if\ (CF_p) \geq Min\ (CFp) + (2 \cdot I);\ then\ (I_{high});\ else\ (I_{medium}))$$

where

I_{low} – low levels of carbon footprint;

I_{medium} – medium levels of carbon footprint;

I_{high} – high levels of carbon footprints.

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.

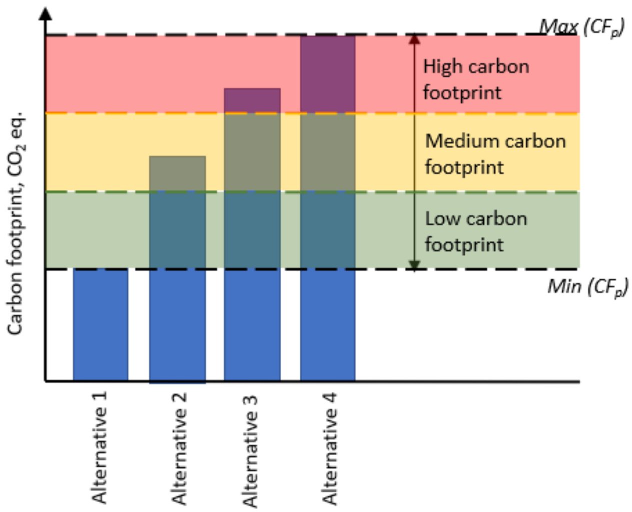

Fig. 3.33. Colour visualization of carbon footprint calculation for packaging alternatives.

The carbon footprint calculation results can be presented to the online marketplace client using color indicators to distinguish these levels. As shown in Fig. 3.33, low, medium, and high carbon footprint levels can be visualized in green, yellow, and red color indicators. Notably, 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, policymakers should enforce and 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. This presents an exceptional opportunity, with cellulose, starch, and PHA packaging materials also positioned to seize significant market interest. The study stresses the complexity of assessing a product's full sustainability and market potential. 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 policymakers 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 plans, 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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PUBLICATIONS ARISING FROM THIS THESIS

A set of publication in the following order:

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, Pages 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, Pages 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, Pages 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, Pages 323-338, https://doi.org/10.2478/rtuect-2023-0025.
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Agro Biopolymer: A Sustainable Future of Agriculture – State of Art Review

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***Abstract* – Due to the rising demand for food and feed, agricultural waste increases, while plastic pollution increases due to hostile human activities. The sustainable way to utilize agricultural waste and promote the bioeconomy concept is to produce an alternative product of plastic, i.e., 'bioplastic'. This paper used different keywords to perform the bibliometric analysis of the scientific publication related to bioplastic, agricultural waste, and sustainability. Remarkably, results show the increasing research interest in bioplastic with the key developing trends in sustainable bioplastic production, agriculture waste management, biopolymer, and biological processes. The identified developing trends can be used for further research to create a sustainable agricultural sector and produce higher added-value products. Moreover, this study discovered that the agro-biopolymer area needs more focus on sustainable development considering the economic, social, and environmental dimensions.**

***Keywords* – Agricultural waste, bibliometric analysis, bioplastic, biopolymer, research gap**

1. INTRODUCTION

The worldwide population is increasing day by day; therefore, the production and distribution of food have increased to fulfil the need of the continuously growing population. The agency of food and feed activities were established in 1945 by the United Nations, known as the 'Food and Agricultural Organization (FAO)'. Agriculture has become more productive worldwide after the FAO was introduced [1]. The agro-industry is one of the significant waste production sectors, including a vast amount of production processing waste [2]. The agricultural sector is facing a diverse problem due to over-consumption of land, forage, and food production [3]. The excessive use of resources and waste generation can cause substandard environmental conditions. Such aspects may disrupt environmental stability on a global scale [4].

Firstly, modern agricultural technology has become more adventitious for increasing crop production. However, modern technology has an adverse effect and creates long-lasting footprints on the environmental, social, and economic sectors [5]. Secondly, waste generation by agricultural activities has become a significant problem. According to [6], humans generate 150 billion metric tons of agricultural waste yearly through intensive farming, harvesting, cultivation, and industrial processes. Unfortunately, this waste resolves by random burning or landfilling activities, which leads to environmental pollution and inappropriate use of resources [7].

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Over the past seven decades from the 1950s [8], plastic demand has increased because it is lightweight, affordable, varied, and readily available. The production of plastic causes a significant environmental impact, considering climate change, greenhouse gas emissions, and marine ecosystems. Plastic pollution affects socio-economic and ecological issues as well [9]. Fossil fuel is a primary resource used in the production of plastic, leading to greenhouse emissions at each stage of the life cycle life cycle stage from extraction to end-of-life [10].

In this regard, the bioeconomy can be one of the ideal solutions to resolve agricultural waste concerns while tackling the plastic pollution problem. The bioeconomy allows valorizing agricultural waste into value-added products using bioconversion processes. Agro-industrial waste includes significant grain, dairy, and food waste. Only a tiny portion of the waste is used as animal feed, manure, and other products. Most of the waste is unutilized, which can be a potential source in the production of bioplastics [11]. Agricultural waste includes livestock, agro-industrial, and aquacultural waste [12].

The modern approach to bioeconomy also involves many technological innovations, for example, large-scale biotechnology applications. New opportunities can be established using modern biotechnology to produce bioplastics from bioresources. The bioeconomy also ensures that the use of bioresources in the bioeconomy is sustainable, efficient, and economical [13]. Bioeconomy improves resource efficiency and waste management streams by providing a replacement for fossil fuel-based resources. It helps to reduce the production cost by promoting agricultural feedstock as a substrate to produce bioplastics [14].

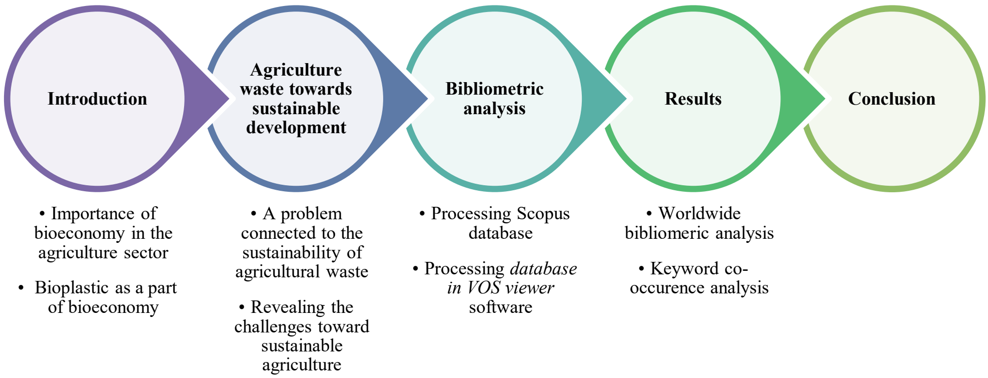

Fig. 1. The overall structure of the study.

This study applies the bibliometric analysis methodology and reviews agriculture waste and bioplastics, considering the sustainable development goals. The overall structure of the study is briefly described in Fig. 1.

2. Agricultural Waste Towards Sustainable Development

2.1. The unsustainability of agricultural waste management

Modern agricultural practices severely affect the environment by releasing polluting compounds (such as heavy metals, excess fertilizers, and chemical substances) into the environment, including soil, surface, and groundwater. These compounds affect crop productivity, human health, and soil and water quality. In addition, chemical substances can cause human diseases through food and water contamination [3]. Due to unfavourable conditions of the environment, crop productivity can decrease by 30–70 % [15]. Farmers are the first to be affected by this uncertainty. The depletion in crop production causes lower crop yields, which leads to a decline in income for the farmers. Moreover, occupational injury, illness, and fatalities can also occur to workers and local communities [16].

In the agriculture sector, crops are long-term investments. Food waste covers the most significant part of the agricultural waste, which can cause a loss of economic value for the agriculture business entities. Globally, food loss and waste value are estimated at one trillion US dollars. Food crops are the primary source of income in some regions, and the seasonal fluctuation in crop prices can affect the international market. Consequently, a significant loss in agricultural product availability arises and affects the overall income of associated agricultural entities [17].

Regarding agricultural waste management, many scientific studies have addressed the three pillars of sustainability, i.e., environmental, social, and economical. Bhuvaneshwari *et al*. address the issue of the burning of agricultural waste in India. Crop residue burning is a major environmental issue worldwide that can cause human health issues and global warming, which leads to climate change. Moreover, burning agricultural residues involves several other sectors, including the environment, agriculture, economy, society, education, and energy. However, the government's efforts toward educational and societal development are insufficient. The burning issue and related impacts can be solved if proper education and awareness are raised among farmers and society [18].

Scarlat *et al*. addressed environmental and economic concerns associated with removing agricultural crop residues, reducing the soil quality, loss of organic matter, soil carbon, and nutrient content, and increasing erosion. The inappropriate disposal of agricultural biomass can cause severe effects such as crop farming practices, soil fertility, moisture, and climate conditions (wind and precipitation) [19], leading to a decline in harvested crops and thus economic loss.

Sabiiti Elly reports concerns regarding the amount of waste generated by the agricultural sector. The increased demand for food leads to large agricultural waste production at various levels, including farmers, municipal, and urban areas. This untreated waste can cause human illness and affect the environment [20]. The improper disposal of agricultural waste can cause an impact on air quality by the emission of odorous substances such as ammonia and greenhouse gas emissions that cause climate change issues [21].

Several barriers are identified by Benyam *et al*. to implementing sustainability in the agricultural sector. The continuously growing farms and demand for food cause resource scarcity and extreme climate change. Modern farming techniques (such as fertilizer and pesticides) undermine the use of naturally derived crop nutrients [22].

The significant economic barrier to sustainability includes the complexity in the efficiency of the technology, lack of knowledge of the production technology, and technology cost limits to the socio-economic benefits for small-scale farmers. The social sustainability barriers are the farmer's lack of expertise in digital technologies, knowledge transfer issues varying the uptake of technologies, and extensive technology adoption that drives unemployment [22].

Agricultural biomass is a vast market for producing bioproducts. However, several barriers can affect the development of sustainability, for example: a) access to information on biomass market functions, b) insufficient knowledge about the benefits of energy efficiency, c) financing sources, d) market infrastructure, and e) agricultural, energy, & environmental policy development. Moreover, other significant concerns identified in developing the agricultural biomass market include a lower possibility of selling biomass profitably, no systematic collection of biomasses, lack of interest in biomass, lack of transportation to supply biomass, and unawareness of the biomass concept [23].

The consequence of agricultural waste production reveals many potential steps that must be taken to prevent environmental impacts and promote the sustainable development of the agricultural sector. A tremendous amount of agricultural waste is produced every year. Still, current approaches to waste reduction are comparatively ineffective due to several barriers such as a lack of farmer's expertise in long-term planning considering sustainability aspects, inconsistent sustainability strategies, and lack of added value approaches. With this concern, the next chapter of this study introduces the approaches that can contribute to resolving a global challenge and establishing sustainable agriculture.

2.2. Resolving the global challenge toward sustainable agriculture

According to the global survey, the assessment of biomass value chains should consider the whole life cycle of a bioproduct from biomass production, pre-treatment, transport, and conversion techniques, to end of life. Several opportunities have been identified for the biomass market, considering economic development, job creation, improvement in production systems, sustainable development, and progress in the supply chains [24].

The transformation of the agricultural industry to circular practices has become a challenge for the industrial revolution. A recent study investigated a circular economy conceptual framework as a way forward to sustainability at the industrial level. The framework of sustainability focuses on the circular economy concept. This framework mainly consists of a) pillars of sustainability (economic, social, and environmental), b) key drivers (feedstock, low carbon product, life cycle, zero-emission, reduce, recycle, and reuse), and c) tools to evaluate and design circularity (material flow analysis, life cycle analysis, and eco-design), and d) the conceptual framework (production stages and integrated assessment methods). This strategic framework can establish sustainability at the industrial level [25].

Belaud *et al*. proposed an integrated approach by integrating big data and sustainability assessment to improve the supply chain design of the agricultural sector. Big data shows the digital and ecological transition for the valorization of agricultural waste. The agricultural by-product valorization is a challenging supply chain, including the operational stages (from biomass to waste disposal), transformation, upstream, and downstream processes. Also, the life cycle assessment methodology has been approached to analyse the impact and various sustainability indicators. However, this approach has a limitation that needs to be explored more: a) addition of specific data sources, methods, and visualization for economic and social areas to improve data inventories and assessment methods, b) the design models for energy, c) development of libraries, sources, and studies for agro-food process engineering, and d) the development of qualitative explanation systems for stakeholders [26].

Barros *et al*. presented a systematic approach to the input-output methodology for agricultural waste valorization. The input (i.e., fuel, water, energy, raw material, animal food, and seed), output (i.e., wastewater, emissions, grains, and agricultural waste), material, and energy flow in the agriculture sector. The input-output flows vary among the different alternatives, such as rural properties containing animal breeding, and the inputs include water, energy, animal food, and medicine. On farms for wheat, corn, and soybean crops, the inputs include water, fuel, seed, and fertilizers. Also, the techno-economic and life cycle analyses have been used to assess the environmental impact of an entire agriculture supply chain, including transportation, processing unknit, and agro-industrial processes. However, the life cycle sustainability assessment method is complex and time-consuming; therefore, limited approaches have been carried out for the sustainability assessment in the agricultural field.

Also, new circular business models need to be created considering the diversity of the circular agricultural economy [27].

A recent study presented an overview of the existing modelling tools to assess the environmental impacts of agricultural waste considering the circular economy concept and industrial ecology, life cycle thinking, and flow analysis. The study finds that life cycle thinking can be a promising tool to assess the effects of and evaluates circular economy characteristics. This study encourages scientists to use such strategies to solve waste problems. The study suggests that the circular economy development policies need in-depth investigation. The integrated approach for the circular economy should be studied more to find more strategies, i.e., suitable for all types of waste categories [28].

A vast amount of agricultural waste is produced yearly, and 50 % of raw materials are discarded without treatment. Amran *et al.* addressed the issue of agricultural waste valorization to improve economic and environmental sustainability. Also, the sustainable strategy in terms of applying green extraction technology. Agricultural waste valorization by using green extraction techniques can increase productivity, social acceptance, and economic stability. Universal problems such as waste management, environmental impacts of landfills, climate change, fossil fuel reduction, and sustainability issues for farm owners can be solved by implementing such strategies. However, this strategy still requires further development to integrate sustainability into the valorization system at the industrial level [29].

Cho *et al*. presented the potential use of biochemical processes to produce biochemicals. Biomass waste is inexpensive, readily available, and renewable. Also, accomplish the fossil fuel demand, manufacturing costs, and address environmental concerns. However, this study identified that conversion technologies need further research to produce competitive products [30]. Overall, the challenges and shortcomings of sustainable agriculture are broader than the already established solutions.

2.3. Agriculture waste to build agro-biopolymer

The industrial revolution in the agricultural sector needs to be implemented by imposing the "resource, recovery, and recycle" concept. The bioeconomy can better balance the environmental, economic, social, and technological aspects of agricultural resources. Besides, the bioeconomy encourages sustainable agricultural sector growth by utilizing resources, providing economic growth to resources, and establishing a balance between consumption and production demand [31].

The agricultural waste valorization pathway has become an evolving approach to producing biopolymers over the last few decades. The conversion of bioplastic from agricultural waste is a more focused area as it leads to sustainable development [32]. Bioplastics can be produced from food, grain, and food waste. Agricultural by-products and inedible food waste are significant sources of bioplastics such as potato peels, sugarcane bagasse, whey protein, eggshells, maize grain, paddy straw, barley straw, rice straw, wheat gluten, and soy protein [33], [34].

Bioplastic production can significantly increase sustainability in the agricultural sector in economic, social, and environmental aspects [14]. Table 1 provides a brief overview of various bioplastics and their versatile applications.

TABLE 1. BIOPLASTIC TYPES AND APPLICATIONS

Type of bioplastic	Example	Description	Application	Source
Aliphatic Polyesters	PLA, PHB, PHA	Include more resistant material, required syntenic biodegradation	Biomedical field, food packaging, film wrap, and utensils	[35]
Protein-based bioplastic	Casein bioplastic	Derived from dairy wastes like milk, wheat gluten, soy protein, and other protein resources	Casein film that extends the shelf life of food products	[36]
Starch-based bioplastic	TPS, Bio-PET	Covers 50% of the global bioplastic market, contain synthetic or natural starch extracts	Food packaging, hygiene products (toothpicks & food service ware)	[37]
Cellulose-based bioplastic	Cellulose acetate, methylcellulose	Derived from cellulose esters or derivatives, they contain glucose molecules	Used as an edible coating for several food items to increase shelf life, biomedical applications like tissue engineering, wound healing, & medical implants	[38]

Notes: PLA- Polylactic acid; PHB- Polyhydroxy butyrate; PHA- Polyhydroxy alkenoate; TPS- Thermoplastic Starch; Bio-PET- Bio-polyethylene terephthalate

3. BIBLIOMETRIC ANALYSIS

Bibliometric analysis is performed based on the Scopus database. Scopus is the largest abstract database and provides exhaustive coverage of scientific journals. Moreover, Scopus provides high-quality assurance of database highly recommended for research assessment, scientific evaluation, and research studies [39]. 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 [40].

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 [41]. 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.

4. RESULTS AND DISCUSSION

4.1. Worldwide bibliometric analysis

Different databases have been used to analyse worldwide research, knowledge, and interest in bioplastics. First, the number of documents published by various countries has been studied using the 'bioplastic' keyword; the first twenty countries with the published papers are shown in Fig. 2. The United States has the highest number of documents (313) among countries, followed by Italy.

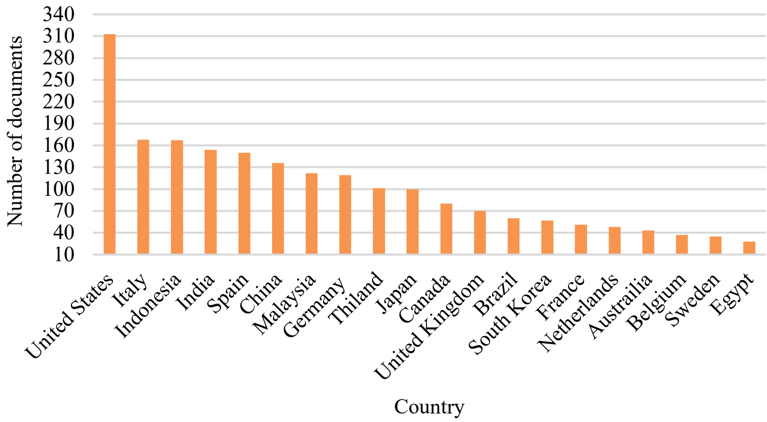

Fig. 2. Documents published per country.

Second, documents published by year have been analysed by choosing the 'bioplastic' keyword. Fig. 3 shows that from 2000, interest has grown in bioplastics, continuously increasing. In 1947, the first technical bioplastic was introduced [42]. Therefore, with the developing trend and interest in bioplastic, by the end of 2021, the highest number of documents were published.

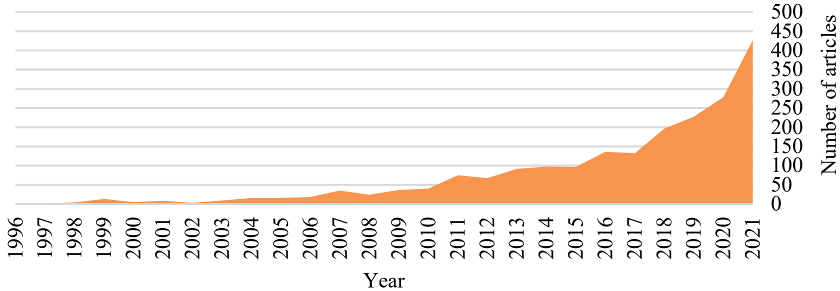

Fig. 3. Documents published per year.

4.2. Keywords co-occurrence analysis

The keyword co-occurrence analysis has been done by analysing the different keywords and combinations. This analysis is done with 2723 scientific documents from the Scopus database. The minimum number of co-occurrences of keywords was set at five.

The global co-occurrences at the abstract and keywords level are shown in Fig. 4. The keywords of each cluster represent its main research area in the domain of bioplastics. The critical research area could be: a) bioplastic properties (green cluster), b) sustainable bioplastic production (blue cluster), c) classification of bioplastics (red cluster), d) biopolymer characteristics (pink cluster), and e) plastic degradation (yellow cluster).

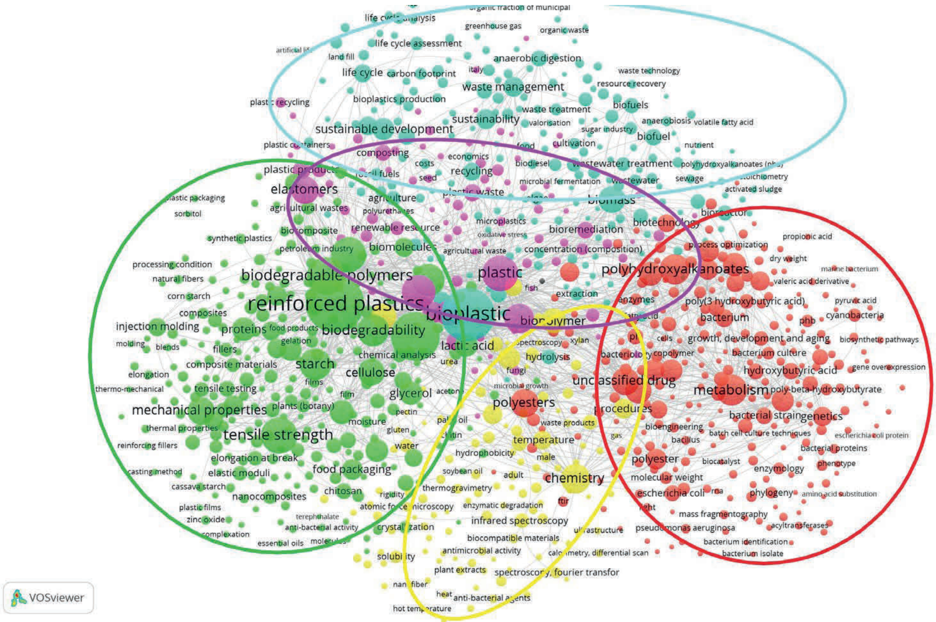

Fig. 4. Visualization of co-occurrences for keyword 'bioplastic'.

The green cluster co-occurrences with mechanical properties, thermal properties, corn starch, biodegradable polymers, and bioplastic components (starch, glucose, glycerol, cellulose, and pectin). The blue cluster has co-occurrence with the bioplastic, life cycle analysis, sustainability, waste management, sustainable development, bioplastic production, resource recovery, and valorization. The red cluster is the third largest and co-occurrences with the classification of bioplastic, which includes polyalkenoates, polyesters, poly (3hydroxybutyric acid), poly-beta hydroxybutyrate, biocatalyst, and enzymology. The fourth cluster shows the co-occurrences between agricultural waste, bioremediation, microplastic, renewable resources, plastic waste, and extraction. The fifth yellow cluster shows the relation between degradation activities which is enzymatic degradation, antimicrobial activities, anti-bacterial agents, solubility, and biocompatible material.

The bibliometric analysis for keywords 'bioplastic' and 'sustainability' is shown in Fig. 5. 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). The green cluster is linked with sustainable development, including bioplastics, biodegradation, packaging materials, renewable sources, and plastic products. The red cluster relates biomass, bioconversion, biopolymer, biorefinery, circular bioeconomy, biotechnology, and sustainability. The yellow cluster shows the link between bioplastic, environmental sustainability, biodegradability, food packaging, and biodegradable plastic. The blue cluster represents the assessment methodologies, including life cycle analysis, economic analysis, and economic and social effects. The purple cluster can be found in different areas and describes terms related to other components.

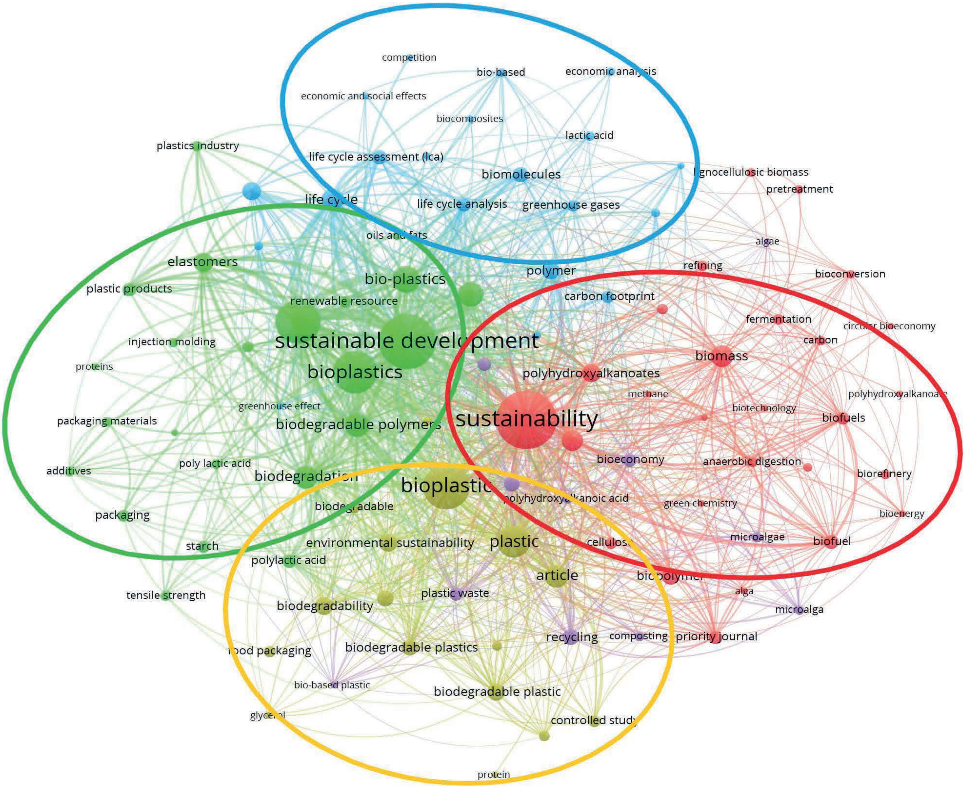

Fig. 5. Visualization of co-occurrences for keywords ‘bioplastic’ and ‘sustainability’.

The bibliometric analysis for the keywords ‘agriculture’ and ‘waste’ and ‘biopolymer’ is shown in Fig. 6. 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 food industry, waste management, sustainability, hydrolysis, and polysaccharide.

The key research area based on co-occurrences for keywords' agriculture' and 'waste' and ‘biopolymer’ could be framed as: a) agriculture waste management (green cluster), b) biopolymers (red cluster), c) bioproducts (blue cluster), d) industrial waste (purple cluster), and e) biological processes (yellow cluster). The green cluster relates to the agricultural activities with agriculture waste, wastewater, and wastewater management with nanotechnology and biocompatibility. The yellow cluster connects 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 bioplastics.

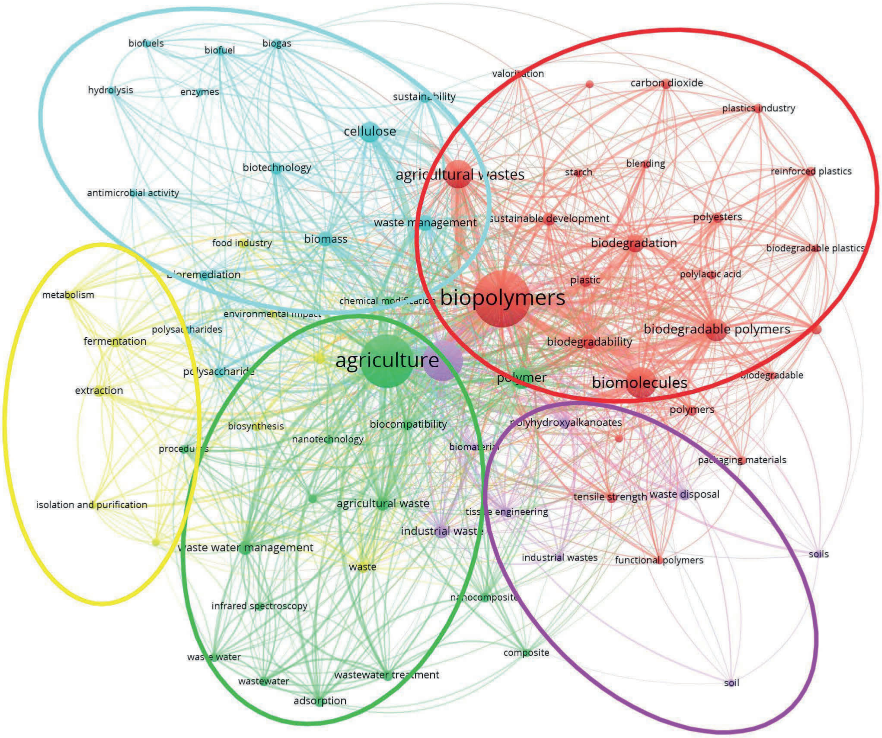

Fig. 6. Visualization of co-occurrences for keywords ‘agriculture’ and ‘waste’ and ‘biopolymer’.

5. CONCLUSION AND RECOMMENDATION

This paper presents a review of agricultural waste challenges and approaches. Also, it evaluates the global research trends in agriculture waste, bioplastic production, and sustainable development. Firstly, the findings in the literature suggest that the main reason behind the hurdles in developing sustainability in the agriculture sector is the lack of sustainability strategies and added value approaches. Agriculture waste valorization can be the potential solution for sustainable development of the agriculture sector and give the added value product (bioplastic) that can drive the sector's economic growth.

Secondly, bibliometric analysis has shown a continuously growing research interest in bioplastics since 1998. The main research areas in ‘bioplastic’ are bioplastic properties, sustainable bioplastic production, classification of bioplastics, biopolymer characteristics, and plastic degradation. The main research areas in ‘bioplastic’ and ‘sustainability’ are sustainable development of bioplastic, assessment methodologies, bioeconomy concept, and biodegradable plastics. The main research areas in ‘agriculture’ and ‘waste’ and ‘biopolymer’ are agriculture waste management, bioproducts, biopolymers, industrial waste, and biological processes.

Lastly, the developing research trends are identified along with the research problem. The identified keyword links of each cluster show the scale of existing research, help identify and determine the relationship between subjects, reveal currently existing boundaries of specific topics, and underline the need for new research directions. The analysis shows main research areas are: a) sustainable bioplastic production, b) agricultural waste management, c) assessment methodology, and d) bioeconomy concept.

The study found that the utilization of agro-waste in bioplastic production is still limited. This is due to the missing link between the bioconversion processes, agricultural waste, and sustainable development goals. While existing research about agro-biopolymer production from agriculture waste focused on environmental aspects, the topic lacks research addressing the economic and social dimensions of sustainability. Therefore, this study recommends more profound content research on agro-biopolymer, bioconversion processes, social and economic aspects.

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Evaluation of bioresource value models: Sustainable development in the agriculture biorefinery sector

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A B S T R A C T

The bioeconomy policies and sustainable development goals are a more focused area in the past few years due to their increasing significance in every sector. This research contributes to developing a better bioeconomy strategy concerning its Sustainability within the agricultural biorefinery sector by reviewing the bioeconomy modeling tools. A review shows the multidisciplinary features of the modeling tools; therefore, to analyze these modeling tools under one frame, specific criteria have been selected and evaluated by using the semi-quantitative analysis. A key idea of this study is to evaluate the five different types of bioeconomy modeling tools to estimate the bioresource added value. The Multi-Criteria Analysis approach has been used to compare the bioeconomy modeling tools considering the multidisciplinary feature of the modeling tools within the frame of sustainability development. The study finds that the LCA is the most suitable model to evaluate the bioresource added values. The methodology provides an accurate analysis, and the bioresource value can be estimated by using this novel approach.

1. Introduction

The European bioeconomy strategy integrates various sustainable pathways for sustainable development. A strategy for sustainable development goals includes different approaches toward the bioeconomy, such as production patterns, industrializations, consumption of resources, green energy, innovation, and climate change issues. The agricultural biorefinery presents a more sustainable way for bio-based industries and the conversion of bioresources into value-added products [1].

The biorefinery concept is suitable for all biomasses (first, second, and third-generation crops). The first-generation biomass includes sugarcane, sugar beet, corn, cassava, soybean, and rapeseed crops. The valorization pathways of first-generation crops are versatile and developed. Second-generation includes the agricultural residues (such as sawdust, rice straw, wheat straw, wheat bran, corn stover, and grasses), agro-industrial waste (such as orange peel, coffee grounds, soybean oil, and apple pomace), and lignocellulosic biomasses [1].

The agroforestry residues and wastes include several types of biomass feedstocks, such as primary agroforestry residues include agricultural and forestry [2], secondary agroforestry wastes include wood processing waste, and food industry [3], and third-generation wastes include marine biomasses [4]. The valorization pathways of these bioresources have the potential to contribute to sustainable development in the EU. According to EU guidelines for bioeconomy, drivers, challenges, and opportunities are already implemented for second-generation biomass.

The implemented challenges for second-generation biomasses are the efficiency of the feedstock supply chains, pretreatment techniques, and conversion technologies. The feedstock supply chain of biorefinery requires significant capital expenditure and feedstock resources at a low cost, which includes food crops, non-food crops, lignocellulosic wastes, and non-food marine biomass. The other challenges are different pretreatment techniques [5] and conversion processes [6], including the steam explosion, chemical, physiochemical, thermochemical, biochemical, and pyrolysis techniques. The total cost, maintenance conditions, and energy consumption during the conversion process are essential for second-generation biomasses.

The existing drivers and opportunities are environmental challenges, food & fuel complexity, and a wide range of potential bioproducts and bioenergy. The environmental challenges include a) environmental concerns such as fossil fuel depletion, intensive agriculture, non-sustainable forest, water resource management, pollution, and poor land use, and b) environmental Sustainability to improve the

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environmental quality standards in the biorefinery sector.

Concerning the environmental challenges, including greenhouse gas emissions, biodiversity loss, and the explosion of natural resources EU established the bioeconomy strategy to manage the environmental drivers. A limited number of bioproducts can drive the biorefinery in the commercial market, such as biochemicals, bio-based food and feed ingredient, and biopolymers. Fig. 1 shows the balance between the challenges, drivers, and opportunities. The drivers and opportunities can potentially influence the challenges for second-generation feedstocks [1].

However, the bioeconomy strategies can be evolute by implementing a more advanced approach. Therefore, this study proposes the novel idea of estimating the bioresource added value by comparing five different bioeconomy modeling tools within the frame of sustainability. These modeling tools have diverse applicability for sustainable bioeconomy, so the bioeconomy modeling tools can be evaluated based on the sustainability pillars. This study contributes to establishing the bioeconomy strategy that can be used to promote sustainable policies within the agriculture biorefinery sector.

2. Literature review

2.1. General trends in sustainable bioeconomy

The vision of the bioeconomy is an efficient use of bio-based products and technologies and the development of bioeconomy policies, which includes the development of green growth, innovation, and resource efficiency by implementing bioeconomy activities [7]. The bioeconomy activities are measures to achieve the aim of bioeconomy strategies, and these activities comply with the economic, social, and environmental challenges [8]. The bioeconomy relates to the sustainability policies such as climate change mitigation, technological progress, employment, and value creation.

The sustainable development goals include economic, social, and environmental development [9]. Sustainability is the fundamental idea behind the bioeconomy in terms of creating long-term value and benefits for these sectors [10]. The sustainable bioeconomy depends on the production and consumption pattern, which can be improved by evolving the fossil fuel-based economy into a bioeconomy by promoting bio-based, recirculated products and renewable energy [11].

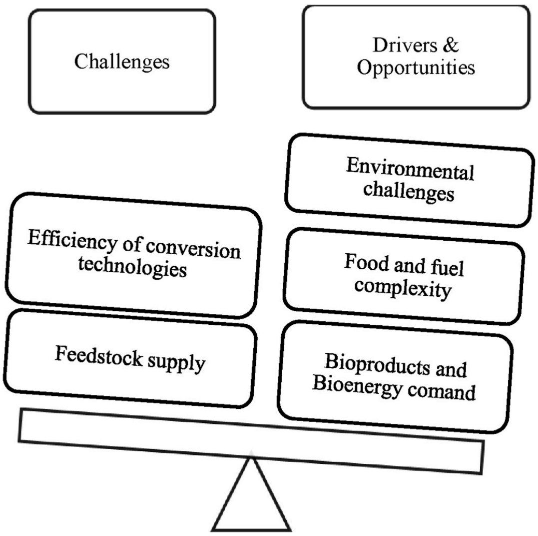

Fig. 1. Challenges, drivers, and opportunities for second-generation feedstocks [1].

In practice, bioeconomy involves using already existing bioprocesses and a wide range of natural bioresources, for example, land, sea, plant, animal, and microbial resources. The modern approach to bioeconomy involves many technological innovations, such as the large-scale application of biotechnology. Modern biotechnology has numerous opportunities to produce new biomaterials and bioproducts from bioresources, as well as ensures that the use of resources in the bioeconomy must be sustainable, efficient, and economical [12]. For example, the conversion of agricultural waste into higher added value products by using a biotechnological process promotes the bioeconomy in the agriculture sector as the agro-industrial waste generates a vast amount of grain waste, dairy waste, and food waste, in which only a tiny portion of the waste uses as animal feed, manure, and other products. Most of the waste is unutilized, which is a potential source in the production of biopolymers [13,14].

Successful implementation of a sustainable bioeconomy requires a novel policy that includes a) replacement of fossil fuel, b) innovative production techniques, and c) well-established Sustainability in bio-based value-chains [15]. The bioeconomy can be developed and improved by including innovative policies, strategies, and legislation in monitoring and measuring the overall framework, as it is the most vital parameter to establishing the bioeconomy [16].

The following sub-chapter represents different bioeconomy modeling tools to improve and develop a new bioeconomy strategy.

2.2. A review of bioeconomy modeling tools

The decision-making process of selecting a biorefinery system is complicated due to various available options and their advantages and disadvantages. The decision-making process is another existing issue in biorefinery prioritization. The indicator analysis provides the opportunity to develop a sustainable decision-making process [17]. Also, establishing three main pillars of Sustainability, i.e., environmental, social, and economic, is the most important for developing a sustainable product. The main environmental indicators, including global warming, pollution, acidification, biodiversity, land usage, and water scarcity, should be considered while performing the quantitative or qualitative analysis of the bioproducts. Regarding social indicators, employment, health, human rights, wages, and child labor needs more focus. Economic indicators include revenue services, production costs, operational costs, maintenance costs, and other economic activities for sustainability [18].

The Mixed Integer Linear Programming (MILP) model is an optimization framework that performs linear and non-linear programming. The MILP model has a vast capacity, flexibility, and rigorousness to detect and solve problems from single-stage multiproduct to general multipurpose processes [19]. The MILP model solves linear programming problems using linear optimization methodology. Integrating the Geographic Information System (GIS) with the MILP model can give the framework to determine the biorefinery production process with specific sub-criteria. A framework to optimize the biorefinery processes using the MILP model and with constraints proposed by Ref. [20]. A potential indicator found in this study is an economic indicator (considering several factors such as feedstock, transportation, biorefinery, and optimization variables). The GIS-based approach can be applied to solve land-based problems with MILP integration [21]. presented an analytical framework for evaluating biorefinery using the environmental and economic indicators in the MILP model. The main economic indicators and soil erosion due to the cultivation, carbon dioxide emission, and carbon sequestration are the establishment cost, selling price, production cost, transportation cost, and harvesting cost. This study's results favor profits on biorefinery applications and environmental and economic benefits. Table A shows the indicators used for the MILP model (see Appendixes) [22].

Modular Applied GeNeral Equilibrium Tool (MAGNET) is a global general equilibrium model with a modular structure and has several critical benefits for modeling bioeconomy, including in the development of the agricultural market, biomass usage for energy, food sector, land supply, land transfer, feed or fertilizer requirement, agricultural activities, labor market, and non-agricultural sector. This model aims to detect the changes in agro-food demand activities [23]. The MAGNET model works on the principle of the Computable General Equilibrium (CGE) model, which can evaluate the global economy with biofuels, agricultural, and energy sectors. Also, this model can integrate with the Global Trade Analysis Project (GTAP) database and includes the whole global economy information. This model has a wide application in terms of extending the policies of agricultural, food security, and bio-based economy in a more secure way. The MAGNET model uses the relative indicators in the GTAP or CGE model, including agricultural land, labor, capital, natural resources, energy, and animal components.

Moreover, the leading indicators considered are capital and labor for agricultural and non-agricultural sectors [24]. One of the studies considered the six drivers as demographics (population growth, education, and human capital), consumer preferences (consumer behavior), economic development, global environmental change, resource availability (land availability), and innovation or technical change. The main impacts are non-renewable resources, greenhouse gases, biodiversity, job creation, and food security. So, these drivers can be used to analyze the specific impacts (economic, environmental, or social) for Sustainability. Table B shows the indicators that can be used for the MAGNET model (see Appendixes) [25].

The Market Allocation-Energy Flow Optimization Model System (TIMES) model allows integrated assessment of social, economic, energy, and environmental issues based on partial equilibrium. The main benefit of using the TIMES model is finding the least-cost options through a dynamic simulation for various technologies. The main scope of the TIMES model is that it addresses the environmental emissions, material, and energy systems [26]. The TIMES model is a bottom-up model used to evaluate energy systems. The model can be applied to long-term horizons, including extraction, transformation, distribution, end-uses, and trade of energy sources. In general, the evaluation is done using the TIMES model's techno-economic assessment (cost & efficiency), but it also analyses the greenhouse gas emissions, fuel consumption, and related environmental processes. The main indicators that can be used for economic sub-criteria are feedstock cost, feedstock availability, investment cost, operating cost (variable or fixed), annual availability factor, and lifespan. These indicators are used for biofuel, electricity, and heat production by using a variety of agricultural feedstocks such as corn, soybean, fish oil, forest residues, agricultural residues, and industrial wastes [27]. One of the studies shows an interesting way to evaluate the increased value of biomass resources considering the biorefinery scenario [28]. The main sub-criteria used for the TIMES model is environmental, economic, and social. Environmental indicators include greenhouse gas emissions, CO2 emissions, soil carbon changes, and carbon sequestration. The economic indicator includes the production cost, feedstock cost, maintenance cost, operational cost, technical cost, and transportation cost. The social indicators include household demands and population. The indicator analysis can be compared and derive the increased value for the biomass resources. Table C (see Appendixes) presents the indicators for the TIMES model [28].

The Global Biosphere Management Model (GLOBIOM) assesses trade-offs among land use and ecosystem services in agricultural, bioenergy, and forestry sectors. The model was developed for impact assessment of climate change mitigations, but over time it also can be used for agricultural, timber market foresight, and economic analysis of climate change. The GLOBIOM model represents the land-use scenario and works on the partial equilibrium principle. The model evaluates the agricultural, forestry, cropland, and other land-based activities. This model uses socio-economic and environmental indicators to perform the evaluation. Also, the GLOBIOM model solves the issues related to an international bioenergy system by incorporating the indicators and drivers. The indicators for the GLOBIOM model are presented in Table D (see Appendixes) [29].

Life Cycle Analysis (LCA) is the method used to solve the environmental problems within all the life cycle stages of a product, process, or service. This method is based on an inventory of a product, including all the energy and materials used within its life cycle, accounts for respective emissions and impacts on the environment, and analyzes social and economic assessment of a product's life cycle [30]. The LCA analysis assesses the product's performance during the whole life cycle. The LCA has a broad approach to analyzing the various aspects of a product, such as environmental, social, and economic. The indicators that can be derived by assessing each aspect are summarized in Table E (see Appendixes) [31,32].

The selection of criteria, sub-criteria, and indicators has been made by analyzing the performance of each model. Moreover, a specific criterion has been selected considering the multi-dimensionality of the modeling tools, which shows the sufficient functionality of the bioeconomy modeling tools [33]. The selection of criteria has been made by analyzing the performance of each bioeconomy modeling tool. Several studies have been done on the assessment of modeling tools by using such criteria.

One study analyzed different criteria, including compatibility, tool features, ease of learning, user-friendliness, efficiency, and the model's capability [34]. Other studies presented a better understanding of criteria to evaluate the modeling tools, such as the documentation category representing the material provided for the tool, i.e., user manual and demo model. The computerized model's category represents verification and user-friendliness. The validation category ensures technical, operational, and data validity. The internal rating of the modeling tool shows efficient use of the model and recommendations [35].

In this study, the criteria selected from McCall's quality factor data include a vast database for the quality criteria to evaluate the modeling tools. The selected criteria are documentation aspects, flexibility, compatibility, diversity, validity, efficiency, and user-friendliness [36]. These criteria ensure the features of bioeconomy modeling tools and show the adequacy of the selected sub-criteria, i.e., economic, social, and environmental. The justification of criteria to analyze and compare the bioeconomy modeling tools are described below:

i. Documentation aspects include the available tool material such as built-in functions, demo models, libraries, online sources, tutorials, manuals, examples, index, and reference cards.
ii. Flexibility- It shows the level of flexibility by analyzing the model's simplicity, standardization, and transformation towards the selected sub-criteria for evaluation.
iii. Compatibility- The compatibility shows the interaction of the model with input data, which enhances the model's ability to create a complex system.
iv. Diversity- It includes the model's reusability, diversification, and variety of applications by using diverse goals and scope.
v. Validity- The validation of the model is determined by examining the adequacy, data exchange capability, and problem-solving technique.
vi. Efficiency- This factor includes several functions of the model, such as robustness, quality of details, and reliability.
vii. User-friendliness- It shows the ease of understanding of input database, output database, learning model, and generating reports.

Overall, the literature analysis shows the diversity of the bioeconomy modeling tools. Each model works on a different principle and has a different framework to perform a modulation for bioresources and their added value. Concerning the transdisciplinary nature of modeling tools, the evaluation has been made by choosing various criteria and sustainability sub-criteria for each criterion. By implementing this approach, these different bioeconomy modeling tools can be categorized under one frame of bioeconomy sustainability.

3. Methodology

The proposed methodology algorithm is briefly described in Fig. 3. Firstly, a vast literature analysis for each modeling tool has been performed using the databases (such as ScienceDirect, Google Scholar, and Scopus database). The literature analysis is done by considering more than 160 scientific documents. Secondly, by analyzing the existing studies, suitable criteria and sub-criteria for each criterion have been selected for each modeling tool. Finally, Multi-Criteria Analysis (MCA) has been performed by integrating the criteria and sub-criteria, followed by interpreting the results and drawing conclusions.

Here, the semi-quantitative analysis has been used for each modeling tool because of the versatility and diversity of the bioeconomy modeling tools. The semi-quantitative analysis is one of the ideal analyses [37], which defines the values that can be used for modulation and calculation. The evaluation scale can be identified according to the experts [38], 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 a criterion 1, 2, and 3 can be defined as unimportant, moderately important, and very important, respectively. Similarly, in this study, the Likert scale has been used 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, then the score is considered score one; if there is no data provided for the model, then 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, but if the interface data and overall model are very complex to learn, then the rank is four. Table 1 briefly presents the semi-quantitative scores for evaluating the bioeconomy modeling tools.

Moreover, the economic, social, and environmental sub-criteria are evaluated for each criterion, showing the sustainability adequacy of each modeling tool. So that simultaneous Sustainability can be examined for bioeconomy modeling tools by implementing our approach. Further evaluation has been done by using the MCA analysis. A technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one of the standard methods for MCA. The TOPSIS method justifies results by considering positive and negative ideal solutions [39]. There are several benefits to performing TOPSIS, such as this method provides the attribute information, provides the ranking of different alternatives and gives accurate results. The following steps are implemented in this study to perform the TOPSIS.

Step 1: Develop a decision-making matrix for bioeconomy modeling tools

The first step in performing the TOPSIS analysis for MCA is the development decision-making matrix (i.e., the results of semi-quantitative analysis Table 2), which shows the main sub-criteria and indicators with the numerical values.

Step 2: Normalization of decision-making matrix

The next step is to normalize all values of the decision-making matrix. All values obtained from the decision matrix are normalized by using Equation (1).

$$r_{ai} = \frac{x_{ai}}{\sum_{a=1}^{n} x_{ai}^2} \quad (1)$$

where, a = alternative, a = 1, …, n

i = criteria, i = 1, …, m

rai = normalized criteria value.

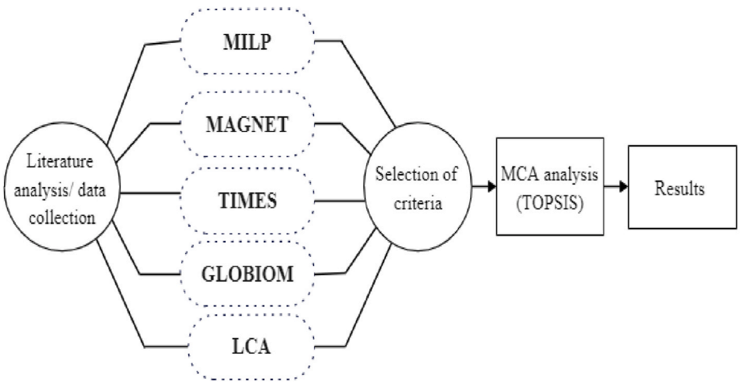

Fig. 3. Methodology algorithm for bioresource value model.

Table 1
Semi-quantitative analysis for selected criteria for modeling tools.

Criteria	Semi-quantitative scale			
	1	2	3	4
Documentation aspects	100% data is provided for a model	70% of data is provided for a model	50% data is provided for a model	No data is provided for a model
Flexibility	Very high adaptability of data	High adaptability of data	Moderate adaptability of data	Low adaptability of data
Compatibility	Very high possibility of exchanging the data (>80%)	High possibility of exchanging the data (<70%>)	Moderate possibility of exchanging the data (<50%>)	Low possibility of exchanging the data (<30%)
Diversity	Very high level of applicability (more than 80%)	High level of applicability (about 70%)	Moderate level of applicability (about 50%)	Low level of applicability (in (less than 30%)
Validity	Relevant data has a very high (90%) adequacy	Relevant data has a high (70%) adequacy	Relevant data has a moderate (50%) adequacy	Reinvent data has no adequacy
Efficiency	Verified data are highly qualitative	Verified data are partly qualitative	Verified data has a moderate quality	Non-qualified data
User-friendliness	Interface data and models are non-complex to learn	Interface data and models are fewer complexes to learn	Interface data and models are complex to learn	Interface data and models are very complex to learn

Table 2
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

Step 3: Weighted standard decision matrix

This step shows the importance of criteria, which means the high weightage criteria have high importance, and in contrast, the low weightage criteria have less importance. In this study, all criteria are considered equally important. The sum of all the criteria should be one, so, in our case, for each criterion, the weight is 0.143. Equation (2) shows the formula to calculate the weight for each criterion.

$$w_i = \frac{1}{n_i} \tag{2}$$

where, w_i = weighted value.
n_i = total number of criterions.

Step 4: Ideal and non-ideal factors

The next step is the determination of ideal positive and ideal negative solutions, which can be derived by using the sum of the weighted standard decision matrix. This study uses the minimum rank for the ideal solution, considering the semi-quantitate analysis. In contrast, for non-ideal solutions, the maximum rank has been used.

Step 5: Development of distance measures

The distance for each ideal and non-ideal solution is calculated by dividing the squares of weighted values (step 3). The distance measure of the ideal solution has been determined by following Equation (3).

$$d_a^+ = \sqrt{\sum_{j=1}^{n}\left(v_i^+ - v_{ai}\right)^2} \tag{3}$$

where, d_a^+ = distance for each action to the ideal solution.
v_i^+ = ideal solution.
v_{ai} = weighted value.
The distance for each action to the non-ideal solution is calculated following Equation (4).

$$d_a^- = \sqrt{\sum_{j=1}^{n}\left(v_i^- - v_{ai}\right)^2} \tag{4}$$

where, d_a^- = distance for each action to the non-ideal solution.
v_i^- = non-ideal solution.
v_{ai} = weighted value.

Step 6: Determination of relative closeness coefficient

For each alternative relative closeness coefficient (Ca) is different, Ca is considered between 0 and 1; but one is considered the most suitable value. Ca ratio shows the distance to the non-ideal solution, which is determined by the sum of the distance to the non-ideal solution divided by the distance to an ideal and non-ideal solution. Equation (5) shows the Equation for the relative closeness coefficient.

$$Ca = \frac{d_a^-}{d_a^+ + d_a^-} \quad (5)$$

where Ca = closeness coefficient.

d_a^- = distance for each action to the non-ideal solution.

$d_a^+ + d_a^-$ = sum of distance for ideal and non-ideal solution.

The sensitivity analysis checks attribute distribution's influence on the TOPSIS method's results. In this analysis, different weights are used to determine the performance of the alternatives. Initial weights are considered from the TOPSIS analysis. The distribution of the weight that will be imposed for the analysis is considered as two types of values, a) values smaller than one and b) values greater than 1, which are 0.1, 0.2, 0.5, 1, 1.5.2, and 3. The following Equations (6) and (7) are used to find the new weight for each factor.

$$\beta_k' = \sum_{k=1}^{n} w' = 1 \quad (6)$$

$$w_{k1}' = \beta_k \times w', \quad k = 1, 2, 3 \ldots n \quad (7)$$

where, β_k' = the unitary variation ratio of w_k after distribution.

w_k = weight being imposed on the distribution.

4. Results & discussion

The key findings of the proposed study have been presented in this section. The evaluation results are presented for the selected criteria and three main sustainability sub-criteria. Firstly, the criteria and sub-criteria were evaluated using the semi-quantitative analysis for bio-economy modeling tools. The semi-quantitative analysis results for selected criteria and sub-criteria for each model have been presented in Table 2.

Secondly, the closeness coefficient values for each model present the model's efficacy, and based on that ranking of the models has been done. Based on the distance derived from the unitary variation ratio, the ranking is done, such as the nearest result from the unitary variation ratio is derived for the LCA model, so it is ranked as 1. The TIMES, MILP, GLOBIOM, and MAGNET models are ranked 2, 3, 4, and 5, respectively. Based on the closeness coefficient, the graph is plotted (see Fig. 4). The unitary variation ratio is ideally considered 1. The graph shows that the multi-criteria analysis 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) model compared to other models, which shows less efficacy in estimating the bioresources. The derived result for the MILP model is 0.58. Lastly, the TIMES model has high documentation available, flexibility, compatibility, and efficiency; therefore, the derived result is 0.60.

Lastly, the sensitivity analysis results were obtained for documentation aspects, flexibility, compatibility, diversity, validity, efficiency, and under-friendliness Criteria. Fig. 5 shows the sensitivity analysis results for the documentation factor. The highest result is obtained for the LCA (0.82) and TIMES model (0.78), and the lowest result is obtained for the GLOBIOM model (0.32) and MAGNET model (0.34) if the weight is three times more than the initial weight (0.25). The derived results for the MILP model are 0.58 for three times higher weights. For weight 0.1, 0.2. Moreover, 0.5 the documentation aspect shows comparable results for all bioeconomy modeling tools. A minor difference in results has been obtained for 1.5- and 2-times higher weights for all bioeconomy modeling tools.

Furthermore, the three times higher weights for the documentation aspect show that for LCA and TIMES model, the material availability, libraries, and online sources are 100% available. On the opposite, for GLOBIOM and MAGNET, sufficient material availability, libraries, and online sources are unavailable in context with the agriculture biorefinery.

The sensitivity analysis results for the flexibility are presented in Fig. 6. If the weight is three times higher than the initial weight, the MILP and GLOBIOM show the highest (0.83) and lowest (0.40) flexibility, respectively. Overall, the MILP and LCA model shows drastic changes for lower and higher weights, but the MAGNET, GLOBIOM, and TIMES model shows a minor change for lower and higher weights.

The higher flexibility for MILP and LCA models shows that the models have a remarkably high level of adaptability and standardization towards the sustainability sub-criteria. The MAGNET and GLOBIOM models show a low level of adaptability and standardization towards the sustainability sub-criteria for the agricultural biorefinery sector. The TIMES model has a moderate standardization toward the sustainability sub-criteria.

Fig. 7 shows the sensitivity results for compatibility. The compatibility factor's higher and lower weight changes show the same results as initial weights for all bioeconomy modeling tools.

The compatibility indicates the interaction of the model with input data and the possibility of exchanging the data. All five models show the constant possibility of exchanging the data. In other words, the interaction of models with their input data, i.e., economic, social, and environmental, is constant for lower and higher weights.

Fig. 8 shows the sensitivity results for the diversity factor. On one side, for lower weights (0.1, 0.2, and 0.5), the highest diversity is obtained for the LCA model, and the lowest diversity is obtained for the GLOBIOM model. On the other side, no significant difference can be seen for higher weights (1.5, 2, and 3). All modeling tools observe a notable change from lower to higher weights.

The diversity indicates the variety of model applications with diverse goals and scope. For lower weights, the LCA model shows the highest

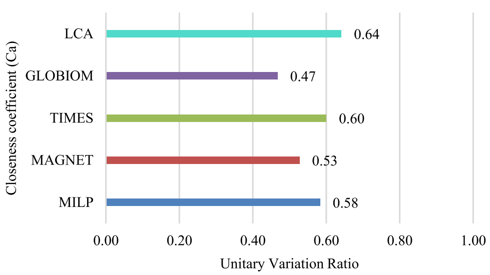

Fig. 4. MCA results for modeling tools.

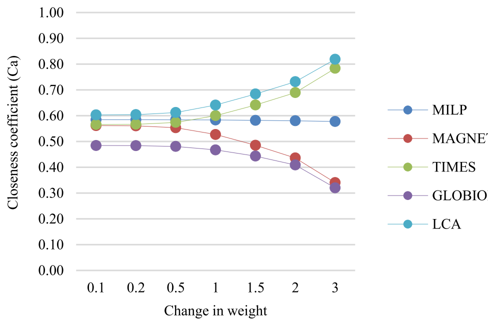

Fig. 5. Sensitivity Analysis results for documentation aspect.

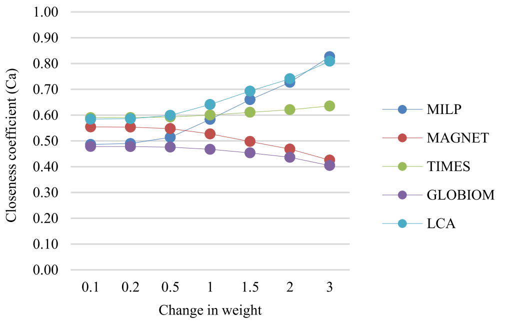

Fig. 6. Sensitivity Analysis results for Flexibility.

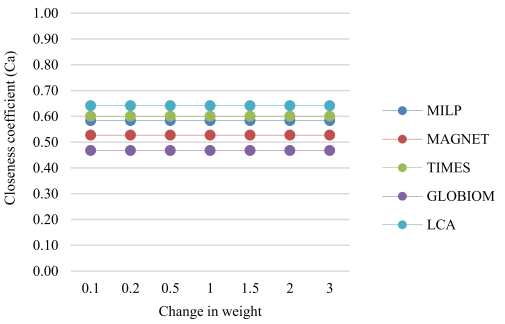

Fig. 7. Sensitivity Analysis results for Compatibility.

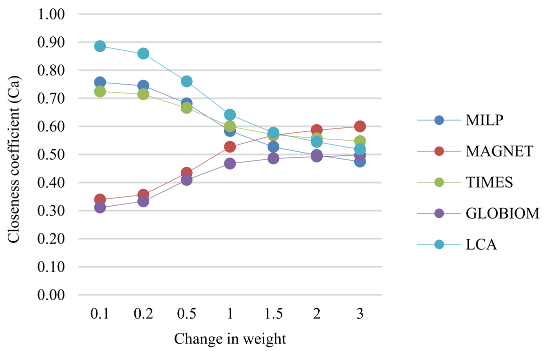

Fig. 8. Sensitivity Analysis results for Diversity.

applicability, which means the model can be used more than 80% in the agricultural biorefinery sector with diverse goals and scopes. However, the GLOBIOM and MAGNET model can be used for less than 30% in the agricultural biorefinery sector. The MILP and TIMES model shows 70% applicability with diverse goals and scope.

For higher weights, all model shows moderate (i.e., about 50%) applicability in the agricultural biorefinery sector, conserving the economic, social, and environmental sub-criteria.

Fig. 9 shows the sensitivity results for validity. The higher and lower

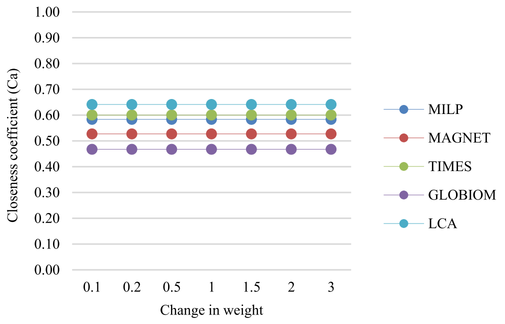

Fig. 9. Sensitivity Analysis results for Validity.

weight changes for the validity factor show equivalent results as initial weights for all bioeconomy modeling tools in all scenarios.

The validity indicates how models are adequate for their relevant data. Each model shows equal adequacies for all weights, which means the models can be used to obtain economic, social, and environmental data considering the study's relevance for the agricultural biorefinery sector as they have constant adequacy.

Fig. 10 shows the sensitivity results for efficiency. The sensitivity analysis for efficiency criteria for higher and lower weight changes shows consistent results as initial weights for all bioeconomy modeling tools.

The efficiency represents the quality of the input data in terms of economic, social, and environmental input data to perform the modulation. All models show the constant values for efficiency, which indicates that all models are qualified to give the qualitative input data.

Fig. 11 shows the sensitivity results for user-friendliness. The user-friendliness for all bioeconomy modeling tools is equal to initial weights for all higher and lower weight changes.

The user-friendliness shows the ease of learning the model and interference data, which indicates the complexity of learning the interference data (i.e., economic, social, and environmental) and model. All model shows the constant complexity for all types of weighting scenario.

Concisely, The MCA 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. In sensitivity analysis, the three times high weight shows that the documentation aspect, flexibility, and diversity are highest for LCA, MILP [19], and MAGNET [23,24] models. For lower weights (0.1), the documentation

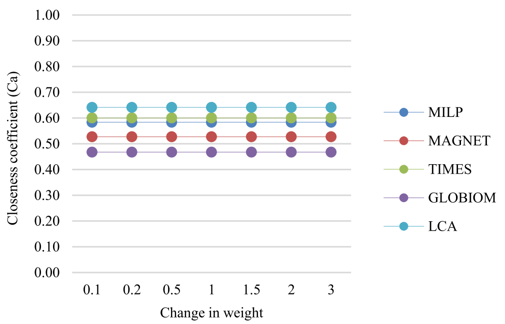

Fig. 10. Sensitivity Analysis results for Efficiency.

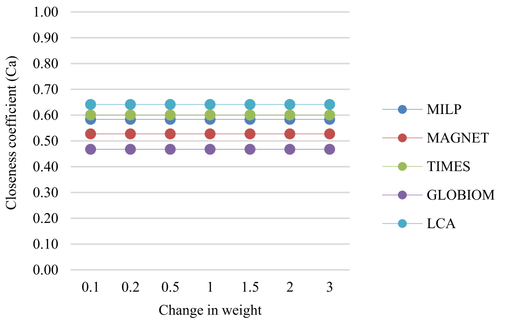

Fig. 11. Sensitivity Analysis results for User-friendliness.

aspect and diversity are higher for LCA models, whereas the flexibility is higher for the TIMES [26] model. The compatibility, validity, efficiency, and user-friendliness criteria are equal for all scenarios.

The LCA model is adequate for the sustainability sub-criteria (economic, social, and environmental) to discuss the anticipated interpretations. The LCA interpretation for documentation shows the highest pick (see Fig. 5), which shows that the learning material, tutorials, and libraries are widely available for the LCA model. The article [40] concluded that the LCA is rapidly becoming more advanced. This article presents the bibliometric analysis considering citation, co-citation, and co-occurrences on the 20,153 articles related to LCA studies with the increasing research interest and publications every year [40]. Coherently with [41], the research has addressed that the LCA model flexibly integrates the economic, social, and environmental aspects, which assists in developing the agricultural sustainability and food security goals. Despite the broad scope of reusability and applications of the LCA model with increasing research interest [42,43], the development of sustainable strategies using the LCA tool in the agriculture sector is minimal. The Life Cycle Inventory database is the gold standard for the LCA tool [41], which bridges the data gaps to provide information for agriculture inputs, outputs, and production processes. However, many authors addressed a concern about the databases due to gaps and not updated data [44]. The reliance on diverse data sources leads to the difficulty of obtaining accurate results for the LCA model [41]. Indirectly, the quality of data might get affected. Overall, this clarifies the consistent interpretation of the LCA model for compatibility, validity, and efficiency criteria.

5. Conclusion and recommendations

The research concludes that the bioeconomy modeling tools can be evaluated by using the MCA analysis to estimate the bioresource added value, considering the different criteria (documentation aspects, flexibility, compatibility, diversity, validity, efficiency, and user-friendliness) and sub-criteria (economic, social, and environmental) for each modeling tools. The results of this study show the adequacy of semi-quantitative analysis for the chosen criteria. The MCA analysis shows that the LCA model is the most suitable for bioresource added value calculation. Also, the sensitivity analysis shows a favorable result for LCA and TIMES model.

The study suggests using bioeconomy modeling tools considering the model's characteristics and multidisciplinary. Also, an exact scenario has been presented for efficient use of the modeling tools that can be adventitious for researchers and scientists; for example, the LCA tool has sufficient documentation, flexibility, and diversity. Similarly, the TIMES model has higher documentation, and the MILP model has high flexibility.

However, these bioeconomy modeling tools strongly depend on a type of scope and analysis. Each model has a different algorithm, sub-criteria, and protocol to perform an analysis, which means the LCA model can be a suitable and efficient tool for bioresources. However, other modeling tools such as MILP and TIMES also have the potential to give the best output for the agricultural biorefinery sector. Similarly, the GLOBIOM model can be an efficient modeling tool for land-use scenario analysis. However, particularly for this study, a significant limitation of the depth of evaluation was the lack of data for a couple of modeling tools (i.e., MAGNET and GLOBIOM).

The study recommends further research and experiments on modeling tools to provide more comprehensive results. Policymakers can use our novel approach to improve the sustainability policy by implementing our bioeconomy strategy within the scope of the agriculture biorefinery sector.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendices.

Table A
Sub criteria and indicators for the MILP model

No.	Sub-criteria	Indicators
1	Economic	Market price Logistic costs Labor costs Gross profit Raw material inventory Selling cost Production cost
2	Social	Number of workers Working time Working conditions
3	Environmental	Global warming Greenhouse gas emissions Soil erosion Carbon sequestration

Table B
Sub criteria and indicators for the MAGNET model

No	Sub-criteria	Indicators
1	Economic	Bioproduct annual turnover & values added
		Biomass and bioproduct net trade
		Wood net trade
		Forest product new trade
		Wood price and forest product price
		Employment
		Turnover
		Value-added
		GDP
		Production
		Trade flows
		Consumption
2	Social	Full-time equivalent job
		Job creation
		Income in the bioeconomy sector
		Quality of life
3	Environmental	Cropland footprint
		The intensity of land use
		Land conversion
		Land for import and export
		GHG emission
		Climate change
		Water scarcity

Table C
Sub criteria and indicators for the TIMES model

No	Sub-criteria	Indicators
1	Economic	GDP
		Resources prices
		Energy costs
		Annual production
		Investment cost
		Total growth rate
		Supply costs
2	Social	Population
		Household demand
3	Environmental	Emissions
		Energy consumption
		Resource use

Table D
Sub criteria and indicators for the GLOBIOM model

No	Sub-criteria	Indicators
1	Economic	Capital income
		Transportation cost
		Product prices
		GDP growth
		Demand and price
		Bioenergy use
2	Social	International trade
3	Environmental	Land use & crop area
		GHG emission
		Productivity
		Carbon stocks

Table E
Sub criteria and indicators for the LCA model

No	Sub-criteria	Indicators
1	Economic	Operational cost Maintenance cost Payback time Revenue GDP growth Net present value The interest rate of returns
2	Social	Health and Safety Local employment Child labor Working hours Social security Forced labor Feedback mechanism Resources Community
3	Environmental	Climate change Radiation Energy Particulate matter Acidification Eutrophication Ozone Material and resources Waste Land Ecosystem

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Sustainability dilemma of hemp utilization for energy production

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ABSTRACT

With global energy demand rising and climate change targets becoming more ambitious, the use of biomass for combustion will become even more important than it already is. As wood supplies become scarce, leading to increased demand for materials and energy, the demand for alternative solid biofuels for energy use is growing. Using various biobased raw materials seem to be the best way to optimize the value chain of solid biomass fuels. Biomass has high energy density, homogeneous physical properties, easy handling and efficient transportation. Combining multi-criteria decision analysis (MCDA) and life cycle analysis (LCA), this article evaluates the utilization of hemp for a number of uses, including energy generation. The methodology developed combines agrotechnological and sustainability criteria with data analytic techniques for more effective application of hemp products in changing environmental, economic, and geopolitical contexts. According to the results of the research conducted, the use of hemp as an energy source is a viable option only in the short term.

1. Introduction

1.1. Hemp availability and production in the world

Industrial hemp (*Cannabis sativa* L.) has been cultivated for generations and is still grown nowadays all over the world. The fact that it can be processed into more than 25 000 different goods classifies it as a crop with multiple uses [1]. Industrial hemp (hemp) belongs to the Cannabaceae family and contains psychoactive substances such as the cannabinoids tetrahydrocannabinol (THC) and cannabidiol (CBD) [2]. However, the notable difference between hemp and cannabis is that the amounts of THC found in hemp are quite low - 0.3% or less [2]. In the EU Member States, the regulation is even stricter and the THC content may not exceed 0.2% [3]. Seeds, flowers, leaves, stems and roots are the primary components of the hemp plant [2].

Although the cultivation of hemp has regained popularity in the last decade, it is one of the oldest plants used for the production of food, textiles, and medicine [4]. Hemp was a widely used crop until the early 1900s, when many countries banned hemp cultivation precisely because of the psychoactive substances it contained, which affected the purpose and use of hemp [2]. In addition, the use of synthetic materials became more common due to their higher profitability [4]. With the focus on sustainability in recent decades, hemp production has increased again.

The cultivation of hemp is more suitable for temperate climates but it can also be grown in other conditions. Industrial hemp is cultivated in about 47 countries (see Fig. 1), and the biggest producers in the world are China, South Korea, Russia, the USA, and Canada [2]. Asia is a major contributor to the industrial hemp market, as China is the largest producer of hemp. About 25% of global demand is cultivated in the EU [2]. Canada has a more well established hemp market than the USA, as hemp cultivation was legalized there back in 1998 [2]. South America and Africa are the least active continents in hemp production [2].

From 2015 to 2019, the total area used for the production of hemp in Europe has increased by 75% [3]. In 2019, it was 34 960 ha, and the total amount of product produced was 152 820 t [3]. France contributes the most to hemp production in the EU, producing about 70% of the total EU volume [3]. About 75 varieties of hemp are registered in the EU catalog and are therefore allowed to be grown. The cultivated hemp is used for the production of fibers, seeds, CBD or for combined purposes [3]. In Latvia, the area under hemp cultivation in 2019 was 868 ha [5].

1.2. Hemp utilization opportunities

Hemp's properties make it an excellent raw material for the production of products that are useful to society, including oils, food products, construction materials, paper, and biofuels (see Fig. 2). Compared to a variety of other industrial crops, hemp's value increases because it can be processed into a variety of different products. Compared to other crops, such as sugar beets or potatoes, the production of hemp requires fewer resources and has a lower overall impact on the environment [6].

Although hemp is a plant with a wide range of practical applications, it is currently not economically feasible to substitute hemp fiber for

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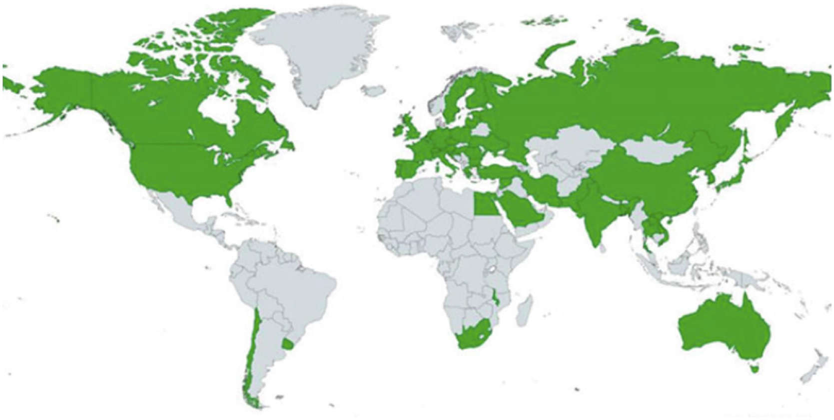


Fig. 1. Countries that produce industrial hemp [2].

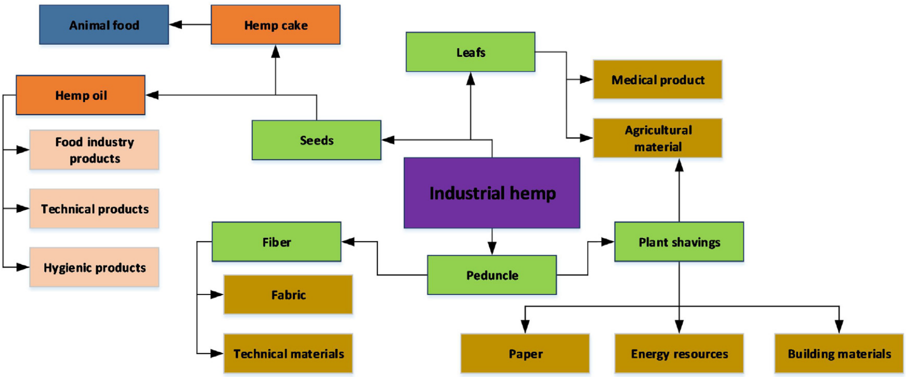


Fig. 2. Hemp application possibilities.

traditional raw materials such as cotton for textiles or wood for papermaking with hemp fiber [7]. Despite subsidies, European hemp producers cannot yet compete with China, where the traditions of hemp cultivation are much older and labor costs are much lower [7]. The production and commercial potential of hemp is considered low in the North American environment, and the growing emphasis reflects support for cannabis grown especially for therapeutic purposes [7]. Currently, hemp's greatest advantage is that it can be used to create environmentally safe goods, such as textiles, building materials, and insulation; however, from a commercial perspective, this may not be economically feasible [7]. The EU is hopeful about the market and production capacity for hemp as a raw material and continues to promote the cultivation of hemp, recognizing its enormous potential as an environmentally friendly material [3,7].

1.3. Hemp as biomass for energy production

Given the world's growing demand for energy and more ambitious climate targets, the use of biomass for combustion will become even more critical. Since wood resources are getting scarcer caused of the growing demand for material and energy use, alternative solid biofuels experience a growing interest in energy utilization. Theoretically, then, it would be possible to consider hemp as a possible source of energy. The use of hemp for energy production could seem appealing for two reasons:

(1) The green crop yield from hemp is in the range of 14 –15 t/ha [8], of which 70–75% are hemp shives, which are often left in the field, constituting an organic fertilizer [9,10];
(2) Hemp is harvested in spring or winter because it has a higher heat value (on average 19.1 MJ/kg) than hemp collected in autumn (around 18.4 MJ/kg) [10]. Hemp biomass shows a substantial deviation in the properties of energy resources: heat value, ash content, and ash melting temperature, which depends on the harvest season [2].

The amount of hemp shives available after harvest is considerable and has a high calorific value. Therefore, the next step in assessment of using hemp shives for thermochemical conversion is to determine the other properties of this biomass. For example, the melting point of the ash [3,5], emissions in the airflow [11,12], and ash content [13,14]. Hemp composition research needs to be implemented [15,16] and the ash should preferably have a high melting point and a solid phase in the furnace. The technical and chemical characteristics of hemp that could indicate its potential for energy generation are given in Table 1 [10].

According to a study by Kraszkiewicz et al. [10], technical and chemical features of hemp biomass are suitable for energy generation. According to the evaluated factors, hemp biomass was among the best biomass

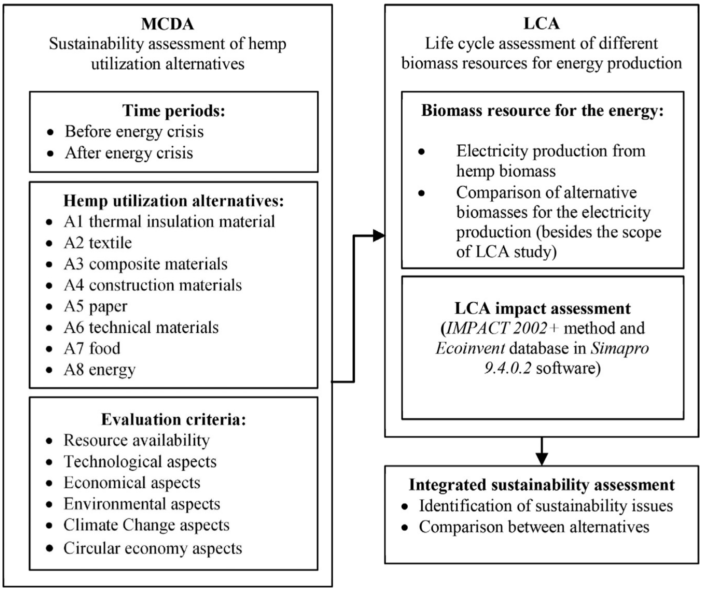


Fig. 3. Visual representation of the methodology.

Table 1
Technical and chemical properties of biomass hemp [10].

Parameter	Symbol	Unit	Hemp biomass value
Total moisture	W	%	10.977
Volatile parts	V^d	%	69.630
Heat of combustion	HHV	MJ/kg	18.089
Calorific value	LHV	MJ/kg	16.636
Ash	A^d	%	2.510
Elemental composition	C^d	%	43.366
	H^d	%	6.669
	N^d	%	0.248
	S^d	%	0.056

sources for energy generation [17,18]. The study by Petlickaite et.al. [19] looks at the properties of pressed solid biofuel of multi-crop plants hemp, maize (*Zea mays L.*), and fava bean (*Vicia faba* L.) as mono, binary and trinomial crops. The behavior of ash melting in hemp biomass demonstrated that hemp ash has the highest shrinkage starting temperature, which reaches 1079 °C [19]. High potassium (K), calcium (Ca), and phosphorus (P) concentrations were found in all types of biomass ash [20].

Elemental analysis was used to calculate the higher heating value of biomass according to the Channiwala-Parikh correlation [21,22].

2. Methodology

The study aims to assess the sustainability of using hemp for energy generation using an integrated set of methods, including Multi-Criteria Decision Analysis (MCDA) and life cycle analysis (LCA) (Fig.3). The application of MCDA allowed the sustainability of different hemp products to be assessed under crisis and non-crisis conditions, taking into account six different criteria. In the next step, LCA was carried out for four biomass energy resources: peat, wood, sweet sorghum, and hemp. The results were aggregated to assess the use of hemp as a bioresource and biomass for energy generation 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 wider use of hemp.

To achieve the objective of this study, a methodology was developed for the integrated application of MCDA and LCA methods. The MCDA method was selected to evaluate eight selected hemp products considering six established criteria (Fig. 3), which allowed the assessment of environmental, economic, and technological aspects. The identified hemp products and the criteria provide the opportunity to use MCDA to evaluate which would be the most sustainable option for the use of hemp as a raw material. In addition, a LCA to evaluate hemp as a biomass for energy production is compared to three other biomass energy options. The results of the MCDA and LCA on the potential uses of hemp provide for a more comprehensive look at the strategic use of hemp in crisis and non-crisis situations to manage its flow better.

2.1. Multi-criteria decision analysis

The MCDA in this part of the work requires a sequential set of steps to ensure that the objective is achieved comprehensibly and transparently. Fig. 4 shows the steps for implementing a MCDA to compare hemp-origin products.

Taking into account the literature sources analyzed in the study [2,4,8,10,19], no examples were found where the potential hemp products (see Figs. 3 and 4.) and their production methods were analyzed and compared with each other using an MCDA. The following hemp products were selected for the MCDA evaluation, ensuring a broad spectrum of products (Fig. 3):

A1 thermal insulation in the building sector;
A2 textile in different sectors;
A3 composite materials in different sectors;
A4 construction materials in different sectors;
A5 paper in the industrial sector;
A6 technical materials in different sectors;
A7 food in the agriculture sector;
A8 energy in the energy sector.

After selecting and grouping the hemp products, sustainability criteria were established. According to the literature reviewed, the criteria

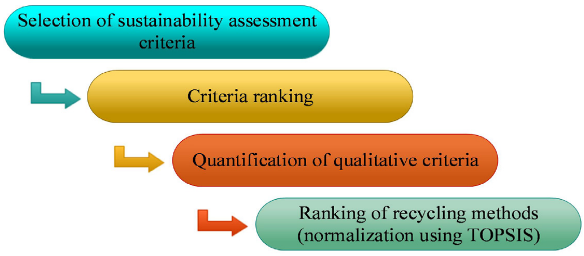


Fig. 4. Sequence of steps to perform a MCDA [23].

for evaluating sustainability are neither clearly defined nor static; but are selected and modified depending on the topic and the issue [24–26]. The three dimensions that usually define the sustainability criteria are environmental, economic, and social dimensions for sustainable development [24,27], although technical, administrative [26], and other dimensions that might indicate the sustainability of a process or product can also be considered. With this in mind, the authors have divided the criteria into six main categories of sustainability criteria, as shown in Fig. 3:

- Resource availability;
- Technological aspects;
- Economical aspects;
- Environmental aspects;
- Climate change aspects;
- Circular economy aspects.

The TOPSIS method was selected as the most appropriate method. TOPSIS is a method used for normalization of multi-criteria analysis. This method helps to find the solution that is closest to the positive ideal solution and farthest from the negative ideal solution [28–30]. This method requires information on the relative importance of indicators, which can be obtained by inheriting subjective weighting methods such as the Analytic Hierarchy Method or objective weighting methods, such as the Entropy Weighting Method [28–30]. The TOPSIS method normalizes the weighted indicators and assigns them a sustainability score, which is used to rank the processes [28–30]. It is a straightforward method that is not difficult to implement. Moreover, the number of steps in the process is constant regardless of the number of indicators [28–30]. The TOPSIS method uses the Euclidean distance, which does not take into account the correlation between indicators. This method has been criticized for the fact that assigning the importance of criteria without becoming subjective can be difficult [28–30]. TOPSIS consists of the following steps [28–30]:

(1) Construction of the evaluation matrix;

This step may be based on available data and information on the criteria, although expert evaluations may also be used. In this study, the authors used expert evaluation. Over 20 experts with experience and expertise in energy and environmental engineering, as well as industry experts were asked to rate each of the above hemp products on a scale of one to five, with one being the lowest and five being the highest. The average ratings were entered in the evaluation matrix. The matrix consists of *m* alternatives and *n* criteria. Each row of the matrix represents one alternative for this work. In the matrix, each unit x_{ij} represents the actual value of an indicator *j* belonging to a process *i* of an alternative.

(1) Deriving a normalized matrix using the equation:

$$R_{ij} = x_{ij} \div \left(\sum_{j=1}^{n} x_{ij^2} \right) Î0,5 \quad (1)$$

Where:
R_{ij} – normalised matrix; x_{ij} – indicator value.

(1) In order to weight the criteria, an additional expert evaluation was carried out, this time with the participation of 16 experts in the field of energy and environmental engineering, who assigned higher or lower values to the weights, resulting in an overall score of 1. Taking into account the fact that sustainability may become less important in a crisis situation, the weighting of the criteria was carried out for a scenario under non-crisis conditions and under conditions of an energy and/or economic crisis situation.

(2) Obtaining the weighted normalized matrix Vij, multiplying each unit of the matrix Rij by its assigned weight vector wj.

$$V_{ij} = R_{ij} * w_j \quad (2)$$

(3) Obtaining the positive ideal and negative ideal solutions using the equations

$$V^{+} = \left(\begin{matrix} 1 \\ 1 \end{matrix} \left(\frac{V_{ij}^{max}}{j} \right), \left(\frac{V_{ij}^{max}}{j'} \right) \right) / (i = 1, 2, \ldots, n), = \left(V_1^{+}, V_2^{+}, V_3^{+}, \ldots, V_m^{+} \right) \quad (3)$$

$$V^{-} = \left(\begin{matrix} 1 \\ 1 \end{matrix} \left(\frac{V_{ij}^{min}}{j} \right), \left(\frac{V_{ij}^{min}}{j'} \right) \right) / (i = 1, 2, \ldots, n), = \left(V_1^{-}, V_2^{-}, V_3^{-}, \ldots, V_m^{-} \right) \quad (4)$$

Where:

V^{+} - the positive ideal solution;
V^{-} - the negative ideal solution;
j=(*j* = 1,2,…,m) is associated with indicators for which higher values are desirable;
j'=(*j* = 1,2,…,m) is associated with indicators for which lower values are desirable.

(1) Determining the distance of each alternative process from the positive ideal solution and the negative ideal solution using the equations

$$S_i^{+} = S\left(\sum_{j=1}^{m} (V_{ij} - V_j^{+})^2 \right)^{0,5}, i = 1, 2, \ldots n \quad (5)$$

$$S_i^{-} = S\left(\sum_{j=1}^{m} (V_{ij} - V_j^{-})^2 \right)^{0,5}, i = 1, 2, \ldots n \quad (6)$$

Where:

S_i^{+} - distance from the positive ideal solution;
S_i^{-} - distance from the negative ideal solution.

(1) Finding the relative proximity of each alternative process to the ideal solution using the equation

$$P_i = \frac{S_i^{-}}{(S_i^{+} + S_i^{-})} \quad (7)$$

Where:
$\boldsymbol{P_i}$ – the ideal solution.

(1) Ranking the obtained values according to their relative closeness to the ideal solution, where the positive ideal solution is 1.00 and the negative ideal solution is 0.00. The TOPSIS method itself does not impose any special requirements on the units. It focuses on the relative rankings and distances between alternatives based on the established criteria, regardless of the units used for the criteria.
(2) A sensitivity analysis was performed to test the effects of indicator weights on the results of the TOPSIS analysis. Equal criteria weights are applied at the beginning of the sensitivity analysis. The initial weights are calculated as shown in the following equation:

$$\boldsymbol{w'} = \frac{1}{\boldsymbol{n}} \tag{8}$$

Where: w' - the initial weight of the criterion.

(1) Sensitivity analysis requires the definition of the proportion of the unitary variation ratio that modifies the weight of the selected criteria according to the equation:

$$w'_{k1} = \beta_k * w' \tag{9}$$

Where:
w'_{k1} - the weight of the selected indicator subject to change;
β_k - the unitary variation ratio of the weight change.

(1) It is not necessary to follow a particular algorithm to select the values for the unitary variation ratio for the sensitivity analysis, but it is necessary to use values both greater than and less than one. The analysis is performed for each criterion used in the TOPSIS analysis by varying its values according to Eq. (8). The weights of the other indicators are varied in each iteration according to equation:

$$w'_{k2} = w'_{k3} = w'_{kn} = \frac{\left(1 - w'_{k1}\right)}{n-1} \tag{10}$$

Where:
w'_{k2} and w'_{k3} - weight of the other criteria.
The weights of the criteria are modified according to the equations described above and then repeatedly applied to the TOPSIS analysis, summarizing the resulting values of relative closeness to the positive ideal solution. Such an analysis is performed for all criteria used in the TOPSIS analysis to assess their impact on the change in outcome and alignment of alternatives. Sensitivity analysis allows simulation of different scenarios for the importance of the criteria and evaluates the stability of the alternatives under changing conditions. A practical application of the above mathematical equations yields the normalized data matrix.

The MCDA was carried out for two different situations in a country:

- A normal scenario under non-crisis conditions;
- Under conditions of energy and/or economic crisis.

For the purpose of 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% [31]. "Under conditions of energy and/or economic crisis," 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 basic necessities or a particular (or all) energy resource, are rising rapidly.

2.2. Life cycle assessment

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 14,040/14,044. It contains four main steps: goal and scope definition, life cycle inventory and impact assessment, and impact assessment, as well as their interpretation.

2.2.1. Goal and scope

The LCA aims to analyze the environmental performance of hemp biomasses. 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. 5), 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 will also be conducted.

2.2.2. Life cycle inventory

The Life Cycle Inventory (LCI) includes material and energy flows, equipment, and infrastructure required for the whole energy generation process. As stated in the ISO Standards 14,044, data must at least ensure their validity in terms of geographic origin, representativeness, technological efficiency, and data sources. In summary:

- The background is from Ecoinvent 3.7.1 [32], and the weight and specification of materials are as specified by the manufacturer;
- The geographic context of the system refers to the Rest-of-World (RoW);
- The data quality is generic;
- Technological characteristics refer to raw biomass processing operations (biomass cultivation, fertilization, harvesting, sowing, and cutting), transportation, and electricity generation (boiling, turbine generation, heat exchange).

The primary data regarding the processing of hemp biomass for electricity production has been presented in Table 2 for the period 2007–2020. The inventory data of fertilizers, transport, source of energy, and agriculture machinery involved were taken from *Ecoinvent 3.7.1* database. To generate 100 kWh of electricity, first, the required amount of hemp biomass (22 kg) is calculated (see Eq. (11)) by normalizing the low heating value of hemp biomass and electric efficiency of the boiler, which is 15.72 kg/MJ [33] and 75% [34], respectively. The value of the dimensionless factor is 0.75, which is calculated from the boiler's efficiency.

$$\frac{Kg}{MJ} = D_f \tag{11}$$

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 [35,36]. 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 biomasses of peat, wood, and sweet sorghum is selected directly from the *Ecoinvent 3.7.1* database [32]. The comparison is made to generate 100 kWh of electricity from 22 kg of biomass, just as for the hemp biomass.

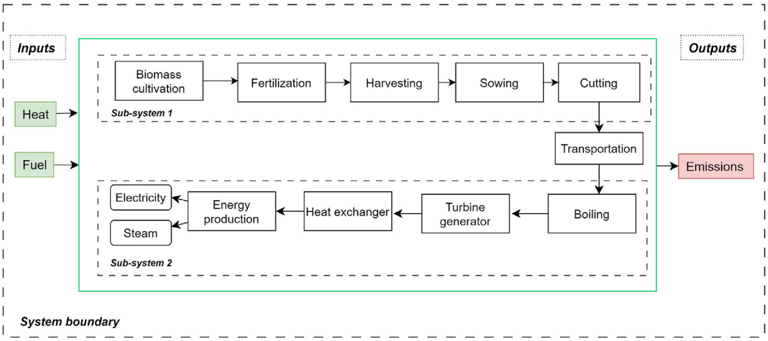


Fig. 5. System boundary for biomass for electricity generation.

Table 2
LCI for electricity generation from hemp biomass [35,36].

Materials	Amount	Unit
Sub-system 1: raw hemp biomass processing		
Inputs from Technosphere		
Ammonium nitrate	0.62	kg N
Triple superphosphate	0.48	kg P2O5
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 Ammonia	22 0.019	Kg kg/ha
Dinitrogen monoxide	0.022	kg/ha
Nitrogen oxide	0.002	kg/ha
Carbon dioxide	0.011	kg/ha
Transportation of hemp biomass	1.1E3	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

2.2.3. Environmental impact assessment

The LCA is performed using the IMPACT 2002+ V2.15 impact assessment methodology in *Sima Pro 9.4.0.2*. The *IMPACT 2002+* is a combination of four methods *IMPACT 2002, Eco-indicator, CML*, and *IPCC*. The method proposes a feasible implementation of the combined midpoint and damage-oriented approach [37]. It analyses 14 midpoint categories, including human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction. The LCA concerns four damage categories and indicates a significant adverse environmental impact. Resources, human health, climate change, and ecosystem quality are the damage categories. A further definition of each damage category is given below [37]:

- Resources account for the percentage of consumption of resources;
- Climate change is the indicator of potential global warming due to greenhouse gas emissions into the air;
- Ecosystem quality shows the protection zone, which is related to impacts on the natural environment;
- Human health shows the impact of human toxicity substances emitted into the environment.

3. Results and discussions

3.1. MCDA results

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 (Table 3). 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 aspects and the environmental aspects as the most important criteria with a weight of 0.20, with the other weights equally weighted at 0.15 (Table 3).

TOPSIS calculations for comparing the eight hemp products under non-crisis conditions, were used to determine the product group closest to the ideal positive solution (1.00), resulting in the results shown in Fig. 6. The closeness proximity of the selected hemp product groups to the ideal positive solution indicates their stronger compliance with the six sustainability criteria, while the closeness proximity to the negative ideal solution (0.00) 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, with the production of building materials only 0.24 units closer to the ideal by half the distance. The best and second-best performances differ by only 0.04 units. However, the sustainability performance of construction materials is almost 50% better than that of paper production from hemp. This is a significant difference, indicating that the MCDA analysis guided by these criteria used in the paper, concludes that construction material production from hemp is more sustainable than paper and energy production from hemp.

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' assessments of scenario for energy and/or economic crisis conditions (Table 4). 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 situation, the experts weight the criterion economic aspects higher with 0.40 points, while aspects such as resource availability, technological aspects and aspects of climate change have a weighting of 0.15. The lowest weighting in a crisis situation is given to environmental aspects with 0.10 and aspects of the circular economy with the lowest weighting of 0.05.

The TOPSIS calculations comparing the eight hemp products under conditions of energy and/or economic crisis, using the method of finding the solution closest to the positive ideal solution (1.00), gave the results

Table 3
Normalized decision matrix for a normal scenario under non-crisis conditions.

Criteria	A1	A2	A3	A4	A5	A6	A7	A8	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

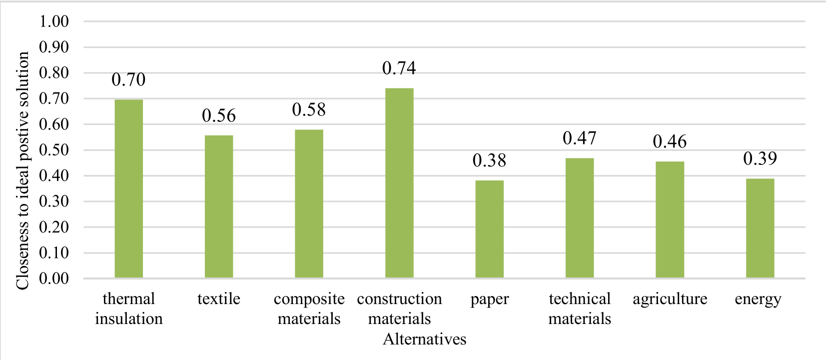


Fig. 6. Ranking of hemp products in a normal scenario under non-crisis conditions.

Table 4
Normalized decision matrix for energy and/or economic crisis situation.

Criteria	A1	A2	A3	A4	A5	A6	A7	A8	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

shown in Fig. 7. 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, with values of 0.25 and 0.17, respectively. Energy generation has moved closer to the ideal by 0.35 over half the distance. Thermal insulation has also moved closer to the ideal positive solution, as it can reduce energy consumption in dwellings. The best and second best performance differ by only 0.05 units. The other six products compared are further away from the positive ideal solution. However, the sustainability performance of energy production is 80% higher than 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.

To assess the stability of the alternatives under changing conditions, a sensitivity analysis was performed for all alternatives. Sensitivity analysis was carried out with unitary variation ratios β_k = 0.1, 0.5, 1, 1.5, 2, 2.5. Sensitivity analyses were performed for all the criteria used in the TOPSIS analysis, but only the sensitivity analysis graphs showing the most significant changes for the products that were closer to the positive ideal solution (1.00) are presented.

The sensitivity analysis for the TOPSIS results for an everyday scenario under non-crisis conditions shows that the products closer to the positive ideal solution in the TOPSIS analysis - construction materials, thermal insulation and composite materials - are affected differently by the change in the unitary variation ratio. Construction materials made from hemp are most positively affected by resource availability, while the other products, with the exception of paper, are negatively affected (Fig. 8). On the other hand, environmental aspects have the most negative impact on construction materials of all the aspects discussed. Almost the opposite is the case for thermal insulation, which is strongly negatively affected by resource availability, while environmental aspects have a moderately positive impact on this and other products, such as composite materials and textile products (Fig. 8).

The sensitivity analysis for the TOPSIS results under conditions of energy and/or economic crisis situation indicates that the products that are closer to the positive ideal solution in the TOPSIS analysis – energy, thermal insulation, construction materials experience the most fluctuations in the influence of resource availability and environmental aspects as well.

Again, it can be seen that each of the alternatives is affected by changes in the unitary variation ratio. In the TOPSIS analysis, energy production from hemp in a crisis situation came closest to the positive ideal solution and ranked first. The resource availability aspect clearly has a positive impact on energy production, construction materials and

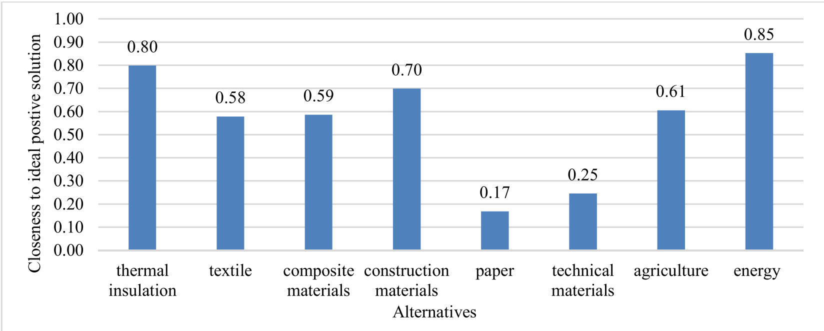
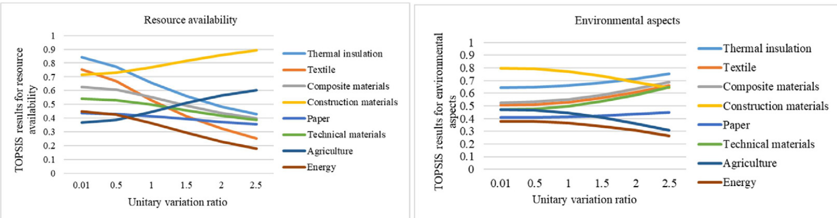


Fig. 7. Ranking of hemp products under conditions of energy and/or economic crisis.



(1.00) are presented.

Fig. 8. Sensitivity analysis for the criteria “Resource availability” and “Environmental aspects" under non-crisis conditions.

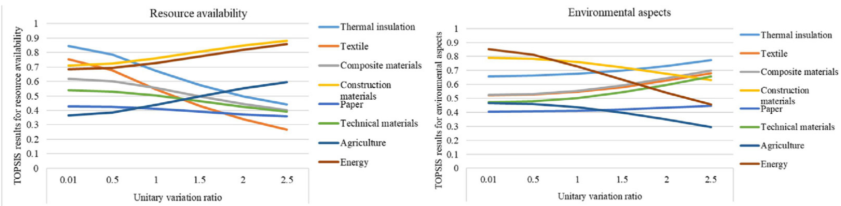


Fig. 9. Sensitivity analysis for the criteria “Resource availability” and “Environmental aspects" under conditions of energy and/or economic crisis situation.

agriculture, while the other products are, on the contrary, negatively affected, as shown by the sensitivity analysis (Fig. 9). Sensitivity analysis for the other products, which scored lower overall in the TOPSIS analysis, showed positive growth trends in the related to environmental aspects. While the use of hemp for energy production performed the worst among all alternatives in terms of environmental aspects, construction materials and agriculture also showed a downward trend.

3.2. Interpretation of LCA results

The results for electricity generation from raw hemp biomass are shown in Table 5. The results show the contribution by 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 5.31E+01 kgCO_2eq per FU. The highest environmental impact share is for the aquatic ecotoxicity 1.4E+04 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. 10. 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 has a high impact on 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. 11. 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 is presented in Table 6 to verify the compatibility of raw hemp biomass for electricity generation. In the global warming impact category, the electricity generation from peat has the highest impact with 1.2E+02 kg CO_2 eq per FU. In contrast, the least influence has sweet sorghum biomass with 2.3E+00 kg CO_2 eq per FU. The electricity generation from peat shares the highest toll for non-renewable energy impact category 1.3E+03 MJ primary per FU. Regarding sweet sorghum and wood biomass, the highest toll share is in the category of aquatic ecotoxicity, 3.4E+03 and 1.1E+04 kg TEG water per FU, respectively. Overall, the raw hemp biomass is competitive with other biomasses.

Table 5
Characterization results for the hemp biomass for electricity production.

Impact category	Unit	Total	Hemp biomass processing	Electricity production
Carcinogens	kg C_2H_3Cl eq	5.7E-01	1.2E-01	4.4E-01
Non-carcinogens	kg C_2H_3Cl eq	2.2E+00	2.0E-01	2.0E+00
Respiratory inorganics	kg PM2.5 eq	1.7E-01	1.2E-02	1.6E-01
Ionizing radiation	kBq C-14 eq	2.1E+02	6.6E+01	1.4E+02
Ozone layer depletion	kg CFC-11 eq	2.2E-06	7.9E-07	1.4E-06
Respiratory organics	kg C_2H_4 eq	1.2E-02	2.8E-03	8.9E-03
Aquatic ecotoxicity	kg TEG water	1.4E+04	7.5E+02	1.3E+04
Terrestrial ecotoxicity	kg TEG soil	5.2E+03	2.9E+02	4.9E+03
Terrestrial acid/nutri	kg SO_2 eq	3.8E+00	4.9E-01	3.3E+00
Land occupation	m2org.arable	8.8E-01	3.7E-01	5.1E-01
Aquatic acidification	kg SO_2 eq	1.4E+00	1.3E-01	1.2E+00
Aquatic eutrophication	kg PO_4 P-lim	1.4E-02	4.2E-03	1.0E-02
Global warming	kg CO_2 eq	6.3E+01	1.0E+01	5.3E+01
Non-renewable energy	MJ primary	3.0E+02	1.2E+02	1.8E+02
Mineral extraction	MJ surplus	1.2E+00	3.6E-01	8.6E-01

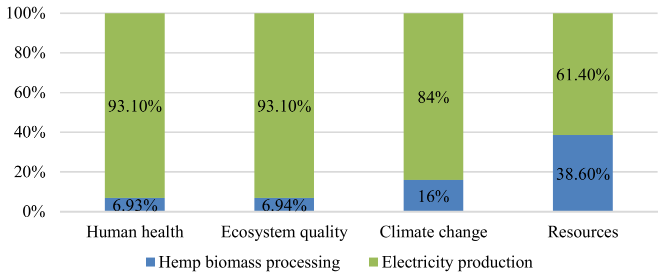


Fig. 10. Damage assessment result for the hemp biomass to electricity production.

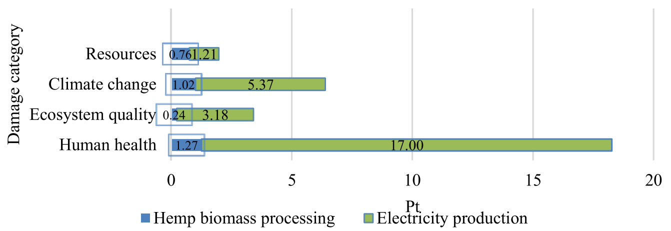


Fig. 11. Weighted totalized results for the use of hemp biomass for electricity production.

Table 6
Comparison of environmental impact assessment to generate electricity from alternate biomasses.

Impact category	Unit	Raw hemp biomass	Peat biomass	Sweet sorghum biomass	Wood biomass
Carcinogens	kg C_2H_3Cl eq	5.7E-01	8.0E-02	1.0E-01	6.3E-01
Non-carcinogens	kg C_2H_3Cl eq	2.2E+00	2.8E-01	2.7E-01	1.7E+00
Respiratory inorganics	kg PM2.5 eq	1.7E-01	5.8E-02	1.7E-02	2.4E-02
Ionizing radiation	kBq C-14 eq	2.1E+02	7.9E+01	1.4E+01	6.8E+01
Ozone layer depletion	kg CFC-11 eq	2.2E-06	6.7E-07	2.4E-07	1.5E-06
Respiratory organics	kg C_2H_4 eq	1.2E-02	2.8E-03	1.3E-03	1.2E-02
Aquatic ecotoxicity	kg TEG water	1.4E+04	7.2E+02	3.4E+03	1.1E+04
Terrestrial ecotoxicity	kg TEG soil	5.2E+03	2.9E+02	5.9E+02	4.0E+03
Terrestrial acid/nutri	kg SO_2 eq	3.8E+00	1.0E+00	2.8E-01	6.4E-01
Land occupation	m2org.arable	8.8E-01	3.4E-01	5.5E+00	3.3E+01
Aquatic acidification	kg SO_2 eq	1.4E+00	3.3E-01	4.3E-02	1.4E-01
Aquatic eutrophication	kg PO_4 P-lim	1.4E-02	7.8E-04	4.7E-03	7.2E-03
Global warming	kg CO_2 eq	6.3E+01	1.2E+02	2.3E+00	1.8E+01
Non-renewable energy	MJ primary	3.0E+02	1.3E+03	3.1E+01	2.1E+02
Mineral extraction	MJ surplus	1.2E+00	1.7E-01	1.1E-01	9.4E-01

Note: The datasets for the peat, wood, and sweet sorghum biomasses to produce electricity is taken from *Ecoinvent 3* databases [32].

3.3. Integrated sustainability assessment results

If hemp can be used to produce about 25 000 different products [1], then it would only be reasonable to produce higher value-added products from it. However, crisis situations can undermine the importance of the sustainability criterion. It is important to set priorities, because sometimes humanitarian and economic indicators take precedence in the short term. The war in Ukraine has led to adjustments in the energy market and it is therefore important to understand the challenges of sustainability in this situation.

3.3.1. Identification of sustainability issues

The multidimensionality of sustainability becomes clear when it comes to the use of hemp. On the one hand, it defines the use of hemp resources for combustion and energy production. This type of use is close to the base of the pyramid [38], indicating low added value. On the other hand, under certain circumstances, such as economic and/or energy crises, the sustainability approach may lose priority and become a minor issue. The Russian war in Ukraine created significant problems for many countries, as they: had to decide on the long-term development of the energy sector and change their long-term development policies. European countries urgently needed to move away from fossil fuels such as natural gas and find ways to replace these fossil fuels with renewable energy sources. In this case, it is important to find criteria that cover the entire spectrum of sustainability.

The MCDA analysis for the everyday scenario 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 result was positive: the use of hemp in the energy sector for energy generation is not sustainable and 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, it will 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.

3.3.2. Comparison between alternatives

The choice of alternatives and how the alternatives are compared are critical to evaluating sustainability. Industrial hemp is an excellent resource from which about 25 000 products can be made [1]. Each product has its niche in its sector, from engineered materials in the construction and automotive industries to the energy sector.

In the first step of testing the methodology, the eight most popular uses for hemp products were selected for MCDA analysis. These were analyzed based on six indicators. Resource availability and technological, economic, environmental, climate change, and circular economy aspects determined the value of the indicators. The development of the MCDA matrix and the results obtained convinced the authors that an emergency can influence priorities and change the choice of alternatives. Therefore, further evaluation of the results of the MCDA analysis is needed, integrating the LCA analysis into the best solution for the economic crisis to confirm its sustainability. In the LCA analysis four alternative technological scenarios for the development of the energy sector were selected: combustion of raw hemp biomass, electricity generation from peat and wood, and sweet sorghum biomass. The results showed that the raw hemp biomass scenario is less environmentally and climate friendly and therefore should not be used in times of crisis. The integration of MCDA into the LCA analysis is a valuable tool for assessing the sustainability of bioresources. Integrating MCDA into the LCA analysis is a valuable tool for assessing the sustainability of bioresources.

4. Conclusion

Given the increasing global demand for energy and ambitious climate targets, the use of biomass for combustion will become even more important. As wood becomes increasingly scarce due to rising demand for wood and energy consumption, there is growing interest in using alternative solid biofuels for energy generation. Biomass has high energy density, homogeneous physical properties, easy handling and efficient transportation. However, the use of biomass for energy production must to be targeted and carefully selected. LCA has shown that the combustion of hemp has a higher impact than other energy sources such as peat, wood and other biomasses. MCDA demonstrated that hemp is an excellent raw material for the production of various products. However, hemp products that can be used in the construction industry, namely: construction materials, and thermal insulation, rank high in the product rankings. However, it should be noted that these results are valid only in everyday, non-crisis conditions. In times of economic and energy crises, the situation changes significantly. The solution closest to the positive ideal is to use hemp in energy generation or in the production of a material (in this case, thermal insulation) that increases energy efficiency. This creates a dilemma between short-term choices and long-term value creation. While in the short term, the cultivation and use of hemp for energy generation can alleviate the challenges of the energy crisis, in the long term a more sustainable solution, both economically and environmentally, would be to consider solutions that allow hemp to be processed to create high value-added products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Evaluation of bioresources validation

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Abstract. A major worldwide problem is the degradation of energy sources and the wide amount of waste products from industries, households, or from any other human activities. But what if both problems can be solved by one solution? Extensive data show that validation of bioresources increases the production of the value-added product. The assessment is based on a scenario approach. A vast literature review was performed, to investigate the alternative application pathways for various types of non-primary bioresources. Multicriteria analysis is considered as the current gold standard technique for bioresources valorisation and is proved for two cases. Firstly, we present tests that evaluate the performance of different pre-treatment methods in order to extract fibre from Hogweed biomass. Secondly, we assess the resilience of our approach using Multi-criteria analysis for brewers' spent grain to find out the best value-added product. The results demonstrate the adequacy of the method for Hogweed biomass and brewers' spent grain valorisation.

Key words: bioeconomy, biorefinery, bioresources, industrial by-products, multi-criteria analysis, valorisation pathways.

INTRODUCTION

Bioeconomy shows the link between natural resources or residues and their conversion into high-qualitative bio-based products. The industrial business and society usually consume bioresources for agribusiness, food, aquaculture, and supply their products to the market (Schmidt et al., 2012). However, each kind of bio-resources has its particular and multi-level applications (Körner, 2019) and each of these applications differs regarding economic competitiveness, environmental sustainability, and real application potential. Bioresource valorisation is indirectly connected to the field of chemistry and related sciences, which shows a significant change due to the transition of fossil to renewable feedstock (Giacobbe et al., 2018). One of the core elements of the bioeconomy is biological resources. Bioresources are renewable and natural; therefore, they are crucial in combat against major worldwide challenges such as rapid population growth, fossil resource depletion, ecological security, and climate change. Bioresources are continuously used in many sectors of the economy (Efken et al., 2016). Bioresources have made life easier for humans by providing green technologies, renewable energies, and alternative sources for various chemicals (such as botulin, maltol, quinine, salicylic acid, etc). In long term scenario, biorefinery valorisation of renewable resources plays a major role in the establishment of the bioeconomy. As a result of recent advances in biotechnological processes, industrial waste can be converted into higher value-added products (Adamowicz, 2017).

Added value can be defined in many different ways, and definitions vary according to the different criteria. For bioresource valorisation, added value means extra value created over the value that could be created during the common application. Bioresource valorisation has the potential to promote the transition to the sustainable bioeconomy through two development pathways: (1) discover the higher added value product and more profitable applications of common primary bioresources (i.e., agriculture, forestry, fishery products), and (2) discover the added value of uncommon bioresources such as by-products, unwanted biomass i.e. generate from territory cleaning and waste biomass. There is some scientific research available on the valorisation of the alternative biomass sources that represent the secondary, tertiary, and quaternary bioresources, however, various alternative bioresource applications must be considered and evaluated regarding their technical, economic, and environmental feasibility. Overall, bioresource valorisation is the pathway to reach the highest levels of bioresource transformation, this represents one of the first attempts towards sustainability and sustainable bioeconomy.

The evaluation of bioresource valorisation and the potential amount of post-industrial by-products are summarized in this research paper to determine the existing situation regarding the utilization and valorisation of these bioresources. To perform the evaluation Multi-Criteria Decision-Making Analysis (MCDA) method has been used. The aim of using this method is to determine the most profitable and environmentally feasible product by choosing the best bioresource. In other words, bioresource valorisation can implant a neutral balance between environment and economy (Dean et al., 2019).

MATERIALS AND METHODS

The main research methods are applied including literature analysis, the building of valorisation pathway schemes, the case study approach, and multi-criteria analysis. A detailed methodology protocol is described below (Fig. 1).

To investigate the possibilities to produce novel and higher added value products from underused biomass, first, the literature analysis was performed. Literature analysis focuses on the definition and applications of bioresource valorisation, as well as the identification of existing and innovative alternatives for bioresource. Secondly, an approach to build a valorisation pathway scheme for each of the assessed bioresources was introduced. The developed schemes can be further used as reference materials by the stakeholders who want to implement the valorisation of a certain bioresource. Also, the literature analysis considers the bioresource cascading approach and biorefinery approach, which are two significant tools to ensure the long-term sustainability and integrated profitability of any bioresource valorisation project.

However, the knowledge of the potential valorisation alternatives is only the first Step towards their comparison and evaluation. There are important aspects (i.e., technical, economical, and environmental) that need to be considered. In order to design an accurate scenario, knowledge of evaluation criteria and an alternative is necessary. In this study, the necessary data have been obtained from international scientific research publications.

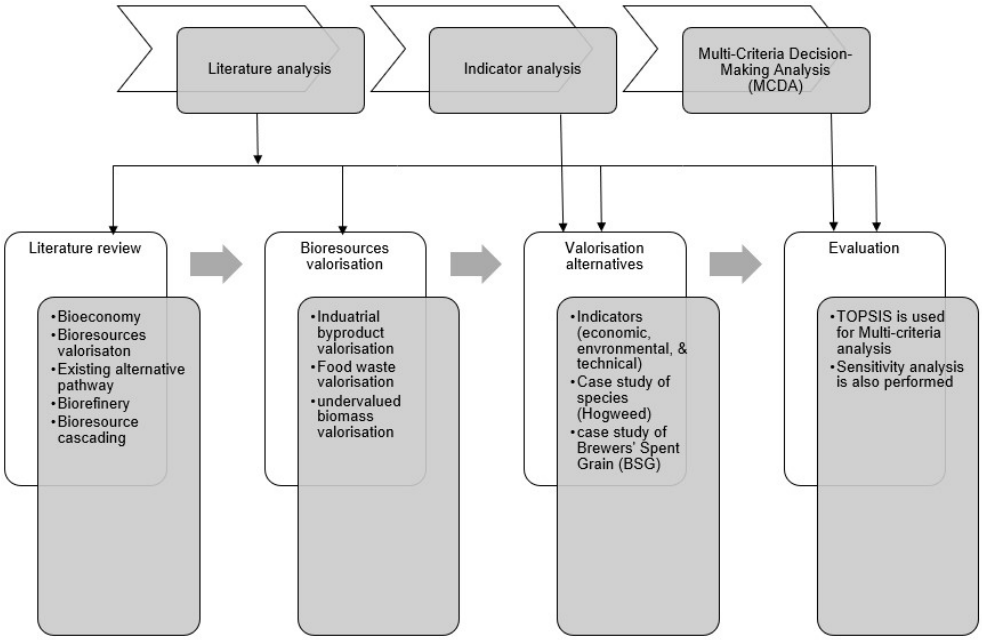

Figure 1. Methodology protocol.

Technically, Multi-Criteria Decision-Making Analysis has multiple properties that explain its application in this research. The following properties can be considered:

a) It looks to take very precise, multiple, and contrast criteria,

b) It helps to define the problem,

c) The provided model by Multi-Criteria Decision-Making Analysis gives focus and direction,

d) It gives a justifiable, manageable, and explainable decision (Belton & Stewart, 2002).

A technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is one of the classic methods used for Multi-criteria analysis (Rozentale & Blumberga, 2019). By using this method several alternatives can be compared with the chosen criteria. The reason behind using the TOPSIS method over any other method is the clarification and specification of the method. By this method, appropriate and justifiable results can be obtained in a remarkably straightforward way. One of the major advantages of this method is that it does not need any special program for evaluation (Rozentale & Blumberga, 2019). The various steps to perform the TOPSIS have been described in detail here.

Step 1: Multi-criteria analysis is used for two cases a) to determine the best pre-treatment method for hogweed invasive plant and b) to choose the best value-added product from brewers' spent grain industrial leftover by using the suitable criteria for each scenario.

Step 2: Development of decision-matrix shows the quantitative or qualitative information for each alternative and criteria. For qualitative data specifically for the TOPSIS method, it is important to derive Multi-criteria analysis scores. This score dependent on technically obtainable data. To obtain these comparative scores for qualitative data, one of the standard scales is used, for example, the Likert scale that can take values from 1 to 3 (poor, average, good performance), from 1 to 4 (very poor, poor, good, very good), or other range of scale depending on the requirements for the necessary investigation (Ward et al., 2016).

Step 3: All values obtained from the decision-matrix (Step 2) need to normalize by using the following Eq. 1.

$$r_{ai} = \frac{x_{ai}}{\sum_{a=1}^{n} x_{ai}^2} \quad (1)$$

where a = alternative, $a= 1,..,n$; i = criteria, $i=1,..,m$; r_{ai} = normalized criteria value.

Step 4: Eq. 2 shows the formula to calculate the weight for each criterion.

$$w_i = \frac{1}{n_i} \quad (2)$$

where w_i = weighted value; n_i = total number of criterions.

Step 5: Normalized matrix value can be derived by multiplication of normalized value (Step 3) and weight which is done by following Eq. 3.

$$v_{ai} = w_i \times r_{ia} \quad (3)$$

where v_{ai} = weighted value; w_i = weight, $w_{i1}+w_{i2}+\ldots+w_{im}=1$, $w_i=1\ldots m$; r_{ia} = normalized criterion value.

Step 6: Distance for each ideal and non-ideal alternative can be calculated by the sum of the squares of weighted criterion values (Step 5). The development of the distance measure of the ideal solution has been done by following Eq. 4.

$$d_a^+ = \sqrt{\sum_{j=1}^{n} (v_i^+ - v_{ai})^2} \quad (4)$$

where d_a^+ = distance for each action to the ideal solution; v_i^+ = ideal solution; v_{ai} = weighted value.

The development of distance for each action to the non-ideal solution has been calculated by following Eq. 5.

$$d_a^- = \sqrt{\sum_{j=1}^{n} (v_i^- - v_{ai})^2} \quad (5)$$

where d_a^- = distance for each action to the non-ideal solution; v_i^- = non-ideal solution; v_{ai} = weighted value.

Step 7: For each alternative relative closeness coefficient (Ca) is different, Ca is considered between 0 and 1; but 1 is considered as the most suitable value. Ca ratio shows the distance to the non-ideal solution, which is determined by the sum of the distance to the non-ideal solution divided by distance to an ideal and non-ideal solution. Eq. 6 shows the Equation for the relative closeness coefficient.

$$\text{Ca} = \frac{d_a^-}{d_a^+ + d_a^-} \quad (6)$$

It is important to perform a sensitivity analysis for each criterion. To find out the new weight for each criterion following Equations (7 and 8) are used. Different weights distributions are changed based on the weight imposed on the distribution.

$$\beta'_k = \sum_{k=1}^{n} w' = 1 \quad (7)$$

$$w'_{k1} = \beta_k \times w', \text{k} = 1,2, 3\text{…. n} \quad (8)$$

where β'_k = the unitary variation ratio of w_k after distribution; w_k = weight being imposed on the distribution.

Case study description

The challenging task for bioresource valorisation is to determine the most appropriate pre-treatment method by which the valorisation can be done. To investigate possibilities to produce novel and higher added value products from underused biomass, Multi-criteria analysis can be applied to analyse the various alternatives.

Case study 1- pre-treatment methods and biomass

Hogweed (*Heracleum Sosnowski*) is an invasive species in Latvia, whose management methods are mostly connected to control and eradication. The only major hazard in the spread of Hogweed is the risk of damage to human health. There are preventing techniques too such as chemical-mechanical treatment. The excessively long times i.e. 2–7 years are needed for successful application of the technique (Blumberga & Zihare, 2017a). Nevertheless, in Latvia hogweed distribution is a significant problem as it covers 10,000 ha area. (Zihare et al., 2019) state that the use of invasive plant species as a type of underused bioresources is important for bioeconomy development. They also suggest that further reuse of the by-products from high added value product production should be used in a cascading or biorefinery approach to producing biofuels or energy (Zihare et al., 2019). The typical application of hogweed biomass is its use as feed for bovine animals or sheep. However, many added-value products could be made from hogweed, for example, bioethanol and biobutanol (Blumberga & Zihare, 2017a). (Zihare et al., 2018) have also investigated the production of solid biofuels in the form of pellets from hogweed. In another study (Zihare et al., 2019) identify that a large share of research on hogweed focuses on its application for food or agricultural feed. Moreover, some studies investigate its application in the pharmaceutical industry, as a fertilizer, antifungal agent, and biofuel. Cellulose can be obtained from hogweed plants and further used in cardboard production (Zihare et al., 2019). One of the potential products that can be obtained from hogweed is fibre. However, there is a lack of research on obtaining fibre from hogweed. To produce biobutanol from Hogweed a mechanical pre-treatment (milling) should be applied first to ensure access to cellulose and hemicellulose. Then enzymatic hydrolysis is applied to convert cellulose and hemicellulose to sugars and fermentation is applied to produce biobutanol. The last stage is biobutanol extraction (Blumberga & Zihare, 2017a).

Multi-criteria analysis has been done to compare and find out the most appropriate method for pre-treatment and obtaining fibres from biomass resources. The main goal to apply the pre-treatment method is to break down the cellulose fibre (Behera et al., 2014). Pre-treatment is accelerating the process and has many advantages such as:

a) Creating pores in biomass, which allows to separate cellulose, hemicellulose, and lignin residues,

b) It also enhances enzyme activity,

c) A cost-effective method in terms of low requirement of heat and power,

d) Extract the valuable component from lignin (Brodeur et al., 2011 & Behera et al., 2014).

Many pre-treatment methods can be applied for the biomass such as physical, chemical, physicochemical, and biological methods. The physical pre-treatment method requires a wide amount of energy; it also depends on the type of biomass. Due to the different porosity and particle size of each biomass physical pre-treatment method requires a different amount of energy consumption. In contrast, the biological pre-treatment method requires microorganisms like fungi, algae, bacteria, etc. to digest hemicellulose and lignin residues. The biological method also requires certain conditions at a laboratory scale, which are not costly but are time-consuming such as microbial pre-treatments. On the other side, the physical method requires less time but it requires a higher amount of energy which is not environmentally friendly (Brodeur et al., 2011). Chemical pre-treatment can be done by using various solvents. Also, this method is costly but, the most promising. Alkali pre-treatment requires a catalyst to access the process, which is expensive, while acid pre-treatment requires costly acids for recovery and specific standard equipment which can resist corrosion (Brodeur et al., 2011). An organic solvent is also one of the chemical pre-treatment methods with remarkable environmental benefits such as the requirement of low temperature and pressure, but with a high capital cost (Verardi et al., 2012).

The case study is conducted for the evaluation of different chemical pre-treatment methods for one biomass source (Hogweed). Three main criteria considered for evaluation are technical, economic, and environmental. The technical evaluation criteria include such aspects as the concentration of substrate, the time requirement for pre-treatment method, and methane generation. In terms of the economic parameter, the cost is considered as the most effective criteria, because pre-treatment scenarios involve equipment cost, maintenance cost, capital cost, the cost for catalysts, and reactors. Environmental evaluation criteria are the use of aggressive chemicals, percentage of by-products (by mass or weight), amount of wastewater, hazardous disposals, etc.

The second possibility for pre-treatment assessment is to use three biomass sources which are *Sorbaria sorbifolia* (false spirea), *Heracleum Sosnowski* (hogweed), and *Solidago canadensis* (goldenrod), and compare their properties with one pre-treatment method. The aim is to take three different biomasses and to compare the potential of maximum fibre extraction. *Sorbaria sorbifolia* species is extremely useful in the medicinal area, it is used to treat the breakdown of bones, swelling, and pain (Qu et al., 2016). However, this area of research is under widespread scrutiny and investigation. Whereas *Solidago canadensis* species has been widely observed as a decorative plant. Different parts of this plant have their specialty to produce valuable products such as flowers, leaves, and stems can produce honey, essential oils, and cellulose (Blumberga & Zihare, 2017b).

Here we compare the performance of seven different chemical pre-treatment methods considering four main criteria for Hogweed biomass. The selection of criteria has been done based on the literature analysis and availability of technical and economic information. After that, the decision-making matrix was compiled. All cost is taken into account to pre-treat 1kg of hogweed (Song et al., 2014), but for KOH cost assumption is based on the literature (Ward et al., 2016), the concentration, required amount of time (i.e. considering the total experiment time & chemical reaction between substrate and chemical), and methane generation capacity for each alternate method is assumed based on literature analysis (Amin et al., 2017). Methane generation capacity is considered a positive criterion because at the end of the process generated methane can be used for bioenergy application. The decision-making matrix, which indicates the numerical information for each criterion and alternative (Table 1).

Table 1. Pre-treatment method alternatives & selected criteria (Song et al., 2014 & Amin et al., 2017)

Criteria		Alternatives						
		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

Case study 2 - Brewers' spent grain valorisation

Due to better data availability, bioresources brewers' spent grain were selected for a case study investigation and evaluation of valorisation alternatives. To compare the alternative pathways of post-industrial bioresource valorisation three scenarios were designed for brewers' spent grain valorisation a) Biogas production, b) production of dog biscuits (feeding), and c) single-use biodegradable dishes. The selected criteria for these alternatives are environmental aspects (CO_2 emissions) and economic aspects (Net present value, capital investments).

Scenario 1 - Biogas production

For scenario 1 it is assumed that 1 ton of brewers' spent grain is used as a supplement to an existing biogas production plant. No drying of brewers' spent grain is needed before adding it into the bioreactor. The methane production yield from brewers' spent grain is 218.89 m^3 CH_4 t^{-1}, methane calorific value is 9.97 kWh m^{-3}, combustion plant efficiency is assumed to be 0.884 (Beloborodko & Rosa, 2015). Thus from 1 ton of brewers' spent grain 218.89 m^3 CH_4 can be produced with a maximal calorific value of 2,181.9 kWh and output obtainable energy of 1928.8 kWh. As brewers' spent grain is bioresource, the CO_2 emissions from the burning of bioresource-based biogas are assumed to be 0. For the economic costs of using brewers' spent grain for biogas production, it is assumed that brewers' spent grain is given to biogas plants at no cost. In detail, the transportation costs should be accounted for in each potential project separately, but to calculate the net present value of this scenario, transportation costs were assumed similar as in (Beloborodko & Rosa, 2015).

Scenario 2 - Production of dog biscuits

One of the potential higher added value applications of brewers' spent grain is the production of dog biscuits (Beer paws, 2020). The price of flour is assumed to be 1 Euro kg^{-1}, the price of peanut butter is assumed to be 13.50 Euro kg^{-1} the price of eggs is assumed to be 0.2 Euro per piece according to retail prices in May 2020. It is assumed that brewers' spent grain is available at no cost for the brewery. As the input mass of the available recipe is approximately 1kg, and the recipe provides that the outcome would be about 100 dog snacks, but it is not mentioned the outcome in weight (weight changes during cooking and drying), it is cautiously assumed that 100 dog snacks equal to 1 commercial package of dog snacks (200 g) for which a retail price of approximately 9.17 Euro per package was found in source (Beer paws, 2020). Therefore, the cost for raw material for 1 batch would be approximately 2.40 Euro, energy cost assuming small scale production (electric oven) - 1.50 Euro per batch. The labour costs are assumed to be negligible for initial assessment, considered that brewery workers could be able to do small-scale production within their day-to-day duties. CO_2 emissions from production arise due to the electricity use of an oven. As the electricity CO_2 emission factor in Latvia is reported 0.149 kg_{CO2eq} kWh^{-1} (Ferreira et al., 2019) the CO_{2eq} emissions for 1 batch of dog biscuits would be 1.3 $kg_{CO2\ eq}$. From 1 ton of brewers' spent grain, approximately 1,950 batches of dog biscuits can be produced, therefore the economic costs for raw materials and energy would account for 7,632.3 euro, the CO_2 emissions due to electricity use would account for 2,470 kg_{CO2eq}, and the profit could account to 17,881 euro. It is assumed that the production process and packaging would be manual work, the costs of packaging materials are not considered, assuming that during start-up simple packaging means could be used and distribution could be organized through breweries' in-house shops of farmers markets.

Scenario 3 - Single-use biodegradable dishes

Recently the production of single-use dishes from brewers spent grain and potato starch by hot-pressing has been reported in the scientific literature (Ferreira et al., 2019). They report that the share of brewers' spent grain can be up to 80% of the final product, but the best flexural strength in comparison to expanded polystyrene was obtained at 60% brewers' spent grain share and addition of chitosan and glyoxal. Examples of single-use plates are produced from a similar material.

Ferreira et al. (2019) report that the moisture of brewers' spent grain is 77% in their used sample, while 68% of initial moisture has been reported for a Latvian sample by (Beloborodko & Rosa, 2015). Therefore, before the hot-pressing of single-use dishes, brewers' spent grain must be dried. The energy amount that is required to dry 680 kg of water is calculated as 490.1 kWh accounting for 88.21 Euro costs if an electric drying oven is used. The requirement for dry components is calculated accordingly to the formulation given in (Regrained, 2017) From 1 ton of wet brewers' spent grain, 320 kg may be obtained. Therefore, according to the formulation, 195.73 kg of starch and 17.6 kg of glycerol would be needed, which would cost 47,0225.6 Euro considering current prices for chemicals. In the current scenario, it is assumed that the water that is further added to form the mixture is evaporated during the hot-pressing process and the mass of the end product equals the weight of dry components. If the weight of a ready plate is assumed to be 100 grams (similar to products available in retail stores (Gemoss, 2020), then around 5,333 plates can be made from 1 ton of brewers' spent grain. The hot-pressing temperature may be from 130 °C to 220 °C and the time required for pressing differs from 2 to 20 minutes (Regrained, 2017). For a cautious assumption, 10 minutes' residence time is assumed, the equipment power requirements are assumed from listings for an automatic flat heat press (Bestsub, 2020).

RESULTS AND DISCUSSION

The key findings are discussed, and recommendations are provided for future research. Firstly, the Multi-criteria analysis allows a more detailed analysis of the comparison between seven different pre-treatment methods. One of the most significant findings in the paper was the identification of the best possible method to produce a valuable product. The Multi-criteria analysis results showed that the $Ca(OH)_2$ chemical pre-treatment method is the most suitable method for pre-treatment. Based on the closeness coefficient graph is plotted (Fig. 2). The graph shows the results obtained from Multi-criteria analysis and unitary variation ratio which is ideally considered as 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.

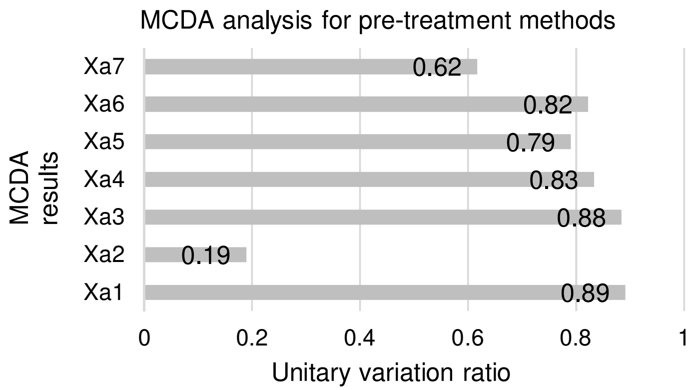

Figure 2. Multi-criteria analysis results for case study 1.

Secondly, the results for the comparison of environmental aspects (CO_2 emissions) and economic aspects (Net present value, capital investments) for all three scenarios are discussed below. As the functional unit for which the initial scenarios were calculated was 1 ton of brewers' spent grain, it is assumed as the monthly amount that a medium-sized brewery can supply. The Net present value values were calculated for all three scenarios based on taken assumptions of capital investments needed, the annual costs, and income. The labour costs were not considered, as it is assumed that a single employee could be employed for each of the scenarios, or in case that the breweries themselves develop the production of additional products them existing employees can be involved. The results of the Net present value, annual CO_2 emissions, and profit are shown below (Fig. 3). The highest CO_2 emissions are for a dog treat production, which is due to the technological process where wet brewers' spent grain is used directly in the mixture but baking of dog treats requires longer residence time in the oven, thus larger energy use and higher CO_2 emissions. On the other hand, the Net present value for dog treat production is also the highest, partly due to lower necessary capital investments and partly due to higher price of the end product (as well, a cautious assumption of half of the price found in a foreign example was used for calculations, considering the lower willingness to pay of Latvian consumers).

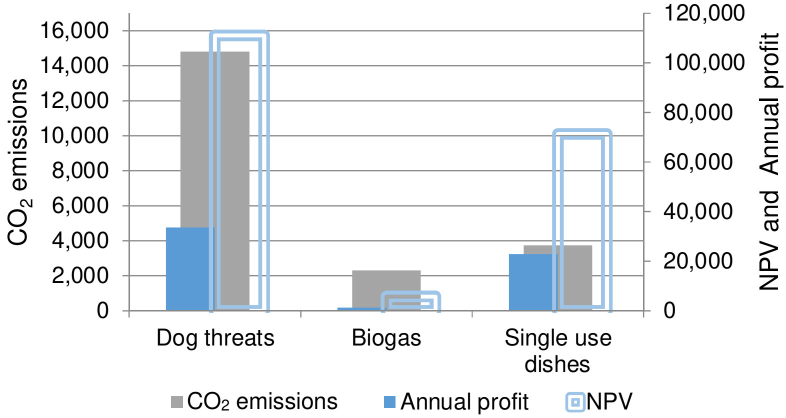

Figure 3. Scenario results for case study 2.

The biogas scenario has the lowest annual CO_2 emissions, and no capital costs are needed, but this scenario also has the lowest Net present value and annual profit, due to only small addition of added value during brewers' spent grain processing into biogas. Besides, to consolidate the effects of various evaluation criteria and provide a single value evaluation for each of the scenarios, a Multi-criteria assessment by the TOPSIS method was applied. For the Multi-criteria assessment, it is assumed that regarding capital costs and CO_2 emissions the ideal solution is minimum, while for the Net present value the ideal solution is maximum (Fig. 4). Finally, Sensitivity analysis is performed in order to check the influence of attribute distribution on the results of the TOPSIS method for both case studies.

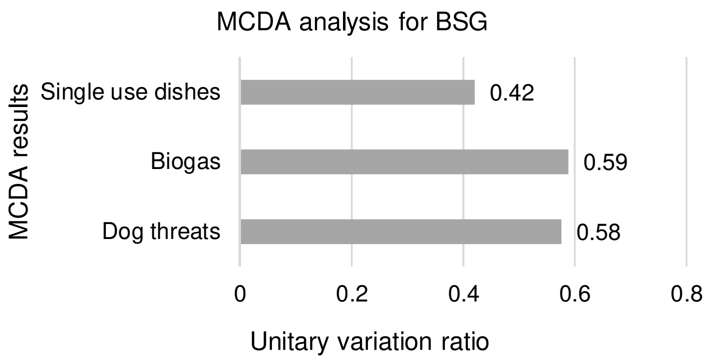

Figure 4. Multi-criteria analysis results for case study 2.

In a nutshell, the results of this work will unravel and shed light on the understanding of bioresource valorisation alternatives. However, a closer look at the literature, reveals a number of gaps and shortcomings. Since several issues remain unaddressed, a future extension is suggested for technical outlook and experiments. This study was limited to the numerical data for some biomass resources but could be extended for future work.

CONCLUSIONS

This research aims to determine an approach for the evaluation of bioresource valorisation alternatives considering various aspects that are significant for sustainable valorisation. Firstly, this objective was approached by investigating the available literature on bioeconomy, bioresource valorisation, value-added products, biorefinery. Secondly, several alternative pathways for bioresource valorisation were identified and generic schemes for the undervalued bioresources valorisation were developed. Lastly, valorisation pathway schemes have been developed for several bioresources that are by-products of industrial production and are commonly available in Latvia.

Based on the data collected from the publicly available database on the amount of post-industrial waste and by-products generated in Latvian enterprises, an analysis of the number of bioresources potentially available for valorisation in Latvia was performed, as well as this information was compiled graphically, providing an opportunity to identify areas better suited to implement valorisation of bioresources.

Within this research, a bioresource valorisation alternative evaluation is performed for the hogweed biomass pre-treatment to extract the fibre by using Multi-criteria analysis. The assessment is based on a scenario approach and a vast literature analysis was performed regarding alternative application pathways for various types of non-primary bioresources.

Another case study has been done to evaluate valorisation alternatives for brewers' spent grain to find out the best value-added product. Multi-criteria analysis results for brewers' spent grain shows that they typically applied alternative to produce biogas from brewers' spent grain achieves the highest score (0.59) in between the developed scenarios, but more innovative and higher net present value alternative scenarios of production of dog treats (0.58) and production of single used dishes (0.42) are also significant competitors. The relatively higher score for biogas production is mainly because it is already an established alternative, no significant capital costs are needed, and this scenario has the least CO2 emissions. However, the higher annual profit and net present value for the other two scenarios indicate their large economic potential, and the environmental potential could be improved if renewable energy sources would be used for technological processes. Also, Multi-criteria analysis can be further applied to the analysis of the valorisation pathways of industrial by-products such as cheese whey and by-products of grain processing.

The research concludes that bioresource valorisation alternatives can be evaluated considering various aspects that are significant for valorisation, economic feasibility as well as environmental sustainability by using a Multi-criteria analysis approach. The Multi-criteria analysis was successfully applied to case studies to evaluate the pre-treatment of hogweed to extract fibre from it and for bioproducts production from brewers' spent grain to find out the best alternative for its management after industrial processes.

However, a significant limitation for the depth of evaluation was the lack of data on technological processes and valorisation pathways for different alternatives. It is therefore suggested to perform more scientific research and experiments, especially by presenting the results in comparable dimensions, to be able to provide more precise results and to be able to evaluate more valorisation options.

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An Analysis of the Extraction Technologies: Fruit Peel Waste

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***Abstract* – Advances in technology over the past few years have allowed us to evolve from waste to value. Food waste has been an increased recognition that more attention needs to be paid to this area. With this concern, research on fruit waste valorization into medicinal products has a rich background. This paper approaches the problem with a broader perspective by introducing the fruit waste valorization pathway. The key idea in this paper is to use the multi-criteria analysis method to choose the best essential oil extraction technique from fruit waste. The performance of four different extraction methods i.e., steam distillation, cold-pressing, solvent extraction, and hydro distillation compared in the approach, considering the environmental, economic, social, and technical criteria. The methodology was developed with two scenarios, by using the Analytic hierarchy process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods. Our research highlighted that cold-pressing extraction is the most effective technique for essential oil extraction in both scenarios.**

***Keywords* – Bioresources; medicinal use; multi-criteria analysis; valorization pathway**

1. INTRODUCTION

With the worldwide increasing population, production and cultivation of fruits and vegetables is also increasing. Besides, food waste has long-lasting footprints in terms of landfills and socio-economic impacts due to the higher moisture and biodegradability [1]. Therefore, food waste management is becoming a major concern over the world but with advanced technology, food waste can be a versatile environmental bioresource that can be converted to biofuel, value-added products, and biomaterial [2].

This research particularly focuses on the fruit waste valorization pathways because enormous studies have been done on the conversion of fruit waste into landfills, anaerobic digestion, composting, etc. [3]. Pfaltzgraff *et al.* argue that fruit waste is not only a wide source of energy but also has incredible ability to produce industrial products such as essential oil, medicines, cosmetics, organic amendment, etc. [4]. Each part of a fruit, for example, peel, pulp, and seed have a unique residual and chemical composition that can be used to produce various organic products.

Traditionally, fruit peels are the most common waste that can be easily found in the environment. Fruit peels have the best medicinal properties such as antimicrobial, antioxidant, anti-inflammatory, anti-healing, anti-infectious, anti-mutagenic, and hepatoprotective. Essential oil is one of the crucial extractions from fruit peels, researchers have been discovered after several experiments that essential oil has antimicrobial activity

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against bacteria, moulds, yeasts, pathogenic and phytopathogenic microorganisms. As a result, it has been proven that essential oil can be used to confront the microorganisms to the antibiotics [5]. To support the current research some of the examples are mentioned in Table 1.

TABLE 1. FRUIT WASTE INTO MEDICINAL USE

Fruit waste	Value-added product	Medicinal use	Methods	Reference
Banana peel	Essential oil	Antioxidant property	Extraction	[5]
Citrus peel	Essential oil	Alleviates pain Relieves inflammation Dissolve's gallstones	Extraction	[6]
Orange peel	Essential oil	Antimicrobial activity Flavoring agent of medicine	Steam distillation Cold pressing Solvent extraction Enfleurage	[5], [7]
Mango peel	Pectin	Health benefits	Extraction	[8]
Grapefruit peel	Essential oil	Antibacterial and Antioxidant properties Biopesticide against mosquito larvae	Paper disc diffusion	[9]

One of the essential components that can be derived from fruit peel (apple pomace, citrus, sugar beet pulp) is pectin. Earlier research shows that pectin is an effective component at the industrial level and also useful in the medical treatment of cancer, cell apoptosis, and cholesterol [10]. Several studies have discovered that fruit peel waste has a potential application to medicinal products.

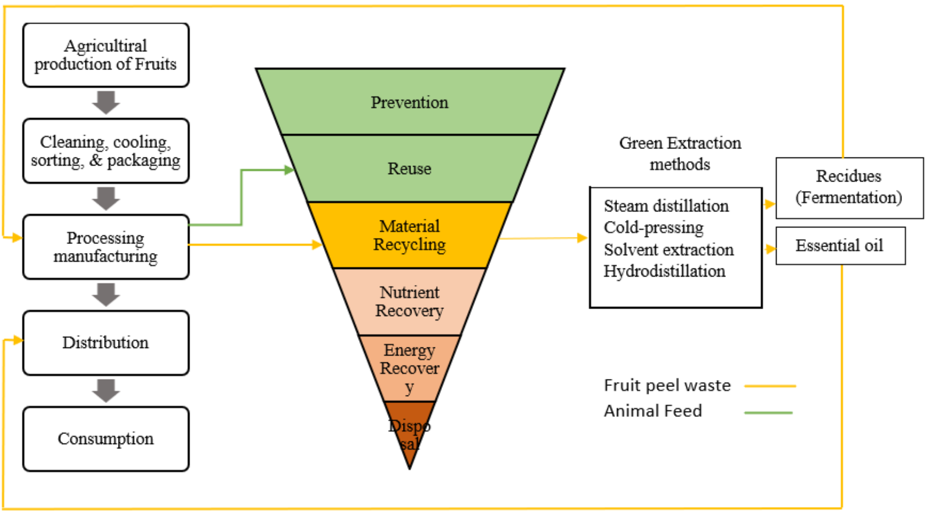

Fig. 1. Essential oil extraction pathway.

Essential oils term is also referred to as volatile oils, ethereal oils, or aethrolea, which contain the essence of a plant fragrance. It is a concentrated hydrophobic liquid, naturally derived from plants [11]. A recent systematic review investigated the extensive use of essential oil in the cosmetic industry, daily life due to the fragrance [12], and pharmaceutical industry [13], which shows the increasing demand for essential oil in the market. A variety of methods can be reliably utilized for extraction. Fig. 1 shows the clear vision of the extraction pathway of essential oil from fruit waste. Here, we presented the essential oil extraction from the fruit peel waste. In the next chapter, a multi-criteria analysis is performed to choose the best extraction technology.

2. METHODOLOGY

The methodology consists of literature review, then it further goes with multiple-criteria decision analysis (MCDA), using Analytic hierarchy process (AHP) with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), after receiving results, which need to be analysed, conclusions should be drawn.

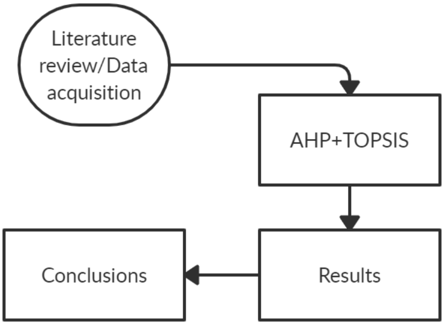

Fig. 2. Research methodology.

MCDA is used to make decisions and analyse the significance of objectives from various types of information and data – qualitative and quantitative data, data from the physical and social sciences, and from politics and ethics to evaluate problem solutions.

TABLE 2. SCALE FOR PAIRWISE COMPARISON

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

The next step is to identify the criteria weights using AHP. AHP method divides and analyses 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 the selected criteria are compared in pairs by experts [14]. Researchers from the Institute of Energy Systems and Environment at Riga Technical University are the experts to define the selected criteria for pairwise comparison. Table 2 provides the scale for pairwise comparison adapted from Saaty Thomas L.

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 needs to be performed to be resolved in a decision-making matrix with AHP 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 on an element above them in the hierarchy and then structured the comparison matrix;
- Step 3: Geometric mean is used to combined questionnaires for all experts and based on the combined questionnaire the problem is solved;
- Step 4: Weights for pairwise comparisons are calculated;
- Step 5: After calculating weights, decision matrixes are formed;
- Step 6: Final weights of alternatives obtain by multiplying decision matrixes from alternatives toward criteria;
- Step 7: Weights obtained in the last step are raw and need to be normalized to be easily comparable;
- Step 8: Inconsistency and weights of pairwise comparisons are calculated. Consistency Index (*CI*) is calculated by Eq. (1) proceeded by Consistency Ratio (*CR*) in Eq. (2).

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \quad (1)$$

where $\lambda_{\max}$ – maximum eigenvalue;

$$CR = \frac{CI}{RI}, \quad (2)$$

where *RI* – Random Index that varies for different matrix.

The next step in the methodology is to use the TOPSIS method. TOPSIS is a popular MCDA developed by Hwang and Yoon in 1981. The method uses the best alternative and worst alternative to define the best alternative [15]. TOPSIS method has been used to compare the possible use of production residues in producing value-added products, such as single-cell oil, from different factories, described in Racko E. *et al.* [16]. The main advantages of TOPSIS are the opportunity of an infinite number of criteria and alternatives, a comparatively simple calculation method, and no need for specific software or specific programming techniques. TOPSIS results provide comparing alternatives in a useful and simply comprehensible form. There should be selected alternatives for the evaluation, which are evaluated by four criteria: technological, economic, environmental, and social. The first step using the TOPSIS method is the normalization of the decision-matrix, followed by calculating the normalized decision-matrix and the best and worst solutions. The best solution corresponds to a theoretical option of the most desirable level of each criterion, while the worst solution corresponds to a theoretical option of the least desirable level of each criterion. Finally, the distance of each alternative is calculated that further allows obtaining the closeness coefficient for the ranking alternatives. Alternatives rank from best to worst [17], in detailed equations for the TOPSIS method that is used in this study are described below.

Step 1: Normalized matrix value can be derived by multiplication of normalized value and weight which is done by following Eq. (3).

$$v_{ai} = w_i \cdot r_{ia} , \quad (3)$$

where

v_{ai} Weighted value;

w_i Weight, $w_{i1} + w_{i2} + \ldots + w_{im} = 1$, $w_i = 1 \ldots m$;

r_{ia} Normalized criterion value.

Step 2: Distance for each ideal and non-ideal alternative can be calculated by the sum of the squares of weighted criterion values. The calculation can be done by following Eq. (4). and Eq. (5).

$$d_a^+ = \sqrt{\sum_{j=1}^{n} (v_i^+ - v_{ai})^2} , \quad (4)$$

where

d^+_a Distance for each action to the ideal solution;

v^+_i Ideal solution.

$$d_a^- = \sqrt{\sum_{j=1}^{n} (v_i^- - v_{ai})^2} , \quad (5)$$

where

d^-_a Distance for each action to the non-ideal solution;

v^-_i Non-ideal solution.

Step 3: Closeness coefficient (Ca) shows the distance to the non-ideal solution, which is determined by Eq. (6).

$$C_a = \frac{d_a^-}{d_a^+ + d_a^-} , \quad (6)$$

where

$d^+_a + d^-_a$ Sum of the distance to the non-ideal solution;

d^-_a Distance to the non-ideal solution.

Our approach is to analyse the best extraction method to extract the essential oil from the fruit waste by using multi-criteria analysis.

TABLE 3. OVERVIEW OF THE SELECTED CRITERION

Extraction methods	Technical aspect	Environmental aspect	Economical aspect	Source
Steam distillation	Pressurized container required	Less fuel & High temperature required	High equipment & operating cost	[18]
Cold pressing	High-quality production possibility	Lack of hazardous organic solvent & environmentally friendly	Low cost & less manpower required	[19]
Solvent extraction	Simple equipment used, Low efficiency	High temperature & production of hazardous waste	Low cost	[19]
Hydro distillation	Simple instrumentation	High consumption of energy, no organic solvent	Low cost	[20]

Here we compare the performance of four different green extraction methods like steam distillation, cold-pressing, solvent extraction, and hydrodistillation. The selection of the criterion i.e., technical, environmental, economic, and social acceptability is based on the vast literature analysis. Table 3 shows the 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, can be applied for the separation of volatile organic compounds [21]. Earlier studies show that 93 % of the proportion of essential oil can be extracted by steam distillation [22]. 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 [23]. The solvent extraction method is also known as liquid-liquid extraction, is a method to separate compounds based on the solubility of their parts [24]. Hydro distillation is a traditional method used to extract oil or bioactive compounds from plants [25]. Overall, comparatively all four methods have different functionality and apparatus.

3. RESULTS

The author compared technological, economic, environmental, and social criteria pairwise. Results of the pairwise comparison of AHP are shown in Table 4.

TABLE 4. AHP PAIRWISE COMPARISON MATRIX OF CRITERIA

Criteria	Technological	Economical	Environmental	Social
Technological	1	3	2	4
Economical	0.33	1	2	3
Environmental	0.5	0.5	1	4
Social	0.25	0.33	0.25	1

The authors calculated the weights of the criteria after the normalization of the matrix. The results show that the weight of the technological criterion is the most important – 0.45, then as the second most crucial weight is economical – 0.25, then the third and fourth criteria are environmental and social, which – 0.22 and 0.08, respectively.

The comparisons are consistent and used in the following calculations, considering that the value of the consistency rate is *CR* = 0.079. If the *CR* is less than or equal to 0.1, then the discrepancy is acceptable, but the subjective assessment must be reconsidered if it is higher than 0.1.

TABLE 5. TOPSIS DECISION-MAKING MATRIX

Alternative technologies	**Criteria**			
	Technological	Economical	Environmental	Social
Steam distillation	4	4	3	4
Cold-pressing	4	5	4	3
Solvent extraction	3	3	3	4
Hydrodistillation	3	3	4	4

The potential for using the four technologies was rated on a scale from 1, which corresponds to the lowest rating, to 5, which corresponds to the highest rating. Table 5 are shown the evaluation values in a decision-making matrix.

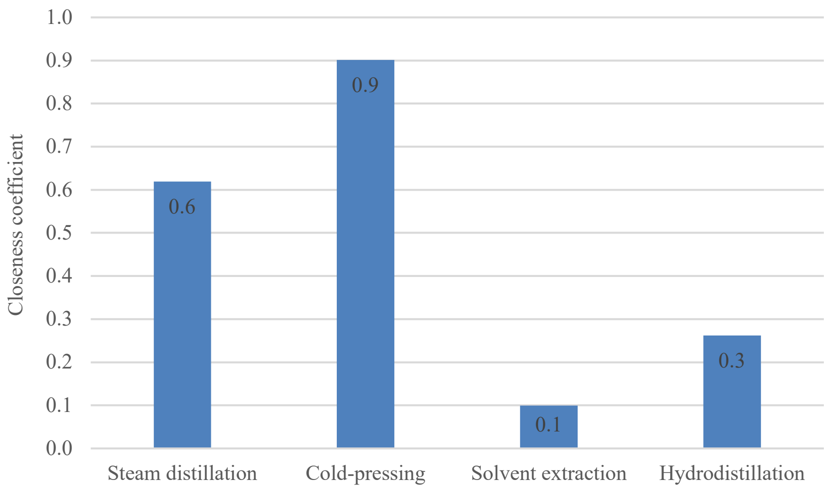

Fig. 3. TOPSIS ranking technologies results.

The TOPSIS analysis results are shown in Fig. 3. Cold pressing (0.9) is the closest alternative for the best solution, not only for the technological criterion that has the highest weight of all criteria (0.45) and good performance in the economical criterion with the second-highest impact on results. Steam distillation ranks as the second technology, with evaluation 0.6, and as a third possible technological solution is hydrodistillation with 0.3, and solvent extraction – 0.1.

4. DISCUSSION

According to the report on the global food waste scenario [26], awareness of food waste has grown. The current research has been made to solve the global problem to some extent. Fruit waste is one of the important areas that need to be focused on. Therefore, this study contributes to minimizing the waste scenario by developing an essential oil extraction pathway from fruit peel waste. The study highlights the use of Multi-Criteria Analysis methods to choose the best extraction technology. By analysing the results, it has been found that in both methodologies AHP and TOPSIS, a cold-pressing method is the best essential oil extraction method.

Several studies have been done on essential oil extraction techniques [22], but our approach provides environmental sustainability by comparing the environmental performances of different alternatives, which leads to the green extraction techniques

However, the MCA methodology requires potential numerical data to perform an analysis. The significant limitation was the lack of quantitative data for the evaluation that cannot negotiate. Therefore, this study suggests that more scientific and laboratory research work is required for more accurate results and to diversify the valorization options.

5. CONCLUSION

The main conclusions of this research are drone together and presented in this section. This research aims to determine an approach for the fruit waste valorization pathway and find the best extraction technique. Firstly, a vast literature analysis was performed to identify the essential oil extraction pathway from fruit waste in a more sustainable way. Secondly, Multi-criteria analysis was performed to find the best extraction technique considering the technical, environmental, economic & social aspects.

Within this research, the publicly available data of existing essential oil extraction pathways were studied, and based on that fruit waste valorization pathway was created. Furthermore, to ensure the extraction technique multi-criteria analysis followed by AHP and TOPSIS was successfully performed.

The outcome of the research leads to the conclusion that essential oil is the most crucial and multi-functional product, which can be extracted by the cold-pressing technique. AHP method is used to evaluate the weight of the criterion, which shows that the most effective criteria are the technical criteria. Based on the AHP weight TOPSIS was performed for further evaluation, which shows that the cold-pressing method is the most suitable technique for the extraction. Overall, fruit waste valorization and various alternative techniques considering the various aspects can be evaluated by the Multi-criteria analysis. This research concludes that the new innovative bioresource valorization pathways can be created and evaluated by Multi-criteria analysis.

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Insights of Bioeconomy: Biopolymer Evaluation Based on Sustainability Criteria

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***Abstract* – Sustainable development in the agriculture sector can be boosted by integrating a sustainable bioeconomy and transforming renewable resources into added-value products. There are various methods to determine, measure, and compare the extent of sustainability. We promote the bioeconomy concept by utilizing agricultural waste in biopolymers considering the sustainable development in the agriculture sector. This research aims to evaluate biopolymer alternatives based on sustainability criteria and indicators using the integrated multi-criteria decision analysis approach under the sustainability umbrella. We evaluated the PLA, PHA/PHB, starch, protein, and cellulose-based biopolymers. As a result, the cellulose-based biopolymer shows the best performance. The research findings provide valuable information to establish a sustainable pathway for biopolymer production for industries.**

***Keywords* – Agriculture; AHP; biopolymer; MCDA; sustainable development.**

1. INTRODUCTION

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 [1]. The already existing regulatory framework and modifications framework show the development and intensification of bioeconomy. In 2004, the Organization for Economic Co-operation and Development (OECD) promoted a need to enhance bio-based society [2], [3]. In 2009, the OECD launched an agenda for bioeconomy based on the analysis of diverse national bioeconomy strategies. In 2012, the European Union established a directive for bioeconomy strategy, and several countries implemented their strategies. In 2015, the International Advisory Council on Global Bioeconomy [4] defined bioeconomy as 'the production and utilization of biological resources to provide products, processes, and services in all sectors within the framework of the sustainable economy.' In 2018, the European Commission [5] said in its recently updated bioeconomy strategy: 'The bioeconomy covers all sectors and systems that rely on biological resources such as animal, plants, microorganisms, and derived biomass including organic waste, their functions, and principles.' Hence, the bioeconomy focuses on replacing non-renewable resources with sustainable resources. The large-scale use of bio-based materials can substitute many fossil resources with renewable resources [4]. It embraces sustainable management of ecological

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sectors and understands land, forests, and sols as fragile resources that wealth by converting resources into products.

However, tremendous and excessive utilization of natural resources leads to economic and environmental imbalance [5]. A global challenge that leads to environmental imbalance is the increased use of plastic and the following increase in the amounts of non-biodegradable waste. The current rate of global plastic production is unsustainable, as more than 400 million tons [6] of plastic waste are generated annually. Integrating sustainability strategies within agriculture is crucial for the sector's overall development [6] and perfectly balances the economy, environment, and society. Agriculture and agri-food processing sectors are significant creators of waste [7]. However, instead of treating it as waste, agriculture waste is considered a valuable additional resource that can drive the agriculture sector's economic growth and promote the bioeconomy [8].

The bioeconomy can potentially establish a revolutionized strategy for agricultural waste [7]. The variety of agricultural feedstocks, including grain, dairy, and food waste, allows the development of many alternative innovative products [9]. The valorization of agricultural residues to higher added value products by implementing the sustainable bioeconomy encourages sustainable agriculture production and cultivation development. So, it is necessary to evaluate the production cost and environmental and social benefits of producing various bioproducts. Consequently, an optimal alternative pathway can be established by implementing the bioeconomy concept [10]. Considering this concern, Tobias Heimann [1] highlighted that the bioeconomy concept is lacking in Sustainable Development Goals (SDGs).

The bioeconomy also provides an opportunity to resolve one of the global problems – plastic pollution. The linear economy concept follows the path of take-make-dispose. It has a long-term footprint on soil, ocean, atmosphere, and animal biomass [11]. Traditionally, synthetic plastics are produced from refined petroleum products where heavy crude oil is used. Consequently, fossil fuel depletion, climate change, and greenhouse gas emissions occur [12]. Notably, the impact of petroleum-based plastics can be reduced by replacing them with bioplastics. Bioplastics are derived from biomass residues using biological extraction techniques, which are biodegradable, bio-based, and compostable. Bioplastics are resource-efficient, sustainable, environmentally friendly, and potentially drive economic growth [12].

Moreover, the Life cycle assessment (LCA) of biopolymer production shows better environmental footprints than petroleum-based plastics. [13] shows that greenhouse gases are a significant factor in the environmental impacts of a product. The LCA study shows that the global warming potential for a biopolymer (18.34 %) is lower than for petroleum-based plastics (20.06 %). More description of each type of bioplastic is given in Annex A1.

One of the potential solutions to utilize agricultural waste wisely is to produce biopolymers from agricultural waste. Biopolymer production from agricultural waste is an eco-friendly and economical process because of the availability of sustainable and cheap feedstocks [14]. A previous study [15] identified a research gap for sustainable biopolymer production. Also, the missing link between agricultural waste, biopolymer production, and sustainable development has been discovered. Therefore, this paper evaluates biopolymer types based on sustainability indicators using the multi-criteria decision analysis (MCDA) methodology. Here, we propose a novel way to establish sustainability in agriculture by selecting the most suitable biopolymer and applying an integrated methodology. Also, the paper develops a sustainable pathway for biopolymers considering environmental, social, and economic aspects. It contributes to establishing a bioeconomy strategy that can promote sustainable policies within the agriculture sector and biopolymer production companies.

2. Materials and Methods

A multidisciplinary approach is selected to develop an integrated methodology for biopolymer comparison. Fig. 1 shows the overall methodology algorithm. The methodology starts with scientific literature analysis from Scopus, ScienceDirect, Web of Science (WoS), EU bioplastics, and other scientific documents. Then algorithm follows:

1. Developing the study design, including a selection of the biopolymer alternative, the evaluation criteria, and particular evaluation indicators considering the sustainability indicators;
2. The quantitative data collection was done for selected indicators for each biopolymer type;
3. The worldwide survey analysis conducted to aid a collective policymaking decision from the stakeholder's perspectives;
4. Analytic hierarchy process (AHP) analysis of each survey response to determining the weights of the criteria, and
5. Four different MCDA have been performed to check the method's robustness.

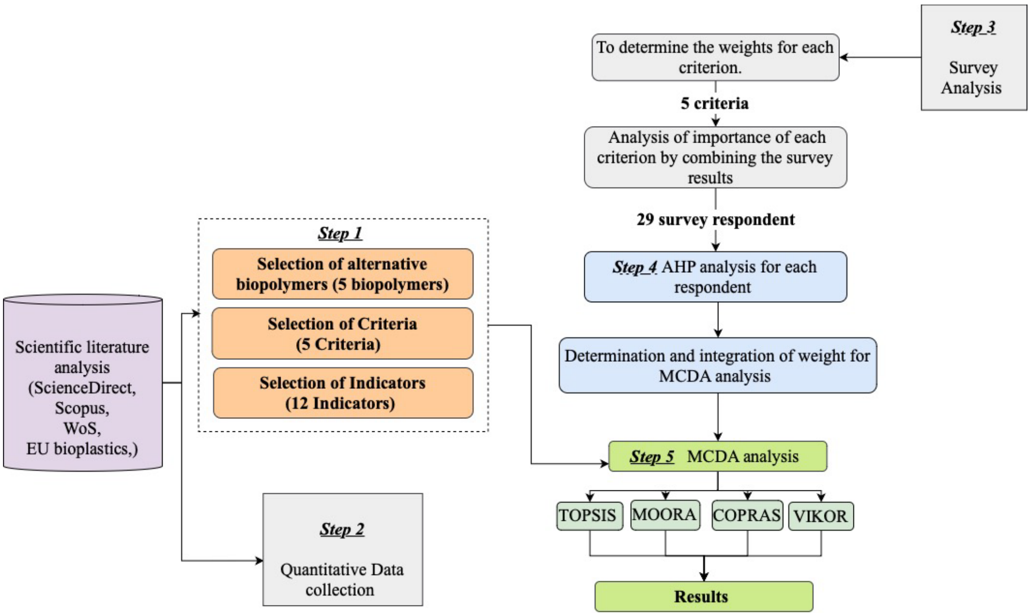


Fig. 1. Methodology algorithm.

2.1. Step 1: Selection of Indicators

A set of indicators are considering aspects from the cradle to the grave, ranging from farm areas to the complete life cycle of biopolymers as boundaries. The criteria were chosen considering literature analysis on sustainable development in the agriculture sector by producing biopolymers. The selected criteria and indicators used to evaluate alternative biopolymers are listed in Table 1.

TABLE 1. SET OF CRITERIA AND INDICATORS USED TO EVALUATE ABIOPOLYMERS

Criteria	Indicator	Unit of measures	Source
Environmental	Carbon footprint	kg CO_2/kg polymer	[16], [17]
	Energy consumption	MJ/kg polymer	[16], [17]
	Acidification	kg/ SO_{2eq}	[16], [18]
Circularity	Biodegradability	%	[19]
	Period of Biodegradability	Days	[19]
Technical	Melting point	°C	[20]
	Density	kg/m^3	[20]
	Tensile Strength	MPa	[20]
Social	Human health	kg 1,4-DB_{eq}	[16], [21]
Economic	Production Cost	USD/kg	[16], [22]
	Market price	USD/kg	[16], [22]
	Global production capacity	%	[23]

Biopolymer production is an effective way to replace fossil fuel-based biopolymers. However, extensive production and consumption generate several adverse effects, including greenhouse gas emissions [24]. The selection of indicators for the environmental aspect is done to achieve sustainable development. Three leading indicators (carbon footprint, energy consumption, and acidification) are selected to evaluate the environmental feasibility. The circular economy concept shows the minimal waste of materials and energy through extensive reuse, recycling, and recovery in production and consumption [19]. Biodegradability and the period of biodegradability indicators depict the efficiency of using biopolymers during and after the lifespan of the biopolymer [25]. The technical aspects represent the properties of biopolymer. Density is a crucial indicator for producing biopolymers, as the environmental impact can change if the density of the biopolymer alters [20]. Tensile strength is defined as stress, which gives the crystallinity of the bioplastic film [26]. The melting point is one of the significant indicators, the high melting point reduces the viscosity and improves the processability of the biopolymer [20]. The human health indicator is considered for the social aspect, which determines the exposure and effects of toxic substances for biopolymer production [27]. Moreover, the migration of nanomaterial (the particles' size, and the biopolymer's consumption rate) affects human health [28]. Three indicators are selected to assess the economic feasibility of the biopolymer: production cost, market price, and global production capacity. The production cost includes product expenses, such as capital, maintenance, and operational costs [29]. Market price shows the economic value of the biopolymer, which is determined by the forces of supply and demand [30]. Global production capacity shows the worldwide production capacities of biopolymers, which are used to determine the growth rate and developing trends in biopolymers [31].

2.2. Step 2: Data Collection

A vast scientific literature analysis is done to collect sustainability criteria and indicators for different biopolymers. To derive solid results, only quantitative values are considered for each indicator. Five types of biopolymers, five criteria, and twelve indicators are analysed in this study, and all the gathered input data are summarized in Table 2. It is a fact that the availability of quantitative data was a significant obstacle to gathering the quantitative input for the indicators.

TABLE 2. DATA COLLECTION FOR BIOPOLYMERS CONSIDERING CRITERIA

	Bioresources	Type of bioplastic	Criteria	Indicator	Unit of measures	Output	Source
1	Sugar cane, maize, wheat, sugar beet	Polylactic acid (PLA)	Environmental	CO_2 emission	kg CO_2/kg polymer	1.8	[32]
				Energy consumption	MJ/kg polymer	54.1	[32]
				Acidification Potential	kg/ SO_2 eq	7.3	[33]
			Circularity	Biodegradability	%	79.7	[34]
				Period of Biodegradability	Days	28	[34]
			Technical	Melting point	°C	180	[35]
				Density	kg/m3	1210	[36]
				Tensile Strength	MPa	15.5–150^	[37]
			Social	Human Toxicity	kg 1,4-DB eq	1.2	[38]
			Economic	Production Cost	USD/kg	1.47	[39]
				Market price	USD/kg	1.50–2.09*^	[40]
				Global production capacity	%	18.9	[41]
2	Spent coffee grounds, waste rapeseed oil, sugarcane bagasse, paddy straw, and molasses (Grain waste)	Polyhydroxy alkenoate (PHA) & Polyhydroxy butyrate (PHB)	Environmental	CO_2 emission	kg CO_2/kg polymer	2.6	[32]
				Energy consumption	MJ/kg polymer	54.1	[32]
				Acidification Potential	kg/ SO_2 eq	24.9	[33]
			Circularity	Biodegradability	%	80	[34]
				Period of Biodegradability	Days	28	[34]
			Technical	Melting point	°C	175	[42]
				Density	kg/m^3	1180	[6]
				Tensile Strength	MPa	20–40^	[42]

			Social	Human Toxicity	kg 1,4-DB eq	0.85	[43]
			Economic	Production Cost	USD/kg	2.65	[44]
				Market price	USD/kg	4.09–4.59*^	[40]
				Global production capacity	%	1.8	[41]
3	Maize, potatoes, cassava, barley, rice, sorghum, sweet potato, and wheat (Food and Grain waste)	Starch-based bioplastic	Environmental	CO_2 emission	kg CO_2/kg polymer	1.14	[32]
				Energy consumption	MJ/kg polymer	25.4	[32]
				Acidification Potential	kg/ SO_2 eq	8.7	[33]
			Circularity	Biodegradability	%	85	[34]
				Period of Biodegradability	Days	90	[34]
			Technical	Melting point	°C	180	[45]
				Density	kg/m^3	1650	[46]
				Tensile Strength	MPa	0.4–25^	[47]
			Social	Human Toxicity	kg 1,4-DB eq	0.0112	[48]
			Economic	Production Cost	USD/kg	0.61	[49]
				Market price	USD/kg	2.59–3.39*^	[40]
				Global production capacity	%	16.4	[41]
4	Wheat gluten, egg white, milk whey, and soy protein (Dairy waste and Soy protein)	Protein-based bioplastic	Environmental	CO_2 emission	kg CO_2/kg polymer	0.115	[38]
				Energy consumption	MJ/kg polymer	2.9	[38]
				Acidification Potential	kg/ SO_2 eq	9.3	[38]
			Circularity	Biodegradability	%	95	[50]
				Period of Biodegradability	Days	30	[50]
			Technical	Melting point	°C	140	[51]
				Density	kg/m^3	1090	[52]
				Tensile Strength	MPa	3.4	[53]
			Social	Human Toxicity	kg 1,4-DB eq	0.28	[38]
			Economic	Production Cost	USD/kg	3.78	[54]
				Market price	USD/kg	2.89–6.88*^	[40]
				Global production capacity	%	1.2	[41]

5	Cotton, bagasse, corn stalk	Cellulose-based bioplastic	Environmental	CO_2 emission	kg CO_2/kg polymer	0.79	[55]
				Energy consumption	MJ/kg polymer	5.4	[56]
				Acidification Potential	kg/ SO_2 eq	0.0078	[55]
			Circularity	Biodegradability	%	35	[34]
				Period of Biodegradability	Days	14	[34]
			Technical	Melting point	°C	233	[57]
				Density	kg/m^3	490	[58]
				Tensile Strength	MPa	1.81	[58]
			Social	Human Toxicity	kg 1,4-DB eq	0.3	[59]
			Economic	Production Cost	USD/kg	1.9	[60]
				Market price	USD/kg	3.99*	[61]
				Global production capacity	%	3.2	[41]

Notes: * market value is considered based on the conversion rate EURO to USD on August 25, 2022.
^ tensile strength and market price are calculated by calculating a range median.

2.3. Step 3 & 4: Survey Analysis & Analytical Hierarchy Process

A survey was circulated worldwide to stakeholders connected to the biopolymer sector, including value chain actors, consumers, small & medium size enterprises, scientists, society, 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 contains 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 are analogously devoted to the importance of environmental, social, and economic criteria over the rest of the four criteria. A survey link is given in Annex A2. Here, semi-quantitative analysis was used to measure the intensity of importance in AHP. The AHP methodology was developed in 1980 by Saaty. The prioritization of criteria and alternatives is mainly done by using the scoring system. Two criteria are compared with the given weights based on their level of importance [62]. The intensity of importance for the AHP method is decided based on Satty's scale (see Table 3) [63].

TABLE 3. SATTY'S SCALE FOR AHP ANALYSIS

Intensity of importance	**Meaning**
1	Equal importance
5	Moderate importance
7	Very importance
9	Extreme importance

By taking a geometric mean of pairwise comparison matrices obtained from the survey, a pairwise comparison matrix (*A*) is formed to be used in calculating the significance of each criterion. Then, the dimension matrix ($n \cdot n$) formed by using the compared criteria in rows and columns of the matrix is square (see Eq. (1)) [64].

$$A = \begin{bmatrix} a11 & a12 & a1n \\ a21 & a22 & a2n \\ an1 & an1 & ann \end{bmatrix}, \tag{1}$$

where *A* is the comparison matrix, and *n* is the matrix's dimensions.

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 Eq. (2).

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{2}$$

Next, the maximum eigenvalue (λ_{max}) is calculated as Eq. (3).

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(AW)_i}{w_i} \tag{3}$$

Next, the Consistency Index (*CI*) for acceptance of the consistency ratio of the comparison matrix *A* is calculated using Eq. (4).

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{4}$$

CI refers to the mean of the remaining solutions of the characteristic equation for cognizant matrix *A* (see Table 4).

TABLE 4. RANDOM CONSISTENCY INDEX [65]

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 Eq. (5).

$$CR = \frac{CI}{RI}, \tag{5}$$

where *RI* is a random index, *CR* measures the judgments of experts. If $CR \leq 0.1$, the inconsistency is acceptable [66]. Further, the derived weights from 29 respondents are aggregated by taking an average mean and integrating it into MCDA.

2.4. Step 5: Multi-Criteria Decision Analysis

The MCDA method is the best choice to assess the sustainability of a product or a system [67]. This study applies four MCDA methods to check the method's robustness and derive comprehensive results. The point must be noted that weights of criteria for each method are considered from AHP analysis. A brief explanation of each method is given below.

The technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) method is the classical method for a single decision maker. In this method, the rating of alternatives and weights are represented by numerical data and analysed by a single decision-maker. The classical algorithm for a TOPSIS method is systematically described in [68].

Multi-Objective Optimization based on Ratio Analysis (MOORA) is the multi-attribute optimization method. This method simultaneously processes the optimization of two or more attributes. The MOORA method cam is applied to solve various complex decision-making problems. The step-by-step calculation formula for the MOORA method is described in [69].

The complex Proportion Assessment Method (COPRAS) is one of the most common methods in MCDA, which analyses various alternatives based on different criteria and indicators by determining a rank of alternatives. COPRAS is a simple, less time-consuming, and transparent computation process. The step-by-step calculation formula for the COPRAS method will be described in [70].

Vlsekriterijumsko kompromisno Rongiranje (VIKOR) method is one of the applicable techniques within MCDA methods. This method solves a discrete decision-making problem with non-commensurable and conflicting criteria. The VIKOR method works based on the ranking system and selects the best alternative based on the compromise solution for a problem with conflicting criteria. The step-by-step calculation formula for the VIKOR method is described in [71]. Overall MCDA method protocol for each method is briefly explained in Fig. 2.

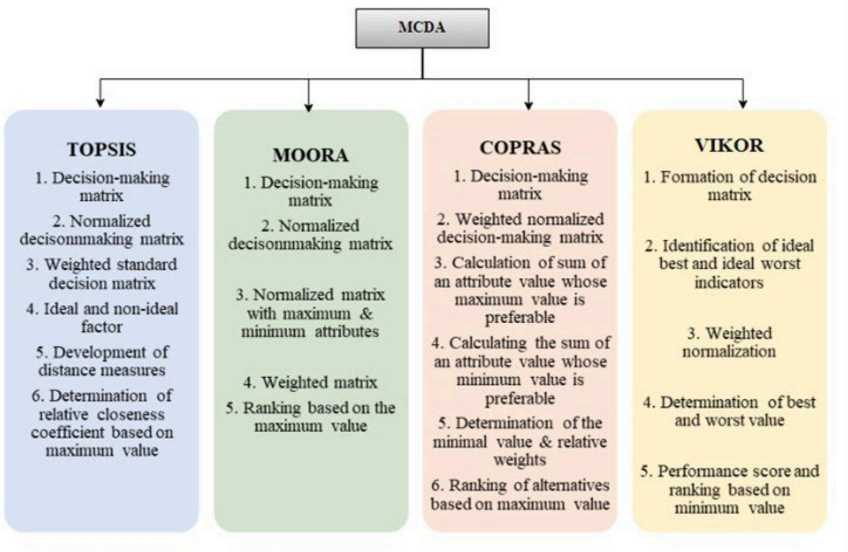


Fig. 2. MCDA methodology steps.

3. Results and Discussion

3.1. Survey & Analytical Hierarchy Process Results

Among the survey results, 41 % were consumers, 14 % were from society, 7 % were from research institutions, and the rest, 38 %, were value-chain actors, government policymakers, scientists, and academic educators. Moreover, the survey respondents were from different countries, including India, Egypt, Latvia, Spain, and 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. 3.

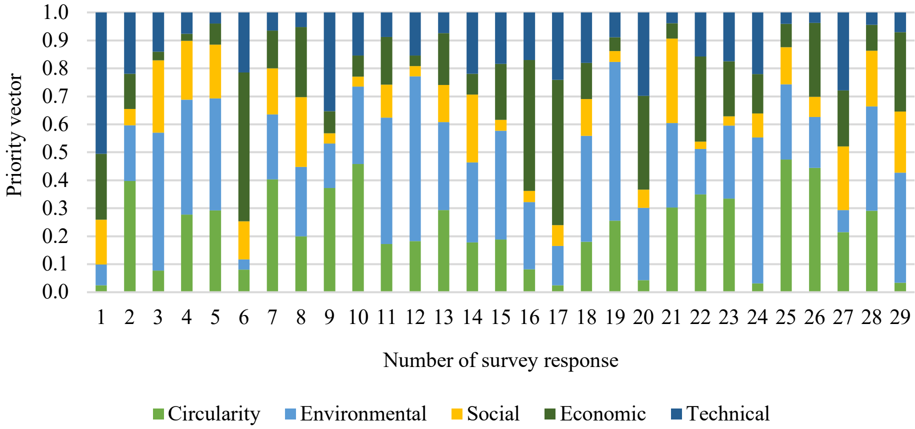
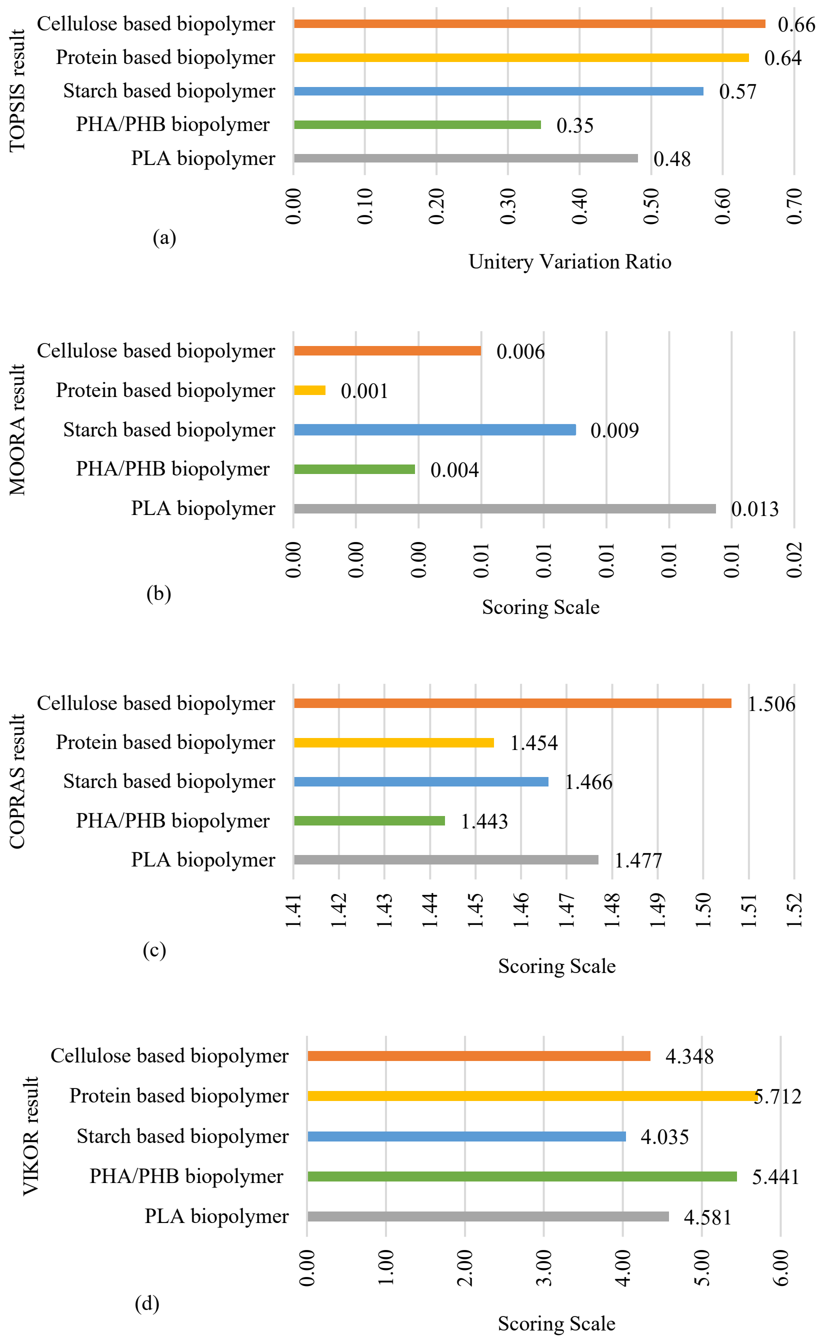


Fig. 3. AHP survey results.

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.

3.2. Multi-Criteria Decision Analysis Results

The MCDA results for TOPSIS, MOORS, COPRAS, and VIKOR are briefly described in this section (see Fig. 4). Integrating the same AHP weights into MCDA methods shows different results for each method. Fig. 5(a) shows the interpretation of TOPSIS results. The best biopolymer alternative derived is the cellulose-based biopolymer (0.66) followed by the protein-based biopolymer (0.64), starch-based biopolymer (0.57), PLA biopolymer (0.48), and PHA/PHB biopolymer (0.35). The alternative ranking is based on the unitary variation ratio's high to a low value.



(d)

Fig. 4. MCDA results: a) TOPSIS results; b) MOORA results; c) COPRAS results; d) VIKOR results.

On the other hand, the MOORA analysis shows that the best biopolymer alternative is the PLA biopolymer (0.013), followed by the starch-based biopolymer (0.009), cellulose-based biopolymer (0.006), PHB/PHA biopolymer (0.004), and protein-based biopolymer (0.001). Fig. 5(b) shows the overall results of the MOORA analysis. The ranking in MOOORA analysis is based on alternatives' high to low-scoring values, which means a high-scoring value derives the first rank.

Fig. 5(c) shows COPRAS analysis results. The ranking of alternatives for COPRAS analysis is based on the high to low scoring value. The highest scoring value and first rank are derived for the cellulose-based biopolymer (1.51). In contrast, the lowest value and fifth rank are derived for the PHA/PHB biopolymer (1.44). The rest of the alternatives PLA (1.48), starch-based (1.47), and protein-based (1.45) biopolymers, ranked second, third, and fourth, respectively.

In VIKOR analysis, alternatives are ranked based on low to high-scoring values, which means the lowest-scoring value derives from the first rank. As shown in Fig. 5(d), the first rank goes to the starch-based biopolymer with the lowest score (4.03), and the last rank goes to the protein-based biopolymer (5.71) with the highest score. The cellulose-based (4.34), PLA (4.58), and PHA/PHB (5.44) biopolymers derived second, third, and fourth ranking, respectively.

[72] performed the comparison of different MCDA methods, which shows different results for each MCDA method. Since 1996, the problem of selecting a proper MCDA method has been a vital discussion topic [73]. 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 [74]. Several factors influence the different results when applying various calculating procedures, such as [75], [76], 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 5 based on the ranking of biopolymers.

TABLE 5. 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 [77]. However, [78] 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 [78]. In contrast, the MOORA and VIKOR method shows that PLA and starch-based biopolymers are the most suitable option, respectively. In our study, the decision was made considering the majority 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.

4. Conclusions

This study emphasizes the importance of quantitative indicators that give an apparent measure of biopolymers and promote the bioeconomy concept together with sustainability. The AHP method can transform subjective opinions into multi-criteria prioritization. Integrating AHP weights into TOPSIS, MOORA, COPRAS, and VIKOR methods shows comprehensive results for the sustainability of agro biopolymers. The best alternative biopolymer derived is a cellulose-based biopolymer from agricultural waste. Further research should be extended on cellulose-based biopolymers. Better and more robust MCDA methods need to develop to derive solid results. This study found that sustainability indicators for biopolymer production from agricultural waste still require attention.

Annex

Available at: https://zenodo.org/record/8121866

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Assessing Biopolymer Packaging in the EU Market for Sustainable Bioeconomy Development

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***Abstract*– The bioeconomy provides tremendous potential for high-value products like pharmaceuticals, food and feed additives, and biopolymers. The potential for developing a bioeconomy is limited to low-value applications such as bulk chemicals, bioenergy, and biofuels. The economic, environmental, and social benefits of a successful transition facilitated by market innovations must be primarily promoted by businesses, government agencies, and consumers. One of the most critical considerations in promoting bioeconomy is evaluating the market potential of biopolymer products. Leveraging the GE-McKinsey Nine-Box Matrix, a decision-making process was developed to assess the market attractiveness and competitive advantage of the four biopolymer packaging materials in the EU market: cellulose, PHA, PLA, and starch. The approach incorporates novel elements for competitive advantage, such as product sustainability, to deliver value-added benefits that render a product competitive in the market. The research findings indicate that the packaging material made of PLA biopolymer has the most marketing potential. The methodology established for selecting biopolymer packaging materials for investments and to advance the bioeconomy through the valorization of agricultural waste is appropriate for decision-makers, as the results demonstrated to be adequate.**

***Keywords* – Agriculture waste; Bioeconomy; Biopolymer packaging materials; Commercialization; GE-McKinsey Matrix**

1. INTRODUCTION

1.1. Advancement of bioeconomy

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 [1]. The existing regulatory framework clearly shows the development and intensification of carbon footprint trends. The European Parliament committed to reducing greenhouse gas emissions by 55% by 2030 and achieving carbon neutrality by 2050. In 2018, the European Commission [2] 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 and produce natural resources, such as forestry, fisheries, aquaculture, and agriculture. The starting point advancing the bioeconomy is the value pyramid that illustrates the valorization of biomass.

Regarding product value, pharmaceuticals add a lot to the product but in small volumes. In

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contrast, energy carriers add little to the product value but in large quantities. Agriculture, horticulture, and stock farming produce the entire value pyramid's 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 agriculture 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. As per data published by [3], starting from lower value-added products, bioenergy, and bulk chemicals and materials show a fragile line for value-added development from 2008 to 2020. The high value-added products, including food and pharmaceuticals, show enormous value-added development. It is clearly seen that biopolymers seek attention for value-added development even after having a vast potential to drive the bioeconomy sustainably (see Fig. 1).

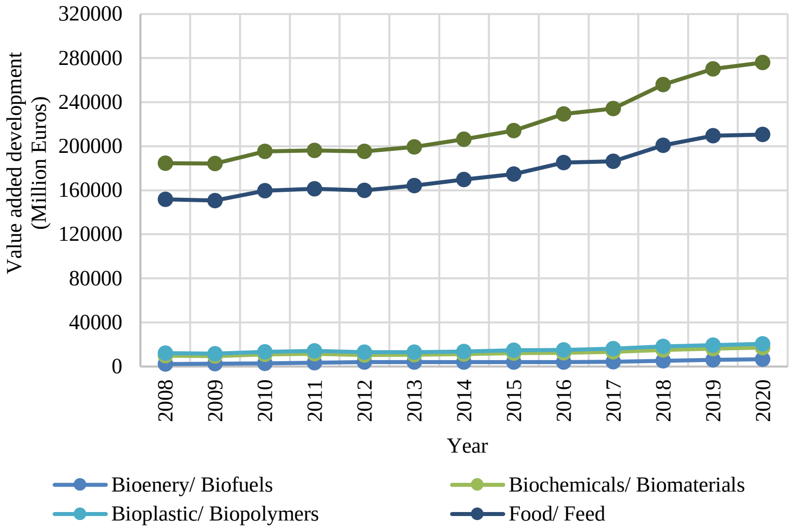

Fig. 1. Bioeconomy added value share of distinct levels of products from agricultural waste [3]

The most recent market data gathered by European Bioplastics indicates that worldwide biopolymer production capacity is expected to rise from 2.2 million tons in 2022 to 6.3 million tons in 2027 [4]. The data shows that the industry is progressing toward a sustainable future with less environmental impact, but it also goes beyond that. It is also anticipated that over the next few decades, the emerging biopolymers sector will reveal enormous economic potential [5]. The biopolymer markets are expanding, encompassing consumer electronics, toys, packaging, horticulture/agriculture, consumer electronics, automotive, and textile industries. Packaging will remain the largest segment in the 48% global bioplastics market in 2022. biopolymers are utilized in various products, including keyboards for consumer electronics, beverage bottles in the packaging sector, and interior car parts [6][7].

Moreover, another concern for the value-added development of biopolymers is to make the right investment choice for biopolymer packaging materials, ensuring their sustainability and profitability in the market. In order to be sustainable, a business model must show society or customers how biopolymers will advance in the future. Companies must establish business models that effectively close the biopolymer life cycle, confront the potential impacts on agricultural production that may surpass those associated with processing and use, and establish industrial standards to guarantee that biopolymer companies promote sustainability throughout the product life cycle [8][9].

1.2. Agriculture waste valorization to biopolymers packaging materials

Agriculture wastes are a core of the bioeconomy as they are a significant sector. In EU-27, almost 70% of the biomass is of agricultural origin, which makes agriculture the largest source of biomass. The vital use of agricultural waste to produce value-added products is an excellent approach to complying with EU regulations. The "resource, recovery, and recycle" paradigm must be imposed to bring about the industrial revolution in the agricultural sector. The technological, social, economic, and environmental aspects of agricultural waste can all be more harmoniously balanced by the bioeconomy. Additionally, by utilizing waste, fostering economic growth for waste, and striking a balance between production and consumption, the bioeconomy promotes sustainable agricultural sector growth [10].

A more concentrated area is biopolymer production from agricultural waste because it promotes sustainable development. Agricultural crop residues, lignocellulosic feedstocks, and organic wastes are significant biopolymer resources from agricultural byproducts and edible food waste [11][12]. Among these resources, agricultural crop residues are more efficient for biopolymers, as they require the least land to grow and produce high yields. It is crucial to have easy access to agricultural residues to produce biopolymers. The total available agricultural residue in Europe is 72,529 kilotons/year [13]. Country-specific annual available agriculture residues are shown in Fig. 2. The production of crops generates copious amounts of agricultural residues. Agricultural practices, crop mix, crop rotation, and crop types affect residue production. The yield and cultivated area determine the amount of residues directly correlated with crop productivity. Remainders are only as available as their competitive use for industrial or agricultural uses and how much can be removed from the land to maintain land fertility [14].

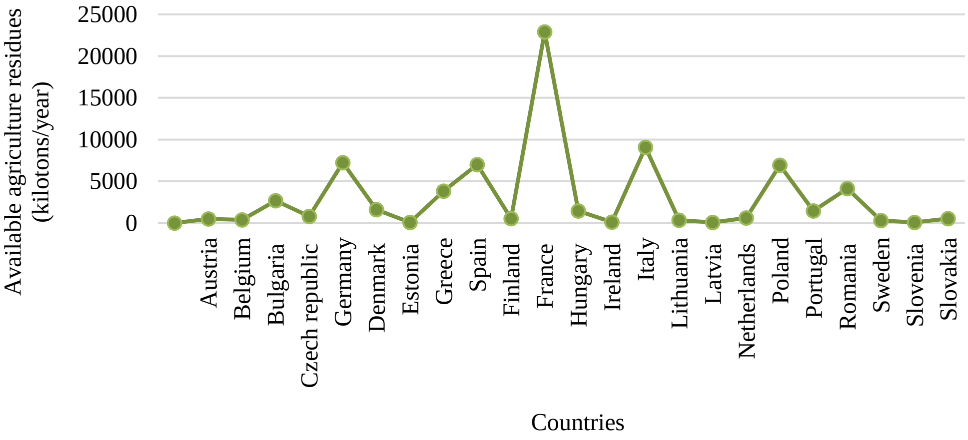

Fig. 2. Availability of agriculture residues in EU [13]

Over the past few decades, the pathway for valorizing agricultural waste has evolved to produce value-added products. As reported by [15], polylactic acid (PLA) production from agricultural residues using a solid-state fermentation technique provides cost-effective, eco-friendly, and large-scale production. Besides, PLA can be produced from multiple agricultural residues such as milled corn cob, sugarcane bagasse, food waste, and cassava [16]. The viable crops for starch-based packaging materials are maize, wheat, cassava, and potato. The most standard method to build starch-based packaging materials is injection molding. This environmentally friendly method uses efficient machinery and durable thermosetting polymer [16].

A process known as enzyme hydrolysis can produce Polyhydroxyalkanoates (PHA) packaging materials circularly while combining renewability and degradability from agriculture residues, including fruit peels, bagasse, and other food crops. It is considered a green method because it can be used in mild environments and does not require harsh chemicals [17].

Cellulose is the most abundant biopolymer packaging material, primarily derived from various agricultural residues such as seeds, grasses, stalks, woody vegetation, sugarcane bagasse, and rice straw. Among them, sugarcane bagasse and rice straw are economic crops and can be obtained from general agro-waste. The most standard step-by-step method to produce cellulose biopolymer packaging material is extraction, pretreatment, and emulsification-diffusion techniques. PLA, PHA, starch, and cellulose biopolymers are the most topical and competitive biodegradable polymers. These biopolymers are linked to using renewable raw materials derived from agricultural resources, such as proteins and polysaccharides [18].

Sustainable packaging is one of the industries with the most incredible growth rate. As such, it must be prioritized by both the market and consumers [19]. However, producing such products is not feasible if they do not have adequate viability. Conducting feasibility studies to produce such innovative products from renewable biomass resources is essential. So that it would be commercially viable in the future to drive a commercial business, a fundamental methodology should be designed to evaluate the new products, as by implementing the GE-McKinsey matrix, we can estimate the current condition of the product's portfolio [20].

Many studies have supported the GE-McKinsey matrix for the corporate business portfolio. For instance, a Russian oil and gas production enterprise has used this method to identify the potential of the business [21], Indonesian university modified and used this method for prioritizing resource allocation by following the mapping the market position of the study programs [22], Italian fashion industry has used it to evaluate the investment opportunities for product portfolio management [23], Chinese case study has used it to determine the sustainable urbanization performance [24], and a market attractiveness of different fruits in agroforestry system has been investigated by using this method [25]. A positive outcome emerged from this research on the market's attractiveness and business strength. To prioritize the biopolymer comprehensively in the bioeconomy, assessing the market opportunity for decision-making in commercializing the packaging materials is imperative.

In our two prior studies, we used an evolving approach to improve the value of biopolymers in the bioeconomy pyramid. Where [26] assesses the biopolymer alternatives in accordance with sustainability criteria and indicators, and [27] provides the system innovation pathway by developing a carbon footprint tool for product packaging meant for online marketplaces. The current study aims to develop a methodology for employing the GE-McKinsey analysis to determine the market potential of biopolymer packaging materials that offer innovative transfer to the market. The study contributes to developing a market opportunity for decision-making in commercializing packaging materials. A case study has been developed for four packaging materials: cellulose, PLA, PHA, and starch.

2. MATERIAL AND METHODS

A successful transition toward bioeconomy is about to emerge through radical innovations promoted primarily by stakeholders, businesses, or government organizations. Fig. 3 shows the strategic scheme for the market innovation transfer of biopolymer packaging materials produced from agricultural waste to advance the bioeconomy. This study performs a market analysis for the four different biopolymer packaging materials from agriculture crop residues.

Step 1: The first stage in fostering agriculture 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 technology is innovative, it should be widely accessible. If not, then it goes to the first stage.

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 is 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: is the last step, visualization of results and suggestions for further investigation into the manufacture of new products in the nation or place where they are now produced and where local resources are available.

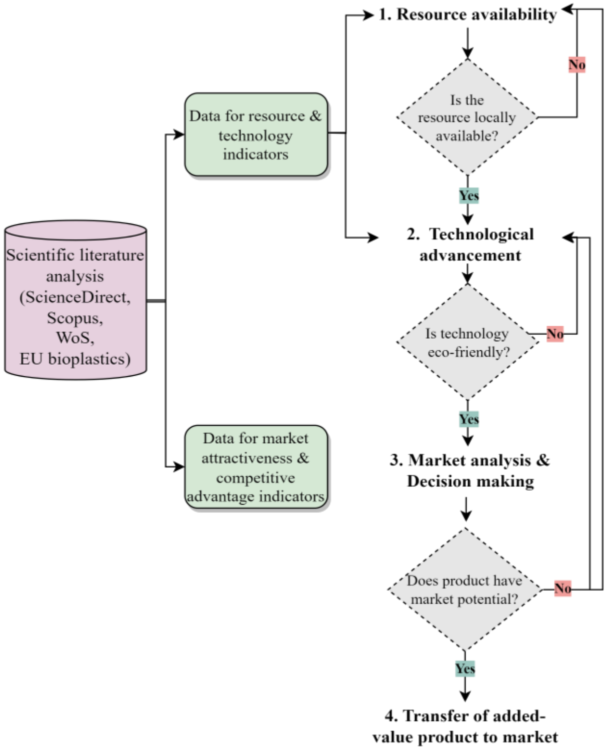

Fig. 3. Methodology Algorithm

2.1. Data collection and evaluation technique

The market analysis is carried out using primary qualitative 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, which are considered for the market competitive advantage to provide value added benefits. Resources play a central role in a business's environmental performance to establish efficiency in the process [28], and the eco-friendliness of technology significantly addresses a business's sustainable practice [29]. For the market attractiveness, six key indicators are evaluated market size, market growth rate, market profit, price sensitivity, access to raw materials, and production cost [30]. The market competitive advantage is evaluated based on the six critical indicators, including demand, market share, availability of resources, selling price, environmental ease of technologies, and product quality [30].

The Likert scale is a commonly used scale that displays the preferences for outcomes derived from quantitative indicators [31]. 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 is very unattractive, and 5 is 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, labour, 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 is 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 represents that the resource is difficult to access, and 5 represents 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 shows a high melting point of biopolymer with a very highly competitive advantage, and 1 shows a low melting point with a very low competitive advantage.

2.2. 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 receive insight into the product's market prospects. This matrix shows a similar approach to the Boston Consulting Group matrix. For product development and evaluating competitive scenarios, the GE-McKinsey matrix is frequently employed [23]. Fig. 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 until they appear in the green boxes [24].

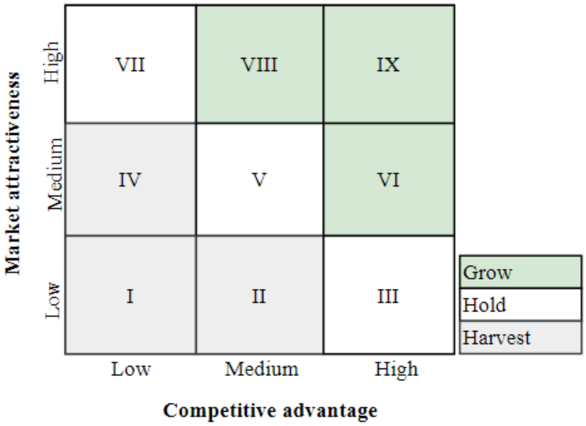

Fig. 4. The GE-McKinsey Matrix example [24]

A green box is a growing area, meaning the product has strong competitiveness and attractiveness for the market. Suppose a product is in a hold area. In that case, it shows that the product needs to adopt proper strategies to maintain its higher value. Suppose the product is in the harvest area. In that case, it has a low competitive advantage and attractiveness to the market [32]. 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, only contains four fields and a two-by-two grid [33].

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 as following Equations 1 and 2.

$$M_a = (z \cdot k) \quad (1)$$

Where,
M_a market attractiveness total score.
Z estimated total rating score.
k

$$k = \frac{100}{(f \cdot B_{max})} \quad (2)$$

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

7

product. A relative competitive advantage can be calculated by following Equation 3.

$$R = \left(\frac{B}{B_{comp}} - 1\right) \cdot 100\% \tag{3}$$

Where,

R Relative indicator of product competitive advantages.

B New product score estimation.

B_{comp} Strongest competitor score estimation

3. RESULTS & DISCUSSIONS

The most available and easy-to-access resource considered is agriculture 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 results for market attractiveness are presented in Table 1. Since all market attractiveness indicators are equally important, every indicator was assigned a weight of 16%.

TABLE 1: EVALUATION RATING RESULTS FOR MARKET ATTRACTIVENESS

Indicators	**Weights**	**External importance scale**	**Very unattractive**	**Unattractive**	**Neutral**	**Attractive**	**Very attractive**	**External importance scale**	**Source**
			1	**2**	**3**	**4**	**5**		
Market size	16.6%	Little	C	P2	S	P1		Great	[4]
Market growth rate	16.6%	Low		C	S	P2	P1	High	[34][35][6][36]
Market profit	16.6%	Low		C	S	P2	P1	High	[4]
Price sensitivity	16.6%	High		C; P2	S		P1	Low	[37][38]
Access to raw material	16.6%	Difficult					C; S; P1; P2	Easy	[39][40][41]
Production cost	16.6%	High		P2		C; P1	S	Low	[42][43][44]

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

The evaluation rating results for market competitiveness advantage are shown in Table 2. 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. MARKET COMPETITIVE ADVANTAGE EVALUATION RATINGS RESULTS

Indicators	Weights	Very low competitive advantage	Low competitive advantage	Moderate competitive advantage	Highly competitive advantage	Very highly competitive advantage	Source
		Rating scale					
		1	2	3	4	5	
Demand	15%		S	P1	P2	C	[34][35][45] [36]
Market share	15%		C	S	P2	P1	[4]
Availability of resources	20%					C; S; P1; P2	[39][40][41]
Selling price	15%		C; P2	S		P1	[37][38]
Environmental ease of technology	20%				P1; P2	S; C	[46][47]
Quality (based on melting point)	15%			P2	P1; S	C	[48][49][50] [51]

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

Table 3 demonstrates the weighted scores for the market attractiveness and competitive advantages. The visualization of GE-McKinsey results is shown in Fig. 5. 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 lowest market price (1.50-2.09 USD/kg) [37] with the highest production capacity of 37.9% [4] compared to other packaging materials. PHA packaging material has the weakest position in the market competitive advantage (3.15).

TABLE 3. RESULTS FOR BIOPOLYMER MARKET ATTRACTIVENESS AND COMPETITIVE ADVANTAGES

Market attractiveness evaluation									
Weights of importance					**Weights**	**Weighted scores**			
Indicators	**Biopolymer packaging materials**								
	Cellulose	**Starch**	**P1-PLA**	**P2-PHA**		**Cellulose**	**Starch**	**P1-PLA**	**P2-PHA**
Market size	1	3	4	2	16.666 %	0.166	0.498	0.664	0.332
Market growth rate	2	3	5	4	16.666 %	0.332	0.498	0.83	0.664
Market profit	2	3	5	4	16.666 %	0.332	0.498	0.83	0.664
Price sensitivity	2	3	5	2	16.666 %	0.332	0.498	0.83	0.332
Access to raw material	5	5	5	5	16.666 %	0.83	0.83	0.83	0.83
Production cost	4	5	4	2	16.666 %	0.664	0.83	0.664	0.332

Total	16	22	28	19	100%	**2.66**	**3.65**	**4.65**	**3.15**

Market competitive advantage evaluation									
Weights of importance						**Weighted scores**			
Indicators	**Biopolymer packaging materials**				**Weights**				
	Cellulose	**Starch**	**P1-PLA**	**P2-PHA**		**Cellulose**	**Starch**	**P1-PLA**	**P2-PHA**
Demand	5	2	3	4	15%	0.75	0.3	0.45	0.6
Market share	2	3	5	4	15%	0.3	0.45	0.75	0.6
Availability of resources	5	5	5	5	20%	1	1	1	1
Selling price	2	2	5	2	15%	0.3	0.3	0.75	0.3
Environmental ease	5	4	3	1	20%	1	0.8	0.6	0.2
Quality (based on melting point)	5	4	4	3	15%	0.75	0.6	0.6	0.45
Total	24	20	25	19	100%	**4.10**	**3.45**	**4.15**	**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 cellulose is only 1.5% [4]. Starch packaging materials show an average position for market attractiveness (3.65) and competitive advantage (3.45). However, improving both ratios can lead to a higher position for starch material.

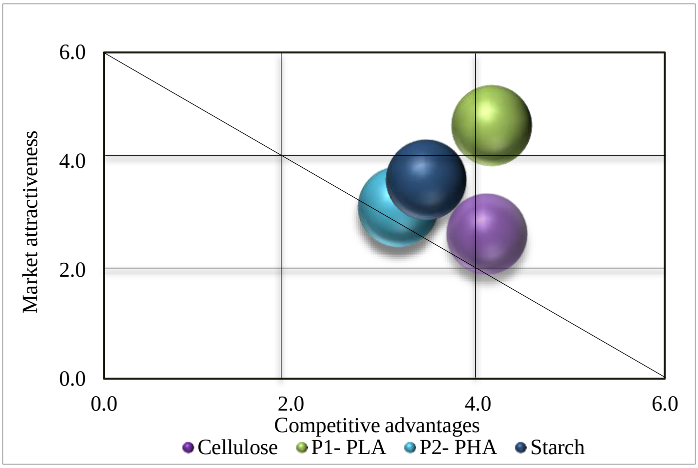

Fig. 5. GE-McKinsey matrix results for biopolymer packaging material alternative

The agriculture industry is a comprehensive source of biomass resources and biomaterial suppliers with significant potential for producing biopolymer packaging materials [52]. Over the time, market demand for biopolymer packaging materials should be raised to ensure environmental safety. According to the recent report from European Bioplastics 2022, 48% of biopolymers are used as packaging applications in Europe [4]. Despite having a tremendous market opportunity, biopolymer packaging materials seek less cost-effective market strategies to complete the synthetic polymers [53]. The results of our study show that cellulose has the second highest position in terms of market competitive advantage but the weakest market attractiveness. However, it is not always straightforward to determine if the product is fully sustainable and has high market potential. Market potential seeks economic benefit more than environmental benefit [54]. The results of this study strongly favour the production of PLA packaging materials 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 agricultural residues and sharing biobased products in the market.

4. CONCLUSIONS

The valorization of agriculture residues for developing bioeconomy and businesses is suitable for Europe. Business strength and attractiveness are also assessed through the systematic step-by-step approach. Also, this business portfolio analysis provides sustainable business solutions for investment or expansion of the business. It assists producers and businesses in expanding their business growth through the originated information. The approach employed here is broadly adaptable and suitable for various products. It can be applied to both novel and existing bio-products produced from agricultural biomass. The study covers four primary attractive biopolymer packaging materials having market attractiveness and competitive strength. The methodology has been demonstrated to be a practical framework for acquiring knowledge of the market for different biopolymer packaging materials.

The GE-McKinsey matrix proved to be an excellent tool for decision-making of a products readiness level to enter the market. Whether the product is sustainable and economically beneficial or requires significant changes in terms of technology used, resource availability, market attractiveness, and competitiveness, it can be modified for various scenarios and parameters. PLA biopolymer packaging material would be an ideal investment option, followed by cellulose, starch, and PHA packaging materials to attract the market. Nowadays, the policies and regulations are more focused on the environmental impact of the businesses. In such cases, this study would help businesses to make a viable choice.

While the study was currently being conducted, certain constraints were identified that might broaden the focus of future research, including a) the absence of extensive data on the biopolymer industry's market size, growth rates, and competitive environment, particularly for biopolymers produced from agricultural waste, could render accurate evaluation challenging, b) evaluating possible growth in the market and competitive advantage could prove challenging when there is a degree of uncertainty regarding the scalability, efficiency, and cost-effectiveness of the technique utilized to create biopolymers from agricultural waste, and c) demand and pricing estimates could become more difficult to determine because the biopolymer industry is rapidly changing competitive dynamics, market trends, and customer preferences.

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Carbon Footprint Evaluation Tool for Packaging Marketplace

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***Abstract* – Businesses willing to reduce their carbon footprint embrace sustainability and positively impact the progress towards achieving climate neutrality. Well-prepared and presented information to the business customer before purchasing can be a strong driver for better decision-making towards less impactful product alternatives. This study presents the development of 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 tool implements a life cycle analysis (LCA) approach, including the stages of raw material extraction, packaging production, and transportation to the customer. The impact assessment in the tool is performed according to Intergovernmental Panel on Climate Change (IPCC) 2021 methodology for assessing greenhouse gas (GHG) emissions based on information obtained from the Ecoinvent database. The final output of carbon footprint calculation is provided with an indicator marking the carbon footprint performance of customer-defined alternatives in a clear, simple, and consistent way. The tool aims to educate customers, foster informed purchasing decisions, and improve the environmental outcomes of their decisions.**

***Keywords* – Climate neutrality; GHG; Life cycle analysis; online tool; packaging material.**

1. INTRODUCTION

Global warming is one of the community's most prominent local, national, and global issues. An increase in the temperature is the most instant effect of global warming, which leads to climate change [1]. The Intergovernmental Panel on Climate Change (IPCC) identifies greenhouse gas (GHG) emissions as a primary contributor to global warming [2]. As a quantifiable representation of GHG emissions from activity, carbon footprint is useful for managing emissions and assessing mitigation strategies [3], [4]. Carbon footprint concept appeared in the 1960s with the growing interest in climate change [5]. According to the Kyoto protocol [6], carbon footprint refers to the total amount of GHG emissions in CO_2 equivalent and other GHG emissions caused by a product's life cycle stages, including production, storage, distribution, usage, and disposal. According to the European Parliament [7], one ton CO_2 equivalent is the total amount of GHG emissions expressed as the product of GHG mass in tonnes and their global warming potential.

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Carbon footprint reduction is one of the critical parts of sustainable development, representing a vital objective of the European Union (EU) sustainable development. The existing regulatory framework clearly shows the development and intensification of carbon footprint trends. In 2008, The European Parliament committed to reducing GHG emissions by 20 % by 2020 and 80–95 % by 2050 [8] in comparison to 1990 level. In 2015, the United Nations proposed 17 specific Sustainable Development Goals (SDGs) to improve the human well-being scale on a global level [9]. Moreover, European countries are actively working toward carbon neutrality following the European Green Deal regulations, which aim for zero GHG emissions from the EU by 2050 [10].

Carbon footprint is a crucial indicator to assess the degree of disturbance of human activities to the climate system [11]. To realize sustainable consumption, it is crucial to show consumers the GHGs of consumer behaviour or action, which shows the CO_2 visualization of the daily goods to the consumers while purchasing [12]. In other words, carbon footprint calculations are anticipated to make producers develop new products with reduced environmental impacts before switching to sustainable production within the cycle of "sustainable consumption and production" [13]. The importance of carbon footprint label reporting [14] carbon emissions is that they provide consumers with a straightforward quantity (kg CO_2) that allows them to immediately compare any two products, independent of their categories [15], [16].

The packaging market is a significant contributor to GHG emissions [17]. In 2009, plastic packaging waste generated 29 kg per capita in the EU. In 2010, global plastic waste production equalled 265 million tonnes [18]. Some packaging manufacturers aspire to measure, develop, and reduce the carbon footprint of their products. Companies have decided to reduce the carbon footprint of their products and educate customers about how their purchasing decisions influence GHG emissions [19]. Direct application of carbon footprint for companies includes several approaches, including [20]:

- Assessment of product lifecycle GHG emissions and their significant reduction;
- Emission impact on decision-making for suppliers, materials, product design, and manufacturing processes;
- Cost saving opportunities;
- Set a benchmark for measuring emission reduction;
- Comparison of GHG emission levels for a product.

In such a context, the Carbon footprint calculation can follow a specific framework called Life Cycle Analysis (LCA) [21]. LCA is an internationally standardized technique [22] for accessing products or systems environmental impacts under analysis. Carbon footprint estimation based on GHG emissions within the frame of LCA is performed according to the Global Warming Impact Assessment Method, which aligns with IPCC criteria [23], [24].

An example of an existing carbon footprint evaluation for packaging products is mentioned in [25], where polyethylene terephthalate (PET) packaging material to polylactic acid (PLA) and polystyrene (PS) are compared. A study by Pasqualino J. *et al.* [26] examined the carbon footprint of PET and glass bottles of various sizes. Another example of an integrated LCA-based approach to assessing the environmental impact of packaging material considering the different life cycle stages is shown in [27]. Carbon footprint evaluation of packaging films made from bioplastics, such as polylactic acid, low-density polyethylene, and polybutylene adipate terephthalate using the LCA database, can be found in [28]. In the study [29] carbon footprint assessment is applied to examine the environmental impact of cardboard box containers to store fruits and vegetables.

Apart from the packaging sector, other examples of carbon footprint tools include [24] a tool for the building design process, which assesses the CO_2 emissions from raw materials and recycled materials through production and transportation, and a tool [30] to analyse carbon footprint or energy and environmental performance in small and medium-sized enterprises. The tool refers to carbon emissions related to the company's operation field, electricity consumption from the operation field, and transportation. The carbon footprint tool for dairy production systems, including the CO_2 emissions from all feed crops, animal production, and manure handling, is presented in [31]. In the study [32] a carbon footprint evaluation tool for the industrial park includes in the carbon footprint calculation the impacts related to purchased electricity, heat, material, energy consumption, industrial process, and waste management. Lastly, the carbon footprint tool for supply chain management considers the economic sustainability of a product is presented in [33].

This study presents the development of a carbon footprint evaluation tool for packaging materials based on the LCA approach, which is designed for an online packaging marketplace. The tool aims to inform the customers about the carbon footprint of their selected packaging types, thus allowing them to select among existing alternatives the ones that have a minor environmental impact.

2. Case Study

The carbon footprint evaluation tool is developed for a specific packaging product online marketplace case. The marketplace acts as a matchmaker for a desired packaging type customizing the standard packaging products according to the customer's choices. The overall process of the marketplace is presented in Fig. 1.

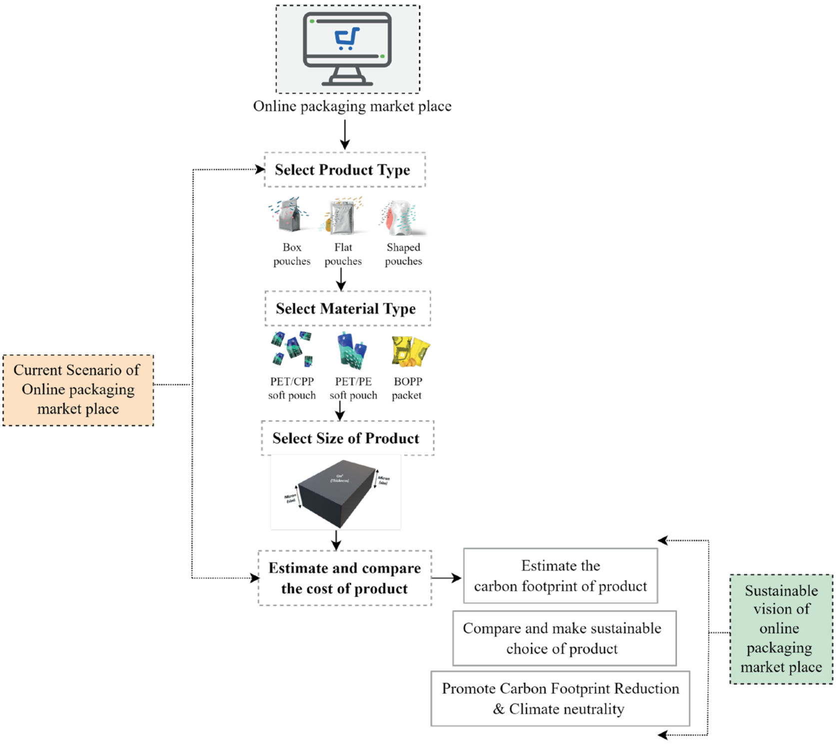

Fig. 1. Schematic presentation of packaging product online marketplace.

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.

3. METHODOLOGY

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. This study shows how the carbon footprint tool can be developed based on the LCA approach according to the ISO 14044 standard.

3.1. Goal & Scope Definition

The study aims 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. 2.

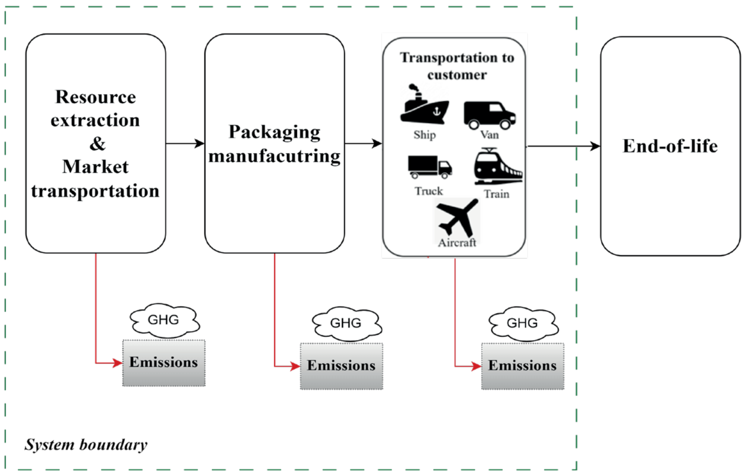

Fig. 2. System boundaries for the case study.

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 lifecycle of packaging in the defined system boundaries.

The study's main limitation is a lack of data on packaging products in different regions. The data used in this study is based on the global average values for the manufacturing process of specific materials and transport modes as given in the *Ecoinvent* database. Moreover, at the tool's current development level, the impacts related to different packaging surface production and additional materials in the packaging (e.g., zipper, slider, and other additional options) are excluded from the scope of the study.

3.2. Life Cycle Inventory

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. Summarizing:

- The background is from *Ecoinvent 3.7.1*, and the weight & specification of materials are according to the manufacturer;
- The geographical context of the system is considered for Europe;
- The data quality is generic;
- The year of data is 2022, and the representativeness per FU is for the year 2021;
- The technological characteristics concern the operations of resource extraction, market transportation, manufacturing, and distribution of packaging materials.

3.3. *Impact Assessment Methodology*

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 [23]. It contains GWP climate change factors of IPCC with 100 years of timeframe. According to the method description, IPCC characterization factors for the GWP of air emissions are [34]:

- Including carbon cycle response;
- Not including the indirect formation of dinitrogen monoxide from nitrogen emissions;
- Not including radiative forcing due to nitrogen dioxide emissions, carbon monoxide, voltaic organic compounds, black carbon, organic carbon, and sulfur oxides;
- Not including the indirect effects of carbon monoxide emissions;

The results can be calculated cumulatively as GWP100 or per category: GWP100 – fossil, GWP100 – biogenic, and GWP100 – land transformation [34].

4. RESULTS & DISCUSSION

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 shown in Fig. 3.

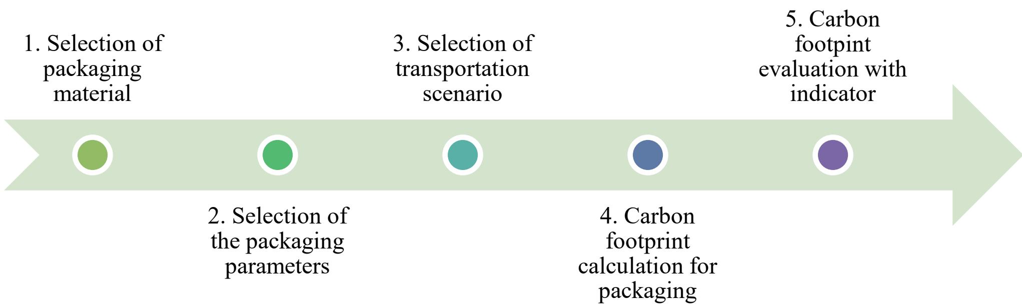

Fig. 3. Steps for carbon footprint evaluation.

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 of the packaging and the thickness of the packaging material. Step three defined the transportation scenario, including information on transportation type and travelled 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 colour 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 parameters of different packaging materials used for further estimations are given in Table 1.

TABLE 1. PARAMETERS OF PACKAGING MATERIALS INCLUDED IN THE TOOL

Material, *x*	**Density, ρ, g/cm^3**	**Thickness variation, *Th*, µm**	**Material in packaging, σ_A, µg/cm^2**
Polyethylene Terephthalate (PET)	1.4	12–30	1680–4200
Low-density polyethylene (LDPE)	0.91	40–120	3640–10 920
Polyethylene (PE)	0.95	45–142	4275–13 490
Recyclable Polyethylene (Recyclable PE)	0.95	25–142	2375–13 490
Kraft paper	1.201	45–80	5405–9608
Brown Kraft Paper	1.201	45–90	5405–10 809
Monoaxial-oriented Polyethylene Film (OPE)	0.95	15–20	1425–1900
Polylactic acid (PLA)	1.24	20–50	2480–6200

Polypropylene (PP)	0.9	15–70	1350–6300
Aluminium (AL)	2.705	7–9	1894–2435
Polyamide (PA)	1.14	50–150	5700–17 100
Paper	1.201	18	2162
Polyamide nylon (OPA)	1.14	15	1710
Wax (paraffin)	0.9	5	450
Biaxially oriented polypropylene (BOPP)	0.946	15–70	1419–6622
Cast polypropylene (CPP)	0.9	25–60	2250–5400

Note: The online marketplace provides density ρ, (g/cm^3) and Thickness variations *Th*, (μm).

The packaging size can differ depending on customer needs [35]. In the marketplace, the customer can select his preferred packaging p such parameters as packaging material x and size from the available option. 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 following Eq. (1):

$$m_p = A_p \cdot \rho_A, \tag{1}$$

where

m_p	Mass of selected packaging *p*, g;
A_p	Area of selected packaging *p*, cm^2;
ρ_A	Area density of material *x*; μg/cm^2.

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 following Eq. (2).

$$CF_p = CF_{xp} \cdot CF_{tp}, \tag{2}$$

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_{xp} and CF_{tp} are estimated according to the following Eq. (3) and (4).

$$CF_{cp} = CF_x \cdot A_p, \tag{3}$$

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.

$$CF_{tp} = \sum_{i=t}^{n} D_t \cdot CF_t \cdot m_p, \tag{4}$$

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_{tp} 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 for compare of carbon footprint values among their selected alternatives, the colour indicators are assigned to the obtained carbon footprint values. The colour indicator is used for the three carbon footprint levels: low, medium, and high. The different carbon footprint levels can be calculated using Eq. (5) and (6).

$$I = \frac{\max(CF_p) - \min(CF_p)}{3}, \tag{5}$$

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.

Eq. (6) is a logical function that assigns the indicator values to every alternative selected:

$$\begin{aligned}&\text{if } (CF_p) < \min(CF_p) + (I), \text{ then } (I_{\text{low}}); \text{ else (if } (CF_p) \geq \min(CF_p) + (2 \cdot I);\\ &\text{then } (I_{\text{high}}); \text{ else } (\text{I}_{\text{medium}})),\end{aligned} \tag{6}$$

where

I_{low}	Shows low levels of carbon footprint;
I_{medium}	Shows medium levels of carbon footprint;
I_{high}	Shows high levels of carbon footprints,

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.

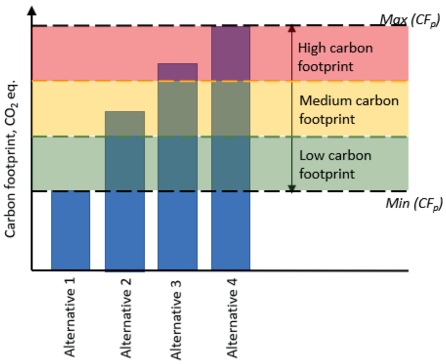

Fig. 4. Colour visualization of carbon footprint calculation for packaging alternatives.

The carbon footprint calculation results can be presented to the online marketplace client using colour indicators to distinguish these levels. As shown in Fig. 4, low, medium, and high carbon footprint levels can be visualized in green, yellow, and red colour 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 the competition in the market and decision-making. This goal can be achieved by following well-defined methods. As a long-term goal, policymakers should enforce to implement carbon footprint schemes for companies.

5. Conclusions

In this work, a simple and stepwise approach is applied to develop a CO_2 calculator to promote the reduction of the carbon footprint of packaging material. The developed carbon footprint tool is used as a strategy to enable CO_2 reduction of an online marketplace company for packaging products. The tool implemented an LCA-based methodology as a viable calculation approach toward the carbon footprint of packaging material using the IPCC 2021 method that provides the unique quantitative value for global warming potential estimation. The tool allows the customer to understand better aspects related to decreasing the carbon footprint, directly contributing to mitigating the intensity of carbon emissions by selecting potentially less impactful choices. Indirectly, the use of this tool promotes climate neutrality. It educates the clients about their purchases and arises as potential support for decision-making companies. The presented case study can be a great starting point for companies with similar packaging strategies and see whether their products are environmentally competitive in the market. Additionally, further research would be worth exploring the parameters, such as packaging surface and additional materials used in the packaging. Moreover, data availability on the regional scale could influence the precision of such tools in the future and, thus, the decision-making in the corporations regarding their sustainability strategies.

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