

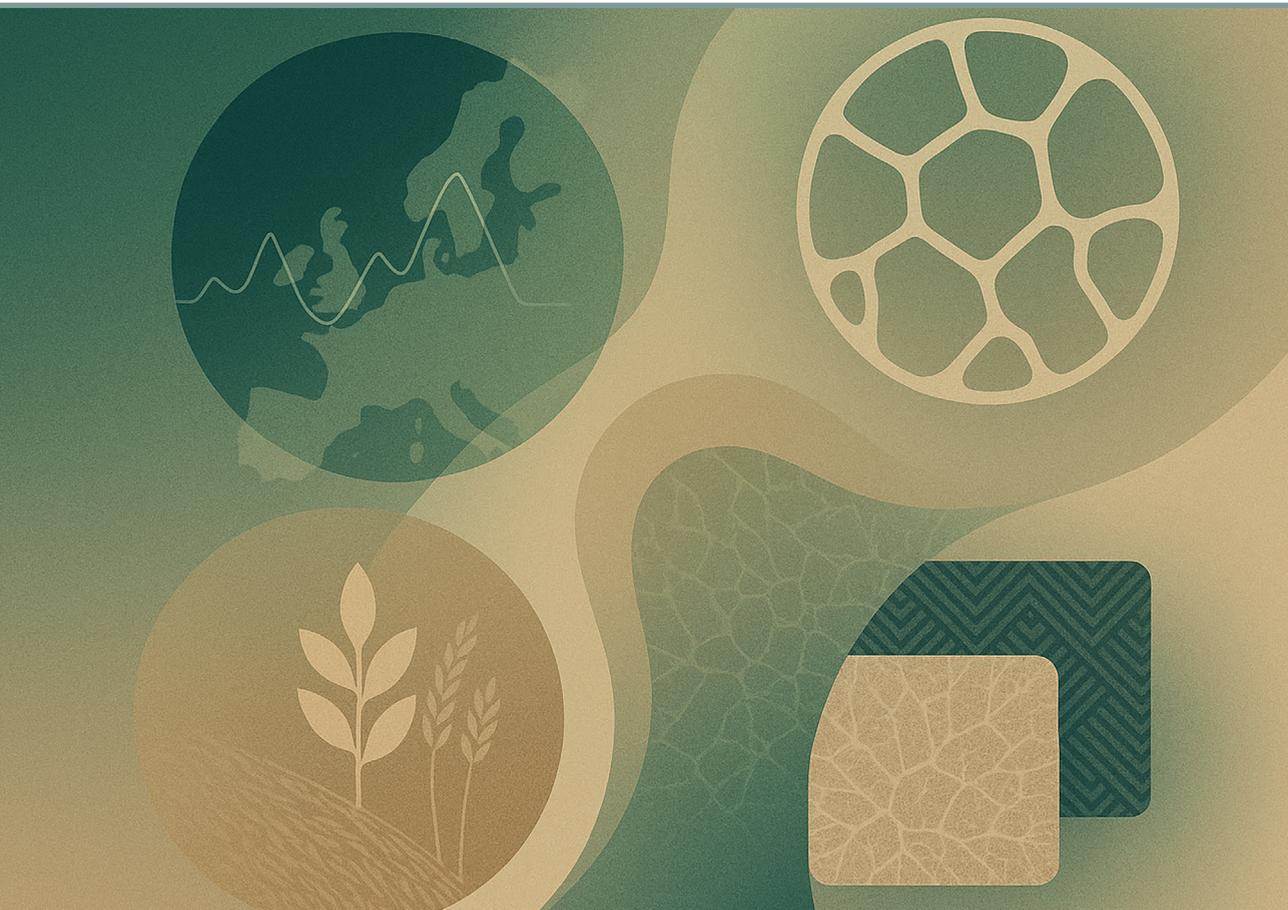


RIGA TECHNICAL
UNIVERSITY

Ilze Luksta

**SUSTAINABLE DEVELOPMENT OF THE
BIOECONOMY. AGRICULTURE TOWARDS
CLIMATE NEUTRALITY**

Doctoral Thesis



RIGA TECHNICAL UNIVERSITY

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**SUSTAINABLE DEVELOPMENT OF THE
BIOECONOMY. AGRICULTURE TOWARDS
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Doctoral Thesis

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ANNOTATION

The doctoral thesis “Sustainable development of the bioeconomy. Agriculture towards climate neutrality” explores the potential of sustainable agricultural practices and the use of bioresources to reduce greenhouse gas (GHG) emissions and promote climate neutrality. The research focuses on the agricultural sector, which significantly contributes to GHG emissions, and explores innovative approaches to improve resource efficiency.

The research is structured in four areas: (1) comparative analysis of agricultural GHG emissions in European countries, (2) use of the Integrated MARKAL-EFOM System (TIMES) model to analyze the use of bioresources in the Latvian agricultural sector, (3) experimental development of a mycelium-based thermal insulation material, and (4) comparison of the developed material with synthetic materials.

The work examines:

- **Analysis of GHG emissions:** The study found significant differences in agricultural emissions across EU countries. Some countries have been able to significantly reduce emissions, while others have difficulty achieving their emission targets. The study highlights the need for tailored mitigation strategies, such as improved feed quality, organic farming, and sustainable land management.

- **Application of the TIMES model:** The TIMES model was adapted to the Latvian agricultural sector to assess scenarios for increasing the added value of bioresources. The results show that integrating new technologies, such as fiber powder production and the use of second-generation biofuels, can significantly improve the economic and environmental sustainability of the sector.

- **Mycelium-based materials:** The development of mycelium-based thermal insulation materials shows their potential as sustainable alternatives to synthetic insulation. These materials have competitive thermal conductivity, low environmental impact and biodegradability.

- **Application of the system dynamics model:** The system dynamics model was used to assess the differences in energy and GHG emissions between mycelium insulation material and synthetic insulation alternatives. The results show that mycelium insulation materials have the potential to reduce total embodied energy and GHG emissions if the same amount of insulation materials is produced. The modelling time horizon is from 2021 to 2050, and it also takes into account the impact of research and development on the efficiency and productivity of the mycelium production process. The thesis concludes that sustainable agricultural practices, efficient use of bioresources and the development of innovative bio-based materials are crucial to achieving climate neutrality. The paper provides practical guidance for policymakers, industry stakeholders and researchers to promote sustainable agriculture and the development of the bioeconomy, in line with the objectives of the European Green Deal.

This paper makes a significant contribution to the discussion on the development of sustainable agriculture and the efficient use of bioresources to mitigate the impact of climate change. The results of the paper can serve as a basis for further scientific research, as well as

practical solutions, facilitating the transition to a more environmentally friendly and resource-efficient agricultural sector.

This Doctoral Thesis is written in English, it comprises 197 pages including appendices and includes 35 figures, 22 tables and 127 references.

ANOTĀCIJA

Promocijas darbs “Bioekonomikas ilgtspējīga attīstība. Lauksaimniecība ceļā uz klimatneitralitāti” pēta ilgtspējīgas lauksaimniecības prakses un bioresursu izmantošanas potenciālu, lai samazinātu siltumnīcefekta gāzu (SEG) emisijas un veicinātu klimatneitralitāti. Pētījums ir vērsts uz lauksaimniecības nozari, kas ir nozīmīgs SEG emisiju veicinātājs, un pēta novatoriskas pieejas, lai uzlabotu resursu efektivitāti.

Pētījums ir strukturēts četrās jomās: (1) lauksaimniecības SEG emisiju salīdzinošā analīze Eiropas valstīs, (2) *TIMES* modeļa izmantošana, lai analizētu bioresursu izmantošanu Latvijas lauksaimniecības sektorā, (3) uz micēlija balstīta siltumizolācijas materiāla eksperimentālā izstrāde, un (4) izstrādātā materiāla salīdzināšana ar sintētiskajiem materiāliem.

Darbā tiek skatīta:

- SEG emisiju analīze: Pētījumā konstatētas ievērojamas atšķirības lauksaimniecības emisijās ES valstīs. Dažas valstis ir spējušas ievērojami samazināt emisijas, savukārt citām ir grūtības sasniegt izvirzītos emisiju mērķus. Pētījums uzsver nepieciešamību pēc pielāgotām seku mazināšanas stratēģijām, piemēram, uzlabotas barības kvalitātes, bioloģiskās lauksaimniecības un ilgtspējīgas zemes apsaimniekošanas.

- *TIMES* modeļa pielietojums: *TIMES* modelis tika pielāgots Latvijas lauksaimniecības nozarei, lai izvērtētu scenārijus bioresursu pievienotās vērtības palielināšanai. Rezultāti rāda, ka jaunu tehnoloģiju integrēšana, piemēram, šķiedru pulvera ražošana un otrās paaudzes biodegvielu izmantošana, var būtiski uzlabot nozares ekonomisko un vides ilgtspējību.

- Micēlija materiāli: Micēlija siltumizolācijas materiālu izstrāde parāda to potenciālu kā ilgtspējīgas alternatīvas sintētiskajai izolācijai. Šiem materiāliem ir konkurētspējīga siltumvadītspēja, zema ietekme uz vidi un bionoārdīšanās spēja.

- Sistēmdinamikas modeļa pielietojums: Sistēmdinamikas modelis tika izmantots, lai izvērtētu micēlija izolācijas materiāla un sintētiskās izolācijas alternatīvu ietvertās enerģijas un SEG emisiju atšķirības. Rezultāti parāda, ka micēlija izolācijas materiāliem ir potenciāls samazināt kopējo ietverto enerģiju un SEG emisijas, ja tiek saražots vienāds izolācijas materiālu daudzums. Modelēšanas laika horizonts ir no 2021. līdz 2050. gadam, un tajā ņemta vērā arī pētniecības un attīstības ietekme uz micēlija ražošanas procesa efektivitāti un produktivitāti. Darbā secināts, ka ilgtspējīgai lauksaimniecības praksei, efektīvai bioresursu izmantošanai un inovatīvu bioloģisku materiālu izstrādei ir izšķiroša nozīme klimata neitralitātes panākšanā. Pētījums sniedz praktiskas vadlīnijas politikas veidotājiem, nozares ieinteresētajām personām un pētniekiem, lai veicinātu ilgtspējīgu lauksaimniecību un bioekonomikas attīstību, saskaņojot to ar Eiropas zaļā kursa mērķiem.

Šis darbs sniedz būtisku ieguldījumu diskusijā par ilgtspējīgas lauksaimniecības attīstību un bioresursu efektīvu izmantošanu, lai mazinātu klimata pārmaiņu ietekmi. Pētījuma rezultāti var kalpot kā pamats turpmākiem zinātniskiem pētījumiem, kā arī praktiskiem risinājumiem, veicinot pāreju uz vidi draudzīgāku un resursu efektīvāku lauksaimniecības nozari.

Šis promocijas darbs ir izstrādāts angļu valodā, tas sastāv no 197 lappusēm, iekļaujot pielikumus, ietver 35 attēlu, 22 tabulas un 127 atsauces.

ACKNOWLEDGMENT

I express my immense gratitude to everyone who has provided support and inspiration in the preparation of this doctoral thesis.

First of all, I would like to thank my scientific supervisor and co-supervisor for their valuable advice, professional guidance and patience throughout the entire process of developing the thesis. I also express my gratitude to other colleagues for their suggestions and discussions that helped improve my research.

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ABBREVIATIONS

ANOVA - Analysis of variance
ANOVA – Analysis of variance
CAP - Common Agricultural Policy
CH₄ – Methane
CO₂ - Carbon dioxide
DW - Durbin-Watson
DW - The Durbin-Watson
E4SMA - Energy Engineering Economic Environment Systems Modelling Analysis
EPS - Expanded polystyrene
Eq. – Equivalent
ESRI - Economic and Social Research Institute
EU - European Union
GDP - Gross domestic product
GHG - Greenhouse gas
Gt – Gigaton
J - Joule
K - Kelvin
kJ - Kilojoule
LCA - Life cycle analysis
MAE - The mean absolute error
MAE - The mean absolute error
MCDA - Multi-criteria decision analysis
MEA - Malt extract agar
MEETA - Modelling Energy and Emissions Trade-offs in Agriculture
MJ - Megajoule
N₂O - Nitrous oxide
O&M - Operation & maintenance
PDA - Potato dextrose agar
PET - Pan European TIMES
R&D - Research and development
SD - System dynamic
SEA - Socio-economic analysis
SEAMLESS-IF - SEAMLESS-Integrated Framework
SEG - Siltunnīcefekta gāzu
SLCA - Social life cycle assessment
SYNERGY - Cross-scale model using complementarity between livestock and crop farms to enhance regional nitrogen self-sufficiency
TIMES - Integrated MARKAL-EFOM System
UCC - University College Cork
USD - United States dollar
W - watts

XPS - Extruded polystyrene

λ - Lambda

ρ - Density

INTRODUCTION

The development of the bioeconomy is becoming increasingly important in today's world, as environmental challenges and the need to balance economic growth with ecological sustainability increase. The concept of bioeconomy encompasses various sectors based on biological resources, including agriculture, forestry, fisheries, and industrial biotechnology. These sectors have a significant impact on both the availability of natural resources and climate change. Agriculture is one of the primary sources of GHG emissions, so its transformation and adaptation to climate neutrality goals are essential steps towards sustainable development and the full use of the bioeconomy's potential.

The European Union (EU) and international commitments in the field of climate change mitigation emphasize the transition to climate-friendly technologies and the use of innovative bioresources to reduce emissions and promote carbon-neutral development. One of the most effective approaches to achieving these goals is to promote the use of by-products and the development of environmentally friendly materials, replacing traditional synthetic materials. The transition to bioeconomy principles in agriculture allows for the efficient use of renewable resources while contributing to the development of sustainable agricultural systems.

The agricultural sector should focus on reducing emissions, promoting improved soil and water management practices, and assessing the economic value and efficiency of various by-products. The growing demand for sustainable and environmentally friendly products creates a need for innovations that are essential for the Latvian economy, where agriculture plays a significant role. In this context, the bioeconomy provides opportunities to develop solutions that are aligned with climate neutrality goals, while ensuring economic benefits. The agricultural sector needs to adapt to new circumstances and strive for greater sustainability, while maintaining production efficiency and competitiveness.

This study analyzes various sustainable approaches to bioresources. The study focuses on evaluating the potential uses of various agricultural by-products and developing environmentally friendly materials. These solutions can potentially create alternative materials that are economically viable and meet climate neutrality goals.

Relevance of the problem

Agriculture is a major source of environmental impact, accounting for around 10 % of total GHG emissions in the EU. Some of these emissions result from inefficient management of agricultural by-products. In order to reduce emissions and optimise resource use, more sustainable by-product treatment and use strategies need to be developed, thereby contributing to climate goals.

Hypothesis

The biological resource optimization model TIMES can serve as an analytical tool for more efficient use of bioresources and the transition to the production of higher value-added products.

In addition, the use of mycelium material as a sustainable insulation could be an important step in reducing greenhouse gas emissions.

The proposed theses

1. The intensity of agricultural GHG emissions varies significantly across the EU, and is influenced not only by agricultural practices but also by policy instruments, population density and gross domestic product (GDP) per capita. More effective emission management approaches are possible, regardless of the specific context of the countries.
2. The optimization model, TIMES, is suitable for bioresource analysis. The model allows for the identification of potential solutions with higher added value, but its application should be expanded in the future to include a more regional and technologically accurate database.
3. The experimentally developed mycelium thermal insulation material is a promising, environmentally friendly solution. The effect of its composition proportions on thermal conductivity and durability is statistically significant.
4. The system dynamics model shows that mycelium material has the potential to reduce GHG emissions in the long term, as it is able to capture CO₂ and replace synthetic materials. However, the current production process is energy-intensive and requires further optimization.

The aim of the research

The main **objective** of the study is to develop and evaluate sustainable bioeconomy solutions in the agricultural sector, focusing on optimizing the added value of bioresources and innovations in the production of thermal insulation materials to promote the transition to a climate-neutral economy.

The main **tasks** of the study are:

- to assess and compare the GHG emissions of EU countries in the agricultural sector;
- to analyze the added value of bioresources in the crop sector using the TIMES model;
- to experimentally develop a mycelium thermal insulation material;
- to compare the developed mycelium and traditional materials, taking into account the embodied energy and GHG emissions.

The novelty of the research

The novelty of the research is based on the adaptation of system dynamics and the TIMES model to the agricultural sector, so that anyone can use these models when analyzing biological resources and materials. The research offers new opportunities for processing agricultural by-products into high-value products, contributing to the achievement of climate neutrality goals and the development of bioeconomy principles.

Practical relevance

The practical significance of the work is expressed as a contribution to the development of sustainable agriculture, providing concrete guidelines for reducing GHG emissions and more efficient use of biological resources. The results help to promote the achievement of climate neutrality goals and develop innovative, environmentally friendly products, while promoting economic growth and competitiveness.

Structure

The Doctoral Thesis is structured in four main thematic areas, which together form a framework for the path to climate neutrality through sustainable agricultural practices and the development of innovative materials.

1. Current situation in emissions in agriculture: The work begins with a comparative analysis of GHG emissions in the European Union agricultural sector, identifying regional differences and emission trends.

2. Use of bioresources: The possibilities of using agricultural by-products are investigated, in particular using the TIMES model. Various plant-based products and by-products with potential for the production of high-added value products are analyzed:

- fiber powder from cereal by-products;
- bioplastics from plant residues;
- biodiesel and bioethanol from grains, oilseeds and vegetable waste.

3. Alternative material: An experimentally developed mycelium-based thermal insulation material using agricultural by-products. This chapter investigates the potential of mycelium materials as an environmentally friendly alternative to traditional insulation materials.

4. Emission reduction: A system dynamics analysis comparing mycelium-based insulation material with synthetic materials.

Together, these four areas form a unified conceptual framework that combines circular economy principles and technological innovations to promote sustainable agriculture and the development of the bioeconomy.

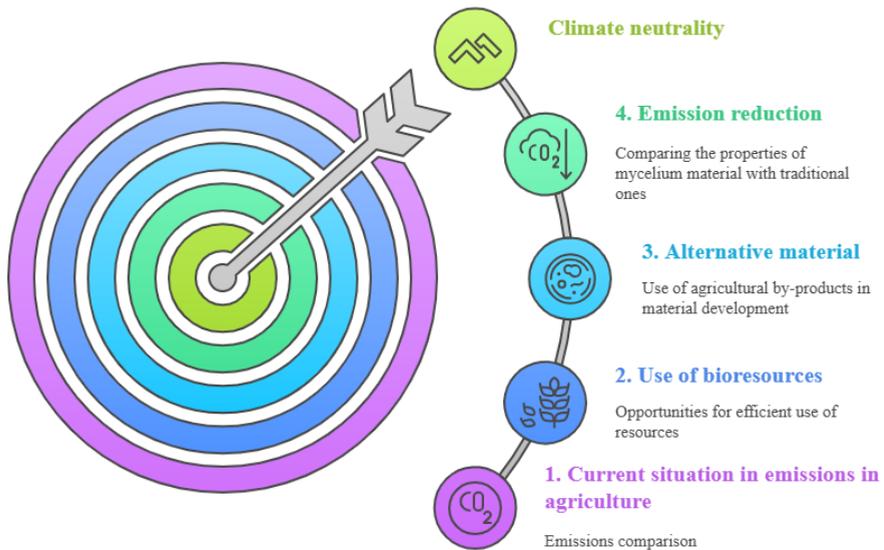


Fig. 1. Structure of the Doctoral Thesis.

Table 1

Thesis Structure and Publications

Method	Publication number	Publication title
GHG emissions analysis	1	Comparative Analysis of Agricultural Emissions Across European Countries
TIMES model	2	Bioresource Value Model: Case of Crop Production
Experimental research	3	Development of a mycelium-based thermal insulation material
System dynamics model	4	Production of Renewable Insulation Material – New Business Model of Bioeconomy for Clean Energy Transition

SCIENTIFIC APPROBATION

1. I. Luksta, I. Pakere, I. Vamža, V. Liberova, D. Blumberga, “Comparative Analysis of Agricultural Emissions Across European Countries,” *Environmental and Climate Technologies*, 2024, Vol. 28, No. 1, 738.–748. lpp. ISSN 1691-5208, doi: 10.2478/rtuct-2024-0057.

2. I. Luksta, P. Asaris, M. Feofilovs, D. Blumberga, “Bioresource Value Model: Case of Crop Production,” *Environmental and Climate Technologies*, 2022, Vol. 26, No. 1, pp.1128-1144. e-ISSN 2255-8837, doi: 10.2478/rtuect-2022-0085.
3. I. Luksta, I. Vamža, D. Blumberga, “Development of a mycelium-based thermal insulation material, ” *Environmental and Climate Technologies* 2025, Vol. 29, no. 1, pp. 201–211. e-ISSN 2255-8837, <https://doi.org/10.2478/rtuect-2025-0014>
4. I. Luksta, Ģ. Bohvalovs, G. Bažbauers, K. Spalviņš, A. Blumberga, D. Blumberga, “Production of Renewable Insulation Material – New Business Model of Bioeconomy for Clean Energy Transition,” *Environmental and Climate Technologies*, 2021, Vol. 25, No. 1, pp. 1061–1074. ISSN 1691-5208. e-ISSN 2255-8837, doi: 10.2478/rtuect-2021-0080.
5. I. Luksta, K. Spalviņš “Methods for Extraction of Bioactive Compounds from Products: A Review,” *Environmental and Climate Technologies*, 2023, Vol. 27, No. 1, pp. 422–437. ISSN 1691-5208. e-ISSN 2255-8837, doi: 10.2478/rtuect-2023-0031.

The research results have been discussed and presented at the following conferences

1. I. Luksta, Ģ. Bohvalovs, G. Bažbauers, K. Spalviņš, A. Blumberga, D. Blumberga, “Production of Renewable Insulation Material – New Business Model of Bioeconomy for Clean Energy Transition,” *International Scientific Conference of Environmental and Climate Technologies*, **CONNECT 2021**, May 12–14, 2021, Riga, Latvia.
2. I. Luksta, P. Asaris, M. Feofilovs, D. Blumberga, “Bioresource Value Model: Case of Crop Production,” *International Scientific Conference of Environmental and Climate Technologies*, **CONNECT 2022**, May 11–13, 2022, Riga, Latvia.
3. I. Luksta, K. Spalviņš “Methods for Extraction of Bioactive Compounds from Products: A Review,” *International Scientific Conference of Environmental and Climate Technologies*, **CONNECT 2023**, May 10–12, 2023, Riga, Latvia.
4. I. Luksta, I. Pakere, I. Vamža, V. Liberova, D. Blumberga, “Comparative Analysis of Agricultural Emissions Across European Countries,” *International Scientific Conference of Environmental and Climate Technologies*, **CONNECT 2024**, May 15–17, 2024, Riga, Latvia.
5. I. Luksta, I. Vamža, D. Blumberga, “Development of a mycelium-based thermal insulation material,” *International Scientific Conference of Environmental and Climate Technologies*, **CONNECT 2025**, May 14–16, 2025, Riga, Latvia.

Other publications

1. I. Vamža, K. Valters, I. Luksta, P. Resnais, D. Blumberga, “Complete Circularity in Cross-Laminated Timber Production,” *Environmental and Climate Technologies*, 2021, Vol. 25, No. 1, pp. 1101–1113. ISSN 1691-5208. e-ISSN 2255-8837, doi:10.2478/rtuect-2021-0083
2. G. Valdmanis, M. Rieksta, I. Luksta, G. Bažbauers, “Solar Energy Based Charging for Electric Vehicles at Fuel Stations,” *Environmental and Climate Technologies*, 2022, Vol. 26, No. 1, pp. 1169–1181. e-ISSN 2255-8837, doi:10.2478/rtuect-2022-0088

3. I. Luksta, T. Mika, K. Spalviņš, “Extraction of Apple Pomace Using Supercritical CO₂ Extraction,” *Environmental and Climate Technologies*, 2023, Vol. 27, No. 1, pp. 980–988. ISSN 1691-5208. e-ISSN 2255-8837, doi:10.2478/rtuect-2023-0071
4. I. Luksta, T. Mika, K. Spalviņš, “Supercritical CO₂ Extraction of Wine and Beer Yeast Residues for Sustainable Bioproduct Recovery,” *Environmental and Climate Technologies*, 2024, Vol. 28, No. 1, pp. 356–366. ISSN 1691-5208. e-ISSN 2255-8837, doi:10.2478/rtuect-2024-0028
5. I. Luksta, T. Mika, K. Spalviņš, “Supercritical CO₂ Extraction of Fish Roe,” *Environmental and Climate Technologies*, 2024, Vol. 28, No. 1, pp. 12–20. ISSN 1691-5208, doi:10.2478/rtuect-2024-0002
6. L. Balode, I. Pakere, I. Luksta, D. Blumberga, “Organic versus Conventional Agriculture: Comparison of Economic and Environmental Sustainability,” *Environmental and Climate Technologies*, 2025, Vol. 29, e-ISSN 2255-8837, doi: 10.2478/rtuect-2025-0001

1. LITERATURE REVIEW

1.1. Greenhouse gas emissions in the European agricultural sector

Agriculture is a major contributor to anthropogenic global warming, and the agricultural sector is the primary producer of methane and nitrogen emissions, which are converted into CO₂ equivalents [1]. The biggest emitters are the energy sector (66,5% of GHG emissions), but the agricultural industry is also one of the biggest polluters (about 13,5% of GHG emissions). It is interesting that of the total emissions, 20% of CO₂, 70% of methane (CH₄), and 90% of nitrous oxide (N₂O) in the atmosphere were released as a result of various activities in the agricultural sector. Additionally, it has been reported that 35% of CO₂, 47% of CH₄, and 53% of N₂O from total agricultural greenhouse gases originate in soil, particularly due to practices like manure management. Globally, a set of measures and many international agreements, such as the Kyoto Protocol in 1997, were implemented to reduce GHG emissions worldwide. Developed countries were required to reduce emissions by 25% to 40% by 2020. The United Kingdom introduced the concept of a low-carbon economy in 2003, followed by Germany, Japan, and the United States since then. In recent decades, many researchers worldwide have studied the relationship between the agricultural sector and GHG emissions, and it has been argued that the interdependence of crop and livestock management could play an essential role in GHG mitigation in the United States. It is also recommended that crop production and crop improvement be invested as a good strategy to reduce future GHG emissions. Also, GHG from the agricultural sector has been found to have increased annually by 1,1% from 2000 to 2010 worldwide [2].

The rapid growth of the population and the increase due to anthropogenic activities create new problems associated with climate change and pose a significant threat to the sustainability of natural resources and the stability of the Earth's biosphere. It should be noted that these problems are already causing an uncontrollable accumulation of gases in the atmosphere. Global GHG concentrations have been rapidly increasing since the beginning of the industrial age; for example, CO₂ concentrations in 1760 were 280 ppm and are expected to reach 590 ppm by the end of 2100. Global tracking of greenhouse gas emissions provides a basis for assessing individual countries contributions to climate change. Climate change indicators define atmospheric concentrations of the most significant GHG emissions from human activities and how emissions and concentrations have changed over time. These indicators use the concept of "global warming potential" to compare emissions of gases to convert amounts of other gases into CO₂ equivalents. Human-caused GHG emissions are increasing and exacerbating climate change. These rising levels of GHG lead to many more climate-related changes locally and globally [3].

European GHG emissions from the agricultural sector were reported to account for 10% of total GHG emissions. The total amount of GHG emissions of European countries in 2021 was 3,6 GtCO₂eq, and GHG emissions from agriculture were almost 500 million tons [4]. This shows that energy is one of the main inputs in the agricultural system. In contrast, the energy produced by forming fossil fuels is mainly used by agriculture and many other activities. For

example, Italy has the highest share of energy used in agriculture at 9,8% (compared with 2020), Slovakia at 9,3% and France at 9,1 %. However, Portugal has the lowest percentage overall (+5,5%) [5]. The increasing amount of energy is due to neoteric agricultural activities, partly responsible for the constant increase in GHG emissions. About half of the energy used in the agricultural sector comes from diesel and gas oil, which account for the largest share of energy used in the agricultural sector in Europe. Regardless of the size and contribution of the agricultural sector to the national GDP in each European Member State, Europe has achieved a 23% reduction in GHG emissions over the past two decades [3].

Agriculture is actually very vulnerable to climate change, as its activities are directly dependent on climatic conditions. However, the impact of climate change on agricultural yields varies across countries and cultures. Some areas could benefit from the actions of some components of climate change (e.g., water scarcity, increased crop variability, reduced yields, etc.) [6]. In fact, in different countries, different combinations of these influences can exacerbate the overall situation. For example, increasing temperatures can have both positive and negative effects on agricultural yields. It should be pointed out that a strong rise in temperature means water shortages, which can significantly worsen agriculture in all countries, especially in semi-arid areas such as southern European countries. In this case, a negative relationship between rising temperatures and agricultural yields is hypothesized. Additionally, increased precipitation may benefit semi-arid areas by increasing soil moisture, but may exacerbate problems in areas with excess water. On the other hand, reducing the amount of precipitation could have the opposite effect. In irrigated areas, the negative effects of altered precipitation and increased temperature are reduced by the availability of irrigation water, making crops more resistant to climate change. In this last case, groundwater and rivers are mitigating factors of climate variability. In summary, each component of climate change has more than one effect, and the distribution of one type of biophysical effect depends on soil conditions, species, and plant type [7].

There is an opportunity to achieve climate-friendly agriculture by both sequestering carbon and reducing emissions. The main strategies are 1) enriching soil carbon (e.g., using perennial plants), 2) promoting climate-friendly livestock systems, 3) reducing the use of inorganic fertilizers, and 4) restoring degraded lands and preventing deforestation, which is mainly for agricultural purposes [8] [9].

Agriculture is the second most important source of GHG emissions [10]; for example, in Latvia, they accounted for approximately 22% of the total GHG emissions in the country in 2022. Emissions from agricultural soils accounted for the largest share of total emissions – 46,5%, and intestinal fermentation emissions were the second largest source – 42%. The proportion of emissions from manure management was estimated to be 7,8% of the total emissions in the sector, and the remaining 3,7% of emissions refer to liming and urea use. GHG emissions in 2022 increased by 0,04% compared to 2021 [11].

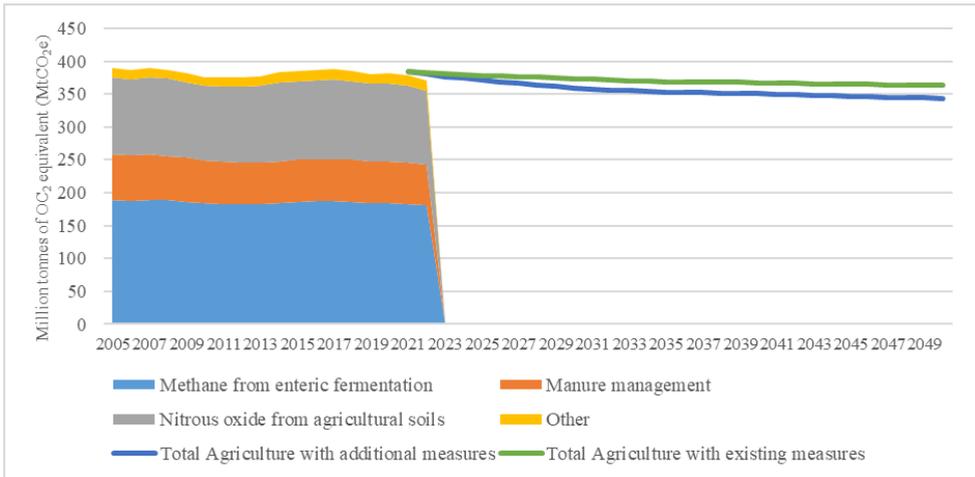


Fig. 1.1. EU agricultural emissions by source and projected emissions [12].

GHG emissions from agriculture, including crop and livestock farming, forestry, and associated land-use change, account for a significant share of anthropogenic emissions, up to 30%, according to the Intergovernmental Panel on Climate Change [13]. The European Climate Law [14] stipulates that Europe will transition to a climate-neutral economy by 2050 with an intermediate goal of reducing GHG emissions by at least 55% by 2030. Also, targets have been set that determine the annual reduction for each member state in the period from 2021 to 2030, respectively [15] [12]. CH₄ emissions from gut fermentation and N₂O emissions from soil account for 48% and 31% of total agricultural GHG emissions, respectively. CH₄ from manure management is the third most important source of emissions, accounting for about 17%. The remaining sources produce relatively small amounts of emissions, accounting for less than 5% of agricultural GHG emissions. Between 2005 and 2021, Europe's agricultural GHG emissions show a slight decrease of 3%, with a decrease of only 2% in 2022. Projections of the member states show that GHG emissions will remain at approximately this level until 2030. If additional measures are taken, taking into account, it could rise to 8% [16].

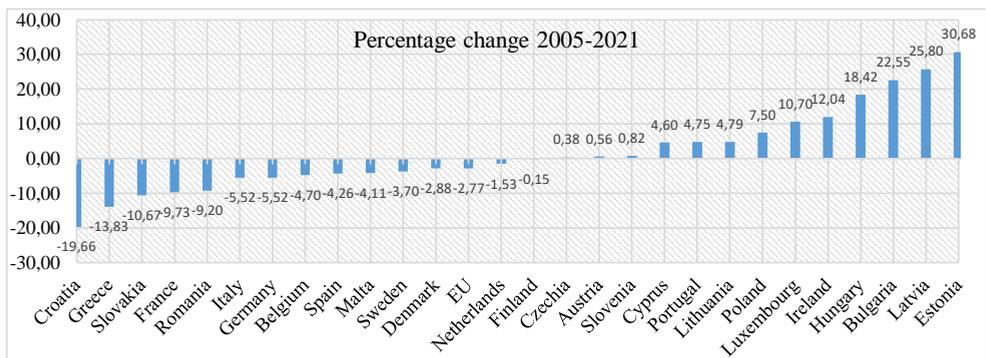


Fig. 1.2. Agricultural emissions and projected emissions by EU Member State [12].

During the time period from 2005 to 2021, the amount of GHG emissions from agriculture in Europe changed very little, but the trends of each country were very different; for example, they increased in 13 countries and decreased in 14 countries. For example, emissions fell by more than 10% in Greece, Croatia, and Slovakia, while they increased by more than 10% in Estonia, Hungary, Bulgaria, Latvia, Ireland, and Luxembourg. Taking into account the forecasts, an increase in emission trends is expected in most European countries if the current situation continues and no measures are taken to mitigate them. Twelve Member States have not reported planned additional measures that could reduce emissions more than existing measures [12].

Given the emissions generated in the agricultural sector, it is important to assess not only how these emissions can be reduced, but also how it is possible to increase the use of by-products and reduce the amount of waste generated using bioeconomy models. In this context, the transition towards a circular and sustainable agricultural system becomes particularly relevant. One of the core principles of the bioeconomy is the efficient and innovative use of resources, including agricultural residues and side-streams that would otherwise go to waste.

By-products in agriculture can account for approximately 20–40% of total agricultural production, depending on the sector and region. This significant proportion highlights the potential for creating new value chains through their reuse and transformation. Therefore, it is essential to explore how these materials can be converted into high-value products, contributing to environmental sustainability, economic development, and resource efficiency.

1.2. Extraction methods for creating value added from by-products

Agricultural product residues (by-products) can be defined as primary or secondary depending on their origin. Primary residues include the production or cultivation of plant products, such as grains, fruits, vegetables and herbs, as well as the transportation, storage and processing of said products (if the products do not change significantly) on the farm and onward delivery to businesses. Secondary residues are obtained in the food processing industry and become residues during the processing stage (peels, pulps, stones, nut shells) [17]. The generation of agricultural waste varies from country to country, for example in Europe more than 40% of the weight of the original agricultural product is thrown away, while in North Africa, East Central Asia and Latin America this percentage is higher. For example, the amount of by-products produced for an artichoke is about 50-60% of the original weight, and for an orange - about 60% [17] [18].

Agricultural by-products such as fruit and vegetable pomace and grain bran contain bioactive compounds that can act as free radical and antioxidant scavengers as well as health-promoting agents. Formative by-products also include substances such as phenol, catechin, epicatechin, anthraquinones, as well as essential oils. Methods involving their extraction using organic solvents such as methanol, ethanol, and acetone have been used to recover these substances. However, these methods are harmful to human health and the environment, as the process uses a large amount of organic solvents, and the methods are time-consuming. Therefore, alternative methods that are effective, cost-effective, environmentally friendly, safe

and fast are being studied and sought to reduce the disadvantages of using organic solvents [19]. Therefore, in this article, the most popular extraction methods have been collected, with both the advantages and disadvantages of their use, as well as the principle of operation of the methods themselves and the type of solvent (environmentally friendly or unfriendly) required. The research conducted in recent years reveals the possibilities of using by-products in the production of products with high value added, however, there are also various disadvantages, such as the lack of appropriate methods for the extraction of these compounds. New extraction methods are emerging and being used from time to time to optimize the extraction of bioactive compounds from byproducts. However, given that progress has been made in this area, research has not been renewed in recent years, despite significant advances in extraction methods. Solvents also play an important role in many chemical and chemical engineering unit operations. Solvents usually need to be used for a limited period of time during the process, as they are most often intended as a solvent, diluent, dispersant or extractant, and then must be separated from the sample [9]. The correct choice of solvent is important and several methods of solvent selection have been developed. Many years ago, choosing the most suitable solvent was purely empirical and was done through error experiments or trials. This approach to solvent selection generally follows the alchemist principle of *similia similibus solventur* [20]. Green extraction methods, which do not cause pollution and use environmentally friendly solvents in their processes, are becoming more and more popular. For example, pressurized liquid extraction and supercritical CO₂ extraction use heat in combination with other parameters to improve the extraction result. Several other non-thermal approaches are also available, such as pulsed electric field extraction and ultrasound extraction, which can be particularly effective for thermally stable compounds. Microwave extraction method is also used to improve the extraction of biologically active compounds of plant origin [21] [22].

By-products are increasingly being used in various industries. As, for example, there are currently no production processes in the pharmaceutical, perfumery, cosmetic, food ingredient, biofuel, or chemical industries that do not use solvents in the extraction process, such as maceration, percolation, steam or hydrodistillation, decoction and infusion. Mainly, the latest trends in extraction methods are focused on finding solutions that replace or reduce the use of petroleum solvents. This should be achieved by ensuring that the quality of the extract does not decrease and that there is less impact on the environment. The article combined the more commonly used extraction methods. The extraction methods reviewed indicated their advantages and disadvantages, the products obtained by these methods, and the extracts that can be obtained by extracting specific products.

A detailed analysis of extraction methods allows for the identification and selection of the most efficient and sustainable technologies for processing bioresources. This step is crucial in optimizing the use of agricultural raw materials and side-streams, ensuring that valuable compounds are not lost but instead converted into high-value products. The effectiveness of these technologies directly influences the economic and environmental viability of bioresource utilization within the framework of the bioeconomy. Moreover, such a methodological approach plays a vital role in the ongoing transformation of the agricultural sector towards higher value-added production. By integrating advanced extraction techniques into agricultural

processing chains, it becomes possible to enhance resource efficiency, diversify income streams for farmers and producers, and reduce environmental burdens.

In this context, the TIMES modeling approach provides a powerful analytical tool for evaluating different technological scenarios and policy impacts. TIMES enables the assessment of long-term strategies for resource allocation, emission reductions, and energy optimization, thereby supporting informed decision-making in the transition to a more sustainable and circular agricultural economy. The following chapter build upon this foundation by exploring how the integration of efficient extraction methods and system modeling tools can contribute to the creation of robust, future-oriented bioeconomy strategies.

1.3. TIMES model for bioeconomy development

Bioeconomy and bioresource value

The bioeconomy concept has lately become a more prominent topic in science and policy. In 2012, the European Commission, within a strategy called “Innovating for Sustainable Growth: A Bioeconomy for Europe,” defined the bioeconomy concept [23]. The strategy defines that bioeconomy is based, first of all, on using renewable biomass by using not only raw material but also biomass residues and, second of all, producing a wide range of high-added value products and energy. Production of high-added value products means that, at first, biomass is used to produce high-added value products like pharmaceuticals and chemicals, and then residues are used for the production of lower-added value products. Therefore, the main aim of bioeconomy is to use bioresources as fully as possible and reduce waste [24].

In Latvia, innovative approaches for the efficient and sustainable exploitation of natural resources are developed and introduced in the bioeconomy industries in order to stimulate the growth of the national economy, provide higher value-added, and promote exports and employment. This shall be achieved while simultaneously balancing economic interests with ensuring environmental quality and preserving and enhancing biodiversity [25]. The successful development of a bioeconomy based on the production of higher value-added products from bio-resources depends on the direction of policy strategies [26].

Latvia is a small country with a limited domestic market and limited resources. Economic growth and wellbeing in Latvia directly depend on its foreign trade, investment, capability to compete and produce high value-added products [27]. The current relevance of the use of biomass in the energy sector compared to other higher value-added products (e.g. composites, fine chemicals and biomedicines) highlights the need for an interdisciplinary assessment of the added value of bio-resources from various sources such as agriculture in to the circular economy [28].

Agriculture sector of Latvia

About one-third of agricultural land in Latvia is used for crop cultivation, and about one-tenth is dedicated to pasture for livestock. Of the crops, grain (mainly rye) is the most important. Cereals account for the largest share of agricultural production (around 30% of total final

agricultural production) [29]. Potatoes, onions, carrots, and sugar beets are the main crops produced for export [30]. The role of two major sectors is becoming stronger with every passing year – cereal production and milk production [31].

In the last 20 years, the sector of agriculture was affected by sharp political changes: in the 90s of the last century, Latvia's land management structure changed fundamentally, the collapse of the collective farm system started, resulting in the emergence of private farms [32]. In the meantime, they dominated in the sector, and a proportion of household plots increased. Whereas in 2004, Latvia acceded to the EU. Upon accession, Latvia transposed its basic legislation and adjusted to EU principles. Therefore, the development of Latvia's agriculture, to a large extent, is associated with the future of the EU Common Agricultural Policy (CAP). CAP objective is ensuring a stable income for farmers and at the same time facilitating production of high-quality products in accordance with the market demands as well as encouraging farmers to seek new development opportunities by diversifying types of activities [31], [33].

To analyze data in the TIMES model (2015 - 2019), it was necessary to conduct a study of the agricultural sector up to 2015. TIMES is an optimization model and it is also possible to adapt it to newer data.

In agriculture, in general and in plant production, in particular one of the major sectors is production of cereals. Providing the country with a sufficient amount of cereals contributes to strengthening of its independence. Production of cereals is particularly important for animal husbandry as neither branch of animal husbandry can exist without cereals. Particularly important production of cereals is for pig breeding and poultry farming. The year 2013 was the second distinguished year after 2012 for cereal producers. In 2013, the total yield of cereals was 175.8 thousand tonnes less than in 2012, reaching 1948.7 thousand tonnes. Total of 32.6% of agriculture areas are accounted for cereals cultivation with the yield of least 4 t per ha. Lately, cereals are used not only for animal husbandry and food production but also in production of alternative energy, including heat production [34].

In 2013, oilseed rape sown area increased (9.1%) however, as compared with a successful 2012, an average productiveness of oilseed rape has dropped. Thanks to enlargement of sown areas, the total yield has stayed on the level of the previous year. Basically, cereal production farms are engaged in growing of oilseed rapes because soil cultivation technologies, cereal sowing and harvesting machinery is similar to that needed for oilseed rape. However, there is a certain risk, as crop rotation on these farms goes between two crops – oilseed rape and wheat, and oilseed rape is being sown on one and the same field every second year or every 2-3 years, at best. This can lead to a situation that in a long run, oilseed rape can be affected by clubroot, resulting in a sharp reduction in yields. It is forecasted that next summer, spring oilseed rape areas could reduce considerably due to the Commission's decision to ban the use of some pesticides and treating oilseed rape with mordant [34].

The entire territory of Latvia is suitable for growing of vegetables but specialization of farms in horticulture is determined by location of markets, mainly closeness to towns and cities [35]. Horticulture farms are mainly situated in Riga neighborhood and Zemgale region. In 2013, Latvia's vegetable area, as compared with 2012, increased by 5%. Field areas increased

by 5% but covered areas reduced by 15%. Although, covered area has reduced, but the total yield of vegetables in covered area increased by 7% in 2013 as compared with 2012. It is due to introduction of new technologies in production of vegetables in covered areas resulting in higher vegetable yields. 98% of covered areas are under tomatoes and cucumbers, leaving only 2% to the rest of covered area species [34].

In 2017, compared to 2016, agricultural output at constant prices rose by 2.0 % (output of crop products by 1.5 %). The increase in agricultural output was mainly influenced by the rise in prices of grain [36]. In 2018, compared to 2017, agricultural output at constant prices fell by 11.2 %, the output of crop products – by 20.6 %. In 2019, compared to 2018, agricultural output at constant prices rose by 20.2 %. The rise was due to the increase in output of crop products (of 42.7 %) caused by the upturn in harvested production of grain (of 53.8 %) [37].

At the end of 2019, in Latvia, there were 75.8 thousand agricultural holdings, the average size whereof constituted 38.3 ha – 8.8 ha or 30 % more than in 2010. The agricultural area on average per holding increased from 19.6 ha in 2010 to 26.0 ha in 2019. Over the period, the total utilised agricultural area in the country grew by 153.9 thousand ha or 8.5 %, reaching 1 959.4 thousand ha in 2019 [37].

Bio-economic models

There is a growing interest in interdisciplinary bio-economic modelling, to provide information to policy makers and to help improve management decisions [38]. A large number of bio-economic models has been developed for different farming systems and agro-ecological conditions. Such models may link biophysical and economic models, [39] but their individual components are typically developed from a single-disciplinary perspective (e.g. economics or agronomy). Bio-economic models tend to be limited in their level of integration, and often involve limited genuinely interdisciplinary teamwork. There have been increasing calls for bio-economic models that focus more on integrating knowledge at conceptual as well as technical implementation levels [38]. This section gives a review of literature on methods used in bio-economic models and assessment frameworks.

Multi-criteria decision analysis (MCDA) is a valuable tool for decision-making in complex process systems, using a number of parameters that influence embedded processes in the value chain [40]. These parameters can be assessed by different actors in the chain as “significant factors”. In addition, by including this flexibility in the scope of this assessment, the MCDA ensures systematic investigation and transparency in its decision-making. The overall aim of the MCDA is to provide an opportunity to explore the knowledge and concerns raised by actors in the chain, to weigh them from an objective point of view, to systematically analyze them, to set key criteria and then to take decisions in complex multi-stakeholder process systems [41].

Studies are being carried out to use two-tier MCDAs to rank biological value chains based on a set of selection criteria, emphasizing the importance of respecting the principles of their circular economy. The results of the analysis highlight the importance of these selection criteria to highlight the features of any bio-based value chain / business model [42]

A mapping methodology has been developed to understand the strengths, weaknesses, opportunities and challenges inherent in the biological value chain associated with the synthesis of different bioproducts, and demonstrates the importance of bottom-up processes and material use in downstream activities (mainly post-consumption and end-of-life management). Different biological value chains have been identified in the EU. This list of tentative value chains is based on a review of the literature above, focusing on the biological value chains / products covered by the EU certification schemes and market demand [43]. The list includes organically produced value chains with (but not limited to) a variety of characteristics, including:

- From virgin food-based feedstock to bio-waste cascading;
- 100% bio-based to partially bio-based, value chains;
- Those with a fully-functional waste management infrastructure to those that lack one;
- Diverse product functionality [44].

A recognized methodology known as GE-McKinsey Matrix [45] uses nine modules or boxes to identify aspects of the potential new bioproducts market. The methodology has been developed and tested on three existing products. The calculations combine economic data and data on technology, as well as data on product competitiveness and market data. The data analysis is based on aggregated data from information sources and is presented in two dimensions - market attractiveness and product competitive advantage. The method provides the results to allow to make recommendations for further evaluation of the production of new products in the current location or in a country where local resources are available [46].

The methodology for the GE-McKinsey Matrix can be modified to include considerations and constraints such as environmental protection, required in the manufacturing process and product sustainability [47]. Instead of the competitive position of the company, it shows the competitive attractiveness of a particular product. After obtaining results, it is possible to gain insight into market opportunities for the product. The GE-McKinsey Matrix is widely used for product portfolio management and in the analysis of competitive scenarios [48]. A similar analysis can be made using the Boston Consulting Group matrix [49], however, the GE-McKinsey Matrix can provide a broader range of factors, while the Boston Consulting Group matrix was found not to be sufficiently flexible and complexity issues are reported [50].

Life cycle analysis (LCA) is a well standardized methodology that can be applied for bioeconomy studies [51]. The LCA selects and analyzes a list of key bioeconomic value chains for each pillar to identify existing and potential biomass conversion technologies and assess their environmental performance. The criteria for selecting value chains are: relevance in the global market, representativeness and / or suitability for competition with similar products of fossil origin [52].

Few studies with application of Socio-economic analysis (SEA) [53] for biorefineries have been found in the literature. Socio-economic performance in the production of various bioenergy products is divided into categories, mainly for positive, neutral or negative effects. In the study of [40] a rural biorefinery was assessed for the development of the territorial integration of economic activities in the region based on the socio-economic framework. In addition, a social life cycle assessment (SLCA) is included as one of the criteria for examining the social dimension of a rural biorefinery [54].

A specific bio-economic model called SYNERGY (cross-Scale model using complementarity between livestock and crop farms to enhance regional nitrogen self-sufficiency) is a static non-linear programming model, which maximizes regional profit under constraints is introduced in study of [55]. It is calibrated to starting conditions using Positive Mathematical Programming. SYNERGY is applied to a particular area called “region” that is divided into several “sectors” to consider a variety of soil and climate conditions. SYNERGY's main originality lies in its ability to represent farm-to-farm exchanges of intermediate products (manure and crops), which occur on a local market (i.e., intra-sector or intra-region). It generates four types of indicators: (1) structural (e.g., crop areas, numbers of animals), (2) technical (e.g., protein self-sufficiency, application of N fertilizers) (3) economic (e.g., regional profit, farm income, farm-to-farm exchanges) and (4) environmental (i.e., N efficiency and potential losses of N). These outputs are provided for each farm type at the sector and regional levels [56].

Another modelling framework MOSAICA can be used for optimising individual farmer's utilities at the regional scale, considering the expected farm revenue and the risk aversion towards price and yield variations [57]. The inputs of the model are: (1) the geographic database of fields, which contains information about the biophysical context and farm structure (e.g., farm size and land tenure); (2) the database of activities, which describes cropping systems and technical-economic coefficients that can be allocated to fields; and (3) the farm typology and the classification algorithm for the eight farm types.

The allocation of cropping systems is modeled through a set of equations that represent farmers' choices of cropping systems at different scales, namely the field, farm, sub-regional, and regional scales. Optimization is performed at the regional scale, as equations introduced at this level limit the total production of some crops due to market size or production quotas. The model results provide estimates of the sustainability range of the trimming system [58].

The SEAMLESS-Integrated Framework (SEAMLESS-IF) aims to assess the impact of agricultural and environmental policies on agricultural systems and sustainability indicators [59]. Integrated evaluation requires that the policy issues addressed by SEAMLESS-IF be translated into scenarios assessed using a set of key economic, environmental, social and institutional indicators. To model key aspects of farming systems from the field to the farm scale, SEAMLESS-IF provides an intelligent combination of crop production system model, bioeconomy farm model and indicators. This modeling chain can be used to identify which farm locations and agro-ecological technologies will be preferred in the implementation of the research policies and agro-ecological technologies and to model their impact [60].

The cropping system model CropSyst [61] can be used to quantify the relationship between crop production and environmental effects at field scale, as the cropping system component of SEAMLESS-IF [62]. CropSyst implements modules capable of simulating crop response to a wide range of weather, soil and management conditions using daily time steps, for periods ranging from one year to a hundred years. CropSyst is a multi-year, multi-crop, daily time step cropping system model. It can simulate the soil water budget, soil–plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate. Crops are simulated using a

generic crop simulator, in which some processes (e.g. photoperiod response, vernalization) can be switched on or off using appropriate parameter values. CropSyst simulates plant growth as potential growth and under water, nitrogen, and temperature stresses [60].

A bio-economic farm model, “MEETA” (Modelling Energy and Emissions Trade-offs in Agriculture) [63]. The objective of the MEETA model is to capture trade-offs between different aspects of the farm system – those that are not captured by the LCA analysis [46]. The MEETA model is a linear programming optimisation model that represents multi-year cropping within a single year framework, based on combinable crops common to cereal farms. Output from crops is a product of straw and grain at representative market values; the model maximises the gross margin between total output and variable costs of seeds, fertilisers and sprays, contract costs and fuel costs. Energy inputs and outputs and emissions data are associated with the main inputs and outputs using secondary data and LCA literature. The major constraints in the model are farm size, crop rotations and availability of on-farm machinery for some operations. The model can optimise for either (maximised) farm gross margin, net farm energy or (minimised) GHG emissions, and produces the optimal crop mix, associated machinery and contract use and the farm gross margin, net energy and GHG emissions for each optimal crop mix [64]. The model structure allows trade-offs between energy, emissions and financial performance to be quantified with a specific focus on bioenergy production. The MEETA model focuses on farm level trade-offs and hence the upper model boundary includes everything that is used on farm, up to the point of sale at the farm gate. The following sections provide more detail on the levels of complexity and boundaries for specific parts of the model [64].

Lastly, the TIMES model [65] is bottom-up, linear programming tool applied for long-term energy systems planning allowing to analyse effect of different scenarios. It optimises the whole energy system including supply and demand services by minimizing the total cost in the considered modelling period [66]. The Irish TIMES model is an energy system model that was developed by University College Cork (UCC) in collaboration with the Economic and Social Research Institute (ESRI), Energy Engineering Economic Environment Systems Modelling Analysis (E4SMA) and KanORS over the period March 2009–November 2011. The Irish TIMES is a model that analyses energy usage, emissions, and natural resources and was extracted from the Pan European TIMES (PET) model of Europe, and was then updated and expanded using local and more detailed data and assumptions [66].

Considering the available methods, it was concluded that it was necessary to develop a new model. TIMES for Agricultural sector is developed with the aim to model bioresource flows and technologies for bioeconomy development and bioresource value-added growth to 2030. In particular, addressing the development of biorefineries from perspectives of natural boundaries for resource utilization capacity, economic feasibility in terms of cost of technologies and their operation and maintenance, and socio-economic aspect as an added value in terms of salaries and indirect taxes [67].

It is important to point out that it is important not only to analyze value-added products in the model, but also to develop them in laboratory conditions, such as using by-products from agricultural processes to produce thermal insulation material.

1.4. Production of mycelial materials from agricultural by-products

The construction industry has come under considerable pressure over the last decade as the supply of traditional building materials such as cement, brick, timber, cladding and partition materials has struggled to cope with increasing demand. Production of these conventional building materials consumes energy, limited natural resources and pollutes air, land and water. Up to 36% of the lifetime energy consumption of a typical dwelling can be attributed to harvesting or extraction of primary materials as well as other production processes, transport and construction of a building. Low-energy buildings, although using less energy, have even larger environmental impact in the construction phase (up to 46% of residential energy demand can be attributed to the building construction) due to increased heat insulation, higher density materials and additional technologies used [68].

The material that provides structural performance with minimal environmental impact is mycelium-based biocomposites [69]. Mycelium composites are a new type of novel, economical, and environmentally sustainable materials that have attracted increasing academic and commercial interests over the past decade. Mycelium is the vegetative growth of filamentous fungi that bonds organic matter through a network of hyphal microfilaments in a natural biological process that can be exploited to produce composite materials [68].

Mycelium composites have customizable material properties due to their composition and manufacturing process, and they can replace foam, wood and plastics for such applications as insulation, panels, floors and furniture. The material has low thermal conductivity, high acoustic absorption and fire safety properties that surpass traditional building materials such as synthetic foam. However, there are limitations, such as mechanical properties, water absorption and other properties, which must be assessed when the composite is used in building materials. Nevertheless, the useful material properties, in addition to low cost, ease of manufacture and environmental sustainability suggest that they will play an important role in the future of environmentally friendly construction [68]. Many natural materials have fiber architecture. Examples are many, including silk spider webs, bone, plant stems such as bamboo, connective tissue. The design of these natural materials has inspired researchers to imitate such synthetic architectural materials, although this has proven to be a difficult task in many cases. A new approach to this problem is designed engineering components, obtained by direct growing of a natural material in the desired form. Such components inherit microstructure and properties of the base materials [70]. Compared to synthetic composites, a composite made from mycelium and other natural materials yields a low-density material with high strength and an opportunity for lowered embodied energy. Furthermore, the inclusion of a natural cellulosic textile for reinforcement allows for reuse of an otherwise-waste material and expands the composite's end of life options [71].

Mycelium has the unique ability to form composite materials quickly and easily [71]. From the perspective of a raw fiber resource, fungi can beat lignocellulosic textiles in terms of energy and physical properties [72]. Due to its unique structure and composition, it may be possible to produce large quantities of mycelium-based materials [73]. Mycelium "acts like a natural, self-assembling glue that digests and binds securely to natural reinforcement materials and agricultural byproducts

with essentially no added energy". Growing mycelium around other natural materials is a sustainable and efficient way to generate various products, as outlined below [71]. In the production of mycelium, it is necessary to completely stop the growth of the fungus before the substrate (such as straw or sawdust) is completely degraded. In this case, the organic fibers or particles of the hypha compound together, thus colonizing the substrates. Fungal growth can be stopped by drying and / or heating the colonized substrate. Heating destroys the fungus, but drying keeps the fungus in the "winter" state [74].

Some recent studies have shown the competitiveness of foam-like mycelium-based composites compared to conventional materials such as expanded polystyrene (EPS) or other foams, or other bio-based composites such as hemp concrete. In general, mycelium-based materials have proven their potential to replace the use of less environmentally friendly materials, such as bioplastics or wood composites [75]. The composite is an environmentally responsible alternative to EPS and other plastics. The material competes directly with petrochemical foams in terms of performance, cost and with low embodied-energy [76]. The whole production process is considered to be an environmentally friendly waste stream due to valorisation, thus preventing the destruction of ecosystems and obtaining resources [77]. Mycelium materials consist entirely of renewable materials and require very little energy to process. Therefore, they are definitely a part of the circular economy model [78]. Due to its unique structure and composition, we anticipate the production of large quantities of mycelium-based materials. To date, mycelium has been used mainly by a US company using raw biomass glued to mycelium, resulting in foaming structures, but there is still much room for improvement and further development of mycelium-based materials [79].

The value chain of forest bio-products can be divided into several groups of activities. Production, collection, processing, storage, transport, marketing and sales are key activities in the forest product value chain, using value-added bio-based products that reach their target customers [13].

Different applications of building materials can have different areas of problems. The main concern for internal insulation materials is a transfer of moisture between the interfaces of insulation and structural materials, as the largest temperature gradient occurs at the interfaces. Condensed liquid can cause swelling and shrinkage of insulation materials or even significant reduction of insulating properties [14]. Only a few research centers and companies around the world have the knowledge and capacity to produce mycelium-related materials for the building and construction industry. Studies on the use of mycelial composites as structural elements date back to 2009, when *Ganoderma lucidum* and sawdust were used to create the tea house [80].

In the figure 1.3. shows the product development steps from materials to the energy efficient building. A new material with good technical properties is not yet ready for the market, but suitable products need to be developed. If the products do not fit into existing building systems, new systems are required for proper integration with the entire building. This requires both technical development and improved know-how in the production process, design, installation, analysis of overall performance, etc. However, radical leaps in innovation can significantly accelerate the emergence of new solutions on the market [81].

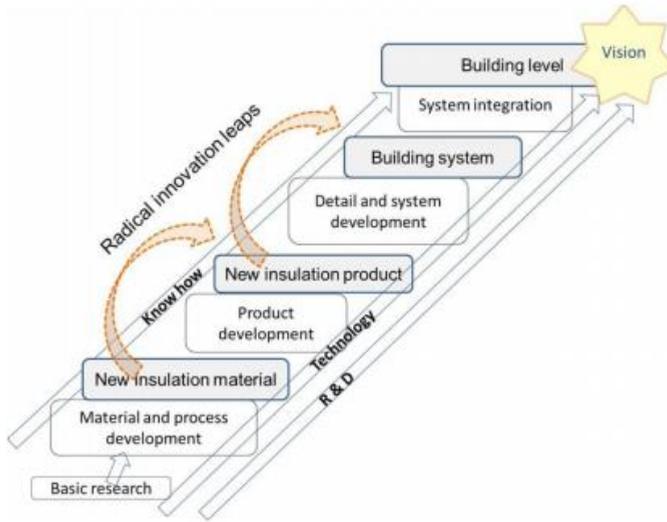


Fig. 1.3. Product development stages from materials to the level of energy efficient building [81].

Table 1.1

Properties of Conventional Insulation Materials [82]

Material	Density	Thermal conductivity	Specific heat capacity	Water vapor diffusion resistance factor	Cost	Embodied energy	Embodied carbon
Unit	[kg/m ³]	[W·m ⁻¹ ·K ⁻¹]	[J/g·°C]	[-]	[USD/m ³]	[MJ/kg]	[kg CO _{2,eq} /kg]
Plant-based							
hemp	25-100	0,039-0,123	1,7-1,8	1-10	15-19,4	18,71	0,14
flax	20-100	0,033-0,09	1,6	1-5,28	15,18	39,5	20
rice husk	130-170	0,048-0,08	1,2-2,7	2	5	1,36	0,6

Table 1.1 (continued)							
wood fiber	50-270	0,038-0,05	1,9-2,1	1-5	26,6-37,8	20,3	0,124
Inorganic (fibrous & foam)							
glass wool	10-100	0,03-0,05	0,8-1	1-1,3	9,3-14,7	14-30,8	1,24
rock wool	40-200	0,033-0,04	0,8-1	1-1,3	12-20	16,8	1,05
Synthetic foams							
EPS	18-50	0,029-0,041	1,25	20-100	8,6-17	80,8-127	6,3-7,3
XPS	32-40	0,032-0,037	1,45-1,7	80-170	18-23	72,8-105	7,55
Polyuret hane	30-160	0,022-0,035	1,3-1,45	50-100	24.91	74-140,4	5,9
Phenolic foam	40-160	0,018-0,024	1,3-1,4	35	23	13-159	4,15-7,21

As shown in Table 1.1, plant-based insulation materials (i.e. hemp, flax, rice husk, wood fibers) have competitive thermal conductivity and possibly lower costs compared to inorganic and synthetic insulation materials. From an environmental point of view, plant-based materials have significantly lower embodied energy and carbon than fossil-based materials [82]. In addition, when designing building envelopes, thermal insulation materials with a higher specific heat output ($\text{kJ} / \text{m}^3\text{K}$), such as plant-based insulation materials, can store the maximum solar radiation that absorbs the building facades and reduce the maximum cooling loads by delaying the maximum indoor temperature. caused by solar radiation during the summer [83].

The Global Sustainable Development Strategy implies the reduction of non-renewable materials by replacing them with bio-based materials. In addition to biological materials, such as bioplastics, bacteria, algae or fungi materials are increasingly being used as innovative bio-based alternatives [73].

Analysis of scientific articles shows that so far, only bog-type fungal materials have been analyzed and used; therefore, within this study, the use of mold fungal in the production of thermal insulation materials was studied. Although molds were considered harmful to human health, not all of them have an adverse effect on the human body, as the experimental fungal are used in the production of fertilizer, as well as the growth of fungal hyphae is stopped and neutralized during the drying process. Drying of the material is necessary because by removing

moisture from the material, the spores of the fungus are no longer able to absorb nutrients and multiply, and are therefore neutralized by returning to a previous safe state. Fungal spores never really “die” because they can always start to multiply again later when new moisture becomes available. Therefore, the mycelium material must be provided with a coating that prevents the formation of moisture in the material, as well as preventing the mold from “reviving” and continuing to grow. Mold can grow in the temperature of ~ 25-30 ° C, as well as provide 90-100% relative humidity in the room. Given these factors, it is possible to avoid the “revival” and the growth of the fungus.

2. METHODOLOGY

To achieve the research objective, several scientific approaches and methods were used. This chapter describes in detail the methodology for GHG emissions analysis, the use of the TIMES model for assessing the bioeconomy potential, the development of a natural thermal insulation material, and the use of a system dynamics model for comparing the developed materials with synthetic materials.

2.1. Greenhouse gas emissions analysis methodology

The agricultural sector is a significant source of GHG emissions in the EU; therefore, accurate and comparative emission analysis methods are necessary to understand the intensity of these emissions and propose solutions to reduce them.

The amounts of GHG emissions in the agricultural sector for all countries of the EU [84], the total population [85], and the country's GDP per capita [86] were analyzed. The calculation of GHG emissions per GDP and population often uses methodological approaches of normalization and comparison. In this process, GHG emissions are expressed as emissions per capita or per unit of GDP.

The approach used for the analysis involves normalizing emissions by population and economic output. This method takes into account the population size and economic potential of different countries, ensuring that these factors do not disproportionately affect the emissions data.

The emissions per capita indicator is calculated by dividing the total agricultural GHG emissions by the total population of each country. By normalizing emissions indicators in this way, the analysis takes into account the population size, making it easier to compare how agricultural emissions relate to the population of each country. Higher emissions per capita indicate a higher agricultural emissions intensity in a country relative to the population.

$$\text{Emissions per population, t CO}_2 \text{ eq} = \text{emissions} / \text{population} \quad (2.1)$$

The emissions per GDP value is obtained by dividing total agricultural emissions by each country's GDP to get a clearer picture of the emissions intensity in relation to the size of their economic output. This calculation shows which countries have higher or lower emissions compared to the size of their economies. It allows us to assess the effectiveness of countries' agricultural sectors in managing emissions in relation to their economic productivity.

$$\text{Emissions per GDP, t CO}_2 \text{ eq/million EUR} = \text{emissions} / \text{GDP} \quad (2.2)$$

The emissions per GDP per capita indicator is obtained by dividing GHG emissions by both GDP and population. It provides a more detailed view of emissions in relation to both the volume of economic output and the individual contribution of residents to the economy. This

method reflects the environmental and economic efficiency of the agricultural sector in different countries, allowing for nuanced comparisons across the EU.

$$\text{Emissions per GDP per Capita, kt CO}_2 \text{ eq/EUR} = \text{emissions} / \text{population} \quad (2.3)$$

Overall, agriculture accounts for around 10–12 % of the EU's total GHG emissions, and this can vary by country, agricultural practices, and policies. For example, more intensive agriculture, such as livestock and industrial farming, can lead to higher levels of emissions [87].

The EU has introduced various policy initiatives to reduce emissions from agriculture and promote more sustainable practices. Examples are the Common Agricultural Policy [88] and the Green Deal [89], which aim to promote environmental and climate goals in agriculture. In addition, research and technological development, such as more efficient fertilization methods or technologies to reduce methane emissions, can be important factors in reducing emissions in the agricultural sector in the EU. EU countries were compared, and each country's agricultural emissions in 2022 were compared. Calculation data are given in in Table 2.1.

Table 2.1

Input Data

Country	Population [90]	Emissions, kt CO ₂ eq [91]	GDP, million EUR [92]
Austria	8956000	7276	405397
Belgium	11590000	9149	508280
Bulgaria	6878000	2808	71084
Coratia	3879000	2467	58428
Czechia	10510000	8422	238434
Denmark	5857000	11522	343146
Estonia	1331000	1593	31457
Finland	5541000	6074	251013
France	67760000	63645	2502864
Germany	83200000	53348	3618929
Greece	10570000	7980	181579
Hungary	9710000	6212	154013
Ireland	5033000	22436	434212
Italy	59130000	30763	1822906
Latvia	1884000	2253	33352
Lithuania	2801000	4058	56501
Luxemburg	640064	665	72387
Malta	518536	86	15298
Netherlands	17530000	18039	870750

			Table 2.1 (continued)
Poland	37750000	33296	576326
Portugal	10360000	6941	216093
Romania	19120000	17987	241712
Slovakia	5447000	1934	100287
Slovenia	2108000	1706	52295
Spain	47420000	34863	1222840
Sweden	10420000	6513	541288

In addition to the analysis of GHG emissions, the study focuses on the use of agricultural by-products, which could reduce emissions and promote more sustainable resource use. In the agricultural sector (crop production), it is essential to analyze the largest product flows in order to be able to identify priority by-products for further use. Therefore, it is valuable to use a bioeconomy model TIMES to search for the best value-added products that can be obtained from agricultural by-products.

2.2. TIMES model

The TIMES model is a linear programming tool that helps to develop sustainable strategies for the development of the bioeconomy. This section analyzes the application of the TIMES model to the agricultural sector, focusing on reducing emissions and increasing economic value.

TIMES is a linear programming model used in long-term planning and optimization of energy systems. This model calculates the balance of energy demand and supply, minimizing the total cost over a given period of time. TIMES includes various components of energy production and consumption technologies and analyzes scenarios based on resource flows and technological capabilities.

In the Doctoral Thesis, the TIMES model is adapted to the Latvian agricultural sector to model the flows of bioresources and technologies for the development of the bioeconomy until 2030. Several scenarios are analyzed, including the baseline scenario and alternative scenarios with the introduction of new technologies and the production of value-added products, for example, the introduction of bioplastics, fiber powder and second-generation biofuels.

Modelling approach

The added value of resources varies depending on the purpose for which they are used, for example, for the production of energy or materials. Historically, the move towards a bioeconomy began with a strong emphasis on bioenergy. Currently, the bioeconomy is moving towards a more progressive use of bioresources for various technologies and material extraction. Therefore, a topical issue for policy planners, decision-makers and other stakeholders is finding optimal resource use scenarios with the highest added value. Taking the above into account, the developed tool aims to increase the added value of agricultural bioresources at the national level by at least 30 % by 2030 by introducing new technologies. In

the TIMES model, the added value of products is calculated by dividing the total value of the product by the volume produced. One of the most recognized methods in the field of energy use of energy resources obtained from bioresources is TIMES. In this study, the TIMES modelling approach has been selected and adapted to the Latvian agricultural sector. TIMES Agricultural Bioresource Value Model is designed to model bioresource flows and technologies for the development of the bioeconomy and the growth of bioresource added value by 2030. The chosen approach is based on investment and technology performance, resource flow and optimization of final demand costs. Historical demand for crop products is taken from the FAOSTAT database, while demand for 2030 is calculated based on future population changes in Latvia. In this way, TIMES allows for the assessment of optimal scenarios for the use of bioresources in energy and in biorefineries for the production of higher value-added products. The development of biorefineries can be viewed by assessing the natural limits of resource utilization capacity, the economic feasibility of technologies and their operation and maintenance costs, and socio-economic aspects in terms of wages and indirect taxes. The proof of concept and hypothesis of the model are tested using a case study of the Latvian crop sector.

Model boundaries and scenarios

The model boundaries are defined based on the TIMES model component classification, structuring the analysis according to commodities and technologies interconnected through material flows.

In this context, commodities are defined as biomass carriers, materials, or products that are treated within the model as inputs (raw materials) or outputs (products) of technological processes. Commodity flows represent the movement of materials through various transformation stages and their conversion into other commodities. In the analysed case, the flows consist of biomass quantified in mass units. Within production processes, raw materials are transformed into new materials or products, such as foodstuffs or energy resources.

The technology component encompasses processes that implement the conversion of commodities and is classified into two main categories:

1. primary production processes, which include the extraction of biomass (including imports);
2. transformation processes, which involve the processing of raw materials, biorefining, and final product manufacturing.

In the model, the final consumption of commodities is determined by end-sector demand, which is interpreted as the outcome of transformation activities, structuring the direction of resource flows and influencing the allocation of technological processes within the model.

The TIMES model precisely defines the production boundaries for specific types of bioresources – grains, vegetables, and oil crops (based on cultivation and harvesting outputs) – as well as for different types of products, including food (both fresh and thermally processed), feed, and alternative fuel products (bioethanol and biodiesel). These commodities and their associated material flows are linked to the corresponding transformation technologies, ensuring a comprehensive analysis of resource utilization and flow dynamics (Fig. 2.1).

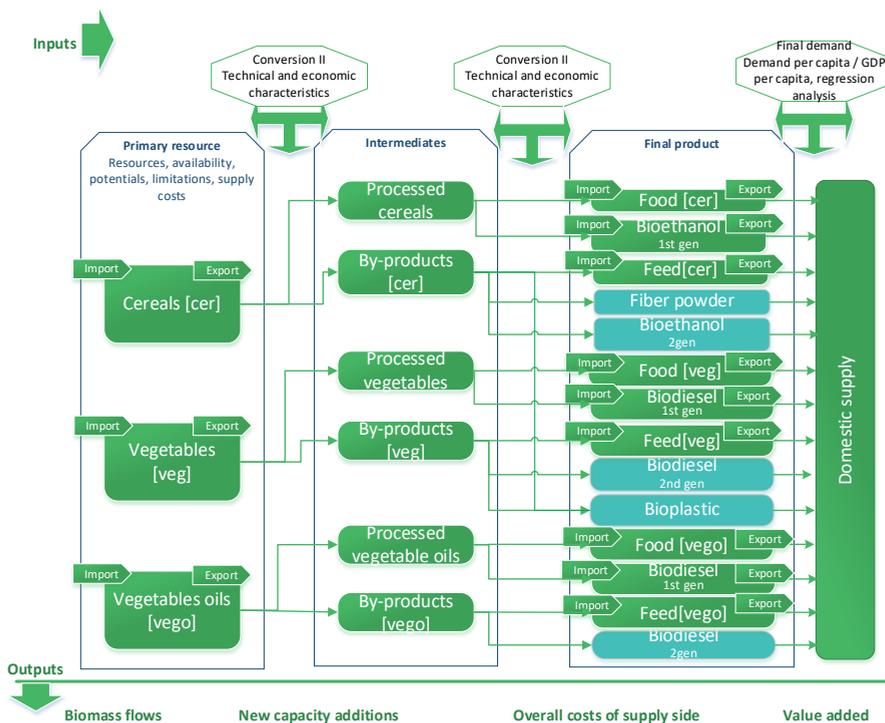


Fig. 2.1. Defined model boundaries for TIMES.

The definition of flows linking commodities and technologies is based on the current Latvian crop sector, where the main source of crop products is locally grown products. Crop products, such as cereals, vegetables and vegetable oils, are used to produce food, feed and other products (biofuels). Cereals, vegetables and vegetable oils are mainly used for the production of food and also first-generation biofuels. By-products are used for the production of animal feed. The production of new food and non-food products from crop products is considered, including the production of fiber powder from grain bran, the production of bioplastics from vegetable and cereal by-products and the production of second-generation biofuels from cereal, vegetable and vegetable oil by-products.

Based on the available information, it is considered that not all crop products in Latvia are processed into food products, some are used in the production of bioethanol and biodiesel. The grain processing process (milling) generates residues that are not used in food production. By-products of crop processing are used for the production of animal feed. Bread production technologies are used to obtain food from cereals. Technologies used in vegetable processing are related to vegetable preservation and vegetable oil production. The production of bioethanol (grains) and biodiesel (vegetables and oil) was considered from other crop products.

In order to increase the added value of bioresources in the crop sector, four new technologies and the production of value-added products have been introduced in the TIMES model: fiber

powder, bioplastics, biodiesel and bioethanol. In general, the following scenarios have been studied: 1) a baseline scenario without the introduction of new technologies; 2) a separate scenario for each new technology (a total of three new technologies); and 3) a combined scenario for all new technologies. In the scenario for the production of fiber powder from crops, by-products of grain pre-processing – bran – are used to produce a new product. In the scenario for the production of bioplastics from cereals, by-products of grain pre-processing – bran and vegetable residues – are used to produce a new product. The scenario for the new technology is the production of second-generation biofuels (bioethanol and biodiesel). In the bioethanol production scenario, it is assumed that the raw materials are by-products of grain processing or bran and vegetable oil residues.

Data inventory

Data are collected for each commodity included in the TIMES (volume and resources, production of food, feed and other products, imports, exports and costs). Most of the data is obtained from the official statistics portal of Latvia [93], as well as the database of the Food and Agriculture Organization of the United Nations [94].

Historical input data from 2015 to 2019 were used to determine the upper and lower limits of the volume of harvested, imported and exported resources in TIMES. These constraints were observed in the optimization of added value for 2030 in order not to exceed the planned limits for cultivated crop products and to minimize the potential impact of changes in imports and exports on the model results. Input data for the final product or industry demand is determined by a forecast based on changes in the population in 2030 in Latvia.

The model includes data on the relevant processing (capacity, efficiency, investments, operation and maintenance costs, service life and availability, as well as the added value of the product production process). Technological costs are taken from the financial statements of Latvian companies. Data on technological capacities are obtained from the permits for polluting activities of companies. The value added of products was calculated using two databases. The total value added of food, feed and biofuel was obtained from the European Commission database [95]. The source of the volume of food, feed and biofuel produced (thousand t) is the database of the Central Statistical Office of the Republic of Latvia. The value added of food, feed and biofuel was calculated by dividing the total value added by the volume of production.

To define the input data for alternative scenarios, the literature on new technologies in the agricultural sector was analyzed. Availability of new technologies is set to begin in 2025. Products with high added value based on the use of new technologies were considered:

- 1) production of fiber powder from grain processing by-products or bran;
- 2) production of bioplastics from grain bran and plant residues;
- 3) production of second-generation biofuels (bioethanol from grain by-products and biodiesel from vegetable oil by-products).

The TIMES model serves as a basis for developing bioeconomy strategies, while the system dynamics approach allows understanding the impact of these strategies at the system level. This

is especially true for mycelium thermal insulation materials, the production of which from agricultural by-products offers sustainable alternatives to traditional materials.

2.3. Mycelium thermal insulation material

The material was developed in the laboratory of the Institute of Energy Systems and Environment at Riga Technical University. The author independently developed the mycelium-based thermal energy materials in the laboratory. At the beginning of the experiments, nine types of molds were used: *Rhizopus oryzae*, *Aspergillus versicolor*, *Penicillium chrysogenum*, *Cladosporium cladosporioides*, *Cladosporium herbarum*, *Stachybotrys chartarum*, *Trichoderma viride*, *Mucor mucedo*, and *Mucor plumbeus*. Initially, several mold species were tested in order to select a fungus capable of forming a dense hyphal network for further work. The growth rate was also considered an important indicator.

The molds were cultivated on two types of media: PDA (potato dextrose agar) and MEA (malt extract agar). Before inoculating the selected substrate (pine chips), the molds were carefully removed from the solid PDA medium and mixed into a liquid PDA medium. This liquid mass was necessary to ensure that the fungal mycelium could be evenly distributed throughout the substrate.

Initially, mycelium samples were prepared by adding 15 mg of a mixture of fungal spores and potato dextrose to 5 mg of pine chips. However, after drying, it was concluded that adding fungal spores to the surface of the chips did not penetrate the sample and form a bond with the chips, and the samples turned out to be very fragile. The samples were wrapped in foil and placed in a closed plastic container, which contained a container of water, which provided relative humidity.

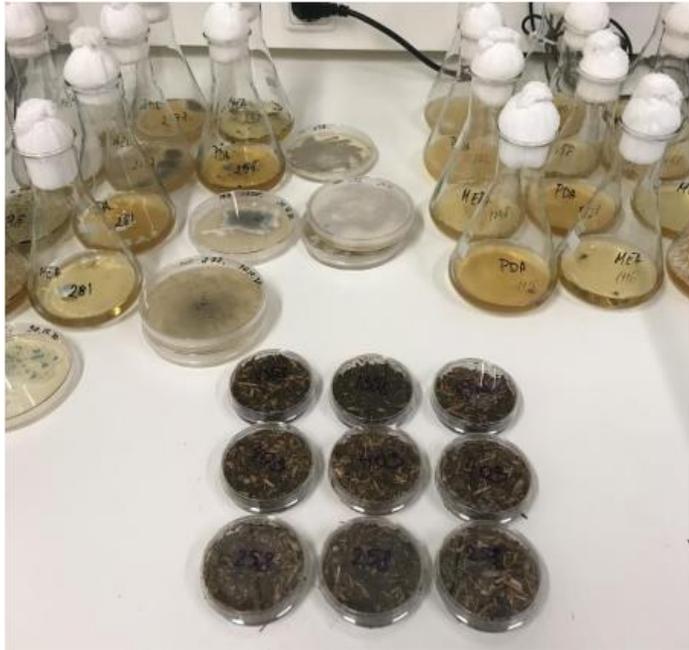


Fig. 2.2. Mycelium samples (weight of each sample: 20 mg).

The next mycelium samples were prepared for cultivation in small plastic dishes, in which 5 mg of pine chips were placed, mixed with 15 mg of fungal mycelium and a mixture of potato dextrose medium. The prepared samples (each separately) were wrapped in foil and placed in a larger plastic container, in which a glass of water was placed to maintain the relative humidity at 100 %. The mycelium samples were grown in the dark and warm (~ 24 °C) conditions.

Following the growth process, it was concluded that one particular fungal species, *Trichoderma viride*, grew significantly faster. Within three days, *Trichoderma viride* formed a thick network in the samples, and the densely grown material became brittle and crumbly after drying.



Fig. 2.3. *Trichoderma viride* spores grown on solid PDA medium.

Considering that several options of mycelium samples had to be made, the fungi were grown in petri dishes on solid PDA medium. During the experiment, they were occasionally subcultured to new plates to ensure the necessary amount of fungal spores for the preparation of mycelium material.

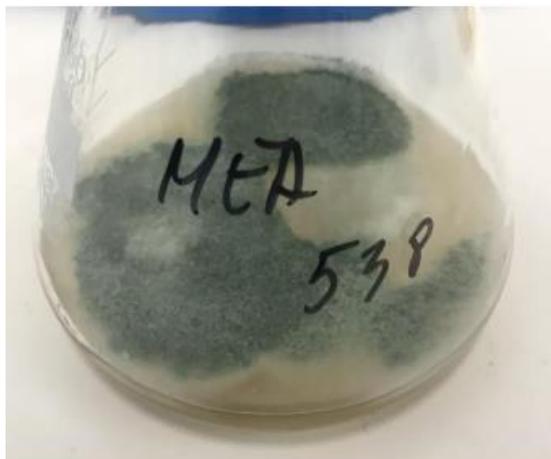


Fig. 2.4. *Trichoderma viride* spores grown on liquid MEA medium.

At the beginning of the experiment, spores were grown on both liquid and solid media; however, as the experiment continued, the fungi were grown only on solid PDA media, on which the approximate growth time of the fungi was four days.



Fig. 2.5. A sample of mycelium prepared from *Trichoderma viride* using only culture medium.

Although the picture shows that the mycelium sample holds together, when you hold this sample in your hands, it crumbles and is very fragile, so a search was made for binders that could make the material more durable. Binders such as xanthan and gluten were considered. Considering that it was not possible to measure the thermal conductivity of the small samples, 20×20 cm samples were prepared.



Fig. 2.6. Mycelium material in 20×20 cm metal molds.

When starting to experimentally create samples, different types of molds were examined, both with a grid and a coating at the bottom of the mold. The coating between the mycelium material and the mold was also different. Initially, cling film was applied; however, during the drying process, the cling film stuck to the mycelium, and other coating materials had to be sought. As the experiment continued, both baking paper and foil were laid; however, baking paper showed the best result after drying, from which the mycelium material separated best without disintegrating. In order for the mycelium material to be more durable, binders and their proportions were sought. During the experiments, different types of binders were examined, such as xanthan, gluten, and starch, so that the mycelium material would be more durable, while at the same time finding a balance between the strength of the material and a low thermal insulation index. Ingredients that help form pores, such as soda, were also added to the material. Nineteen mycelium samples were prepared, and their thermal conductivity was measured.

Table 2.2

Component Distribution of 19 Mycelium Samples

No.	Wood chips, %	Straw, %	Water, %	Xanthan, %	Glycerin, %	Ethanol, %	Gluten, %	Yeast, %	Molasses, %	Sodium carbonate, %	Spores with medium, %	Medium, %	Water, %
S1	24.2	0	3.1	0.2	0	0.1	0	0	0	0	9.8	14.4	48.3
S2	46.7	0	6	0.3	0	0.1	0	0	0	0	18.9	28	0
S3	32.4	11	11.5	0.4	0	0.2	0	0	0	0	18.1	26.3	0
S4	21.9	21.9	11.5	0.4	0	0.2	0	0	0	0	17.8	26.3	0
S5	21.9	21.9	11.5	0.4	0	0.2	0	0	0	0	17.9	26.2	0
S6	10.7	32.1	11.3	0.4	0	0.2	0	0	0	0	17.5	27.7	0
S7	21.5	21.5	11.3	0.4	0	0	0	0	0	2.3	8.8	34.3	0
S8	10.8	32.4	11.4	0.4	0	0.3	0	0	0	0	10	34.7	0
S9	19.8	19.8	10.4	0.4	0	0	0	0	0	2.1	7.8	39.7	0
S10	45.9	15.3	0	0	0	0	0	0	0	0	12.3	26.5	0
S11	21.7	21.7	0	1.3	1.3	0	0.6	0	0	2.3	7	44	0
S12	11.7	35.1	12.3	0.4	0	0	0	0	0	2.5	9.4	28.5	0
S13	11.7	35.1	0	1.4	1.5	0	0.7	0	0	2.5	9.4	37.7	0
S14	3.7	33.7	17.7	0.7	2.9	0	1	0	0	0.9	14	25.4	0
S15	3.7	33.7	17.7	1.2	5	0	0	0	0	1.4	12.9	24.3	0
S16	4.1	36.7	10.7	0.4	0	0	0	4.7	2.5	0	15.8	25.1	0
S17	4.2	37.6	11	0.8	0	0	0	4.8	0	0	14.4	27.3	0
S18	4.2	38	10.9	0.7	0.7	0	0.3	0	1.3	0.6	14.8	28.6	0
S19	12.5	31.3	11	0.7	0.7	0	0.3	0	1.3	0.7	12.2	29.4	0

Table 2.2 shows the proportions of the components of the 19 mycelium samples. It can also be seen how the proportions of wood chips and straw were varied.



Fig. 2.7. Mixture of xanthan, water and ethanol.

During the experiment, a binder had to be added to the mycelium material, and one of the binders was xanthan gum. The xanthan gum had to be mixed with water to get the right consistency and hold the material together. Xanthan gum is insoluble in water, so ethanol was also added. Adding ethanol to the samples helped dissolve the xanthan gum so it could be better mixed into the samples.



Fig. 2.8. Using a mixer to mix samples.

All added ingredients had to be mixed into a homogeneous mass. A mixer was used in the experiment to create a homogeneous mass before pouring it into the mold.



Fig. 2.9. Pouring the mycelium material into the mold.

Figure 2.9 shows that the mycelium material is very loose; however, it should be noted that such a consistency was observed only for the first samples of the material. During the process, it was concluded that the mycelium does not need such a large amount of water for growth. A smaller amount of water reduces the need for drying and, accordingly, for heat. The samples were dried at 105 °C. Initially, the samples were dried longer, but the last samples with a reduced amount of water were dried for approximately 24 hours.



Fig. 2.10. Mycelium samples (S2, S3, S4, S5, S6, S7).

The visual differences in the mycelial material can be explained by the fact that the amount, ratio, and fraction of wood chips and straw were varied in the experiment.



Fig. 2.11. Mycelium samples (S7, S9, S11, S12, S13, S14).



Fig.2.12. Mycelium samples (S15, S16, S17, S18, S19).

In Figs. 2.11 and 2.12, there are no visual differences between the samples of mycelium material, since these samples differ only in the amount of binder.

An experimental design was created, and various ratios of the components of the mycelium material were developed and tested in order to determine their optimal combination. The main factors analyzed were the amount of fungal spores, medium and water, as well as the effect of other additives on the properties of the material.

The experiments included several variants with different proportions of components, such as the ratio of wood chips to straw, the amount of xanthan and soda, as well as different amounts of medium added to the fungal spores. Each variant was tested to assess its density, thermal conductivity and mechanical strength.

After conducting the experiments, it was concluded that the best results were obtained in the variant in which the water content was approximately 12.35 %, fungal spores 0.03 %, and the medium was 37.63 %. The experiment used multivariate regression analysis to determine which variables significantly affect thermal conductivity and material quality.

The results revealed that both the ratio of wood chips to straw and the amount of xanthan gum had a significant effect on the properties of the mycelium material. Based on the experimental data, mathematical models were developed to predict the optimal component ratios for future material production.

Table 2.3

Experimental Matrix of Mycelium-Based Composite Formulations: Component Proportions and Composition Variants

Parameter/ experiment	Wood chips:straw	Xanthan	Sodium carbonate	Fungal spores	Medium	Water
1	0.11	0.31	2.50	0.03	37.25	12.22
2	2.96	1.44	2.53	0.03	37.67	12.36
3	0.11	1.44	2.53	0.03	37.67	12.36
4	2.96	0.31	2.50	0.03	37.25	12.22
5	1.54	0.875	2.52	0.03	37.46	12.29

The data obtained in nineteen samples were analyzed using multivariate regression analysis (multiple/multiregression analysis), which is a method of statistical data processing and is used to assess the relationship between the dependent variable and several independent variables. During regression, all analyzed parameters are filtered out, which are statistically insignificant (do not significantly affect the final result) in the case of the studied quantity (thermal conductivity). The adjusted coefficient of determination (R-squared adjusted) characterizes how much of the results are described by the specific equation, with the included variables. In the equation, the sign before the coefficients characterizes the direction of influence of the specific parameter (+ increases, - decreases).

1. The best option:

$$\lambda = 0,0474555 + 0,00800692 \times Xanthan - 0,0013548 \times Glycerin + 0,0169894 \times Ethanol - 0,00038181 \times Medium + 0,0000477635 \times \rho \quad (2.4)$$

R-squared = 88,0398 percent

R-squared (adjusted for d.f.) = 79,4969 percent

Standard Error of Est. = 0,00132086
 Mean absolute error = 0,000814346
 Durbin-Watson statistic = 2,34332 (P=0,4848)
 Lag 1 residual autocorrelation = -0,181436

The results of fitting a multiple linear regression model to describe the relationships between λ_{avg} , W / (mK) and 12 independent variables are presented.

Since the P value in the ANOVA table is less than 0,05, there is a statistically significant relationship between the variables at the 95,0% confidence level.

The R-Squared statistic indicates that the fitted model explains 88,0398% of the variability in λ_{avg} , W/(mK). The adjusted R-squared statistic, which is more appropriate for comparing models with different numbers of independent variables, is 79,4969%. The standard error of the estimate shows that the standard deviation of the residuals is 0,00132086. This value can be used to create new prediction limits for observations by selecting Reports from the text menu. The mean absolute error (MAE) of 0,000814346 is the mean of the residuals. The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on the order in which they appear in your data file. Since the P-value is greater than 0.05, there is no indication of serial autocorrelation in the residuals at the 95,0% confidence level.

Table 2.4

Correlation Matrix of Predictor Coefficients in the Multivariate Regression Model for Thermal Conductivity

	Constant	Xanthan, %	Glycerin, %	Ethanol, %	Medium, %	P_{avg} , kg/m ³
Constant	1.0000	0.3839	-0.6231	-0.0306	-0.7912	-0.6434
Xanthan, %	0.3839	1.0000	-0.7408	0.4683	-0.7477	-0.1396
Glycerin, %	-0.6231	-0.7408	1.0000	-0.0535	0.6718	0.3604
Ethanol, %	-0.0306	0.4683	-0.0535	1.0000	-0.2936	-0.0814
Medium, %	-0.7912	-0.7477	0.6718	-0.2936	1.0000	0.2168
P_{avg} , kg/m ³	-0.6434	-0.1396	0.3604	-0.0814	0.2168	1.0000

The density depends on the amount of straw in the sample.

Multicriteria regression – ρ_{avg} , kg/m³

Dependent variable: ρ_{avg} , kg/m³

Independent variables:

- Wood chips, %
- Straw, %
- Xanthan, %
- Glycerin, %
- Ethanol, %
- Fungal spores with medium, %
- Water, %
- Gluten, %
- Sodium carbonate, %
- Meadium, %
- Wd, % real

Number of observations: 13

Table 2.5

Regression Coefficients and Statistical Significance for the Model Predicting Average
Density of Bio-Composite Samples

		Standart	T	
Parametrs	Estimate	Error	Statistic	P-Value
CONSTANT	173.805	16.660	10.433	0.000
Straw, %	-2.553	0.626	-4.081	0.002

The results of fitting a multiple linear regression model to describe the relationship between ρ_{avg} , kg/m³ and 11 independent variables are shown. The fitted model equation is

$$\rho_{\text{avg}}, \text{ kg/m}^3 = 173,805 - 2,5532 * \text{Straw, \%}$$

Since the P value in the ANOVA table is less than 0,05, there is a statistically significant relationship between the variables at the 95,0% confidence level.

The R-Squared statistic indicates that the fitted model explains 60,2228% of the variability in ρ_{vid} , kg/m³. The adjusted R-squared statistic, which is more appropriate for comparing models with different numbers of independent variables, is 56,6067%. The standard error of the estimate shows that the standard deviation of the residuals is 23,0039. This value can be used to create prediction limits for new observations by selecting Reports from the text menu. The MAE of 14,4666 is the mean value of the residuals. The DW statistic tests the residuals to determine if there is any significant correlation based on the order in which they appear in your data file. Since the P value is greater than 0,05, there is no indication of serial autocorrelation in the residuals at the 95,0% confidence level.

When determining whether the model can be simplified, note that the largest P value for the independent variables is 0,0018, which belongs to Straw,%. Since the P value is less than 0,05, this term is statistically significant at the 95,0% confidence level.

Second best option:

$$\lambda = 0,0313074 + 0,000503398 \times \text{Mycelium with medium} + 0,0000727497 \times m(2.5)$$

R-squared = 81,002 percent

R-squared (adjusted for d.f.) = 77,202 percent

Standard Error of Est. = 0,001

Mean absolute error = 0,001

Durbin-Watson statistic = 2,607 (P=0,794)

Lag 1 residual autocorrelation = -0,355

The result shows the results of fitting a multiple linear regression model to describe the relationship between λ_{avg} , W/(mK) and 12 independent variables.

Since the P value in the ANOVA table is less than 0,05, there is a statistically significant relationship between the variables at the 95,0% confidence level.

The R-Squared statistic indicates that the fitted model explains 81,0018% of the variability in λ_{avg} , W/(mK). The adjusted R-squared statistic, which is more appropriate for comparing models with different numbers of independent variables, is 77,2022%. The standard error of the estimate shows that the standard deviation of the residuals is 0,00139281. This value can be

used to create prediction limits for new observations by selecting the Reports option from the text menu. The MAE of 0,000993757 is the mean value of the residuals. The DW statistic tests the residuals to determine if there is any significant correlation based on the order in which they appear in your data file. Since the P value is greater than 0,05, there is no indication of serial autocorrelation in the residuals at the 95,0% confidence level.

Best case with only ingredients (no density, mass, moisture content).

After several analyses with different parameter combinations, the parameters 100% screened out: woodchip content, straw content, and gluten. The result is the same as the following.

Multiple Regression - Thermal conductivity, W/(mK)

Dependent variable: Thermal conductivity, W/(mK)

Independent variables:

Wood chips, %

Straw, %

Xanthan, %

Ethanol, %

Water, %

Medium, %

Number of observations: 13

Table 2.6

Reduced Predictive Model of Thermal Conductivity Based on Key Component Proportions

		Standard	T	
Parameter	Estimate	Error	Statistic	P-Value
CONSTANT	0.0647372	0.00499563	12.9588	0.0000
Ethanol, %	0.0150421	0.00570246	2.63782	0.0270
Water, %	-0.000531995	0.000144989	-3.66922	0.0052
Medium, %	-0.000462444	0.00012353	-3.74357	0.0046

$$\lambda = 0,0647372 - 0,000531995 \times Water + 0,0150421 \times Ethanol - 0,000462444 \times Meidum$$

(2.6)

R-squared = 69,3842 percent

R-squared (adjusted for d.f.) = 59,1789 percent

Standard Error of Est. = 0,00186375

Mean absolute error = 0,00106101

Durbin-Watson statistic = 2,64489 (P=0,8673)

Lag 1 residual autocorrelation = -0,335278

The result shows the results of fitting a multiple linear regression model to describe the relationship between λ_{avg} , W / (mK) and 7 independent variables.

Since the P value in the ANOVA table is less than 0,05, there is a statistically significant relationship between the variables at the 95,0% confidence level.

The R-Squared statistic indicates that the fitted model explains 69,3842% of the variability in λ_{avg} , W / (mK). The adjusted R-squared statistic, which is more appropriate for comparing models with different numbers of independent variables, is 59,1789%. The standard error of the estimate shows that the standard deviation of the residuals is 0,00186375. This value can be used to create prediction limits for new observations by selecting the Reports option from the text menu. The MAE of 0,00106101 is the mean value of the residuals. The DW statistic tests the residuals to determine whether there is any significant correlation based on the order in which they appear in your data file. Since the P value is greater than 0,05, there is no evidence of serial autocorrelation in the residuals at the 95,0% confidence level.

When determining whether the model can be simplified, note that the largest P value for the independent variables is 0,0270, which is for ethanol,%. Since the P value is less than 0,05, this term is statistically significant at the 95,0% confidence level. Therefore, you probably do not want to remove any variables from the model.

Table 2.7

Inter-Coefficient Correlation Matrix for the Reduced Thermal Conductivity Model

	CONSTANT	Water, %	Ethanol, %	Medium, %
CONSTANT	1.0000	-0.8392	0.0287	-0.9702
Water, %	-0.8392	1.0000	-0.1388	0.7270
Ethanol, %	0.0287	-0.1388	1.0000	-0.1156
Medium, %	-0.9702	0.7270	-0.1156	1.0000

This table shows the estimated correlations between the coefficients in the fitted model. These correlations can be used to detect the presence of serious multicollinearity, i.e. correlations between the predictor variables. In this case, there is 1 correlation with an absolute value greater than 0,5 (excluding the constant number). The design has chosen a reduced number of experiments, considering the practical implementation. The straw proportion implicitly includes changes in density.

Table 2.8

Experimental Plan for Five Parameters

run	Wood chips	Straw	Ethanol	Medium	Water	Thermal conductivity
	%	%	%	%	%	$W/(m*K)$
1	3.74	35.14	0.29	24.31	0.0	
2	25.21	17.57	0.145	34.155	8.87	
3	25.21	17.57	0.145	34.155	8.87	
4	3.74	0.0	0.0	44.0	17.74	Small amount of biomass – may have implementation problems
5	3.74	35.14	0.0	24.31	17.74	
6	25.21	17.57	0.145	34.155	8.87	
7	46.68	35.14	0.29	44.0	17.74	
8	46.68	0.0	0.29	24.31	17.74	
9	3.74	0.0	0.29	44.0	0.0	Small amount of biomass – may have implementation problems

Table 2.8 (continued)						
10	46.68	0.0	0.0	24.31	0.0	
11	46.68	35.14	0.0	44.0	0.0	

Considering that the ratios of medium, spores and water were determined in the previous experiment, the experimental plan was drawn up based on the ratios of wood chips and straw, as well as the amount of xanthan. Initially, sample numbers were simplified (e.g., from S1-S19), however, as experiments continued, sample numbers were specified (e.g., indicating substrate proportions or, if a particular experiment focused on differences in binder amounts, indicating the percentages of binders added).

Table 2.9

Proportions of Mycelium Samples According to the Experimental Plan

No.	Wood chips, %	Straw, %	Water, %	Xanthan, %	Sodium carbonate, %	Spores, %	Medium, %
ŠS0.11K1.43	4.66	41.90	12.22	1.43	2.50	0.03	37.25
ŠS0.33K0.31	35.32	11.77	12.36	0.31	2.53	0.03	37.67
ŠS0.11K0.31	4.71	42.38	12.36	0.31	2.53	0.03	37.67
ŠS0.33K1.43	34.92	11.64	12.22	1.43	2.50	0.03	37.25
ŠS0.74K0.88	19.90	26.93	12.29	0.88	2.52	0.03	37.46

According to the obtained results, it can be concluded that the ratio of wood chips to straw, as well as the amount of xanthan, significantly affects the strength and thermal conductivity of the material. Continuing the study, the best proportions recommended in the equations were tested to improve the thermal conductivity of the mycelium material. Considering the results obtained in the samples containing wood chips, wood chips were no longer used in further experiments. The experiments were continued using only hay and straw. The proportions of hay and straw were varied (25 % straw and 75 % hay, 75 % straw and 25 % hay, as well as 50 % straw and 50 % hay).

Table 2.10

Proportions of Hay and Straw Samples

No.	Hay, %	Straw, %	Water, %	Xanthan, %	Glycerin, %	Molasses, %	Spores, %	Starch solution, %
Sa25Sie75	35.1	11.5	12.2	1.2	0.9	1.8	0.03	37.3
Sa75Sie25	11.5	35.1	12.2	1.2	0.9	1.8	0.03	37.3
Sa50Sie50	23.3	23.3	12.2	1.2	0.9	1.8	0.03	37.3

2.4. System dynamics model

The study uses a systems dynamics approach, which is a mathematical method for studying and managing complex systems that change over time due to causes and feedback loops. This approach was developed at the Massachusetts Institute of Technology in 1956 by Professor Jay Wright Forrester[96]. Stella Architect has been used as a software tool for structuring building stocks and flows, as well as for simulating system behavior. The model is used to compare the differences between the production of mycelium insulation material and four synthetic insulation materials: EPS, extruded polystyrene (XPS), polyurethane and phenolic foam. The average values of the synthetic insulation materials were taken from the literature [82]. The comparison was made based on the amount of insulation materials produced that provide the same thermal insulation properties, taking into account differences in thermal conductivity. The focus of the comparison was the difference between GHG emissions and the energy embodied in the materials over the entire life cycle. The results are expressed per cubic meter of insulation material, also as cumulative values of embodied GHG emissions and embodied energy. The calculation period is set from 2021 to 2050. A 30-year period has been chosen for the simulation, as most EU climate policies target the period up to 2050, when climate neutrality should be achieved. The simulation includes not only the increase in capacity for the production of mycelium insulation materials, but also the impact of research and development (R&D) on the efficiency of material production, so the period considered must be long enough to reflect this impact.

Structure of the model

A causal loop diagram (CLD) was used to describe the structure of the modeled system. It was developed prior to the construction of the model (Fig. 2.13). The CLD represents the system's mechanics without involving numerical calculations [97]. It illustrates the core feedback structure of the system and highlights the drivers of its dynamic behavior. The system under study is represented by three reinforcing loops and four balancing loops (Fig. 2.13). The reinforcing loops show exponential growth. The reinforcing loop R1 shows how the production of mycelium insulation material increases the amount of reduced (avoided) GHG emissions, as the material replaces a synthetic material with a higher amount of GHG emissions. The more emissions are reduced, the more carbon credits can be sold, generating revenue. Part of the revenue can be invested in increasing the land available for production, which in turn increases the capacity of production technologies, allowing for even greater use of renewable insulation materials. The reinforcing loop R2 describes a feedback loop, where part of the revenue from the sale of carbon credits is invested in research and development to increase the energy efficiency of production. Increasing energy efficiency further increases the amount of reduced emissions. Research and development takes time, and this is modeled by assuming that investment in research and development reduces the time needed for these activities. Production capacity is limited by the availability of raw materials, and the energy efficiency limit is set as a maximum value. The reinforcing loop R3 shows how investment in R&D increases the amount of insulation material produced, i.e. the production output. As productivity increases, the use of renewable insulation materials further reduces emissions compared to synthetic insulation materials, thereby increasing the revenue from the sale of carbon credits. This in turn further increases the potential investment in R&D.

Balancing or negative feedback loops lead to the purposeful behavior of the system. The first balancing loop B1 shows how the availability of raw materials interacts with the consumption of raw materials for the production of mycelium insulation material. By consuming raw materials, insulation material is produced, and the more insulation material is produced, the fewer raw materials are left for production. The second balancing loop B2 shows how energy efficiency interacts with the remaining potential for increasing energy efficiency. Energy efficiency is increased by investing in R&D. This investment generates revenue from the sale of carbon credits. As energy efficiency increases, the potential for further increases decreases. A similar depletion effect affects the potential for productivity improvement (balancing loop B3) and the land area available for production (B4).

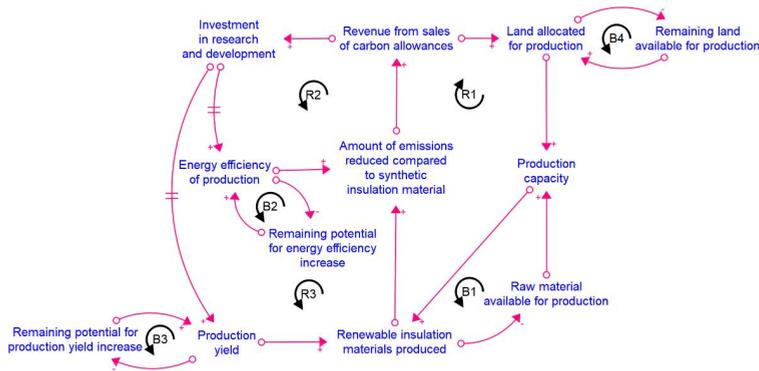


Fig. 2.13. Causal loop diagram portraying the structure of the system dynamics model for mycelium insulation material production.

Data collection

To calculate the embodied emissions of the mycelium insulation material, it is necessary to obtain an emission factor, data on the material's emission absorption capacity, and information on electricity and heat consumption during the production process. The same principle applies to the calculation of embodied energy, except that the emission factor is replaced by the material's embodied energy factor. The quantities of materials required to produce 1 m³ of mycelium insulation material were derived from laboratory experiments conducted at Riga Technical University. The system dynamics model was based on data from samples utilizing straw and wood chips, which demonstrated the best thermal conductivity performance. Hay and straw samples were experimentally produced after the initial development of the model and the publication of preliminary results. Data on the embodied emissions and embodied energy of the mycelium itself were not included, as a portion of the raw materials is used in the bioreactor for the cultivation of mycelium. The required quantities of materials, electricity, and heat, as well as the emission factors, emission absorption rates, and embodied energy input data, are presented in Table 2.11.

Table 2.11

Emission Factors and Embodied Energy of Production Inputs per 1 m³ of Mycelium Insulation Material

Input	Input in production (unit/m ³)	Emission factor (kgCO _{2eq} /unit)	Emission absorption (kgCO _{2eq} /unit)	Embodied energy (MJ/unit)
Mycelium (kg)	0.117	–	0.0025 [13]	–
Distilled water (kg)	259.3	0.0008 [14]	0	23 [15]
Molasses (kg)	7.5	0.074 [16]	0.1 [17]	1 [17]
Starch (kg)	6.4	2.4 [18]	0.174* [19]	0.0014 [19]
Whey powder (kg)	7.5	0.082 [20]	0.98 [17]	20 [17]
Carbamide (kg)	0.97	1.85 [21]	0.73 [22]	49 [22]

		Table 2.11 (continued)		
Xanthan (kg)	2.3	0.00497 [23]	0.048 [24]	7.6 [25]
Soda (kg)	13.6	0.00059 [14]	0.524 [26]	26.9 [26]
Wood Chips (kg)	189.3	0.000187 [27]	1.835*	17 [28]
Straw (kg)	63.1	0.1036 [29]	1.468* [30]	2.125 [31]
Electricity (kWh)	988	0.1019 [32]	0	3.6
Heat (kWh)	754	0.0942 [32]	0	3.6

* Value was calculated for this study.

Modeling

Some elements of the model were taken from the already existing model made for bioeconomy sector at Riga Technical University [24] then modified and further developed for the needs of this study. The model was adapted to simulate a factory-like environment for material comparison. Several changes were made concerning raw material availability, available area, production, research and development, emissions, and new parameters were introduced – “energy” and “functional cubic meters”. The data used in the modelling are attached in the annex (Annex 6 - Annex 11).

To determine the area available for material production, it was assumed that the total land available for production is 10,000 m². Initially, 1,000 m² are used, while the remaining 9,000 m² are available for production based on the initial land allocation time and income from carbon trading. As income from carbon trading increases, the land allocation time decreases, thereby increasing the land allocation rate and the area allocated for production.

Mycelium insulation production requires nine input materials. Raw materials are restocked annually based on the production area and the yield of input materials.

Raw material inputs are accumulated in a single stock and summed up to determine the annual potential production volume. The stock acts as a production constraint since it is not possible to produce more material than the amount of raw materials accumulated. Production depends not only on the accumulated material and potential production but also on the available production capacity. Production capacity determines the maximum possible production output, as it is not possible to produce more insulation material than the technical equipment can handle.

It is assumed that electricity consumption for production can be reduced by 30%, and heat consumption by 45%. The initial research period for energy efficiency improvements is set at five years, while the time needed to develop solutions from the laboratory to the implementation phase is set at three years. The initial production yield is set at 90 (m³/m²)/year, which can be increased up to 120 (m³/m²)/year. The initial research period for yield improvement is set at 50 years, while the implementation period is 25 years. An additional 10-year period is needed for education and training regarding new solutions, which is independent of the research and development timeline. The duration of research and development activities can be influenced by the amount of financial support provided. Funding for R&D is obtained from selling avoided

CO₂ emissions. Such investments can reduce both the “time to research” and the “time to development” by up to two times.

Each material used in production generates a certain amount of emissions per ton used. Knowing the amount of raw materials used in mycelium insulation production, the embodied emissions were calculated by multiplying the amount of raw material used by its respective emission factor. Similarly, the amount of CO₂ absorbed was calculated using an absorption factor instead of the emission factor.

The annual emissions from each material were summed to determine the total emissions from material use. For electricity and heat emissions, the annual consumption was multiplied by the respective emission factor, and the results were summed to determine the total annual emissions from energy consumption. To calculate the emission factor of mycelium insulation material, the annual material use emissions and the energy consumption emissions were summed and divided by the total amount of produced mycelium insulation material.

Emission factors of other synthetic materials were used to calculate the emission difference per cubic meter of insulation material. This difference was used to determine the amount of emissions avoided by producing mycelium insulation material instead of synthetic materials. Additionally, a comparison of cumulative emissions was performed for each insulation material.

The approach to calculating embodied energy was very similar to that of embodied emissions. The embodied energy of input materials was multiplied by the quantity of input material used, then electricity and heat consumption were added, and the total energy was divided by the amount of material produced. The difference between the mycelium insulation material and other materials was used to determine avoided energy consumption. The cumulative energy consumption during the production process of each material was also determined.

Since the considered insulation materials have different thermal conductivities, a correction had to be made to enable comparison based on the amount of material required to provide the same insulation performance. Therefore, the concept of “functional cubic meters” (fm³) was introduced – the amount of insulation material needed to achieve the same heat flux value as the compared material. The correction was performed by calculating the ratio of the thermal conductivity of the considered materials to the thermal conductivity of the mycelium insulation material (Table 2.12). To calculate functional embodied emissions and functional embodied energy, these ratios were multiplied by the embodied emissions and embodied energy of the respective insulation materials.

To determine the thermal conductivity of the mycelium material, the thermal conductivity values of its raw material components were taken from the literature and averaged.

Table 2.12

Insulation Material's Thermal Conductivity Values and
Thermal Conductivity to Mycelium Thermal Conductivity Ratio

Material	Thermal conductivity, W/(m*K)	Ratio to mycelium thermal conductivity, unitless
Mycelium insulation	0,04	1
EPS	0,035	0,875
XPS	0,0345	0,863
Polyurethane	0,0285	0,713
Phenolic foam	0,021	0,525

3. RESULTS

The results chapter presents the results of the GHG emissions analysis, the evaluation of the TIMES model application, the results of the mycelium thermal insulation material and the system dynamics model analysis. These results provide insight into the sustainable development opportunities of the bioeconomy, adapted to the Latvian and EU contexts.

3.1. Greenhouse gas emissions analysis

After presenting the methodology for analyzing GHG emissions, this section presents results that illustrate the differences in emission intensity between European Union countries and identifies the main problems.

Figure 2.1 shows data on GHG emissions (expressed as kilotonnes of carbon dioxide equivalent) per million euros of GDP in different European countries. This indicator provides an insight into the environmental efficiency of each country's economy, showing how much GHG is emitted.

- Austria and Belgium stand out with relatively low emissions per million euros of GDP, which indicates efficient use of resources in the economy.

- Countries such as Bulgaria, Croatia, Greece, Latvia, Lithuania, Poland and Romania show higher emissions per million euros of GDP, which indicates less environmentally friendly production.

- Ireland stands out with high emissions, probably due to specific economic activities. Ireland is a major livestock and dairy country, with a large proportion of greenhouse gas emissions coming from animal husbandry, particularly methane, which is produced by animal digestion. The use of chemically treated soil and fertilisers can also increase nitrogen oxide emissions.

- Malta has the lowest emissions per million euros of GDP, indicating a relatively green economic development in terms of GHG emissions per unit of economic output.

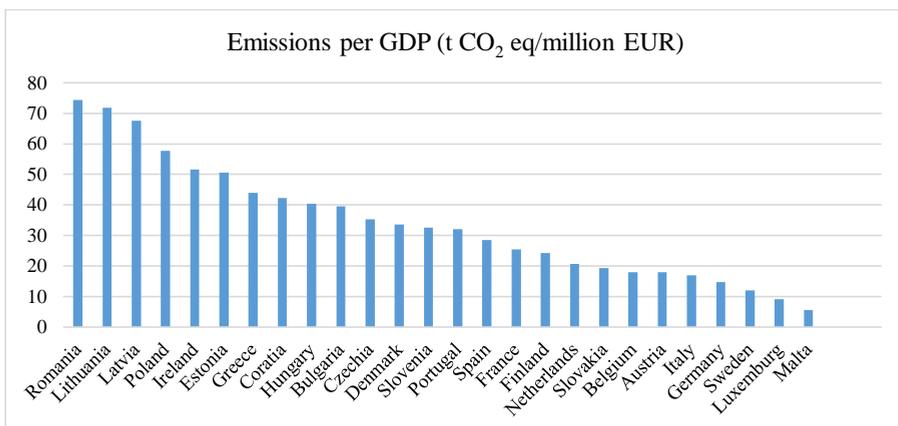


Fig. 3.1. Emissions in agriculture per GDP.

Figure 3.2 shows data on the amount of GHG in the agricultural sector relative to GDP per capita in different countries. It is expressed as kilotonnes of carbon dioxide equivalent per euro of GDP per capita. This indicator helps to assess the environmental impact of the agricultural sector in each country, taking into account the volume of emissions, economic activity and population.

- Countries such as Poland, France, Romania, Spain and Germany have relatively high emissions in the agricultural sector relative to GDP per capita, which may indicate a high environmental impact of the agricultural sector in these countries.

- Countries such as Malta and Luxembourg have very low emissions in the agricultural sector relative to GDP per capita, possibly due to the small size of the agricultural sector or environmentally friendly agricultural practices.

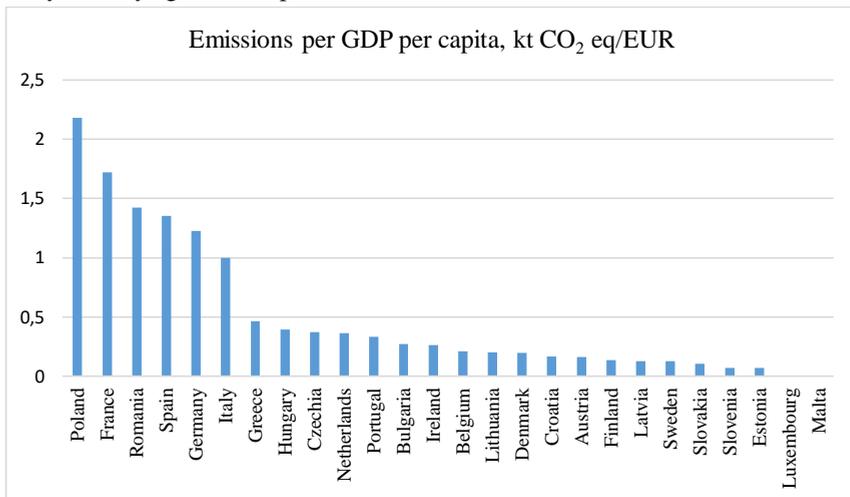


Fig. 3.2. Emissions in agriculture per GDP per capita.

Figure 3.3 shows data on the amount of GHG in the agricultural sector per capita in different countries, expressed in kt CO₂ eq. per capita. This indicator is an indicator of how much GHG a country emits in the agricultural sector per capita.

- Countries such as Ireland and Denmark have relatively high emissions from the agricultural sector per capita, which may indicate that their agricultural sector generates a large amount of GHG emissions relative to their population.

- Countries such as Malta and Slovakia have relatively low emissions from the agricultural sector per capita, possibly due to the small size of the agricultural sector or effective environmental protection practices in these countries.

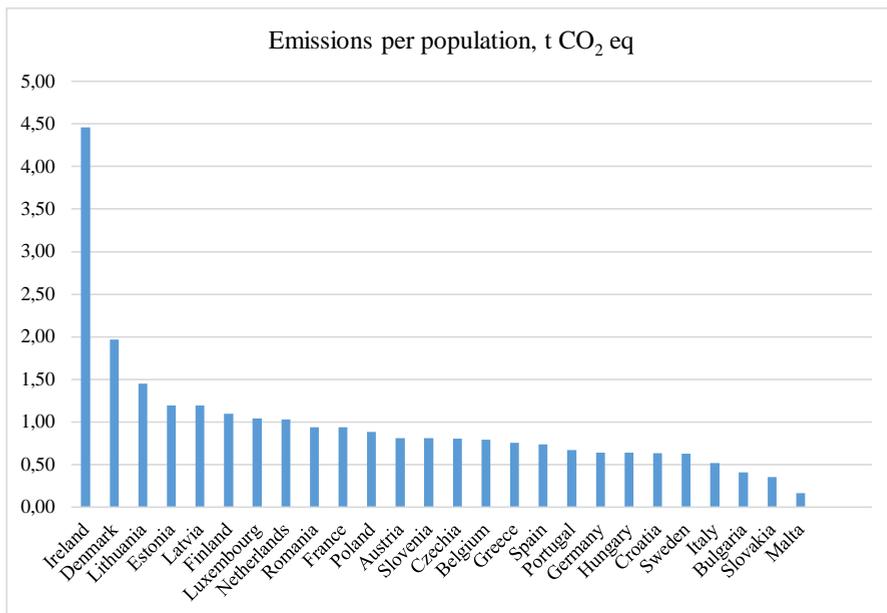


Fig. 3.3. Emissions in agriculture per population.

Despite the EU’s ambitious targets to reduce GHG emissions from agriculture by 2030, current trends show a mixed picture of progress towards achieving these targets. While some Member States have made significant progress in limiting emissions, others still face challenges in meeting their reduction targets.

Several Member States, including Croatia, Greece and Slovakia, have achieved significant reductions in agricultural emissions since 2005. These countries are examples of successful emission reduction measures, demonstrating that effective mitigation measures are possible. In Europe, total GHG emissions from agriculture have decreased slightly between 2005 and 2021, indicating some progress towards the 2030 reduction targets. This trend suggests that current measures have had some impact on reducing emissions in the agricultural sector [118]. Despite overall reductions, agricultural emissions have increased in some Member States, such as Bulgaria, Estonia, Hungary, Ireland, Latvia and Luxembourg. These countries face challenges in implementing sufficient mitigation measures. They may have structural barriers that hinder emission reduction efforts. Projections suggest that without further intervention, some Member States are expected to reverse their emission reduction trends. For example, Greece and Romania expect emissions to increase if current measures continue, highlighting the need to increase efforts to meet the targets [119]. There are large differences between Member States in terms of emission levels and progress towards the targets. Factors such as agricultural practices, land use patterns and policy frameworks contribute to these differences. The European Commission’s impact assessment highlights the challenges of further reducing non-CO₂ GHG emissions from agriculture, indicating the need for innovative strategies and targeted measures [120]. To accelerate progress towards agricultural emission reduction targets, Member States should prioritise effective mitigation measures tailored to their specific context

and challenges. Promoting sustainable agricultural practices, investing in research and innovation, and providing appropriate support and incentives for farmers are essential to achieving emission reduction targets. Collaborative efforts at European level, including the exchange of best practices, knowledge sharing and coherent policy frameworks, can foster collective action and progress towards common goals [121].

In addition to the analysis of GHG emissions, it is essential to examine the agricultural by-products generated in the sector and explore how these resources can be utilized to their full potential. Using the TIMES model, it is possible to assess the availability, value, and optimal application of such by-products in various technological and production scenarios. This analysis enables the identification of sustainable pathways for integrating agricultural residues into bioeconomic processes, such as bioenergy production, material development, and soil improvement, thereby contributing to both emissions reduction and the creation of higher value-added products within the sector.

3.2. TIMES model

The TIMES model scenario analysis offers an integrated view of bioresource flows and their potential for the development of the future bioeconomy. This section discusses the results and their interpretation in the context of climate neutrality. The TIMES model provides a detailed view of the potential of various agricultural by-products and crops (e.g. grains, vegetables and vegetable oils) to create added value by integrating innovative technologies, such as the production of second-generation biofuels or fiber powder. This analysis allows modeling scenarios in which it is possible to reorient agriculture towards higher added value products with lower GHG intensity.

The TIMES value-added analysis tool for the use of bioresources in the agricultural sector has been developed and tested in a case study of the Latvian agricultural sector, taking into account the limitations of the method and the availability of data. The case study scenarios include a baseline scenario for the agricultural sector and alternative development scenarios with new technologies and added value products. The results are shown for the base scenario separately for each agricultural resource group (cereals, vegetable oils and vegetables), as well as for the alternative scenarios together. The forecasts are based on historical data, as well as changes in the population of Latvia and taking into account that the world population will increase, so will exports. The results are shown in Sankey diagrams..

Baseline scenario for cereals

Figure 3.4 shows the bioresource flows in the baseline scenario for 2015 with fixed input commodity parameters to provide a historical view of the crop sector. The results show that the majority of crop products are grown in Latvia and the imported share is smaller. The mass balance of commodity flows creates discrepancies. Therefore, to meet demand, some crop products of unknown origin are consumed in processes that do not appear in the statistics. Thus, the model uses crop products of unknown origin to fill the gap between supply and demand, taking into account the efficiency of current crop processing technologies.

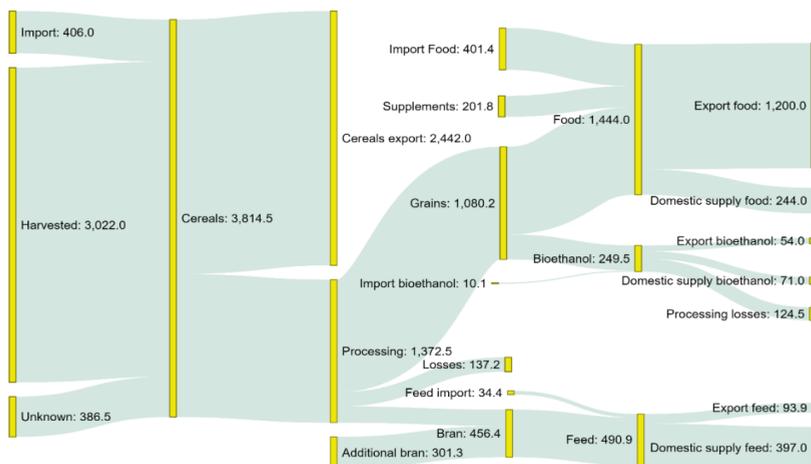


Fig. 3.4. Sankey diagram for bioresource flows of the base scenario in 2015 for cereals, thousand tonnes.

Figure 3.4 shows that the main finished cereal product flows in 2015 are food for domestic consumption and export, followed by animal feed for domestic consumption and export. Additives are added to cereal products, and they make up a large part of the final food. When producing food from cereals, by-products are obtained during primary processing, from which animal feed is produced. Part of the cereals is used for the production of first-generation bioethanol.

Figure 3.5 shows the flow of commodities for the 2030 baseline scenario. The main changes, compared to 2015, are in the production of cereal food and animal feed, as the demand for food has decreased by 20%, which can be explained by the decrease in the population of Latvia, however, taking into account the growing world population, cereal exports are increasing. Demand for animal feed has also decreased, as the total number of livestock is expected to decrease slightly, but demand for bioethanol has increased, which can be explained by the increase in demand for biofuels.

Figure 3.7 shows the flow of commodities for the 2030 baseline scenario. The main changes compared to 2015 are in the production of vegetable oils for food and feed, as demand for food has decreased by 17%, which can be explained by the decrease in population. Demand for feed has also decreased, as the total number of livestock is projected to decrease slightly, while demand for biodiesel has increased.



Figure 3.7. Sankey diagram for bioresource flows of the base scenario in 2030 for vegetable oils, thousand tonnes.

Baseline scenario for vegetables

In Figure 3.8, the main flows of finished vegetable products in 2015 are food for domestic consumption and export, followed by animal feed for domestic consumption and export. Additives are added to vegetable products, and they constitute a small part of the final product. When producing food from vegetables, by-products are obtained during primary processing, from which animal feed is produced.



Fig. 3.8. Sankey diagram for bioresource flows of the base scenario in 2015 for vegetables, thousand tonnes.

Figure 3.9 shows the results of the flow of commodities for the 2030 baseline scenario. The main changes compared to 2015 are in the production of vegetables for food and animal feed, as the demand for food has decreased by 22%, which can be explained by the decrease in the population of Latvia, but due to the increase in the world population, vegetable exports are increasing. The demand for animal feed has also decreased, as the total number of livestock is expected to decrease slightly.

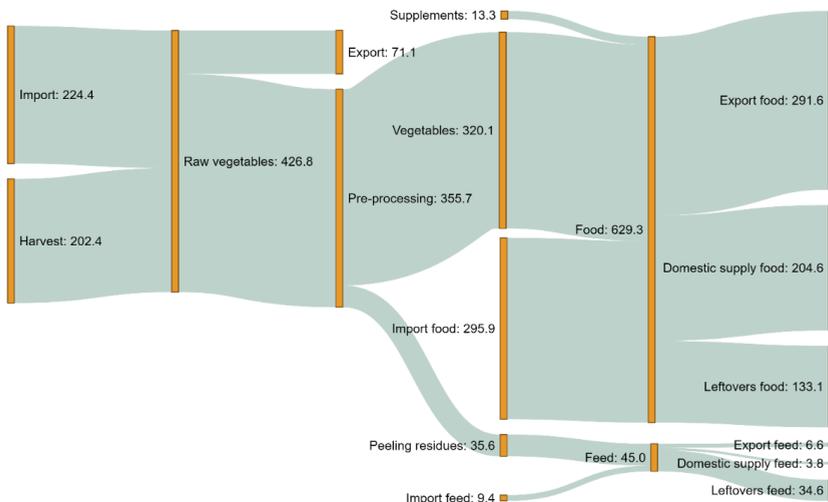


Fig. 3.9. Sankey diagram for bioresource flows of the base scenario in 2030 for vegetables, thousand tonnes.

Alternative scenario analysis

In addition to the baseline scenario, four alternative scenarios were used for the TIMES crop case study. The alternative scenario includes the availability of new technologies after 2025. The results of the alternative scenarios are compared with the baseline scenario in terms of value added in 2030 (Fig. 3.10).

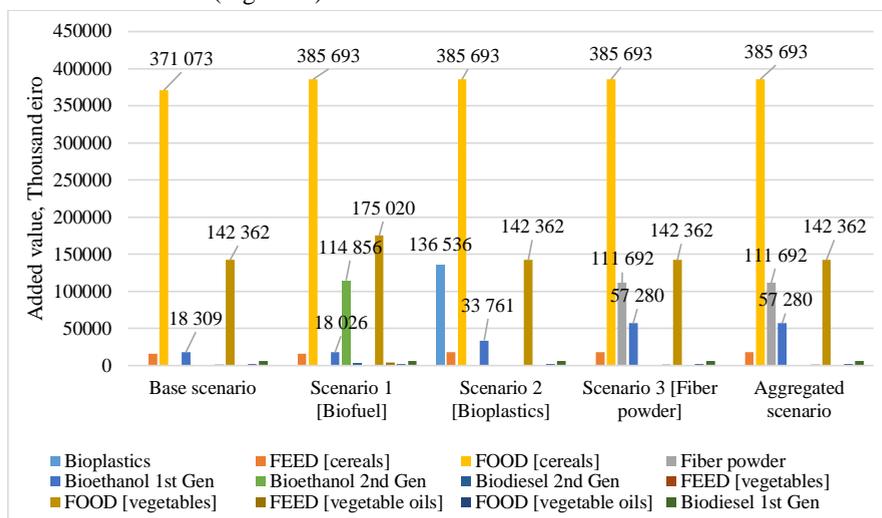


Fig. 3.10. Scenario analysis for new technologies in agriculture sector in Latvia, year 2030.

The baseline scenario shows that the highest added value is achieved from the production of cereal food and vegetable food products. If the value added target is set at +30 % of the baseline scenario, in the first scenario, the added value is achieved by increasing food production, production of other products and adding a new technology (production of second-generation biofuels). In the second scenario, the added value is achieved by increasing food production from cereals and bioethanol production from cereals, but the largest contribution to achieving the added value target is made by the production of bioplastics (new technology). In the third scenario, the production of food and other products from cereals shows an increase, and the use of new technologies appears in the production of fiber powder. The following factors were taken into account in the analysis:

- capacity, efficiency, investment and operating costs, service life and availability of technologies;
- value added of products, calculated using data from the European Commission and the Central Statistical Office of Latvia;
- market demand and production volumes.

The analysis found that the most advantageous alternative scenario is the production of fiber powder from grain bran. The aggregated scenario results show that the added value objective can be achieved by introducing fiber powder production, which has a higher added value than biofuels or bioplastics and is economically viable. The production of fiber powder from grain processing by-products (bran) is economically advantageous because:

Therefore, in the next stage of the study, attention was paid to the evaluation of an alternative biological material – a mycelium-based thermal insulation material. This material not only offers an opportunity to reduce agricultural waste, but also promotes the implementation of circular economy principles in the construction sector. The following sections analyze the experimental results obtained in the process of developing the mycelium material, evaluating its properties and comparing it with traditional materials.

3.3. Mycelium thermal insulation material results

To evaluate the properties of mycelium as a thermal insulation material, several experiments were conducted, in which its thermal conductivity and density were analyzed. These parameters are important because they determine the material's ability to reduce heat loss and its suitability for various construction and insulation applications.

The tables below summarize the results of the experiments, which reflect the measured values of the thermal conductivity coefficient and density for various samples of mycelium materials. These data allow us to compare the effects of different compositions and processing methods on the insulation efficiency of mycelium.

Table 3.1

Thermal Conductivity Results of 17 Mycelium Material Samples

No.	λ_1 , W/(mK)	λ_2 , W/(mK)	λ_3 , W/(mK)	Λ_{avg} , W/(mK)
S2	0.049	0.049	0.049	0.049
S3	0.048	0.047	0.048	0.048
S5	0.053	0.053	0.054	0.053
S4	0.047	0.048	0.047	0.047
S6	0.05	0.046	0.045	0.047
S7	0.048	0.046	0.046	0.047
S8	0.045	0.042	0.042	0.043
S9	0.044	0.044	0.044	0.044
S11	0.045	0.045	0.045	0.045
S12	0.043	0.044	0.044	0.043
S13	0.049	0.047	0.047	0.047
S14	0.044	0.044	0.044	0.044
S15	0.044	0.044	0.044	0.044
S16	0.044	0.043	0.044	0.044
S17	0.044	0.043	0.044	0.044
S18	0.045	0.045	0.045	0.045
S19	0.045	0.045	0.045	0.045

Table 3.1 shows the results of the thermal conductivity of 17 mycelium materials. They could not be determined for samples S1 and S10. Sample S1 was too liquid, and the excessive amount of water did not allow the mycelium to grow through the material. For sample S10, an oyster mycelium species was used, which was unable to grow through the material; therefore, this species was not used in further experiments. According to the results obtained, it was concluded that a larger amount of straw and a smaller amount of wood chips reduce the thermal conductivity coefficient. The addition of binders is also of great importance in the material, because when too many binders are added (for example, xanthan and glutinous rice), the material becomes stiff; however, increasing the stiffness of the material blocks the pores and increases the thermal conductivity coefficient. Ingredients were experimentally searched for that help the material to create the necessary porosity inside it. The addition of soda showed good results, and its use was continued in further experiments.

Table 3.2

Density of 17 Samples of Mycelial Material

No.	$\rho_1, \text{kg/m}^3$	$\rho_2, \text{kg/m}^3$	$\rho_3, \text{kg/m}^3$	$P_{\text{avg}}, \text{kg/m}^3$
S2	178	182	180	180
S3	140	145	146	144
S5	168	177	178	174
S4	81	82	83	82
S6	81	79	76	79
S7	120	119	116	118
S8	90	89	89	89
S9	103	103	104	103
S11	115	114	115	115
S12	106	106	105	105
S13	95	95	94	95
S14	84	85	85	85
S15	74	74	75	74
S16	76	79	79	78
S17	74	75	76	75
S18	81	81	82	81
S19	102	103	103	103

Table 3.2 shows the density of the mycelium material. The highest density was found in samples with better strength but worse thermal conductivity. Considering that the required amount of mycelium to be added to the material was not tested during the experiment, an experimental plan was developed to determine the ratio of mycelium, medium and water.

Table 3.3

Experimental Plan Testing the Amount of Mycelium Required and Thermal Conductivity Results

	Wood chips	Straw	Water	Xanthan	Sodium carbonate	Mycelium	Medium	$\Delta_{avg}, W/(mK)$
Original, g	62.5	187.5	65.63	2.29	13.44	0.177	200	
%	11.76	35.28	12.35	0.43	2.53	0.03	37.63	
Option 1, g	62.5	187.5	65.63	2.29	13.44	0.177	200	0.04037
%	11.76	35.28	12.35	0.43	2.53	0.03	37.63	
Weight in the experiment, g	39	117	40.95	1.429	8.39	0.11	124.8	
Option 2, g	62.5	187.5	65.72	2.29	13.44	0.089	200	0.04098
%	11.76	35.28	12.36	0.43	2.53	0.02	37.63	
Weight in the experiment, g	39	117	41	1.43	8.39	0.055	124.8	
Option 3, g	62.5	187.5	65.453	2.29	13.44	0.354	200	0.04068
%	11.76	35.28	12.31	0.43	2.53	0.07	37.63	
Weight in the experiment, g	39	117	40.84	1.43	8.39	0.22	124.8	
Option 4, g	62.5	187.5	130.63	2.29	13.44	0.177	135	0.04182
%	11.76	35.28	24.58	0.43	2.53	0.03	25.40	
Weight in the experiment, g	39	117	81.51	1.43	8.39	0.11	84.24	
Option 5, g	62.5	187.5	0.63	2.29	13.44	0.177	265	0.04197
%	11.76	35.28	0.12	0.43	2.53	0.03	49.86	
Weight in the experiment, g	39	117	0.39	1.43	8.39	0.11	165.36	
Option 6, g	62.5	187.5	81.36	0	0	0.177	200	
%	11.76	35.28	15.31	0.00	0.00	0.03	37.63	
Weight in the experiment, g	39	117	50.78	0	0	0.11	124.8	

Table 3.3. shows the results obtained in the part of the experiment that sought the best amount of fungal spores, PDA, and water needed for the fungus to grow in the material.

Table 3.4

Density of Variants of Mycelium Samples

No.	$\rho_1, \text{kg/m}^3$	$\rho_2, \text{kg/m}^3$	$\rho_3, \text{kg/m}^3$	$\rho_{\text{vid}}, \text{kg/m}^3$
Option 1	82	81	80	81
Option 2	72	72	72	72
Option 3	80	79	80	80
Option 4	72	71	69	70
Option 5	80	80	78	79
Option 6	–	–	–	–

An experimental design was drawn up to determine the best ratios of medium, mycelium and water, and from the results obtained it can be concluded that the ratio of wood chips to straw, as well as the amount of xanthan, significantly affects the strength of the material and the coefficient of thermal conductivity. Continuing the research, the best proportions suggested in the equations were tested to improve the thermal conductivity of the mycelium material.

Table 3.5

Thermal Conductivity Results of Mycelium Samples

No.	$\lambda_1, \text{W/(mK)}$	$\lambda_2, \text{W/(mK)}$	$\lambda_{\text{avg}}, \text{W/(mK)}$
ŠS0.11K1.43	0.04263	0.04331	0.04297
ŠS0.33K0.33	0.05153	0.04971	0.05062
ŠS0.11K0.31	0.04295	–	0.04295
ŠS0.33K1.43	0.04949	0.04972	0.04961
ŠS0.74K0.88	0.04214	0.04253	0.04234

Table 3.5. shows the thermal conductivity results obtained in the experimental design; unfortunately, sample No. ŠS0.11K0.31 was too fragile and its thermal conductivity could only be measured once.

Table 3.6

Density of Mycelium Samples

No.	$\rho_1, \text{W/(mK)}$	$\rho_2, \text{W/(mK)}$	$\rho_{\text{avg}}, \text{W/(mK)}$
ŠS0.11K1.43	64	64	64
ŠS0.33K0.33	141	139	140
ŠS0.11K0.31	66	–	66
ŠS0.33K1.43	134	135	135
ŠS0.74K0.88	83	82	83



Fig. 3.12. Mycelium sample No. ŠS0.33K1.43.

Figure 3.12. shows a sample with 75 percent wood chips and 25 percent straw, and xanthan gum added at 1.43 percent of the total mass.



Fig. 3.13. Mycelium sample No. ŠS0.11K0.31.

Figure 3.13. shows a sample with 10 percent wood chips and 90 percent straw, and xanthan gum added at 0.31 percent of the total mass.



Figure 3.14. Mycelium sample No. ŠS0.33K0.31.

Figure 3.14. shows a sample to which wood chips make up 75 percent and straw makes up 25 percent, and xanthan was added in the amount of 0.31 percent of the total mass.



Fig. 3.15. Mycelium sample No. ŠS0.74K0.88.

Figure 3.15. shows a sample with 42 percent wood chips and 58 percent straw, and with xanthan added at 0.88 percent of the total mass.

Considering the results obtained. Experiments were conducted using wood chips and straw, but to improve the results, the mycelium was grown on straw and hay.

Table 3.7

Properties of Hay and Straw Materials

No.	λ_{avg} , W/(mK)	P_{avg} , kg/m ³
Sa25Sie75	0.0391	72
Sa75Sie25	0.0403	78
Sa50Sie50	0.0393	79

The results show that the best thermal conductivity is achieved by samples containing 25 % hay and 75 % straw.

3.4. System dynamics model results

Embodied emissions and embodied energy

The initial embodied emission value of the mycelium heat insulation material is 213 kgCO₂eq/m³, and as R&D decrease the amount of electricity and heat required to produce 1 m³ of material, the embodied emissions are reduced to 159 kgCO₂eq/m³. Material use initially contributes to 19 % of production emissions or 40 kgCO₂eq/m³, heat use 33 % or 71 kgCO₂eq/m³ and electricity 48 % or 101 kgCO₂eq/m³. In 2050, emissions from the material use stay the same, only having a higher share of 27 %, emissions from heat have lowered to 26 % or 39 kgCO₂eq/m³, and emissions from electricity 47 % or 70 kgCO₂eq/m³. The mycelium insulation material has lower embodied emission values than other examined materials (Table 3.8). When counting in CO₂ absorption, mycelium insulation material embodied emission value initially is -244 kgCO₂eq/m³, and with the decrease of energy requirement, embodied emissions are reduced to -298 kgCO₂eq/m³. When the values of embodied emissions are compared on the basis of “functional m³”, then differences between the mycelium and synthetic materials are smaller (Table 3.8) due to the lower thermal conductivity of the synthetic materials.

Table 3.8

The Initial Embodied Emission and Energy Values per 1 m³ and Functional 1 m³ of Mycelium Insulation and Synthetic Insulation Materials

Material	Embodied emissions, kgCO ₂ eq/m ³	Embodied emissions, kgCO ₂ eq/fm ³	Embodied energy, MJ/m ³	Embodied energy, MJ/fm ³
Mycelium insulation	213	213	16176	16176
Mycelium insulation (including CO ₂ absorption)	-244	-244		
EPS	231.2	202	3532	3091
XPS	271.8	234	3200	2760
Polyurethane	560.5	399	10184	7256
Phenolic foam	1136	596	8600	4515

A decrease in electricity and heat requirements also reduces the embodied energy of the mycelium insulation. The initial embodied energy of mycelium insulation material is 16,176 MJ/m³, and in 2050, with the decrease of heat and electricity requirements, the value of embodied energy is reduced to 14,071 MJ/m³. Most of the embodied energy comes from material use. Initially, materials result in 61 % of all embodied emissions, but as heat and electricity requirement decreases, the material embodied energy share goes up to 71 %. All synthetic materials have lower per 1 m³ of insulation material embodied energy values than the mycelium insulation. The compared material embodied emission and embodied energy values stay constant during the production period.

Accumulated GHG emissions

The mycelium insulation material has the lowest emissions per cubic meter of material (Fig. 3.16), therefore, the cumulative emission value during the production process is the lowest. Mycelium insulation cumulatively emits 3.58 MtCO₂eq. If CO₂ absorption is included, then it is estimated that the mycelium insulation material absorbs 6.26 MtCO₂eq. Emissions of the synthetic materials are: EPS – 4.3 MtCO₂eq, XPS – 4.98 MtCO₂eq, polyurethane – 8.48 MtCO₂eq, and phenolic foam – 12.7 MtCO₂eq. Correction of the amounts of the materials due to differences in thermal conductivity was done as described above. The same applies to cumulative energy consumption.

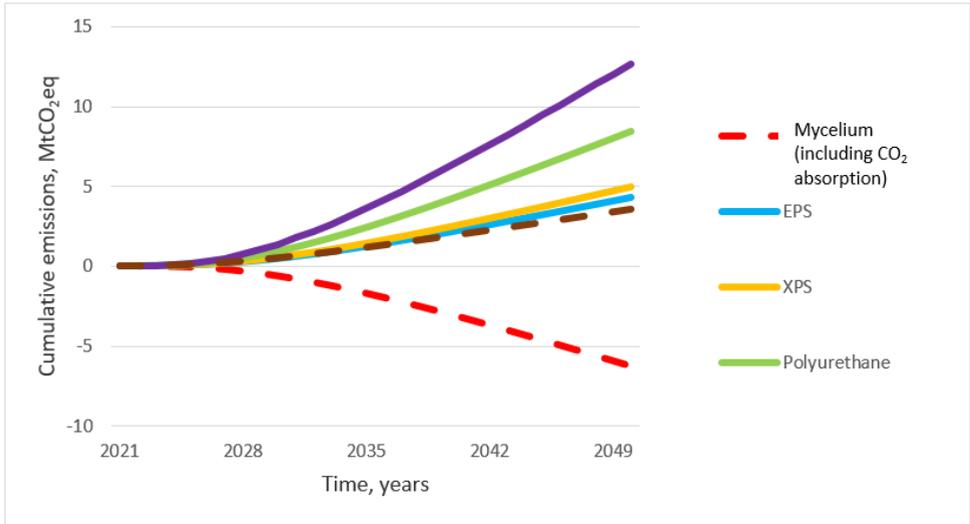


Fig. 3.16. Cumulative GHG emissions from insulation material production.

Accumulated energy consumption

Results of the embodied energy show that the mycelium insulation material has the highest embodied energy per cubic meter of material (Fig. 3.17). Therefore, the mycelium insulation cumulative energy consumption value is the highest, equal to 337 PJ. The cumulative energy consumption of the synthetic materials is: EPS – 65.6 PJ, XPS – 58.6 PJ, polyurethane – 154.1 PJ, and phenolic foam – 95.9 PJ.

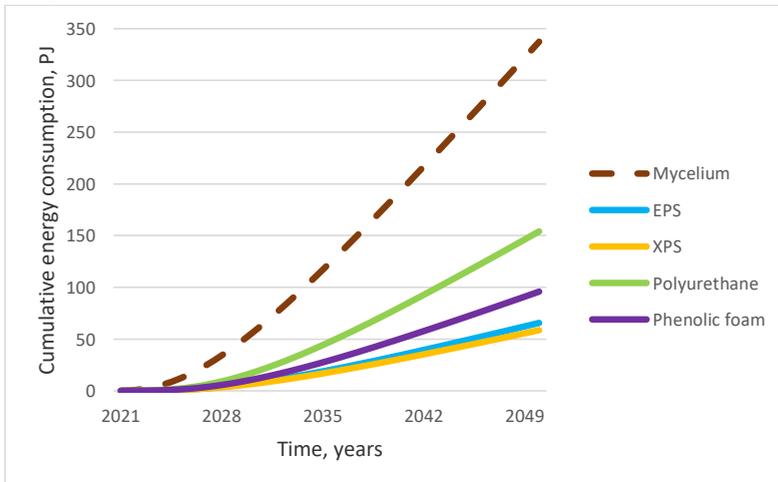


Fig. 3.17. Cumulative energy consumption from insulation material production.

Feedback effects on avoided emissions

If the revenue from carbon emissions sales is used in the feedback loop to finance research and development and allocate land for the production of renewable thermal insulation materials (Fig. 3.18), then the cumulative avoided emissions, comparing the use of synthetic materials with the use of mycelium insulation materials, reach almost 19 MtCO₂eq (Fig. 3.18). If the feedback loop is not taken into account, the cumulative avoided emissions are only about 2 MtCO₂eq.

Including the feedback effects, the revenue from the sale of carbon quotas is invested in research and development, which increases the productivity of the land used and the energy efficiency of production (both in electricity and heat use). These revenues also allow for the allocation of additional land for production. If the feedback loop is not considered, these effects do not exist.

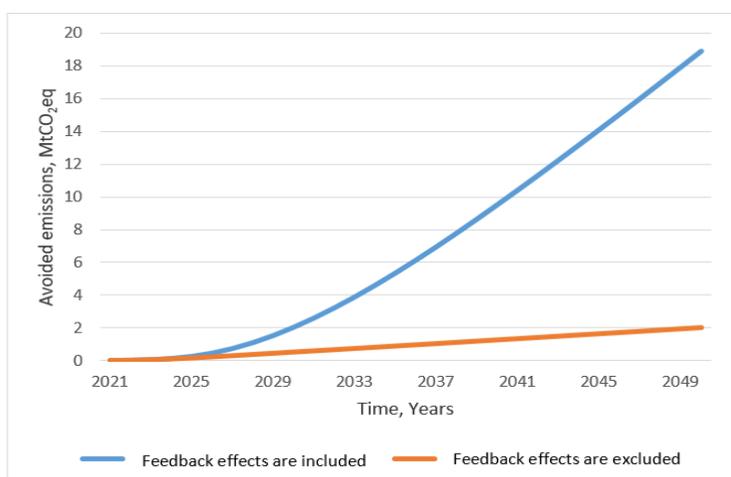


Fig. 3.18. Cumulative avoided GHG emissions when the emissions of the mycelium material is compared with the emissions resulting from phenolic foam, with feed-back effects included and excluded.

The results shown in Fig. 3.18 were obtained by comparing the emissions from the production of mycelium material with the emissions from the production of phenolic foam insulation. In the doctoral thesis, the impact of the feedback loop was assessed only in comparison with phenolic foam, mainly due to several considerations. Phenolic foam is one of the most technologically advanced and efficient traditional thermal insulation materials, characterized by low thermal conductivity and high fire safety. Therefore, it serves as a representative benchmark in the group of synthetic thermal insulation materials, allowing a more accurate assessment of the potential of the new mycelium-based material to reduce the total embodied energy and GHG emissions.

CONCLUSIONS

1. The TIMES biological resource optimization model can be an analytical tool for more efficient use of bioresources and the transition to producing higher value-added products. Based on the experimental results, using mycelium as a sustainable insulation material could significantly reduce GHG emissions. Thus, the hypothesis proposed in the Doctoral Thesis has been confirmed.
2. Multiple factors, including agricultural practices, economic structure, policy frameworks, environmental conditions, technological development, and social factors, influence differences in agricultural emission intensity across Europe. More sustainable agriculture, improved resource efficiency, and supportive policy mechanisms can contribute to emission reduction. To reduce agricultural emissions, improving animal feed quality and promoting organic farming practices are essential.
3. The TIMES model has proven effective in optimizing bioresource use, enabling scenario analysis based on supply, demand, technology, and resource costs. However, research on the Latvian agricultural sector reveals data limitations that affect the analysis. Future research should include new technologies and regional-scale modelling. Due to Latvia's population decline, food demand is expected to decrease by 2030; therefore, the focus should shift toward the production of higher-value-added products.
4. Among the nine fungal species tested, *Trichoderma viride* showed the best performance, demonstrating rapid growth on agricultural substrates. The thermal conductivity of the material ranged from 0.039 W/m·K to 0.053 W/m·K, and the density from 72 kg/m³ to 120 kg/m³. Mechanical strength tests showed that xanthan and gluten increased material durability; however, excessive amounts also increased thermal conductivity. The proportion of wood chips significantly influenced mechanical strength, while hay and straw-based samples showed the best thermal performance. The study provides valuable insight into the application of mycelium-based materials.
5. Mycelium insulation generates lower GHG emissions compared to synthetic materials, as CO₂ is absorbed during the production process. Calculations show that mycelium insulation can sequester up to 298 kgCO₂/m³, making it a carbon-negative material. Compared to phenolic foam, the use of mycelium insulation could reduce GHG emissions by 18.9 MtCO₂eq over the studied period (2021–2050). However, its production is currently more energy-intensive than that of synthetic materials, highlighting the need for further research to optimize energy consumption and evaluate alternative production methods.

ANNEX

Annex 1

Data inputs for cereals components

Component	Input parameter	Units	Initial value	Source
Domestic supply of cereals	Cost	Euro/Tt	144340	[122]
	Annual production	Thousand tons, Tt	3022	[122]
Import of cereals	Cost	Euro/Tt	188988	[122]
	Annual production	Thousand tons, Tt	406	[122]
Export of cereals	Cost	Euro/Tt	167336	[122]
	Annual production	Thousand tons, Tt	2442	[122]
Import of cereals food	Cost	Euro/Tt	290423	[123]
	Annual production	Thousand tons, Tt	435	[123]
Export of cereals food	Cost	Euro/Tt	371188	[123]
	Annual production	Thousand tons, Tt	1200	[123]
Import of cereals feed	Cost	Euro/Tt	152172	[123]
	Annual production	Thousand tons, Tt	60	[123]
Export of cereals feed	Cost	Euro/Tt	276758	[123]
	Annual production	Thousand tons, Tt	56	[123]
Import of cereals other products	Cost	Euro/Tt	821928	[123]
	Annual production	Thousand tons, Tt	10	[123]
Export of cereals other products	Cost	Euro/Tt	819572	[123]
	Annual production	Thousand tons, Tt	54	[123]
Pretreatment of cereals	Efficiency	Numeric value	0,9	Company specific data
	Fixed O&M cost	Euro/Tt	41760	
	Lifetime	Years	50	
Generic technology for primary supply of cereals food	Efficiency	Numeric value	1,24	Company specific data
	Fixed O&M cost	Euro/Tt	348240	
	Lifetime	Years	50	
	Added value	Euro/Tt	427597	[124]
Generic technology for primary supply of cereals feed	Efficiency	Numeric value	1	Company specific data
	Fixed O&M cost	Euro/Tt	195748	
	Lifetime	Years	50	
	Added value	Euro/Tt	38366	[124]
Generic technology for primary supply of cereals other products	Efficiency	Numeric value	0,48	Company specific data
	Fixed O&M cost	Euro/Tt	147858	
	Lifetime	Years	50	
	Added value	Euro/Tt	88492	[124]
Demand for cereals food	Annual production	Thousand tons, Tt	244	[122]
Demand for cereals feed	Annual production	Thousand tons, Tt	397	[122]
Demand for cereals other products	Annual production	Thousand tons, Tt	71	[122]

Data inputs for vegetables components

Component	Input parameter	Units	Initial value	Source
Domestic supply of vegetables	Cost	Euro/ Thousand tons	530290	[122]
	Annual production	Thousand tons	195	[122]
Import of vegetables	Cost	Euro/Thousand tons	869974	[122]
	Annual production	Thousand tons	130	[122]
Export of vegetables	Cost	Euro/ Thousand tons	1101719	[122]
	Annual production	Thousand tons	36	[122]
Import of vegetable food	Cost	Euro/ Thousand tons	365232	[123]
	Annual production	Thousand tons	134	[123]
Export of vegetable food	Cost	Euro/ Thousand tons	957862	[123]
	Annual production	Thousand tons	76	[123]
Import of vegetable feed	Cost	Euro/Thousand tons	85010	[123]
	Annual production	Thousand tons	51	[123]
Export of vegetable feed	Cost	Euro/Thousand tons	130920	[123]
	Annual production	Thousand tons	15	[123]
Pretreatment of vegetables	Efficiency	Numeric value	0,9	Company specific data
	Fixed O&M cost	Euro/Thousand tons	56000	
	Lifetime	Years	50	
Generic technology for primary supply of vegetable food	Efficiency	Numeric value	1,04	Company specific data
	Fixed O&M cost	Euro/Thousand tons	73743	
	Lifetime	Years	50	
	Added value	Euro/Thousand tons	427597	[124]
Generic technology for primary supply of vegetable feed	Efficiency	Numeric value	1	Company specific data
	Fixed O&M cost	Euro/Thousand tons	50320	
	Lifetime	Years	50	
	Added value	Euro/Thousand tons	38366	[124]
Demand for vegetable food	Annual production	Thousand tons	265	[122]
Demand for vegetable feed	Annual production	Thousand tons	6	[122]

Data inputs for vegetable oils components

Component	Input parameter	Units	Initial value	Source
Domestic supply of vegetable oils	Cost	Euro/ Thousand tons	500	[122]
	Annual production	Thousand tons	64	[122]
Import of vegetable oils	Cost	Euro/ Thousand tons	761	[122]
	Annual production	Thousand tons	86	[122]
Export of vegetable oils	Cost	Euro/ Thousand tons	817	[122]
	Annual production	Thousand tons	23	[122]
Import of vegetable oils food	Cost	Euro/ Thousand tons	1425	[123]
	Annual production	Thousand tons	9	[123]
Export of vegetable oils food	Cost	Euro/ Thousand tons	2083	[123]
	Annual production	Thousand tons	1	[123]
Import of vegetable oils feed	Cost	Euro/ Thousand tons	387	[123]
	Annual production	Thousand tons	99	[123]
Export of vegetable oils feed	Cost	Euro/ Thousand tons	384	[123]
	Annual production	Thousand tons	22	[123]
Import of vegetable oils other products	Cost	Euro/ Thousand tons	822	[123]
	Annual production	Thousand tons	17	[123]
Export of vegetable oils other products	Cost	Euro/ Thousand tons	820	[123]
	Annual production	Thousand tons	60	[123]
Pretreatment of vegetable oils	Efficiency	Numeric value	1	Company specific data
	Fixed O&M cost	Euro/ Thousand tons	55000	
	Lifetime	Years	50	
Generic technology for primary supply of vegetable oils food	Efficiency	Numeric value	0.75	Company specific data
	Fixed O&M cost	Euro/ Thousand tons	347996	
	Lifetime	Years	50	
	Added value	Euro/ Thousand tons	427597	
Generic technology for primary supply of vegetable oils feed	Efficiency	Numeric value	1	Company specific data
	Fixed O&M cost	Euro/ Thousand tons	36000	
	Lifetime	Years	50	
	Added value	Euro/ Thousand tons	38366	
Generic technology for primary supply of vegetable oils other products	Efficiency	Numeric value	0.5	Company specific data
	Fixed O&M cost	Euro/ Thousand tons	147858	
	Lifetime	Years	50	
	Added value	Euro/ Thousand tons	88492	
Demand for vegetable oils food	Annual production	Thousand tons	29	[122]
Demand for vegetable oils feed	Annual production	Thousand tons	89	[122]
Demand for vegetable oils other products	Annual production	Thousand tons	27	[122]

Data inputs for new technologies in agriculture sector

Component	Input parameter	Units	Initial value	Source
New generic technology for primary supply of vegetable other products (bioplastic)	Efficiency	Numeric value	1	[125]
	Investment costs		1850000	[125]
	Fixed O&M cost	Euro/Thousand tons	665000	[125]
	Lifetime	Years	50	Experts opinion
	Starting year for availability of technology	Year	2025	Experts opinion
	Added value	Euro/ Thousand tons	160734.7	[124]
New generic technology for primary supply of vegetable other products (biodiesel)	Efficiency	Numeric value	1	[126]
	Investment costs		161265	[126]
	Fixed O&M cost	Euro/ Thousand tons	174179	[126]
	Lifetime	Years	50	Experts opinion
	Starting year for availability of technology	Year	2025	Experts opinion
	Added value	Euro/ Thousand tons	88492	[124]
New generic technology for primary supply of cereals food (fiber powder)	Efficiency	Numeric value	1	[127]
	Investment costs		2350000	[127]
	Fixed O&M cost	Euro/Tt	600000	[127]
	Lifetime	Years	50	Experts opinion
	Availability of technology	Year	2025	Experts opinion
	Added value	Euro/Tt	427597	[124]
New generic technology for primary supply of cereals other products (bioethanol)	Efficiency	Numeric value	0.5	[126]
	Investment costs		165778	[126]
	Fixed O&M cost	Euro/Tt	122681	[126]
	Lifetime	Years	50	Experts opinion
	Starting year for availability of technology	Year	2025	Experts opinion
	Added value	Euro/Tt	88492	[124]

Types of grains, vegetables and vegetable oils used in the model [122]

Area	Element	Item
Latvia	Production	Wheat and products
Latvia	Import quantity	Wheat and products
Latvia	Stock Variation	Wheat and products
Latvia	Export quantity	Wheat and products
Latvia	Domestic supply quantity	Wheat and products
Latvia	Feed	Wheat and products
Latvia	Seed	Wheat and products
Latvia	Losses	Wheat and products
Latvia	Processing	Wheat and products
Latvia	Food	Wheat and products
Latvia	Import quantity	Rice and products
Latvia	Stock Variation	Rice and products
Latvia	Export quantity	Rice and products
Latvia	Domestic supply quantity	Rice and products
Latvia	Food	Rice and products
Latvia	Production	Barley and products
Latvia	Import quantity	Barley and products
Latvia	Stock Variation	Barley and products
Latvia	Export quantity	Barley and products
Latvia	Domestic supply quantity	Barley and products
Latvia	Feed	Barley and products
Latvia	Seed	Barley and products
Latvia	Losses	Barley and products
Latvia	Processing	Barley and products
Latvia	Food	Barley and products
Latvia	Import quantity	Maize and products
Latvia	Stock Variation	Maize and products
Latvia	Export quantity	Maize and products
Latvia	Domestic supply quantity	Maize and products
Latvia	Feed	Maize and products
Latvia	Processing	Maize and products
Latvia	Food	Maize and products
Latvia	Production	Rye and products
Latvia	Import quantity	Rye and products
Latvia	Stock Variation	Rye and products
Latvia	Export quantity	Rye and products
Latvia	Domestic supply quantity	Rye and products
Latvia	Feed	Rye and products
Latvia	Seed	Rye and products
Latvia	Food	Rye and products

Latvia	Production	Oats
Latvia	Import quantity	Oats
Latvia	Stock Variation	Oats
Latvia	Export quantity	Oats
Latvia	Domestic supply quantity	Oats
Latvia	Feed	Oats
Latvia	Seed	Oats
Latvia	Losses	Oats
Latvia	Food	Oats
Latvia	Production	Cereals, other
Latvia	Import quantity	Cereals, other
Latvia	Stock Variation	Cereals, other
Latvia	Export quantity	Cereals, other
Latvia	Domestic supply quantity	Cereals, other
Latvia	Feed	Cereals, other
Latvia	Seed	Cereals, other
Latvia	Losses	Cereals, other
Latvia	Residuals	Cereals, other
Latvia	Food	Cereals, other
Latvia	Import quantity	Soyabean Oil
Latvia	Stock Variation	Soyabean Oil
Latvia	Export quantity	Soyabean Oil
Latvia	Domestic supply quantity	Soyabean Oil
Latvia	Processing	Soyabean Oil
Latvia	Food	Soyabean Oil
Latvia	Production	Sunflowerseed Oil
Latvia	Import quantity	Sunflowerseed Oil
Latvia	Domestic supply quantity	Sunflowerseed Oil
Latvia	Food	Sunflowerseed Oil
Latvia	Production	Rape and Mustard Oil
Latvia	Import quantity	Rape and Mustard Oil
Latvia	Stock Variation	Rape and Mustard Oil
Latvia	Export quantity	Rape and Mustard Oil
Latvia	Domestic supply quantity	Rape and Mustard Oil
Latvia	Processing	Rape and Mustard Oil
Latvia	Other uses (non-food)	Rape and Mustard Oil
Latvia	Food	Rape and Mustard Oil
Latvia	Import quantity	Palm Oil
Latvia	Domestic supply quantity	Palm Oil
Latvia	Other uses (non-food)	Palm Oil
Latvia	Import quantity	Olive Oil
Latvia	Export quantity	Olive Oil
Latvia	Domestic supply quantity	Olive Oil
Latvia	Food	Olive Oil
Latvia	Production	Oilcrops Oil, Other

Latvia	Import quantity	Oilcrops Oil, Other
Latvia	Stock Variation	Oilcrops Oil, Other
Latvia	Export quantity	Oilcrops Oil, Other
Latvia	Domestic supply quantity	Oilcrops Oil, Other
Latvia	Other uses (non-food)	Oilcrops Oil, Other
Latvia	Food	Oilcrops Oil, Other
Latvia	Production	Tomatoes and products
Latvia	Import quantity	Tomatoes and products
Latvia	Export quantity	Tomatoes and products
Latvia	Domestic supply quantity	Tomatoes and products
Latvia	Losses	Tomatoes and products
Latvia	Food	Tomatoes and products
Latvia	Production	Onions
Latvia	Import quantity	Onions
Latvia	Export quantity	Onions
Latvia	Domestic supply quantity	Onions
Latvia	Losses	Onions
Latvia	Residuals	Onions
Latvia	Food	Onions
Latvia	Production	Vegetables, other
Latvia	Import quantity	Vegetables, other
Latvia	Stock Variation	Vegetables, other
Latvia	Export quantity	Vegetables, other
Latvia	Domestic supply quantity	Vegetables, other
Latvia	Feed	Vegetables, other
Latvia	Losses	Vegetables, other
Latvia	Food	Vegetables, other

Mycelium model input data (2017-2022)

Years	2017	2018	2019	2020	2021	2022
Mycelium model.Absorption mycelium	0,0025	0,0025	0,0025	0,0025	0,0025	0,0025
Mycelium model.Alfalfa	6	6	6	6	6	6
Mycelium model.Annual wage	12000	12000	12000	12000	12000	12000
Mycelium model.Area Available	10000	10000	10000	10000	10000	10000
Mycelium model.Average construction time	3	3	3	3	3	3
Mycelium model.Carbon price	5,84	16,03	22	22	22,89329	51,75092
Mycelium model.Current electricity efficiency	12169	12169	12169	12169	12169	12169
Mycelium model.Current heat efficiency	9285	9285	9285	9285	9285	9285
Mycelium model.Decrease rate	0,01	0,01	0,01	0,01	0,01	0,01
Mycelium model.dT/q`	5	5	5	5	5	5
Mycelium model.Electricity emission factor	0,000102	0,000102	0,000102	0,000102	0,000102	0,000102
Mycelium model.Electricity tariff	100	100	100	100	100	100
Mycelium model.Energy tax amount	5	5	5	5	5	5
Mycelium model.Energy efficiency	50	50	50	50	50	50
Mycelium model.Final material mass fraction	0,147654	0,147654	0,147654	0,147654	0,147654	0,147654
Mycelium model.Floor Height	2,5	2,5	2,5	2,5	2,5	2,5
Mycelium model.Floor Length	80	80	80	80	80	80
Mycelium model.Floor Width	25	25	25	25	25	25
Mycelium model.Floors in a building	6	6	6	6	6	6
Mycelium model.Fraction of initial capacity	0,001	0,001	0,001	0,001	0,001	0,001
Mycelium model.Heating emission factor	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05
Mycelium model.Initial current yield	90	90	90	90	90	90
Mycelium model.Initial market share[Mycelium]	0,01	0,01	0,01	0,01	0,01	0,01
Mycelium model.Initial market share[Rockwool]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial market share[Glasswool]	0,29	0,29	0,29	0,29	0,29	0,29
Mycelium model.Initial market share[EPS]	0,3	0,3	0,3	0,3	0,3	0,3
Mycelium model.Initial market share[XPS]	0,2	0,2	0,2	0,2	0,2	0,2
Mycelium model.Initial market share[Polyurethane]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial Time of land allocation	5	5	5	5	5	5
Mycelium model.Insulation material embodied emissions[Mycelium]	0	-0,25014	-0,29417	-0,3388	-0,37168	-0,38463

Years	2017	2018	2019	2020	2021	2022
Mycelium model.Insulation material embodied emissions[Rockwool]	0,126	0,126	0,126	0,126	0,126	0,126
Mycelium model.Insulation material embodied emissions[Glasswool]	0,0682	0,0682	0,0682	0,0682	0,0682	0,0682
Mycelium model.Insulation material embodied emissions[EPS]	0,2312	0,2312	0,2312	0,2312	0,2312	0,2312
Mycelium model.Insulation material embodied emissions[XPS]	0,2718	0,2718	0,2718	0,2718	0,2718	0,2718
Mycelium model.Insulation material embodied emissions[Polyurethane]	0,5605	0,5605	0,5605	0,5605	0,5605	0,5605
Mycelium model.Insulation material embodied energy[Mycelium]	0	15989,26	14381,15	12750,84	11550,13	11077,24
Mycelium model.Insulation material embodied energy[Rockwool]	2016	2016	2016	2016	2016	2016
Mycelium model.Insulation material embodied energy[Glasswool]	1232	1232	1232	1232	1232	1232
Mycelium model.Insulation material embodied energy[EPS]	3532,6	3532,6	3532,6	3532,6	3532,6	3532,6
Mycelium model.Insulation material embodied energy[XPS]	3200,4	3200,4	3200,4	3200,4	3200,4	3200,4
Mycelium model.Insulation material embodied energy[Polyurethane]	10184	10184	10184	10184	10184	10184
Mycelium model.Insulation material prices[Mycelium]	110,52	323,3339	289,7771	253,803	226,1717	215,2212
Mycelium model.Insulation material prices[Rockwool]	13,4	13,4	13,4	13,4	13,4	13,4
Mycelium model.Insulation material prices[Glasswool]	10,1	10,1	10,1	10,1	10,1	10,1
Mycelium model.Insulation material prices[EPS]	10,75	10,75	10,75	10,75	10,75	10,75
Mycelium model.Insulation material prices[XPS]	17,22	17,22	17,22	17,22	17,22	17,22
Mycelium model.Insulation material prices[Polyurethane]	20,08	20,08	20,08	20,08	20,08	20,08
Mycelium model.Insulation material thermal conductivity[Mycelium]	0,04	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[Rockwool]	0,0365	0,0365	0,0365	0,0365	0,0365	0,0365
Mycelium model.Insulation material thermal conductivity[Glasswool]	0,04	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[EPS]	0,035	0,035	0,035	0,035	0,035	0,035
Mycelium model.Insulation material thermal conductivity[XPS]	0,0345	0,0345	0,0345	0,0345	0,0345	0,0345
Mycelium model.Insulation material thermal conductivity[Polyurethane]	0,0285	0,0285	0,0285	0,0285	0,0285	0,0285
Mycelium model.kWh to J	3600000	3600000	3600000	3600000	3600000	3600000

Years	2017	2018	2019	2020	2021	2022
Mycelium model.kWh to MJ	3,6	3,6	3,6	3,6	3,6	3,6
Mycelium model.Market reaction time	1	1	1	1	1	1
Mycelium model.Material absorption factors[Destilled water]	0	0	0	0	0	0
Mycelium model.Material absorption factors[Wood chips]	1,835	1,835	1,835	1,835	1,835	1,835
Mycelium model.Material absorption factors[Mollases]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Material absorption factors[Xanthan]	0,048	0,048	0,048	0,048	0,048	0,048
Mycelium model.Material absorption factors[Soda]	0,524	0,524	0,524	0,524	0,524	0,524
Mycelium model.Material absorption factors[Starch]	0,174	0,174	0,174	0,174	0,174	0,174
Mycelium model.Material absorption factors[Whey powder]	0,98	0,98	0,98	0,98	0,98	0,98
Mycelium model.Material absorption factors[Straw]	1,468	1,468	1,468	1,468	1,468	1,468
Mycelium model.Material absorption factors[Carbamide]	0,73	0,73	0,73	0,73	0,73	0,73
Mycelium model.Material costs	929	929	929	929	929	929
Mycelium model.Material density	0,081205	0,081205	0,081205	0,081205	0,081205	0,081205
Mycelium model.Material emission factors[Destilled water]	0,0008	0,0008	0,0008	0,0008	0,0008	0,0008
Mycelium model.Material emission factors[Wood chips]	0,000187	0,000187	0,000187	0,000187	0,000187	0,000187
Mycelium model.Material emission factors[Mollases]	0,074	0,074	0,074	0,074	0,074	0,074
Mycelium model.Material emission factors[Xanthan]	0,00497	0,00497	0,00497	0,00497	0,00497	0,00497
Mycelium model.Material emission factors[Soda]	1,17	1,17	1,17	1,17	1,17	1,17
Mycelium model.Material emission factors[Starch]	2,4	2,4	2,4	2,4	2,4	2,4
Mycelium model.Material emission factors[Whey powder]	0,00082	0,00082	0,00082	0,00082	0,00082	0,00082
Mycelium model.Material emission factors[Straw]	0,1036	0,1036	0,1036	0,1036	0,1036	0,1036
Mycelium model.Material emission factors[Carbamide]	1,85	1,85	1,85	1,85	1,85	1,85
Mycelium model.Mycelium fraction	0,000213	0,000213	0,000213	0,000213	0,000213	0,000213
Mycelium model.Other costs	432	432	432	432	432	432
Mycelium model.Perceived electricity efficiency	-596281	-596281	-596281	-596281	-596281	-596281
Mycelium model.Perceived heat efficiency	-454965	-454965	-454965	-454965	-454965	-454965
Mycelium model.Perceived maximum current yield	100	100	100	100	100	100
Mycelium model.Perceived maximum development yield	110	110	110	110	110	110
Mycelium model.Perceived maximum yield	120	120	120	120	120	120
Mycelium model.Raw material fractions[Destilled water]	0,47148	0,47148	0,47148	0,47148	0,47148	0,47148

Years	2017	2018	2019	2020	2021	2022
Mycelium model.Raw material fractions[Wood chips]	0,344201	0,344201	0,344201	0,344201	0,344201	0,344201
Mycelium model.Raw material fractions[Mollases]	0,013637	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Xanthan]	0,004182	0,004182	0,004182	0,004182	0,004182	0,004182
Mycelium model.Raw material fractions[Soda]	0,024729	0,024729	0,024729	0,024729	0,024729	0,024729
Mycelium model.Raw material fractions[Starch]	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637
Mycelium model.Raw material fractions[Whey powder]	0,013637	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Straw]	0,114734	0,114734	0,114734	0,114734	0,114734	0,114734
Mycelium model.Raw material fractions[Carbamide]	0,001764	0,001764	0,001764	0,001764	0,001764	0,001764
Mycelium model.Raw material used in production[Distilled water]	0	1,28E-07	0,007501	0,052621	0,094765	0,132873
Mycelium model.Raw material used in production[Wood chips]	0	9,33E-08	0,005476	0,038416	0,069183	0,097003
Mycelium model.Raw material used in production[Mollases]	0	3,70E-09	0,000217	0,001522	0,002741	0,003843
Mycelium model.Raw material used in production[Xanthan]	0	1,13E-09	6,65E-05	0,000467	0,000841	0,001179
Mycelium model.Raw material used in production[Soda]	0	6,70E-09	0,000393	0,00276	0,00497	0,006969
Mycelium model.Raw material used in production[Starch]	0	3,15E-09	0,000185	0,001299	0,002339	0,00328
Mycelium model.Raw material used in production[Whey powder]	0	3,70E-09	0,000217	0,001522	0,002741	0,003843
Mycelium model.Raw material used in production[Straw]	0	3,11E-08	0,001825	0,012805	0,023061	0,032334
Mycelium model.Raw material used in production[Carbamide]	0	4,78E-10	2,81E-05	0,000197	0,000355	0,000497
Mycelium model.Subsidies	0	0	0	0	0	0
Mycelium model.Time to develop energy	10	10	10	10	10	10
Mycelium model.Time to educate	10	10	10	10	10	10
Mycelium model.Time to research energy	20	20	20	20	20	20
Mycelium model.Time to sell	0,25	0,25	0,25	0,25	0,25	0,25
Mycelium model.Transformities[Distilled water]	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11
Mycelium model.Transformities[Wood chips]	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13
Mycelium model.Transformities[Mollases]	2E+15	2E+15	2E+15	2E+15	2E+15	2E+15
Mycelium model.Transformities[Xanthan]	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16
Mycelium model.Transformities[Soda]	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15
Mycelium model.Transformities[Starch]	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15
Mycelium model.Transformities[Whey powder]	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15

Years	2017	2018	2019	2020	2021	2022
Mycelium model.Transformities[Straw]	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15
Mycelium model.Transformities[Carbamide]	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15
Mycelium model.Transformity electricity	290000	290000	290000	290000	290000	290000
Mycelium model.Transformity EUR	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11

Mycelium model input data (2023-2028)

Years	2023	2024	2025	2026	2027	2028
Mycelium model.Absorption mycelium	0,0025	0,0025	0,0025	0,0025	0,0025	0,0025
Mycelium model.Alfa	6	6	6	6	6	6
Mycelium model.Annual wage	12000	12000	12000	12000	12000	12000
Mycelium model.Area Available	10000	10000	10000	10000	10000	10000
Mycelium model.Average construction time	3	3	3	3	3	3
Mycelium model.Carbon price	53,85221	56,03883	58,31423	60,68202	63,14596	65,70994
Mycelium model.Current electricity efficiency	12169	12169	12169	12169	12169	12169
Mycelium model.Current heat efficiency	9285	9285	9285	9285	9285	9285
Mycelium model.Decrease rate	0,01	0,01	0,01	0,01	0,01	0,01
Mycelium model.dT/q`	5	5	5	5	5	5
Mycelium model.Electricity emission factor	0,000102	0,000102	0,000102	0,000102	0,000102	0,000102
Mycelium model.Electricity tariff	100	100	100	100	100	100
Mycelium model.Emergy tax amount	5	5	5	5	5	5
Mycelium model.Energy efficiency	50	50	50	50	50	50
Mycelium model.Final material mass fraction	0,147654	0,147654	0,147654	0,147654	0,147654	0,147654
Mycelium model.Floor Height	2,5	2,5	2,5	2,5	2,5	2,5
Mycelium model.Floor Length	80	80	80	80	80	80
Mycelium model.Floor Width	25	25	25	25	25	25
Mycelium model.Floors in a building	6	6	6	6	6	6
Mycelium model.Fraction of initial capacity	0,001	0,001	0,001	0,001	0,001	0,001
Mycelium model.Heating emission factor	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05
Mycelium model.Initial current yield	90	90	90	90	90	90
Mycelium model.Initial market share[Mycelium]	0,01	0,01	0,01	0,01	0,01	0,01
Mycelium model.Initial market share[Rockwool]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial market share[Glasswool]	0,29	0,29	0,29	0,29	0,29	0,29
Mycelium model.Initial market share[EPS]	0,3	0,3	0,3	0,3	0,3	0,3
Mycelium model.Initial market share[XPS]	0,2	0,2	0,2	0,2	0,2	0,2
Mycelium model.Initial market share[Polyurethane]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial Time of land allocation	5	5	5	5	5	5
Mycelium model.Insulation material embodied emissions[Mycelium]	-0,39094	-0,39437	-0,39637	-0,39763	-0,39856	-0,39933

Years	2023	2024	2025	2026	2027	2028
Mycelium model. Insulation material embodied emissions[Rockwool]	0,126	0,126	0,126	0,126	0,126	0,126
Mycelium model. Insulation material embodied emissions[Glasswool]	0,0682	0,0682	0,0682	0,0682	0,0682	0,0682
Mycelium model. Insulation material embodied emissions[EPS]	0,2312	0,2312	0,2312	0,2312	0,2312	0,2312
Mycelium model. Insulation material embodied emissions[XPS]	0,2718	0,2718	0,2718	0,2718	0,2718	0,2718
Mycelium model. Insulation material embodied emissions[Polyurethane]	0,5605	0,5605	0,5605	0,5605	0,5605	0,5605
Mycelium model. Insulation material embodied energy[Mycelium]	10846,51	10721,24	10648,4	10602,26	10568,43	10540,16
Mycelium model. Insulation material embodied energy[Rockwool]	2016	2016	2016	2016	2016	2016
Mycelium model. Insulation material embodied energy[Glasswool]	1232	1232	1232	1232	1232	1232
Mycelium model. Insulation material embodied energy[EPS]	3532,6	3532,6	3532,6	3532,6	3532,6	3532,6
Mycelium model. Insulation material embodied energy[XPS]	3200,4	3200,4	3200,4	3200,4	3200,4	3200,4
Mycelium model. Insulation material embodied energy[Polyurethane]	10184	10184	10184	10184	10184	10184
Mycelium model. Insulation material prices[Mycelium]	209,9075	207,1107	205,6039	204,7667	204,2253	203,7942
Mycelium model. Insulation material prices[Rockwool]	13,4	13,4	13,4	13,4	13,4	13,4
Mycelium model. Insulation material prices[Glasswool]	10,1	10,1	10,1	10,1	10,1	10,1
Mycelium model. Insulation material prices[EPS]	10,75	10,75	10,75	10,75	10,75	10,75
Mycelium model. Insulation material prices[XPS]	17,22	17,22	17,22	17,22	17,22	17,22
Mycelium model. Insulation material prices[Polyurethane]	20,08	20,08	20,08	20,08	20,08	20,08
Mycelium model. Insulation material thermal conductivity[Mycelium]	0,04	0,04	0,04	0,04	0,04	0,04
Mycelium model. Insulation material thermal conductivity[Rockwool]	0,0365	0,0365	0,0365	0,0365	0,0365	0,0365
Mycelium model. Insulation material thermal conductivity[Glasswool]	0,04	0,04	0,04	0,04	0,04	0,04
Mycelium model. Insulation material thermal conductivity[EPS]	0,035	0,035	0,035	0,035	0,035	0,035
Mycelium model. Insulation material thermal conductivity[XPS]	0,0345	0,0345	0,0345	0,0345	0,0345	0,0345

Years	2023	2024	2025	2026	2027	2028
Mycelium model.Insulation material thermal conductivity[Polyurethane]	0,0285	0,0285	0,0285	0,0285	0,0285	0,0285
Mycelium model.kWh to J	3600000	3600000	3600000	3600000	3600000	3600000
Mycelium model.kWh to MJ	3,6	3,6	3,6	3,6	3,6	3,6
Mycelium model.Market reaction time	1	1	1	1	1	1
Mycelium model.Material absorption factors[Distilled water]	0	0	0	0	0	0
Mycelium model.Material absorption factors[Wood chips]	1,835	1,835	1,835	1,835	1,835	1,835
Mycelium model.Material absorption factors[Mollases]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Material absorption factors[Xanthan]	0,048	0,048	0,048	0,048	0,048	0,048
Mycelium model.Material absorption factors[Soda]	0,524	0,524	0,524	0,524	0,524	0,524
Mycelium model.Material absorption factors[Starch]	0,174	0,174	0,174	0,174	0,174	0,174
Mycelium model.Material absorption factors[Whey powder]	0,98	0,98	0,98	0,98	0,98	0,98
Mycelium model.Material absorption factors[Straw]	1,468	1,468	1,468	1,468	1,468	1,468
Mycelium model.Material absorption factors[Carbamide]	0,73	0,73	0,73	0,73	0,73	0,73
Mycelium model.Material costs	929	929	929	929	929	929
Mycelium model.Material density	0,081205	0,081205	0,081205	0,081205	0,081205	0,081205
Mycelium model.Material emission factors[Distilled water]	0,0008	0,0008	0,0008	0,0008	0,0008	0,0008
Mycelium model.Material emission factors[Wood chips]	0,000187	0,000187	0,000187	0,000187	0,000187	0,000187
Mycelium model.Material emission factors[Mollases]	0,074	0,074	0,074	0,074	0,074	0,074
Mycelium model.Material emission factors[Xanthan]	0,00497	0,00497	0,00497	0,00497	0,00497	0,00497
Mycelium model.Material emission factors[Soda]	1,17	1,17	1,17	1,17	1,17	1,17
Mycelium model.Material emission factors[Starch]	2,4	2,4	2,4	2,4	2,4	2,4
Mycelium model.Material emission factors[Whey powder]	0,00082	0,00082	0,00082	0,00082	0,00082	0,00082
Mycelium model.Material emission factors[Straw]	0,1036	0,1036	0,1036	0,1036	0,1036	0,1036
Mycelium model.Material emission factors[Carbamide]	1,85	1,85	1,85	1,85	1,85	1,85
Mycelium model.Mycelium fraction	0,000213	0,000213	0,000213	0,000213	0,000213	0,000213
Mycelium model.Other costs	432	432	432	432	432	432
Mycelium model.Perceived electricity efficiency	-596281	-596281	-596281	-596281	-596281	-596281
Mycelium model.Perceived heat efficiency	-454965	-454965	-454965	-454965	-454965	-454965
Mycelium model.Perceived maximum current yield	100	100	100	100	100	100

Years	2023	2024	2025	2026	2027	2028
Mycelium model.Perceived maximum development yield	110	110	110	110	110	110
Mycelium model.Perceived maximum yield	120	120	120	120	120	120
Mycelium model.Raw material fractions[Distilled water]	0,47148	0,47148	0,47148	0,47148	0,47148	0,47148
Mycelium model.Raw material fractions[Wood chips]	0,344201	0,344201	0,344201	0,344201	0,344201	0,344201
Mycelium model.Raw material fractions[Mollases]	0,013637	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Xanthan]	0,004182	0,004182	0,004182	0,004182	0,004182	0,004182
Mycelium model.Raw material fractions[Soda]	0,024729	0,024729	0,024729	0,024729	0,024729	0,024729
Mycelium model.Raw material fractions[Starch]	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637
Mycelium model.Raw material fractions[Whey powder]	0,013637	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Straw]	0,114734	0,114734	0,114734	0,114734	0,114734	0,114734
Mycelium model.Raw material fractions[Carbamide]	0,001764	0,001764	0,001764	0,001764	0,001764	0,001764
Mycelium model.Raw material used in production[Distilled water]	0,164755	0,187874	0,201485	0,206417	0,204443	0,197071
Mycelium model.Raw material used in production[Wood chips]	0,120278	0,137156	0,147093	0,150693	0,149252	0,14387
Mycelium model.Raw material used in production[Mollases]	0,004765	0,005434	0,005828	0,00597	0,005913	0,0057
Mycelium model.Raw material used in production[Xanthan]	0,001461	0,001666	0,001787	0,001831	0,001813	0,001748
Mycelium model.Raw material used in production[Soda]	0,008641	0,009854	0,010568	0,010827	0,010723	0,010336
Mycelium model.Raw material used in production[Starch]	0,004066	0,004637	0,004973	0,005095	0,005046	0,004864
Mycelium model.Raw material used in production[Whey powder]	0,004765	0,005434	0,005828	0,00597	0,005913	0,0057
Mycelium model.Raw material used in production[Straw]	0,040093	0,045719	0,049031	0,050231	0,049751	0,047957
Mycelium model.Raw material used in production[Carbamide]	0,000616	0,000703	0,000754	0,000772	0,000765	0,000737
Mycelium model.Subsidies	0	0	0	0	0	0
Mycelium model.Time to develop energy	10	10	10	10	10	10
Mycelium model.Time to educate	10	10	10	10	10	10
Mycelium model.Time to research energy	20	20	20	20	20	20
Mycelium model.Time to sell	0,25	0,25	0,25	0,25	0,25	0,25
Mycelium model.Transformities[Distilled water]	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11
Mycelium model.Transformities[Wood chips]	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13
Mycelium model.Transformities[Mollases]	2E+15	2E+15	2E+15	2E+15	2E+15	2E+15

Years	2023	2024	2025	2026	2027	2028
Mycelium model.Transformities[Xanthan]	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16
Mycelium model.Transformities[Soda]	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15
Mycelium model.Transformities[Starch]	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15
Mycelium model.Transformities[Whey powder]	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15
Mycelium model.Transformities[Straw]	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15
Mycelium model.Transformities[Carbamide]	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15
Mycelium model.Transformity electricity	290000	290000	290000	290000	290000	290000
Mycelium model.Transformity EUR	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11

Mycelium model input data (2029-2034)

Years	2029	2030	2031	2032	2033	2034
Mycelium model.Absorption mycelium	0,0025	0,0025	0,0025	0,0025	0,0025	0,0025
Mycelium model.Alfalfa	6	6	6	6	6	6
Mycelium model.Annual wage	12000	12000	12000	12000	12000	12000
Mycelium model.Area Available	10000	10000	10000	10000	10000	10000
Mycelium model.Average construction time	3	3	3	3	3	3
Mycelium model.Carbon price	68,37802	71,15444	74,0436	77,05007	80,17861	83,43418
Mycelium model.Current electricity efficiency	12169	12169	12169	12169	12169	12169
Mycelium model.Current heat efficiency	9285	9285	9285	9285	9285	9285
Mycelium model.Decrease rate	0,01	0,01	0,01	0,01	0,01	0,01
Mycelium model.dT/q`	5	5	5	5	5	5
Mycelium model.Electricity emission factor	0,000102	0,000102	0,000102	0,000102	0,000102	0,000102
Mycelium model.Electricity tariff	100	100	100	100	100	100
Mycelium model.Energy tax amount	5	5	5	5	5	5
Mycelium model.Energy efficiency	50	50	50	50	50	50
Mycelium model.Final material mass fraction	0,147654	0,147654	0,147654	0,147654	0,147654	0,147654
Mycelium model.Floor Height	2,5	2,5	2,5	2,5	2,5	2,5
Mycelium model.Floor Length	80	80	80	80	80	80
Mycelium model.Floor Width	25	25	25	25	25	25
Mycelium model.Floors in a building	6	6	6	6	6	6
Mycelium model.Fraction of initial capacity	0,001	0,001	0,001	0,001	0,001	0,001
Mycelium model.Heating emission factor	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05
Mycelium model.Initial current yield	90	90	90	90	90	90
Mycelium model.Initial market share[Mycelium]	0,01	0,01	0,01	0,01	0,01	0,01
Mycelium model.Initial market share[Rockwool]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial market share[Glasswool]	0,29	0,29	0,29	0,29	0,29	0,29
Mycelium model.Initial market share[EPS]	0,3	0,3	0,3	0,3	0,3	0,3
Mycelium model.Initial market share[XPS]	0,2	0,2	0,2	0,2	0,2	0,2
Mycelium model.Initial market share[Polyurethane]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial Time of land allocation	5	5	5	5	5	5
Mycelium model.Insulation material embodied emissions[Mycelium]	-0,40013	-0,4012	-0,40281	-0,405	-0,40748	-0,40977

Years	2029	2030	2031	2032	2033	2034
Mycelium model.Insulation material embodied emissions[Rockwool]	0,126	0,126	0,126	0,126	0,126	0,126
Mycelium model.Insulation material embodied emissions[Glasswool]	0,0682	0,0682	0,0682	0,0682	0,0682	0,0682
Mycelium model.Insulation material embodied emissions[EPS]	0,2312	0,2312	0,2312	0,2312	0,2312	0,2312
Mycelium model.Insulation material embodied emissions[XPS]	0,2718	0,2718	0,2718	0,2718	0,2718	0,2718
Mycelium model.Insulation material embodied emissions[Polyurethane]	0,5605	0,5605	0,5605	0,5605	0,5605	0,5605
Mycelium model.Insulation material embodied energy[Mycelium]	10510,94	10471,75	10413,14	10333	10242,54	10158,88
Mycelium model.Insulation material embodied energy[Rockwool]	2016	2016	2016	2016	2016	2016
Mycelium model.Insulation material embodied energy[Glasswool]	1232	1232	1232	1232	1232	1232
Mycelium model.Insulation material embodied energy[EPS]	3532,6	3532,6	3532,6	3532,6	3532,6	3532,6
Mycelium model.Insulation material embodied energy[XPS]	3200,4	3200,4	3200,4	3200,4	3200,4	3200,4
Mycelium model.Insulation material embodied energy[Polyurethane]	10184	10184	10184	10184	10184	10184
Mycelium model.Insulation material prices[Mycelium]	203,26	202,2789	200,4354	197,5525	194,0085	190,5177
Mycelium model.Insulation material prices[Rockwool]	13,4	13,4	13,4	13,4	13,4	13,4
Mycelium model.Insulation material prices[Glasswool]	10,1	10,1	10,1	10,1	10,1	10,1
Mycelium model.Insulation material prices[EPS]	10,75	10,75	10,75	10,75	10,75	10,75
Mycelium model.Insulation material prices[XPS]	17,22	17,22	17,22	17,22	17,22	17,22
Mycelium model.Insulation material prices[Polyurethane]	20,08	20,08	20,08	20,08	20,08	20,08
Mycelium model.Insulation material thermal conductivity[Mycelium]	0,04	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[Rockwool]	0,0365	0,0365	0,0365	0,0365	0,0365	0,0365
Mycelium model.Insulation material thermal conductivity[Glasswool]	0,04	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[EPS]	0,035	0,035	0,035	0,035	0,035	0,035
Mycelium model.Insulation material thermal conductivity[XPS]	0,0345	0,0345	0,0345	0,0345	0,0345	0,0345
Mycelium model.Insulation material thermal conductivity[Polyurethane]	0,0285	0,0285	0,0285	0,0285	0,0285	0,0285
Mycelium model.kWh to J	3600000	3600000	3600000	3600000	3600000	3600000

Years	2029	2030	2031	2032	2033	2034
Mycelium model.kWh to MJ	3,6	3,6	3,6	3,6	3,6	3,6
Mycelium model.Market reaction time	1	1	1	1	1	1
Mycelium model.Material absorption factors[Destilled water]	0	0	0	0	0	0
Mycelium model.Material absorption factors[Wood chips]	1,835	1,835	1,835	1,835	1,835	1,835
Mycelium model.Material absorption factors[Mollases]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Material absorption factors[Xanthan]	0,048	0,048	0,048	0,048	0,048	0,048
Mycelium model.Material absorption factors[Soda]	0,524	0,524	0,524	0,524	0,524	0,524
Mycelium model.Material absorption factors[Starch]	0,174	0,174	0,174	0,174	0,174	0,174
Mycelium model.Material absorption factors[Whey powder]	0,98	0,98	0,98	0,98	0,98	0,98
Mycelium model.Material absorption factors[Straw]	1,468	1,468	1,468	1,468	1,468	1,468
Mycelium model.Material absorption factors[Carbamide]	0,73	0,73	0,73	0,73	0,73	0,73
Mycelium model.Material costs	929	929	929	929	929	929
Mycelium model.Material density	0,081205	0,081205	0,081205	0,081205	0,081205	0,081205
Mycelium model.Material emission factors[Destilled water]	0,0008	0,0008	0,0008	0,0008	0,0008	0,0008
Mycelium model.Material emission factors[Wood chips]	0,000187	0,000187	0,000187	0,000187	0,000187	0,000187
Mycelium model.Material emission factors[Mollases]	0,074	0,074	0,074	0,074	0,074	0,074
Mycelium model.Material emission factors[Xanthan]	0,00497	0,00497	0,00497	0,00497	0,00497	0,00497
Mycelium model.Material emission factors[Soda]	1,17	1,17	1,17	1,17	1,17	1,17
Mycelium model.Material emission factors[Starch]	2,4	2,4	2,4	2,4	2,4	2,4
Mycelium model.Material emission factors[Whey powder]	0,00082	0,00082	0,00082	0,00082	0,00082	0,00082
Mycelium model.Material emission factors[Straw]	0,1036	0,1036	0,1036	0,1036	0,1036	0,1036
Mycelium model.Material emission factors[Carbamide]	1,85	1,85	1,85	1,85	1,85	1,85
Mycelium model.Mycelium fraction	0,000213	0,000213	0,000213	0,000213	0,000213	0,000213
Mycelium model.Other costs	432	432	432	432	432	432
Mycelium model.Perceived electricity efficiency	-596281	-596281	-596281	-596281	-596281	-596281
Mycelium model.Perceived heat efficiency	-454965	-454965	-454965	-454965	-454965	-454965
Mycelium model.Perceived maximum current yield	100	100	100	100	100	100
Mycelium model.Perceived maximum development yield	110	110	110	110	110	110
Mycelium model.Perceived maximum yield	120	120	120	120	120	120
Mycelium model.Raw material fractions[Destilled water]	0,47148	0,47148	0,47148	0,47148	0,47148	0,47148

Years	2029	2030	2031	2032	2033	2034
Mycelium model.Raw material fractions[Wood chips]	0,344201	0,344201	0,344201	0,344201	0,344201	0,344201
Mycelium model.Raw material fractions[Mollases]	0,013637	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Xanthan]	0,004182	0,004182	0,004182	0,004182	0,004182	0,004182
Mycelium model.Raw material fractions[Soda]	0,024729	0,024729	0,024729	0,024729	0,024729	0,024729
Mycelium model.Raw material fractions[Starch]	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637
Mycelium model.Raw material fractions[Whey powder]	0,013637	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Straw]	0,114734	0,114734	0,114734	0,114734	0,114734	0,114734
Mycelium model.Raw material fractions[Carbamide]	0,001764	0,001764	0,001764	0,001764	0,001764	0,001764
Mycelium model.Raw material used in production[Distilled water]	0,186768	0,177405	0,173963	0,181816	0,205873	0,249893
Mycelium model.Raw material used in production[Wood chips]	0,136349	0,129513	0,127001	0,132734	0,150296	0,182433
Mycelium model.Raw material used in production[Mollases]	0,005402	0,005131	0,005032	0,005259	0,005955	0,007228
Mycelium model.Raw material used in production[Xanthan]	0,001657	0,001574	0,001543	0,001613	0,001826	0,002217
Mycelium model.Raw material used in production[Soda]	0,009796	0,009305	0,009124	0,009536	0,010798	0,013107
Mycelium model.Raw material used in production[Starch]	0,00461	0,004379	0,004294	0,004488	0,005081	0,006168
Mycelium model.Raw material used in production[Whey powder]	0,005402	0,005131	0,005032	0,005259	0,005955	0,007228
Mycelium model.Raw material used in production[Straw]	0,04545	0,043171	0,042334	0,044245	0,050099	0,060811
Mycelium model.Raw material used in production[Carbamide]	0,000699	0,000664	0,000651	0,00068	0,00077	0,000935
Mycelium model.Subsidies	0	0	0	0	0	0
Mycelium model.Time to develop energy	10	10	10	10	10	10
Mycelium model.Time to educate	10	10	10	10	10	10
Mycelium model.Time to research energy	20	20	20	20	20	20
Mycelium model.Time to sell	0,25	0,25	0,25	0,25	0,25	0,25
Mycelium model.Transformities[Distilled water]	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11
Mycelium model.Transformities[Wood chips]	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13
Mycelium model.Transformities[Mollases]	2E+15	2E+15	2E+15	2E+15	2E+15	2E+15
Mycelium model.Transformities[Xanthan]	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16
Mycelium model.Transformities[Soda]	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15
Mycelium model.Transformities[Starch]	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15
Mycelium model.Transformities[Whey powder]	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15

Years	2029	2030	2031	2032	2033	2034
Mycelium model.Transformities[Straw]	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15
Mycelium model.Transformities[Carbamide]	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15
Mycelium model.Transformity electricity	290000	290000	290000	290000	290000	290000
Mycelium model.Transformity EUR	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11

Mycelium model input data (2035-2040)

Years	2035	2036	2037	2038	2039	2040
Mycelium model.Absorption mycelium	0,0025	0,0025	0,0025	0,0025	0,0025	0,0025
Mycelium model.Alfalfa	6	6	6	6	6	6
Mycelium model.Annual wage	12000	12000	12000	12000	12000	12000
Mycelium model.Area Available	10000	10000	10000	10000	10000	10000
Mycelium model.Average construction time	3	3	3	3	3	3
Mycelium model.Carbon price	86,82194	90,34726	94,01573	97,83314	101,8056	105,9393
Mycelium model.Current electricity efficiency	12169	12169	12169	12169	12169	12169
Mycelium model.Current heat efficiency	9285	9285	9285	9285	9285	9285
Mycelium model.Decrease rate	0,01	0,01	0,01	0,01	0,01	0,01
Mycelium model.dT/q`	5	5	5	5	5	5
Mycelium model.Electricity emission factor	0,000102	0,000102	0,000102	0,000102	0,000102	0,000102
Mycelium model.Electricity tariff	100	100	100	100	100	100
Mycelium model.Energy tax amount	5	5	5	5	5	5
Mycelium model.Energy efficiency	50	50	50	50	50	50
Mycelium model.Final material mass fraction	0,147654	0,147654	0,147654	0,147654	0,147654	0,147654
Mycelium model.Floor Height	2,5	2,5	2,5	2,5	2,5	2,5
Mycelium model.Floor Length	80	80	80	80	80	80
Mycelium model.Floor Width	25	25	25	25	25	25
Mycelium model.Floors in a building	6	6	6	6	6	6
Mycelium model.Fraction of initial capacity	0,001	0,001	0,001	0,001	0,001	0,001
Mycelium model.Heating emission factor	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05
Mycelium model.Initial current yield	90	90	90	90	90	90
Mycelium model.Initial market share[Mycelium]	0,01	0,01	0,01	0,01	0,01	0,01
Mycelium model.Initial market share[Rockwool]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial market share[Glasswool]	0,29	0,29	0,29	0,29	0,29	0,29
Mycelium model.Initial market share[EPS]	0,3	0,3	0,3	0,3	0,3	0,3
Mycelium model.Initial market share[XPS]	0,2	0,2	0,2	0,2	0,2	0,2
Mycelium model.Initial market share[Polyurethane]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial Time of land allocation	5	5	5	5	5	5
Mycelium model.Insulation material embodied emissions[Mycelium]	-0,41159	-0,41292	-0,41385	-0,41451	-0,41498	-0,41532

Years	2035	2036	2037	2038	2039	2040
Mycelium model.Insulation material embodied emissions[Rockwool]	0,126	0,126	0,126	0,126	0,126	0,126
Mycelium model.Insulation material embodied emissions[Glasswool]	0,0682	0,0682	0,0682	0,0682	0,0682	0,0682
Mycelium model.Insulation material embodied emissions[EPS]	0,2312	0,2312	0,2312	0,2312	0,2312	0,2312
Mycelium model.Insulation material embodied emissions[XPS]	0,2718	0,2718	0,2718	0,2718	0,2718	0,2718
Mycelium model.Insulation material embodied emissions[Polyurethane]	0,5605	0,5605	0,5605	0,5605	0,5605	0,5605
Mycelium model.Insulation material embodied energy[Mycelium]	10092,39	10043,93	10009,82	9985,851	9968,756	9956,293
Mycelium model.Insulation material embodied energy[Rockwool]	2016	2016	2016	2016	2016	2016
Mycelium model.Insulation material embodied energy[Glasswool]	1232	1232	1232	1232	1232	1232
Mycelium model.Insulation material embodied energy[EPS]	3532,6	3532,6	3532,6	3532,6	3532,6	3532,6
Mycelium model.Insulation material embodied energy[XPS]	3200,4	3200,4	3200,4	3200,4	3200,4	3200,4
Mycelium model.Insulation material embodied energy[Polyurethane]	10184	10184	10184	10184	10184	10184
Mycelium model.Insulation material prices[Mycelium]	187,5852	185,3229	183,6214	182,3254	181,306	180,4716
Mycelium model.Insulation material prices[Rockwool]	13,4	13,4	13,4	13,4	13,4	13,4
Mycelium model.Insulation material prices[Glasswool]	10,1	10,1	10,1	10,1	10,1	10,1
Mycelium model.Insulation material prices[EPS]	10,75	10,75	10,75	10,75	10,75	10,75
Mycelium model.Insulation material prices[XPS]	17,22	17,22	17,22	17,22	17,22	17,22
Mycelium model.Insulation material prices[Polyurethane]	20,08	20,08	20,08	20,08	20,08	20,08
Mycelium model.Insulation material thermal conductivity[Mycelium]	0,04	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[Rockwool]	0,0365	0,0365	0,0365	0,0365	0,0365	0,0365
Mycelium model.Insulation material thermal conductivity[Glasswool]	0,04	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[EPS]	0,035	0,035	0,035	0,035	0,035	0,035
Mycelium model.Insulation material thermal conductivity[XPS]	0,0345	0,0345	0,0345	0,0345	0,0345	0,0345
Mycelium model.Insulation material thermal conductivity[Polyurethane]	0,0285	0,0285	0,0285	0,0285	0,0285	0,0285
Mycelium model.kWh to J	3600000	3600000	3600000	3600000	3600000	3600000

Years	2035	2036	2037	2038	2039	2040
Mycelium model.kWh to MJ	3,6	3,6	3,6	3,6	3,6	3,6
Mycelium model.Market reaction time	1	1	1	1	1	1
Mycelium model.Material absorption factors[Destilled water]	0	0	0	0	0	0
Mycelium model.Material absorption factors[Wood chips]	1,835	1,835	1,835	1,835	1,835	1,835
Mycelium model.Material absorption factors[Mollases]	0,1	0,1	0,1	0,1	0,1	0,1
Mycelium model.Material absorption factors[Xanthan]	0,048	0,048	0,048	0,048	0,048	0,048
Mycelium model.Material absorption factors[Soda]	0,524	0,524	0,524	0,524	0,524	0,524
Mycelium model.Material absorption factors[Starch]	0,174	0,174	0,174	0,174	0,174	0,174
Mycelium model.Material absorption factors[Whey powder]	0,98	0,98	0,98	0,98	0,98	0,98
Mycelium model.Material absorption factors[Straw]	1,468	1,468	1,468	1,468	1,468	1,468
Mycelium model.Material absorption factors[Carbamide]	0,73	0,73	0,73	0,73	0,73	0,73
Mycelium model.Material costs	929	929	929	929	929	929
Mycelium model.Material density	0,081205	0,081205	0,081205	0,081205	0,081205	0,081205
Mycelium model.Material emission factors[Destilled water]	0,0008	0,0008	0,0008	0,0008	0,0008	0,0008
Mycelium model.Material emission factors[Wood chips]	0,000187	0,000187	0,000187	0,000187	0,000187	0,000187
Mycelium model.Material emission factors[Mollases]	0,074	0,074	0,074	0,074	0,074	0,074
Mycelium model.Material emission factors[Xanthan]	0,00497	0,00497	0,00497	0,00497	0,00497	0,00497
Mycelium model.Material emission factors[Soda]	1,17	1,17	1,17	1,17	1,17	1,17
Mycelium model.Material emission factors[Starch]	2,4	2,4	2,4	2,4	2,4	2,4
Mycelium model.Material emission factors[Whey powder]	0,00082	0,00082	0,00082	0,00082	0,00082	0,00082
Mycelium model.Material emission factors[Straw]	0,1036	0,1036	0,1036	0,1036	0,1036	0,1036
Mycelium model.Material emission factors[Carbamide]	1,85	1,85	1,85	1,85	1,85	1,85
Mycelium model.Mycelium fraction	0,000213	0,000213	0,000213	0,000213	0,000213	0,000213
Mycelium model.Other costs	432	432	432	432	432	432
Mycelium model.Perceived electricity efficiency	-596281	-596281	-596281	-596281	-596281	-596281
Mycelium model.Perceived heat efficiency	-454965	-454965	-454965	-454965	-454965	-454965
Mycelium model.Perceived maximum current yield	100	100	100	100	100	100
Mycelium model.Perceived maximum development yield	110	110	110	110	110	110
Mycelium model.Perceived maximum yield	120	120	120	120	120	120
Mycelium model.Raw material fractions[Destilled water]	0,47148	0,47148	0,47148	0,47148	0,47148	0,47148

Years	2035	2036	2037	2038	2039	2040
Mycelium model.Raw material fractions[Wood chips]	0,344201	0,344201	0,344201	0,344201	0,344201	0,344201
Mycelium model.Raw material fractions[Mollases]	0,013637	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Xanthan]	0,004182	0,004182	0,004182	0,004182	0,004182	0,004182
Mycelium model.Raw material fractions[Soda]	0,024729	0,024729	0,024729	0,024729	0,024729	0,024729
Mycelium model.Raw material fractions[Starch]	0,011637	0,011637	0,011637	0,011637	0,011637	0,011637
Mycelium model.Raw material fractions[Whey powder]	0,013637	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Straw]	0,114734	0,114734	0,114734	0,114734	0,114734	0,114734
Mycelium model.Raw material fractions[Carbamide]	0,001764	0,001764	0,001764	0,001764	0,001764	0,001764
Mycelium model.Raw material used in production[Distilled water]	0,315968	0,404326	0,513543	0,64095	0,783073	0,936063
Mycelium model.Raw material used in production[Wood chips]	0,230671	0,295176	0,374909	0,467922	0,571678	0,683367
Mycelium model.Raw material used in production[Mollases]	0,009139	0,011695	0,014854	0,018539	0,022649	0,027075
Mycelium model.Raw material used in production[Xanthan]	0,002803	0,003586	0,004555	0,005685	0,006946	0,008303
Mycelium model.Raw material used in production[Soda]	0,016572	0,021207	0,026935	0,033618	0,041072	0,049096
Mycelium model.Raw material used in production[Starch]	0,007799	0,00998	0,012675	0,01582	0,019328	0,023104
Mycelium model.Raw material used in production[Whey powder]	0,009139	0,011695	0,014854	0,018539	0,022649	0,027075
Mycelium model.Raw material used in production[Straw]	0,07689	0,098392	0,12497	0,155974	0,19056	0,22779
Mycelium model.Raw material used in production[Carbamide]	0,001182	0,001513	0,001921	0,002398	0,00293	0,003502
Mycelium model.Subsidies	0	0	0	0	0	0
Mycelium model.Time to develop energy	10	10	10	10	10	10
Mycelium model.Time to educate	10	10	10	10	10	10
Mycelium model.Time to research energy	20	20	20	20	20	20
Mycelium model.Time to sell	0,25	0,25	0,25	0,25	0,25	0,25
Mycelium model.Transformities[Distilled water]	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11
Mycelium model.Transformities[Wood chips]	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13
Mycelium model.Transformities[Mollases]	2E+15	2E+15	2E+15	2E+15	2E+15	2E+15
Mycelium model.Transformities[Xanthan]	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16
Mycelium model.Transformities[Soda]	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15
Mycelium model.Transformities[Starch]	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15
Mycelium model.Transformities[Whey powder]	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15

Years	2035	2036	2037	2038	2039	2040
Mycelium model.Transformities[Straw]	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15
Mycelium model.Transformities[Carbamide]	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15
Mycelium model.Transformity electricity	290000	290000	290000	290000	290000	290000
Mycelium model.Transformity EUR	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11

Mycelium model input data (2041-2045)

Years	2041	2042	2043	2044	2045
Mycelium model.Absorption mycelium	0,0025	0,0025	0,0025	0,0025	0,0025
Mycelium model.Alfalfa	6	6	6	6	6
Mycelium model.Annual wage	12000	12000	12000	12000	12000
Mycelium model.Area Available	10000	10000	10000	10000	10000
Mycelium model.Average construction time	3	3	3	3	3
Mycelium model.Carbon price	110,2408	114,7171	119,375	124,2221	129,266
Mycelium model.Current electricity efficiency	12169	12169	12169	12169	12169
Mycelium model.Current heat efficiency	9285	9285	9285	9285	9285
Mycelium model.Decrease rate	0,01	0,01	0,01	0,01	0,01
Mycelium model.dT/q`	5	5	5	5	5
Mycelium model.Electricity emission factor	0,000102	0,000102	0,000102	0,000102	0,000102
Mycelium model.Electricity tariff	100	100	100	100	100
Mycelium model.Energy tax amount	5	5	5	5	5
Mycelium model.Energy efficiency	50	50	50	50	50
Mycelium model.Final material mass fraction	0,147654	0,147654	0,147654	0,147654	0,147654
Mycelium model.Floor Height	2,5	2,5	2,5	2,5	2,5
Mycelium model.Floor Length	80	80	80	80	80
Mycelium model.Floor Width	25	25	25	25	25
Mycelium model.Floors in a building	6	6	6	6	6
Mycelium model.Fraction of initial capacity	0,001	0,001	0,001	0,001	0,001
Mycelium model.Heating emission factor	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05
Mycelium model.Initial current yield	90	90	90	90	90
Mycelium model.Initial market share[Mycelium]	0,01	0,01	0,01	0,01	0,01
Mycelium model.Initial market share[Rockwool]	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial market share[Glasswool]	0,29	0,29	0,29	0,29	0,29
Mycelium model.Initial market share[EPS]	0,3	0,3	0,3	0,3	0,3
Mycelium model.Initial market share[XPS]	0,2	0,2	0,2	0,2	0,2
Mycelium model.Initial market share[Polyurethane]	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial Time of land allocation	5	5	5	5	5
Mycelium model.Insulation material embodied emissions[Mycelium]	-0,41557	-0,41577	-0,41592	-0,41604	-0,41614
Mycelium model.Insulation material embodied emissions[Rockwool]	0,126	0,126	0,126	0,126	0,126
Mycelium model.Insulation material embodied emissions[Glasswool]	0,0682	0,0682	0,0682	0,0682	0,0682
Mycelium model.Insulation material embodied emissions[EPS]	0,2312	0,2312	0,2312	0,2312	0,2312
Mycelium model.Insulation material embodied emissions[XPS]	0,2718	0,2718	0,2718	0,2718	0,2718
Mycelium model.Insulation material embodied emissions[Polyurethane]	0,5605	0,5605	0,5605	0,5605	0,5605

Years	2041	2042	2043	2044	2045
Mycelium model.Insulation material embodied energy[Mycelium]	9946,984	9939,866	9934,303	9929,867	9926,265
Mycelium model.Insulation material embodied energy[Rockwool]	2016	2016	2016	2016	2016
Mycelium model.Insulation material embodied energy[Glasswool]	1232	1232	1232	1232	1232
Mycelium model.Insulation material embodied energy[EPS]	3532,6	3532,6	3532,6	3532,6	3532,6
Mycelium model.Insulation material embodied energy[XPS]	3200,4	3200,4	3200,4	3200,4	3200,4
Mycelium model.Insulation material embodied energy[Polyurethane]	10184	10184	10184	10184	10184
Mycelium model.Insulation material prices[Mycelium]	179,7602	179,1301	178,5534	178,011	177,4902
Mycelium model.Insulation material prices[Rockwool]	13,4	13,4	13,4	13,4	13,4
Mycelium model.Insulation material prices[Glasswool]	10,1	10,1	10,1	10,1	10,1
Mycelium model.Insulation material prices[EPS]	10,75	10,75	10,75	10,75	10,75
Mycelium model.Insulation material prices[XPS]	17,22	17,22	17,22	17,22	17,22
Mycelium model.Insulation material prices[Polyurethane]	20,08	20,08	20,08	20,08	20,08
Mycelium model.Insulation material thermal conductivity[Mycelium]	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[Rockwool]	0,0365	0,0365	0,0365	0,0365	0,0365
Mycelium model.Insulation material thermal conductivity[Glasswool]	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[EPS]	0,035	0,035	0,035	0,035	0,035
Mycelium model.Insulation material thermal conductivity[XPS]	0,0345	0,0345	0,0345	0,0345	0,0345
Mycelium model.Insulation material thermal conductivity[Polyurethane]	0,0285	0,0285	0,0285	0,0285	0,0285
Mycelium model.kWh to J	3600000	3600000	3600000	3600000	3600000
Mycelium model.kWh to MJ	3,6	3,6	3,6	3,6	3,6
Mycelium model.Market reaction time	1	1	1	1	1
Mycelium model.Material absorption factors[Distilled water]	0	0	0	0	0
Mycelium model.Material absorption factors[Wood chips]	1,835	1,835	1,835	1,835	1,835
Mycelium model.Material absorption factors[Mollases]	0,1	0,1	0,1	0,1	0,1
Mycelium model.Material absorption factors[Xanthan]	0,048	0,048	0,048	0,048	0,048
Mycelium model.Material absorption factors[Soda]	0,524	0,524	0,524	0,524	0,524
Mycelium model.Material absorption factors[Starch]	0,174	0,174	0,174	0,174	0,174
Mycelium model.Material absorption factors[Whey powder]	0,98	0,98	0,98	0,98	0,98
Mycelium model.Material absorption factors[Straw]	1,468	1,468	1,468	1,468	1,468
Mycelium model.Material absorption factors[Carbamide]	0,73	0,73	0,73	0,73	0,73

Years	2041	2042	2043	2044	2045
Mycelium model.Material costs	929	929	929	929	929
Mycelium model.Material density	0,081205	0,081205	0,081205	0,081205	0,081205
Mycelium model.Material emission factors[Distilled water]	0,0008	0,0008	0,0008	0,0008	0,0008
Mycelium model.Material emission factors[Wood chips]	0,000187	0,000187	0,000187	0,000187	0,000187
Mycelium model.Material emission factors[Mollases]	0,074	0,074	0,074	0,074	0,074
Mycelium model.Material emission factors[Xanthan]	0,00497	0,00497	0,00497	0,00497	0,00497
Mycelium model.Material emission factors[Soda]	1,17	1,17	1,17	1,17	1,17
Mycelium model.Material emission factors[Starch]	2,4	2,4	2,4	2,4	2,4
Mycelium model.Material emission factors[Whey powder]	0,00082	0,00082	0,00082	0,00082	0,00082
Mycelium model.Material emission factors[Straw]	0,1036	0,1036	0,1036	0,1036	0,1036
Mycelium model.Material emission factors[Carbamide]	1,85	1,85	1,85	1,85	1,85
Mycelium model.Mycelium fraction	0,000213	0,000213	0,000213	0,000213	0,000213
Mycelium model.Other costs	432	432	432	432	432
Mycelium model.Perceived electricity efficiency	-596281	-596281	-596281	-596281	-596281
Mycelium model.Perceived heat efficiency	-454965	-454965	-454965	-454965	-454965
Mycelium model.Perceived maximum current yield	100	100	100	100	100
Mycelium model.Perceived maximum development yield	110	110	110	110	110
Mycelium model.Perceived maximum yield	120	120	120	120	120
Mycelium model.Raw material fractions[Distilled water]	0,47148	0,47148	0,47148	0,47148	0,47148
Mycelium model.Raw material fractions[Wood chips]	0,344201	0,344201	0,344201	0,344201	0,344201
Mycelium model.Raw material fractions[Mollases]	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Xanthan]	0,004182	0,004182	0,004182	0,004182	0,004182
Mycelium model.Raw material fractions[Soda]	0,024729	0,024729	0,024729	0,024729	0,024729
Mycelium model.Raw material fractions[Starch]	0,011637	0,011637	0,011637	0,011637	0,011637
Mycelium model.Raw material fractions[Whey powder]	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Straw]	0,114734	0,114734	0,114734	0,114734	0,114734
Mycelium model.Raw material fractions[Carbamide]	0,001764	0,001764	0,001764	0,001764	0,001764
Mycelium model.Raw material used in production[Distilled water]	1,096048	1,259415	1,423029	1,584403	1,741965
Mycelium model.Raw material used in production[Wood chips]	0,800163	0,919428	1,038873	1,156683	1,271711
Mycelium model.Raw material used in production[Mollases]	0,031702	0,036427	0,041159	0,045827	0,050384
Mycelium model.Raw material used in production[Xanthan]	0,009722	0,011171	0,012622	0,014054	0,015451
Mycelium model.Raw material used in production[Soda]	0,057487	0,066056	0,074637	0,083102	0,091366

Years	2041	2042	2043	2044	2045
Mycelium model.Raw material used in production[Starch]	0,027053	0,031085	0,035123	0,039106	0,042995
Mycelium model.Raw material used in production[Whey powder]	0,031702	0,036427	0,041159	0,045827	0,050384
Mycelium model.Raw material used in production[Straw]	0,266722	0,306477	0,346292	0,385562	0,423905
Mycelium model.Raw material used in production[Carbamide]	0,004101	0,004712	0,005324	0,005928	0,006517
Mycelium model.Subsidies	0	0	0	0	0
Mycelium model.Time to develop energy	10	10	10	10	10
Mycelium model.Time to educate	10	10	10	10	10
Mycelium model.Time to research energy	20	20	20	20	20
Mycelium model.Time to sell	0,25	0,25	0,25	0,25	0,25
Mycelium model.Transformities[Distilled water]	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11
Mycelium model.Transformities[Wood chips]	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13
Mycelium model.Transformities[Mollases]	2E+15	2E+15	2E+15	2E+15	2E+15
Mycelium model.Transformities[Xanthan]	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16
Mycelium model.Transformities[Soda]	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15
Mycelium model.Transformities[Starch]	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15
Mycelium model.Transformities[Whey powder]	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15
Mycelium model.Transformities[Straw]	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15
Mycelium model.Transformities[Carbamide]	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15
Mycelium model.Transformity electricity	290000	290000	290000	290000	290000
Mycelium model.Transformity EUR	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11

Mycelium model input data (2046-2050)

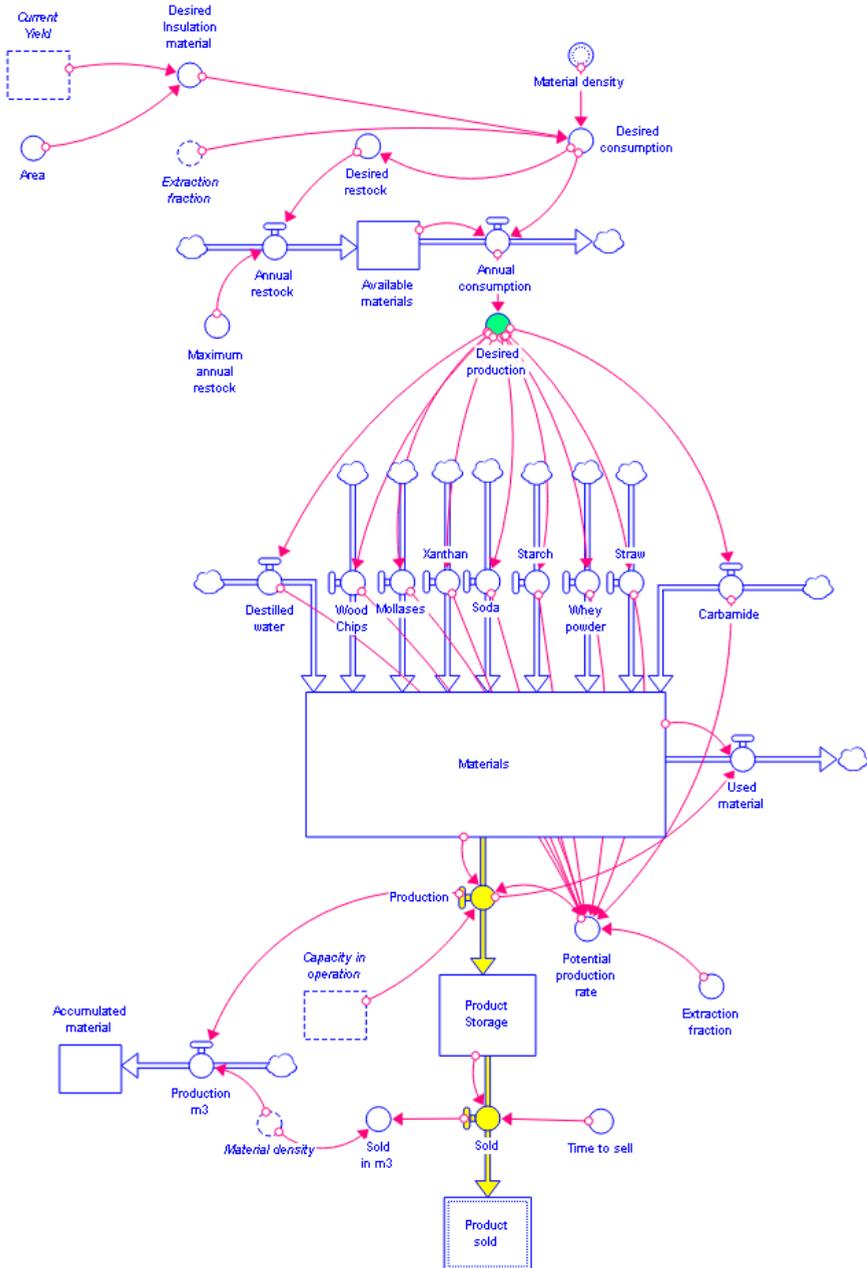
Years	2046	2047	2048	2049	2050
Mycelium model.Absorption mycelium	0,0025	0,0025	0,0025	0,0025	0,0025
Mycelium model.Alfalfa	6	6	6	6	6
Mycelium model.Annual wage	12000	12000	12000	12000	12000
Mycelium model.Area Available	10000	10000	10000	10000	10000
Mycelium model.Average construction time	3	3	3	3	3
Mycelium model.Carbon price	134,5148	139,9766	145,6602	151,5746	157,7291
Mycelium model.Current electricity efficiency	12169	12169	12169	12169	12169
Mycelium model.Current heat efficiency	9285	9285	9285	9285	9285
Mycelium model.Decrease rate	0,01	0,01	0,01	0,01	0,01
Mycelium model.dT/q`	5	5	5	5	5
Mycelium model.Electricity emission factor	0,000102	0,000102	0,000102	0,000102	0,000102
Mycelium model.Electricity tariff	100	100	100	100	100
Mycelium model.Energy tax amount	5	5	5	5	5
Mycelium model.Energy efficiency	50	50	50	50	50
Mycelium model.Final material mass fraction	0,147654	0,147654	0,147654	0,147654	0,147654
Mycelium model.Floor Height	2,5	2,5	2,5	2,5	2,5
Mycelium model.Floor Length	80	80	80	80	80
Mycelium model.Floor Width	25	25	25	25	25
Mycelium model.Floors in a building	6	6	6	6	6
Mycelium model.Fraction of initial capacity	0,001	0,001	0,001	0,001	0,001
Mycelium model.Heating emission factor	9,42E-05	9,42E-05	9,42E-05	9,42E-05	9,42E-05
Mycelium model.Initial current yield	90	90	90	90	90
Mycelium model.Initial market share[Mycelium]	0,01	0,01	0,01	0,01	0,01
Mycelium model.Initial market share[Rockwool]	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial market share[Glasswool]	0,29	0,29	0,29	0,29	0,29
Mycelium model.Initial market share[EPS]	0,3	0,3	0,3	0,3	0,3
Mycelium model.Initial market share[XPS]	0,2	0,2	0,2	0,2	0,2
Mycelium model.Initial market share[Polyurethane]	0,1	0,1	0,1	0,1	0,1
Mycelium model.Initial Time of land allocation	5	5	5	5	5
Mycelium model.Insulation material embodied emissions[Mycelium]	-0,41622	-0,41629	-0,41635	-0,4164	-0,41644
Mycelium model.Insulation material embodied emissions[Rockwool]	0,126	0,126	0,126	0,126	0,126
Mycelium model.Insulation material embodied emissions[Glasswool]	0,0682	0,0682	0,0682	0,0682	0,0682
Mycelium model.Insulation material embodied emissions[EPS]	0,2312	0,2312	0,2312	0,2312	0,2312
Mycelium model.Insulation material embodied emissions[XPS]	0,2718	0,2718	0,2718	0,2718	0,2718
Mycelium model.Insulation material embodied emissions[Polyurethane]	0,5605	0,5605	0,5605	0,5605	0,5605
Mycelium model.Insulation material embodied energy[Mycelium]	9923,289	9920,795	9918,679	9916,868	9915,309

Years	2046	2047	2048	2049	2050
Mycelium model.Insulation material embodied energy[Rockwool]	2016	2016	2016	2016	2016
Mycelium model.Insulation material embodied energy[Glasswool]	1232	1232	1232	1232	1232
Mycelium model.Insulation material embodied energy[EPS]	3532,6	3532,6	3532,6	3532,6	3532,6
Mycelium model.Insulation material embodied energy[XPS]	3200,4	3200,4	3200,4	3200,4	3200,4
Mycelium model.Insulation material embodied energy[Polyurethane]	10184	10184	10184	10184	10184
Mycelium model.Insulation material prices[Mycelium]	176,9821	176,4809	175,9828	175,4845	174,9831
Mycelium model.Insulation material prices[Rockwool]	13,4	13,4	13,4	13,4	13,4
Mycelium model.Insulation material prices[Glasswool]	10,1	10,1	10,1	10,1	10,1
Mycelium model.Insulation material prices[EPS]	10,75	10,75	10,75	10,75	10,75
Mycelium model.Insulation material prices[XPS]	17,22	17,22	17,22	17,22	17,22
Mycelium model.Insulation material prices[Polyurethane]	20,08	20,08	20,08	20,08	20,08
Mycelium model.Insulation material thermal conductivity[Mycelium]	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[Rockwool]	0,0365	0,0365	0,0365	0,0365	0,0365
Mycelium model.Insulation material thermal conductivity[Glasswool]	0,04	0,04	0,04	0,04	0,04
Mycelium model.Insulation material thermal conductivity[EPS]	0,035	0,035	0,035	0,035	0,035
Mycelium model.Insulation material thermal conductivity[XPS]	0,0345	0,0345	0,0345	0,0345	0,0345
Mycelium model.Insulation material thermal conductivity[Polyurethane]	0,0285	0,0285	0,0285	0,0285	0,0285
Mycelium model.kWh to J	3600000	3600000	3600000	3600000	3600000
Mycelium model.kWh to MJ	3,6	3,6	3,6	3,6	3,6
Mycelium model.Market reaction time	1	1	1	1	1
Mycelium model.Material absorption factors[Distilled water]	0	0	0	0	0
Mycelium model.Material absorption factors[Wood chips]	1,835	1,835	1,835	1,835	1,835
Mycelium model.Material absorption factors[Mollases]	0,1	0,1	0,1	0,1	0,1
Mycelium model.Material absorption factors[Xanthan]	0,048	0,048	0,048	0,048	0,048
Mycelium model.Material absorption factors[Soda]	0,524	0,524	0,524	0,524	0,524
Mycelium model.Material absorption factors[Starch]	0,174	0,174	0,174	0,174	0,174
Mycelium model.Material absorption factors[Whey powder]	0,98	0,98	0,98	0,98	0,98
Mycelium model.Material absorption factors[Straw]	1,468	1,468	1,468	1,468	1,468
Mycelium model.Material absorption factors[Carbamide]	0,73	0,73	0,73	0,73	0,73
Mycelium model.Material costs	929	929	929	929	929

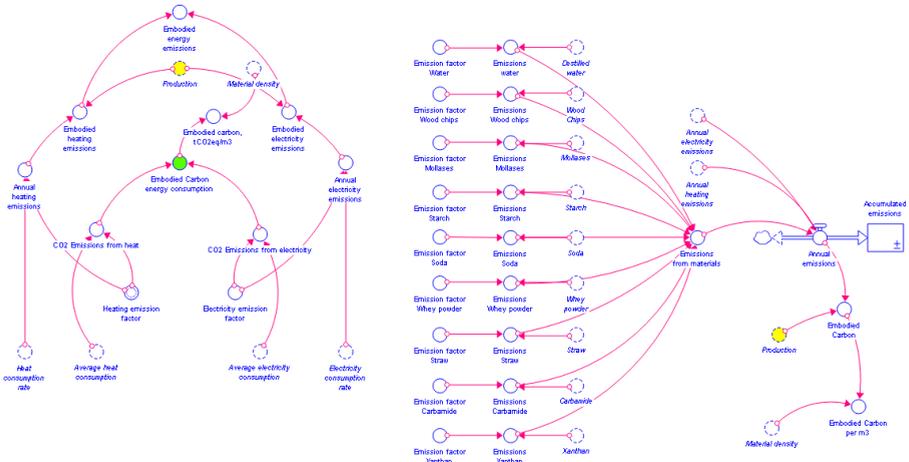
Years	2046	2047	2048	2049	2050
Mycelium model.Material density	0,081205	0,081205	0,081205	0,081205	0,081205
Mycelium model.Material emission factors[Distilled water]	0,0008	0,0008	0,0008	0,0008	0,0008
Mycelium model.Material emission factors[Wood chips]	0,000187	0,000187	0,000187	0,000187	0,000187
Mycelium model.Material emission factors[Mollases]	0,074	0,074	0,074	0,074	0,074
Mycelium model.Material emission factors[Xanthan]	0,00497	0,00497	0,00497	0,00497	0,00497
Mycelium model.Material emission factors[Soda]	1,17	1,17	1,17	1,17	1,17
Mycelium model.Material emission factors[Starch]	2,4	2,4	2,4	2,4	2,4
Mycelium model.Material emission factors[Whey powder]	0,00082	0,00082	0,00082	0,00082	0,00082
Mycelium model.Material emission factors[Straw]	0,1036	0,1036	0,1036	0,1036	0,1036
Mycelium model.Material emission factors[Carbamide]	1,85	1,85	1,85	1,85	1,85
Mycelium model.Mycelium fraction	0,000213	0,000213	0,000213	0,000213	0,000213
Mycelium model.Other costs	432	432	432	432	432
Mycelium model.Perceived electricity efficiency	-596281	-596281	-596281	-596281	-596281
Mycelium model.Perceived heat efficiency	-454965	-454965	-454965	-454965	-454965
Mycelium model.Perceived maximum current yield	100	100	100	100	100
Mycelium model.Perceived maximum development yield	110	110	110	110	110
Mycelium model.Perceived maximum yield	120	120	120	120	120
Mycelium model.Raw material fractions[Distilled water]	0,47148	0,47148	0,47148	0,47148	0,47148
Mycelium model.Raw material fractions[Wood chips]	0,344201	0,344201	0,344201	0,344201	0,344201
Mycelium model.Raw material fractions[Mollases]	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Xanthan]	0,004182	0,004182	0,004182	0,004182	0,004182
Mycelium model.Raw material fractions[Soda]	0,024729	0,024729	0,024729	0,024729	0,024729
Mycelium model.Raw material fractions[Starch]	0,011637	0,011637	0,011637	0,011637	0,011637
Mycelium model.Raw material fractions[Whey powder]	0,013637	0,013637	0,013637	0,013637	0,013637
Mycelium model.Raw material fractions[Straw]	0,114734	0,114734	0,114734	0,114734	0,114734
Mycelium model.Raw material fractions[Carbamide]	0,001764	0,001764	0,001764	0,001764	0,001764
Mycelium model.Raw material used in production[Distilled water]	1,895186	2,044333	2,190143	2,333596	2,475737
Mycelium model.Raw material used in production[Wood chips]	1,383569	1,492452	1,5989	1,703627	1,807396
Mycelium model.Raw material used in production[Mollases]	0,054816	0,05913	0,063347	0,067497	0,071608
Mycelium model.Raw material used in production[Xanthan]	0,01681	0,018133	0,019426	0,020699	0,02196
Mycelium model.Raw material used in production[Soda]	0,099402	0,107225	0,114872	0,122396	0,129852
Mycelium model.Raw material used in production[Starch]	0,046777	0,050458	0,054057	0,057597	0,061106

Years	2046	2047	2048	2049	2050
Mycelium model.Raw material used in production[Whey powder]	0,054816	0,05913	0,063347	0,067497	0,071608
Mycelium model.Raw material used in production[Straw]	0,461191	0,497486	0,532968	0,567877	0,602467
Mycelium model.Raw material used in production[Carbamide]	0,007091	0,007649	0,008194	0,008731	0,009263
Mycelium model.Subsidies	0	0	0	0	0
Mycelium model.Time to develop energy	10	10	10	10	10
Mycelium model.Time to educate	10	10	10	10	10
Mycelium model.Time to research energy	20	20	20	20	20
Mycelium model.Time to sell	0,25	0,25	0,25	0,25	0,25
Mycelium model.Transformities[Distilled water]	6,65E+11	6,65E+11	6,65E+11	6,65E+11	6,65E+11
Mycelium model.Transformities[Wood chips]	1,84E+13	1,84E+13	1,84E+13	1,84E+13	1,84E+13
Mycelium model.Transformities[Mollases]	2E+15	2E+15	2E+15	2E+15	2E+15
Mycelium model.Transformities[Xanthan]	3,58E+16	3,58E+16	3,58E+16	3,58E+16	3,58E+16
Mycelium model.Transformities[Soda]	2,02E+15	2,02E+15	2,02E+15	2,02E+15	2,02E+15
Mycelium model.Transformities[Starch]	2,43E+15	2,43E+15	2,43E+15	2,43E+15	2,43E+15
Mycelium model.Transformities[Whey powder]	3,26E+15	3,26E+15	3,26E+15	3,26E+15	3,26E+15
Mycelium model.Transformities[Straw]	4,58E+15	4,58E+15	4,58E+15	4,58E+15	4,58E+15
Mycelium model.Transformities[Carbamide]	5,33E+15	5,33E+15	5,33E+15	5,33E+15	5,33E+15
Mycelium model.Transformity electricity	290000	290000	290000	290000	290000
Mycelium model.Transformity EUR	4,6E+11	4,6E+11	4,6E+11	4,6E+11	4,6E+11

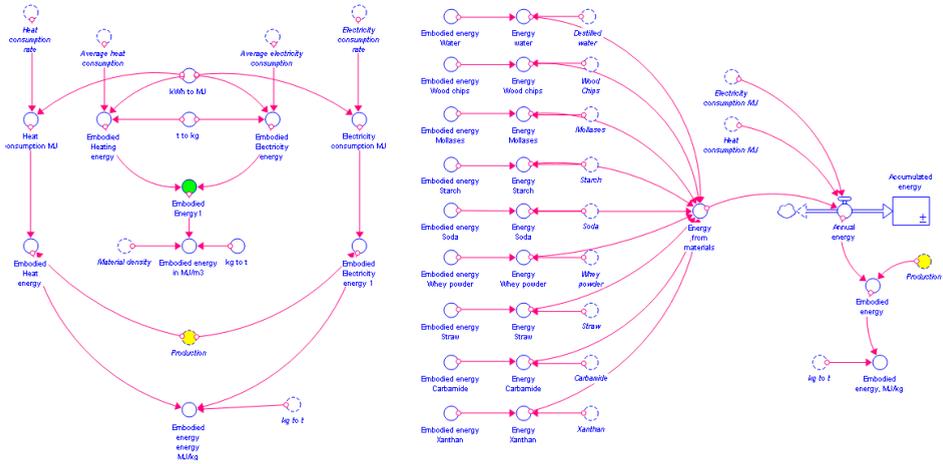
Structure of a system dynamics model for the production of mycelium thermal insulation



Structure of a system dynamics model for emissions



Structure of a system dynamics model for energy



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Doctoral Thesis publications

1. I. Luksta, I. Pakere, I. Vamža, V. Liberova, D. Blumberga, “Comparative Analysis of Agricultural Emissions Across European Countries,” *Environmental and Climate Technologies*, 2024, Vol. 28, No. 1, 738.–748. lpp. ISSN 1691-5208, doi: 10.2478/rtuect-2024-0057.
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Comparative Analysis of Agricultural Emissions Across European Countries

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Abstract – Agriculture is one of the main sources of greenhouse gas (GHG) emissions and has great potential for mitigating climate change. For example, agriculture in Latvia was the second largest sector of GHG emissions after energy with a 22.2 % share of total GHG emissions in 2022. The study aims to compare and analyse the amount of GHG emissions generated by agriculture per domestic product (GDP) and population in different European countries. The ambitious goals set in Europe for 2030 envisage a 30 % reduction in the industry, however, in some countries, these indicators have not only decreased in recent years but also increased. The structure of GHG emissions in 2022 in Europe is as follows: intestinal fermentation (181.1 MtCO_{2e}), agricultural soils (112.9 MtCO_{2e}), and manure management (61.7 MtCO_{2e}). Agriculture is one of the main sources of GHG emissions and has great potential for mitigating climate change. This study aims to compare and analyze GHG emissions from agriculture in European countries against GDP, GDP against population, and population in 2022.

Keywords – Agriculture; carbon dioxide; Europe; Generated per domestic product (GDP); methane; nitrogen oxide.

1. INTRODUCTION

Agriculture is a major contributor to anthropogenic global warming, and the agricultural sector is the main producer of methane and nitrogen emissions, which are converted into CO₂ equivalents [1]. The biggest emitters are the energy sector (66.5 % of GHG emissions), but the agricultural sector is also one of the biggest polluters (about 13.5 % of GHG emissions). It is interesting that of the total emissions, 20 % of carbon dioxide (CO₂); 70 % of methane (CH₄), and 90 % of (nitrous oxide) N₂O in the atmosphere were released as a result of various activities in the agricultural sector, and it is also reported that 35 % of CO₂; 47 % CH₄ and 53 % N₂O of total agricultural greenhouse gases originate in soil (e.g. manure management). Globally, a set of measures and many international agreements (i.e. Kyoto Protocol in 1997) were implemented to reduce GHG emissions worldwide, where developed countries have been required to reduce emissions by 25 % to 40 % by 2020. The United Kingdom introduced the concept of a low-carbon economy in 2003, followed by Germany, Japan, and the United States since then. In recent decades, many researchers around the world have studied the relationship between the agricultural sector and GHG emissions, and it has been argued that

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the interdependence of crop and livestock management could play an important role in GHG mitigation in the United States. It is also recommended to invest in crop production and crop improvement as a good strategy to reduce future GHG emissions. Also, GHG from the agricultural sector has been found to have increased annually by 1.1 % from 2000 to 2010 worldwide [2].

The rapid growth of the population and the increase due to anthropogenic activities create new problems associated with climate change and pose a great threat to the sustainability of natural resources and the stability of the Earth's biosphere. It should be noted that these problems are already causing an uncontrollable accumulation of gases in the atmosphere. Global GHG concentrations have been rapidly increasing since the beginning of the industrial age, for example, CO₂ concentrations in 1760 were 280 ppm and are expected to reach 590 ppm by the end of 2100. Global tracking of greenhouse gas emissions provides a basis for assessing individual countries' contributions to climate change. Climate change indicators define atmospheric concentrations of the most significant GHG emissions from human activities and how emissions and concentrations have changed over time. These indicators use the concept of 'global warming potential' to compare emissions of gases to convert amounts of other gases into CO₂ equivalents. Human-caused GHG emissions are increasing and exacerbating climate change. These rising levels of GHG lead to many more climate-related changes locally and globally [3].

European GHG emissions from the agricultural sector were reported to account for 10 % of total GHG emissions. The total amount of GHG emissions of European countries in 2021 was 3.6 GtCO₂e and GHG emissions from agriculture were almost 500 million tons [4]. This shows that energy is one of the main inputs in the agricultural system, while the energy produced by the formation of fossil fuels is mainly used by agriculture and many other activities. For example, the Italy has the highest share of energy used in agriculture at 9.8 % (compared with 2020), followed by Slovakia at 9.3 % and France at 9.1 %. However, Portugal has the lowest percentage overall (+5.5 %) [5]. The increasing amount of energy is due to neoteric agricultural activities, which are partly responsible for the constant increase in GHG emissions. About half of the energy used in the agricultural sector comes from diesel and gas oil, which account for the largest share of energy used in the agricultural sector in Europe. Regardless of the size and contribution of the agricultural sector to the national GDP in each European Member State, Europe has achieved a 23 % reduction in GHG emissions over the past two decades [3].

Agriculture is actually very vulnerable to climate change, as its activities are directly dependent on climatic conditions. However, the impact of climate change on agricultural yields varies across countries and cultures. Some areas could benefit from the actions of some components of climate change (e.g. water scarcity, increased crop variability, reduced yields, etc.) [6]. In fact, in different countries, different combinations of these influences can exacerbate the overall situation. For example, increasing temperatures can have both positive and negative effects on agricultural yields. It should be pointed out that a strong rise in temperature means water shortages, which can significantly worsen agriculture in all countries, especially in semi-arid areas such as southern European countries. In this case, a negative relationship between rising temperatures and agricultural yields is hypothesized. Additionally, increased precipitation may benefit semi-arid areas by increasing soil moisture, but may exacerbate problems in areas with excess water. On the other hand, reducing the amount of precipitation could have the opposite effect. In irrigated areas, the negative effects of altered precipitation and increased temperature are reduced by the availability of irrigation water, making crops more resistant to climate change. In this last case, groundwater and rivers are mitigating factors of climate variability. In summary, each component of climate change

has more than one effect, and the distribution of one type of biophysical effect depends on soil conditions, species, and plant type [7].

There is an opportunity to achieve climate-friendly agriculture by both sequestering carbon and reducing emissions. The main strategies are 1) enriching soil carbon (e.g. using perennial plants), 2) promoting climate-friendly livestock systems, 3) reducing the use of inorganic fertilizers and 4) restoring degraded lands and preventing deforestation, which is mainly for agricultural purposes [8], [9].

Agriculture is the second most important source of GHG emissions [10], for example, in Latvia they accounted for approximately 22 % of the total GHG emissions in the country in 2022. Emissions from agricultural soils accounted for the largest share of total emissions – 46.5 %, and intestinal fermentation emissions were the second largest source – 42 %. The proportion of emissions from manure management was estimated as 7.8 % of the total emissions in the sector, the remaining 3.7 % of emissions refer to liming and urea use. GHG emissions in 2022 increased by 0.04 % compared to 2021 [11].

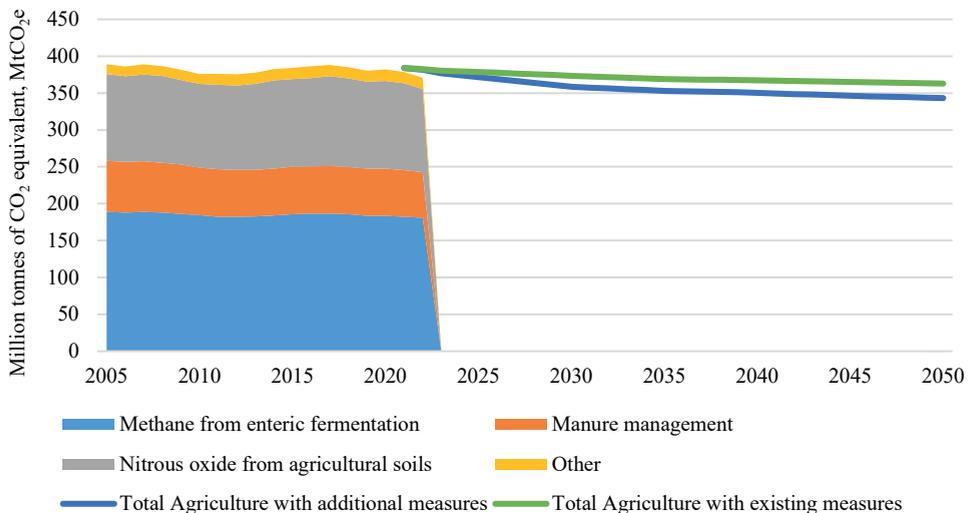


Fig. 1. EU agricultural emissions by source and projected emissions [12].

GHG emissions from agriculture, including crop and livestock farming, forestry, and associated land-use change, account for a significant share of anthropogenic emissions, up to 30 % according to the Intergovernmental Panel on Climate Change (IPCC) [13]. The European Climate Law [14] stipulates that Europe will transition to a climate-neutral economy by 2050 with an intermediate goal of reducing GHG emissions by at least 55 % by 2030. Also, targets have been set that determine the annual reduction for each member state in the period from 2021 to 2030, respectively [15], [12]. CH₄ emissions from gut fermentation and N₂O emissions from soil account for 48 % and 31 % of total agricultural GHG emissions, respectively. CH₄ from manure management is the third most important source of emissions, accounting for about 17 %. The remaining sources produce relatively small amounts of emissions, accounting for less than 5 % of agricultural GHG emissions. Between 2005 and 2021, Europe agricultural GHG emissions show a slight decrease of 3 %, with a decrease of only 2 % in 2022. Projections of the member states show that GHG emissions will remain at approximately this level until 2030. If additional measures are taken into account, GHG emissions could rise to 8 % [16].

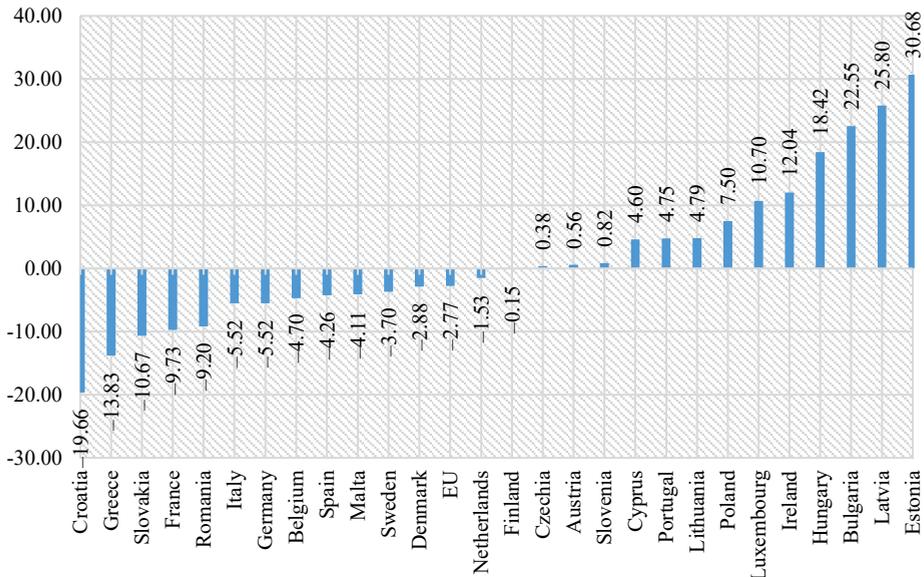


Fig. 2. Agricultural emissions and projected emissions by EU Member State in percentage change 2005–2021.

During the period from 2005 to 2021, the amount of GHG emissions from agriculture in Europe changed very little, but the trends of each country were very different, for example, they increased in 13 countries and decreased in 14 countries. For example, emissions fell by more than 10 % in Greece, Croatia, and Slovakia, while they increased by more than 10 % in Estonia, Hungary, Bulgaria, Latvia, Ireland, and Luxembourg. Taking into account the forecasts, an increase in emission trends is expected in most European countries if the current situation continues and no measures are taken to mitigate them. Twelve Member States have not reported planned additional measures that could reduce emissions more than existing measures [12]. The study aims to compare the emissions generated in the agricultural sector of the European Union countries against GDP, population, and GDP against population. The studies carried out so far have shown a comparison of the relationship with GHG emissions in agriculture, but no emphasis has been placed on their comparison with GDP and population [17], [18].

2. METHODOLOGY

The amounts of GHG emissions in the agricultural sector for all countries of the European Union [19], the total population [20], and the country's GDP per capita [21] were analysed. The calculation of GHG emissions per GDP and population often uses methodological approaches of normalization and comparison. In this process, GHG emissions are expressed as emissions per capita or per unit of GDP. This allows an objective comparison to be made between countries or regions, regardless of their population or economic size. Such an approach enables the identification and analysis of trends and differences in the intensity of GHG emissions in relation to population and economic activity. In the European Union,

agriculture is an important source of emissions, especially for GHG emissions such as methane and nitrogen oxides, as well as ammonia and sulfur dioxide.

Normalization and Comparative Analysis: The approach used for the analysis involves normalizing emissions by population size and economic output to facilitate meaningful comparisons between European Union countries. This method accounts for varying population sizes and economic capacities across countries, ensuring that emissions data is not disproportionately influenced by these factors.

Emissions per population: This metric was calculated by dividing the total GHG emissions from agriculture by the total population of each country. By normalizing emissions in this way, the analysis accounts for the population size, making it easier to compare how agricultural emissions relate to each country's population size. Countries with higher emissions per capita indicate a higher intensity of agricultural emissions relative to their population.

$$\text{Emissions per population, kt CO}_2 \text{ eq} = \text{emissions} / \text{population} \quad (1)$$

Emissions per GDP: This value was derived by dividing total agricultural emissions by the GDP per country, allowing for a clearer view of emissions intensity in relation to economic output. This calculation highlights which countries have higher or lower emissions in comparison to their economic size, providing insight into the efficiency of their agricultural sectors in managing emissions relative to their economic productivity.

$$\text{Emissions per GDP, kt CO}_2 \text{ eq/million EUR} = \text{emissions} / \text{GDP} \quad (2)$$

Emissions per GDP per Capita: By dividing the GHG emissions by both GDP and population, this indicator gives a more detailed look at emissions relative to both economic output and individual contribution to the economy. This method captures both the environmental and economic efficiency of agricultural sectors in different countries, allowing for a nuanced comparison across the EU.

$$\text{Emissions per GDP per Capita, kt CO}_2 \text{ eq/EUR} = \text{emissions} / \text{population} \quad (3)$$

Overall, agriculture accounts for around 10–12 % of the EU's total GHG emissions, and this can vary by country, agricultural practices, and policies. For example, more intensive agriculture, such as livestock and industrial farming, can lead to higher levels of emissions [25].

The EU has introduced various policy initiatives to reduce emissions from agriculture and promote more sustainable practices. Examples are the Common Agricultural Policy [26] and the Green Deal [27], which aim to promote environmental and climate goals in agriculture. In addition, research and technological development, such as more efficient fertilization methods or technologies to reduce methane emissions, can be important factors in reducing emissions in the agricultural sector in the EU. 27 European Union countries were compared, as well as each country's agricultural emissions in 2022; calculation data are given in Table A1, see the Annex.

3. RESULTS

Fig. 3 shows data on the amount of greenhouse gas emissions (expressed as kilotons of carbon dioxide equivalent) per million euros of GDP in different European countries. This indicator provides an insight into the environmental efficiency of each country's economy, showing how much greenhouse gas is emitted to produce one million euros worth of GDP:

- Austria and Belgium stand out with relatively low emissions per million euros of GDP, which indicates efficient use of resources in the economy.

- Countries such as Bulgaria, Croatia, Greece, Latvia, Lithuania, Poland and Romania demonstrate higher emissions per million euros of GDP, indicating a less environmentally friendly mode of economic production.
- Ireland stands out with high emissions, possibly due to specific economic activities such as agriculture.
- Malta shows the lowest emissions per million euro of GDP, which indicates a relatively environmentally friendly economic development, in terms of greenhouse gas emissions per unit of economic output.

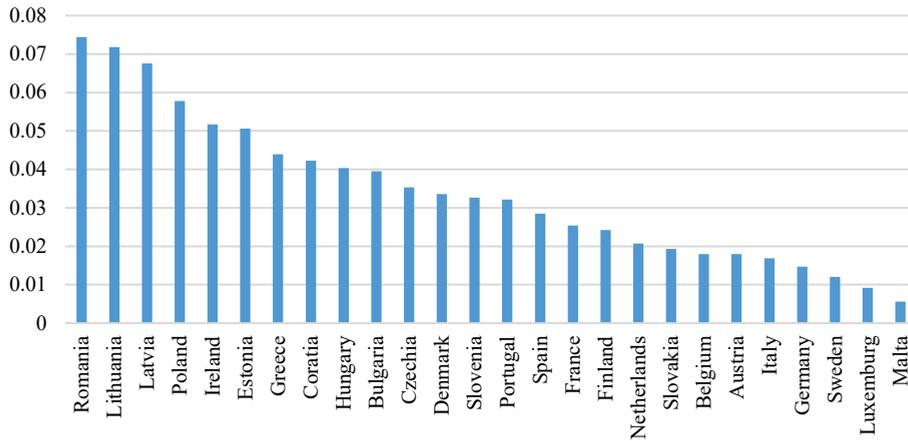


Fig. 3. Emissions in agriculture per GDP.

Fig. 4 shows data on the amount of GHG in the agricultural sector in relation to GDP per capita in different countries, expressed as kilotons of carbon dioxide equivalent per euro of GDP per capita.

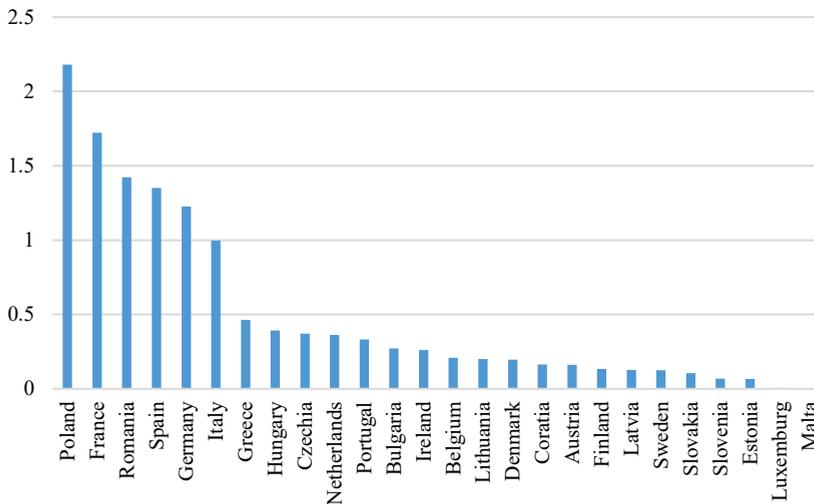


Fig. 4. Emissions in agriculture per GDP per capita.

This indicator helps to assess the environmental impact of the agricultural sector in each country, taking into account the amount of emissions, economic activity, and population:

- Countries such as Poland, France, Romania, Spain, and Germany have relatively high emissions in the agricultural sector in relation to GDP per capita, which may indicate a large environmental impact of the agricultural sector in these countries.
- On the other hand, in countries such as Malta and Luxembourg, emissions in the agricultural sector in terms of GDP per capita are very low, possibly due to the small importance of the agricultural sector or environmentally friendly agricultural practices.

Fig. 5 shows data on the amount of GHG in the agricultural sector per capita in different countries, expressed as kt CO₂eq per capita. This indicator indicates how much greenhouse gases are emitted per capita in the country's agricultural sector:

- Countries such as Ireland and Denmark have relatively high per capita emissions from the agricultural sector, which may indicate that the agricultural sector in these countries produces a larger amount of greenhouse gas emissions relative to the population.
- On the other hand, in countries such as Malta and Slovakia, emissions in the agricultural sector per capita are relatively low, possibly due to the small importance of the agricultural sector or effective environmental protection practices in these countries.

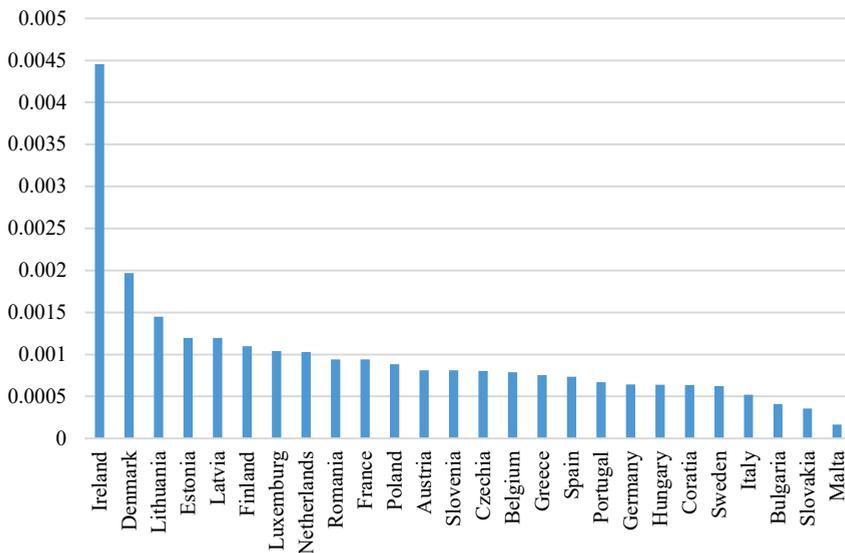


Fig. 5. Emissions in agriculture per population.

Despite the EU's ambitious targets to reduce GHG emissions from agriculture by 2030, current trends show a mixed picture of progress towards achieving these targets. While some Member States have made significant progress in curbing emissions, others still face challenges in meeting reduction targets.

Several Member States, including Croatia, Greece, and Slovakia, have achieved significant reductions in agricultural emissions since 2005. These countries are examples of successful emission reduction measures, demonstrating that effective mitigation measures are possible. In Europe, total agricultural GHG emissions have decreased slightly between 2005 and 2021,

indicating some progress towards the 2030 reduction targets. This trend shows that current measures have had some impact on reducing emissions in the agricultural sector [28]. Despite overall reductions, agricultural emissions have increased in some Member States, such as Bulgaria, Estonia, Hungary, Ireland, Latvia and Luxembourg. These countries face challenges in implementing sufficient mitigation measures or may have structural barriers that hinder emissions reduction efforts. Projections show that, without further intervention, some Member States foresee a reversal of emission reduction trends. Greece and Romania, for example, expect emissions to rise if existing measures continue, underscoring the need to step up efforts to meet targets [29]. There are large differences between Member States in terms of emission levels and progress towards targets. Factors such as agricultural practices, land use patterns, and policy structures contribute to these differences. The European Commission's impact assessment highlights the challenges of further reducing non-CO₂ GHG emissions from agriculture, pointing to the need for innovative strategies and targeted measures [30]. To accelerate progress towards agricultural emission reduction targets, Member States should prioritize the implementation of effective mitigation measures tailored to their specific contexts and challenges. Promoting sustainable agricultural practices, investing in research and innovation, and providing adequate support and incentives to farmers are critical to achieving emission reduction targets. Cooperative efforts at the European level, including the exchange of best practices, knowledge sharing, and coherent policy frameworks, can foster collective action and drive progress toward common goals [31].

In conclusion, although some progress has been made in Europe in reducing agricultural emissions, there are still challenges to achieve the ambitious goals set for 2030. Tackling these challenges requires concerted efforts, innovative approaches, and continued commitment by Member States to a more sustainable transition. and a climate-resilient agricultural sector.

4. CONCLUSIONS AND DISCUSSION

The results of the comparative analysis reveal differences in emission intensity between European countries, providing valuable insight into the factors that influence these differences. A number of factors contribute to differences in emission intensity, including agricultural practices, economic structure, policy guidelines, and environmental considerations. Differences in agricultural practices, including livestock management, cropping methods and land use patterns, have a significant impact on emissions intensity. Countries with intensive livestock farming or extensive fertilizer use may have higher emissions compared to countries with more sustainable and environmentally friendly agricultural practices. The economic structure of a country, including the composition of its GDP and the relative importance of the agricultural sector, affects the intensity of emissions. Countries with a larger agricultural sector may have a higher emission intensity relative to their GDP because they are more dependent on emission-intensive agricultural activities [32]. The presence of strong environmental policies, regulations, and incentives can play a crucial role in shaping emission intensity levels. Countries with strong regulations and supportive policy systems that promote sustainable agriculture and emission reduction measures tend to show lower emission intensities compared to countries with less comprehensive policies. Emissions intensity is also influenced by environmental factors such as climate, soil conditions, and geographical features. In countries with favorable environmental conditions, agriculture may have a lower emission intensity due to higher productivity and efficiency of resource use. Improved technologies and practices such as precision agriculture, renewable

energy, and methane capture systems can help reduce emission intensity by improving resource efficiency and reducing emissions from agricultural activities. Socio-economic factors, including population density, income levels, and cultural preferences, can affect the intensity of emissions. Countries with higher population density or higher demand for agricultural products may have higher emissions intensity due to increased pressure on land and resources. Historical factors, including past land-use practices, industrialization trajectories, and agricultural development policies, can also affect emissions intensity. Countries with legacy effects from historical land management practices or industrial activities may face challenges in reducing emission intensity. In summary, differences in emission intensity between European countries are multifaceted and are influenced by agricultural practices, economic structures, policy frameworks, environmental considerations, technological developments, socio-economic factors, and historical context. Understanding these factors is essential to develop tailored strategies and measures to effectively reduce agricultural emissions and promote sustainable agriculture across Europe. To limit and reduce the emissions caused by the agricultural sector, significant improvements must be made not only in the reduction of animals but also in the improvement of feed, because improving the quality of feed improves the reduction of emissions caused by animals (livestock). Also, more emphasis should be placed on the transition to organic agriculture.

ACKNOWLEDGEMENT

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ANNEX

TABLE A1. INPUT DATA

Country	Population [22]	Emissions, kt CO ₂ eq [23]	GDP, million EUR [24]	Emissions per population, kt CO ₂ eq	Emissions per GDP (kt CO ₂ eq/million EUR)	Emissions per GDP per capita, kt CO ₂ eq/EUR
Austria	895 6000	7276.88	405 397.2033	0.000813	0.01795	0.16076
Belgium	11 590 000	9149.05	508 280.2418	0.000789	0.018	0.20862
Bulgaria	6 878 000	2808.4	71 084.94004	0.000408	0.039508	0.271734
Coratia	3 879 000	2467.91	58 428.90211	0.000636	0.042238	0.163841
Czechia	10 510 000	8422.28	23 8434.8938	0.000801	0.035323	0.371247
Denmark	5 857 000	11 522.98	343 146.5434	0.001967	0.03358	0.19668
Estonia	1 331 000	1593.02	31 457.89412	0.001197	0.05064	0.067402
Finland	5 541 000	6074.92	251 013.0132	0.001096	0.024202	0.134101
France	67 760 000	63 645.38	2 502 864.265	0.000939	0.025429	1.72307
Germany	83 200 000	53 348.73	3 618 929.196	0.000641	0.014742	1.226499
Greece	10 570 000	7980.46	181 579.6321	0.000755	0.04395	0.464554
Hungary	9 710 000	6212.06	154 013.5113	0.00064	0.040335	0.391648
Iceland	372 520	595.98	21 649.04487	0.0016	0.027529	0.010255
Ireland	5 033 000	22 436.76	434 212.6252	0.004458	0.051672	0.260067
Italy	59 130 000	30 763.81	1 822 906.004	0.00052	0.016876	0.997892
Latvia	1 884 000	2253.83	33 352.32449	0.001196	0.067576	0.127314
Lithuania	2 801 000	4058.76	56 501.79608	0.001449	0.071834	0.201208
Luxemburg	640 064	665.57	72 387.03445	0.00104	0.009195	0.005885
Malta	518 536	86.09	15 298.15764	0.000166	0.005627	0.002918
Netherlands	17 530 000	18 039.53	870 750.7288	0.001029	0.020717	0.363173
Norway	5 408 000	4642.65	414 665.5865	0.000858	0.011196	0.060549
Poland	37 750 000	33 296.98	576 326.4876	0.000882	0.057775	2.180988
Portugal	10 360 000	6941.3	216 093.2062	0.00067	0.032122	0.332782
Romania	19 120 000	17 987.73	241 712.1949	0.000941	0.074418	1.422872
Slovakia	5 447 000	1934.43	100 287.4474	0.000355	0.019289	0.105066
Slovenia	2 108 000	1706.32	52 295.70784	0.000809	0.032628	0.06878
Spain	47 420 000	34 863.24	1 222 840.592	0.000735	0.02851	1.351946
Sweden	10 420 000	6513.09	541 288.5084	0.000625	0.012033	0.125379
Switzerland	8 705 000	5887.6	688 017.0023	0.000676	0.008557	0.074492

Methods for Extraction of Bioactive Compounds from Products: A Review

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Abstract – Most agricultural by-products are not recycled or fully utilized. Most of them end up in waste and cause economic, social and environmental problems. Today, much of the by-products are considered waste, although they can be appropriately recycled to produce new value-added products. By-products have great potential to create, for example, food additives. Many of these byproducts are a source of valuable compounds such as proteins, lipids, starches, trace elements, bioactive compounds and dietary fiber. A wide variety of extraction methods are currently available, but several factors must be considered to determine which of these methods can efficiently and environmentally produce high-value-added products from by-products. The article examines, summarizes and compares various extraction methods, as well as products that are currently obtained using specific methods.

Keywords – Agriculture; by-products; extraction; value added products.

1. INTRODUCTION

Agricultural product residues (by-products) can be defined as primary or secondary depending on their origin. Primary residues include the production or cultivation of plant products, such as grains, fruits, vegetables and herbs, as well as the transportation, storage and processing of said products (if the products do not change significantly) on the farm and onward delivery to businesses. Secondary residues are obtained in the food processing industry and become residues during the processing stage (peels, pulps, stones, nut shells) [1]. The generation of agricultural waste varies from country to country, for example in Europe more than 40 % of the weight of the original agricultural product is thrown away, while in North Africa, East Central Asia and Latin America this percentage is higher. For example, the amount of by-products produced for an artichoke is about 50–60 % of the original weight, and for an orange – about 60 % [1], [2].

Agricultural by-products such as fruit and vegetable pomace and grain bran contain bioactive compounds that can act as free radical and antioxidant scavengers as well as health-promoting agents. Formative by-products also include substances such as phenol, catechin, epicatechin, anthraquinones, as well as essential oils. Methods involving their extraction using organic solvents such as methanol, ethanol, and acetone have been used to recover these substances. However, these methods are harmful to human health and the environment, as the process uses a large amount of organic solvents, and the methods are time-consuming. Therefore, alternative methods that are effective, cost-effective,

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environmentally friendly, safe and fast are being studied and sought to reduce the disadvantages of using organic solvents [3]. Therefore, in this article, the most popular extraction methods have been collected, with both the advantages and disadvantages of their use, as well as the principle of operation of the methods themselves and the type of solvent (environmentally friendly or unfriendly) required. The research conducted in recent years reveals the possibilities of using by-products in the production of products with high added value, however, there are also various disadvantages, such as the lack of appropriate methods for the extraction of these compounds. New extraction methods are emerging and being used from time to time to optimize the extraction of bioactive compounds from byproducts. However, given that progress has been made in this area, research has not been renewed in recent years, despite significant advances in extraction methods. Solvents also play an important role in many chemical and chemical engineering unit operations. Solvents usually need to be used for a limited period of time during the process, as they are most often intended as a solvent, diluent, dispersant or extractant, and then must be separated from the sample [9]. The correct choice of solvent is important and several methods of solvent selection have been developed. Many years ago, choosing the most suitable solvent was purely empirical and was done through error experiments or trials. This approach to solvent selection generally follows the alchemist principle of *similia similibus solventur* [10]. Green extraction methods, which do not cause pollution and use environmentally friendly solvents in their processes, are becoming more and more popular [6]. For example, pressurized liquid extraction and supercritical CO₂ extraction use heat in combination with other parameters to improve the extraction result. Several other non-thermal approaches are also available, such as pulsed electric field extraction and ultrasound extraction, which can be particularly effective for thermally stable compounds. Microwave extraction method is also used to improve the extraction of biologically active compounds of plant origin [7], [8].

By-products are increasingly being used in various industries. As, for example, there are currently no production processes in the pharmaceutical, perfumery, cosmetic, food ingredient, biofuel, or chemical industries that do not use solvents in the extraction process, such as maceration, percolation, steam or hydrodistillation, decoction and infusion. Mainly, the latest trends in extraction methods are focused on finding solutions that replace or reduce the use of petroleum solvents. This should be achieved by ensuring that the quality of the extract does not decrease and that there is less impact on the environment. The article combined the more commonly used extraction methods. The extraction methods reviewed indicated their advantages and disadvantages, the products obtained by these methods, and the extracts that can be obtained by extracting specific products.

2. EXTRACTION METHODS

In most analytical situations, the sample to be analyzed is a complex mixture consisting of many components. Usually only one or two components of a sample are of interest for research or production purposes, but these compounds are present in the matrix along with many other compounds. In order to quantify the compounds of interest, they must first be isolated from the other compounds in the sample [4], [5].

Extraction is the step to separate the desired natural products from the raw materials. Extraction methods include solvent extraction, distillation method, pressing and sublimation according to the extraction principle. Solvent extraction is the most widely used method. The extraction of natural products takes place in the following steps: (1) the solvent penetrates the solid matrix; (2) solute dissolves in solvents; (3) the solute is separated from the solid matrix;

(4) the extracted solutes are collected. Any factor that improves diffusion and solubility in the above steps will facilitate extraction. Extraction solvent properties, raw material particle size, solvent-to-solid ratio, extraction temperature, and extraction duration affect extraction efficiency [14], [15]. These are the most important aspects that must be taken into account when performing the extraction, because the specific by-products are effectively extracted only when the necessary parameters are specified in the process.

Refer to Table 1. the extraction methods, the products that can be obtained by the specific methods, the extracts obtained, as well as the efficiency of the extraction methods. Of course, traditional methods are more environmentally friendly because they use large amounts of solvents, however, as the methods develop and come out, they are more environmentally friendly and do not harm the environment during their processes, and researchers have worked to ensure that the efficiency of the technology is not lost and is improved.

TABLE 1. COMPOUNDS USED IN EXTRACTION METHODS, BIOACTIVE SUBSTANCES FOUND AND EFFICIENCY

Method	Compounds	Bioactives	Efficiency
Percolation	Medicinal plants [6], [4] Plants with bioactive constituents [7]	Essential oils	35 % to 50 % [8]
Reflux extraction	Pepper [6] Bamboo [9] Chinese ginseng [10] Medicinal herbs [11]	Spice oleoresin polyphenols	70 % [9]
Soxhlet extraction	algal biomass [12] Plants Soybeans [5] Soils, sediments, and animal and plant tissues [13]	Lipids Proteins and carbohydrates	80–90 % [14]
Pressurized liquid extraction	Medicinal plants [12] Fruits skin(ex. grapes) [15]	Essential oils	48 % [16]
Pulsed electric field extraction	Microalgae [17] Flower seeds and olive by-products [18] Pomace (ex. apple, carrot) [19] [20] Waste (ex. berries, vegetable) [20]	Lipids Oils [18] [19]	50 % [21]
Maceration	Coarsely powdered drug material, either leaves or stem bark or root bark [22]	Alkaloids, flavonoids, terpenes, saponins, steroids, and glycosides [22]	91 % [23]
Supercritical CO ₂ extraction	Sources - plant parts, such as leaves, stem, roots, seeds, flowers, and fruits [24] [25] Meat, meat products and fish	Natural substances, aromas, fats, oils, waxes, polymers, enzymes and colourants [26] flavonoids, essential oils, seed oils, carotenoids, and fatty acids [24] lipids and cholesterol	95 % [27]
Enzyme assisted extraction	Sources - plants, bacteria, fungi, algae, and animals [28] Tuna and mussel [29]	Oils, proteins, carbohydrates, and phenolics [28] Enzymes (pronase E and subtilisin) [29]	90 % [30]

Ultrasound-assisted extraction	Sources - animal and plant protein sources [31]	Vitamins, carotenoids and phenolic compounds [31]	90 % [35]
	brown seaweed species [32]	Polyphenols, aromas, polysaccharides from plant [32]	
	microalgae, yeasts, food and plant materials [33]	Alkaloids, flavonoids, glycosides [34] Phenolics, phlorotannins, flavonoids [32] Antioxidants, oils [33]	
Heat reflux extraction	Source – plants [36][37]	Essential oils, polysaccharide, polyphenolics and flavonoids [39]	60 % [40]
	<i>Pleioblastus amarus</i> (Keng) Shell [38]		
Mechanochemical-assisted extraction	Source – plant [41] (bamboo leaves, <i>Eleutherococcus senticosus</i> , Ginkgo leaves, <i>Camellia oleifera</i> Abel. Meal, <i>Magnolia officinalis</i> , <i>Hibiscus mutabilis</i> L., Siberian fir needles) [42]	Flavonoids, magnolol, rutin and polysaccharides [43]	50 % [42]
	Raw tea, animal material (ex., Shark cartilage [43])		
Microwave-assisted extraction	Source – plants (ex. grape skin, citrus peel, apple pomace, soybean, tea leaves, tomatoes, basil, garden mint, thyme, green pepper, yellow pepper, sea buckthorn) [44]	Anthocyanins, phenolic acids, pectin, vitamin E: γ -tocopherol and α -tocopherol, lycopene, essential oil, Ascorbic acid, vitamin C [44]	28 % [45]
Instant controlled pressure drop extraction	Fruits peels Plants (ex. green cardamom) [46]	Essential oil and antioxidants [46]	86 % [47]

The Table 1 describes the extraction methods as well as the products that can be extracted by these methods. Next, each method will be discussed and the advantages and disadvantages of these methods will be indicated.

2.1. Percolation

Given that the process is continuous, this method is more efficient than the maceration method, and the saturated solvent in the process is independently replaced by fresh solvent. However, it should be noted that during the extraction, high concentrations and larger amounts of ethanol are required, in which the sample is soaked (about 12 - 24 hours) [48]. Percolation extraction is a traditional extraction method used in traditional Chinese medicine processing. After placing the medicinal material powder in the percolation tank, the extraction solvent is continuously added and the percolation extract is collected at the same time. The percolation equipment and operation is simple. This applies to a wide range of medicinal materials. Components that are unstable under thermal conditions can be effectively extracted by the percolation process. However, there are also disadvantages, such as high solvent consumption, long extraction times, and high energy consumption in subsequent concentration processes [49].

2.2. Reflux extraction

Reflux extraction is a solid-liquid extraction process that takes place at a constant temperature with repeated evaporation and condensation of the solvent over a period of time so that no solvent is lost. The system is easy to use, efficient and cost effective [50]. This process is useful in industrial and laboratory settings where distillation is used. In addition, this technique is useful in chemistry for supplying energy to sustain reactions for long periods of time. In industrial distillation processes, reflux is useful for bulk distillation columns and fractionators, including oil refineries, petrochemical plants, chemical plants, and natural gas processing plants. In laboratory applications, the reagents and solvent mixture are placed in a round-bottomed flask. It is then connected to a water-cooled condenser, which is usually open to the atmosphere above. The round-bottomed flask is then heated, allowing the reaction mixture to boil. The vapors formed from the mixture are condensed through the condenser, thus returning by gravity to the round-bottomed flask. This technique is important because it can thermally accelerate the reaction by carrying out the process at an elevated and controlled temperature at ambient pressure, instead of losing a large amount of the mixture [51]. Extraction has the advantage of being more efficient than, for example, maceration or percolation extraction, as less solvent is needed and the extraction time is shorter. However, it cannot be used to obtain thermolabile natural products [52].

2.3. Soxhlet extraction

In this method, a finely ground sample is placed in a porous bag or “thimble” made of cellulose or filter paper and placed in the thimble chamber of a Soxhlet apparatus. The extraction solvents are heated in the lower flask, the sample evaporates in the “thimble”, condenses in the condenser and drips back to the starting position. When the liquid content reaches the siphon arm, the liquid content is again emptied into the lower flask and the process continues [4]. This method requires a smaller amount of solvent compared to, for example, maceration. Soxhlet extraction also has disadvantages, such as exposure to hazardous and flammable liquid organic solvents that can produce toxic emissions during extraction. The solvents used in the extraction system must be of high purity, which can increase the cost of the extraction method. This procedure is not environmentally friendly and can cause pollution compared to, for example, supercritical fluid extraction. The ideal sample for Soxhlet extraction is a dry and finely divided solid, and the method requires consideration of many factors such as temperature, solvent-to-sample ratio, and stirring speed [4].

2.4. Pressurized liquid extraction

Pressurized fluid extraction is considered an advanced extraction technology because of its advantages over traditional extraction methods. Pressurized liquid extraction uses solvent extraction at high temperatures and pressures that are always below this critical point so that the solvent remains in a liquid state throughout the extraction process. This technique is also known as accelerated solvent extraction, pressurized liquid extraction, pressurized hot solvent extraction, high pressure solvent extraction, high pressure high temperature solvent extraction and subcritical solvent extraction [53]. The use of these special pressure and temperature conditions causes changes in the physicochemical properties of the solvent. For example, the rate of mass transfer is increased while reducing the surface tension and viscosity of the solvent and increasing the solubility of the analyte. This allows the solvent to penetrate more easily and deeply into the sample to be extracted. As a result, the extraction process is more efficient and it is possible to obtain a larger amount of extract compared to conventional extraction methods. Low-pressure liquid extraction provides not only faster extraction

processes, but also less solvent consumption for solid sample preparation. In addition, most instruments used for pressurized fluid extraction are automated, allowing for less labor-intensive methods and improved reproducibility [53]. This method has many advantages, for example, it is not time-consuming (starting from 20 minutes), more environmentally friendly and less toxic compared to traditional extraction methods, and this technology is mainly used in the pharmaceutical and food industries. Various applications of pressurized liquid extraction have been developed for the extraction of contaminants from various food products; for organic pollutants from various solid and semi-solid environmental samples, such as soil matrices, sediments and sewage sludge; and for the extraction of bioactive compounds from natural matrices. In the field of natural products, the most studied specimens are plants. However, various studies have described the extraction of bioactive compounds from seaweed, microalgae and other food by-products. Pressurized liquid extraction is mainly used to extract antioxidants (such as phenolic compounds and carotenoids) and other bioactive compounds with anti-inflammatory, antimicrobial and antiviral properties [53]. However, a drawback of pressurized fluid extraction is that the presence of relatively high water percentages in the samples to be treated strongly decreases analyte extraction efficiency when using hydrophobic organic solvents as water hinders contact between the solvent and the analyte [54].

2.5. Pulsed electric field extraction

The pulsed electric field method uses moderate to high electric field strengths ranging from 100–300 V/cm in discontinuous mode and 20–80 kV/cm in continuous mode. Food or other materials (residues, by-products, plants) are placed between the electrodes and the high voltage electric field. The cell membrane is punctured, creating hydrophilic pores that open protein channels. A force per unit charge, called the electric field, is applied to the sample when high-voltage electrical pulses are applied through the electrodes. The membrane loses its structural functionality and is extracted like plant material [18]. The electric field can be applied in exponentially decaying, oscillating square waves, unipolar triangular or bipolar pulses. The electroporation that occurs is either reversible or irreversible, but depending on the application, this effect can be controlled. Generally, low specific energy (1–10 kJ/kg) and pulse cycle time (nanoseconds to milliseconds) are effective in the extraction process. High electric field strength increases cell membrane permeability, which depends on cell size and cell geometry. For fragile plant tissue, an electric field strength of 0.1–10 kV/cm is sufficient; however, resistant materials such as seeds require high intensities (i.e., 10–20 kV/cm) for efficient extraction. It also provides some additional benefits such as maintaining the nutritional value and sensory properties of liquid food [18].

2.6. Maceration

Very simple extraction method with low extraction efficiency and long extraction time (three days). This method can be used to extract thermolabile components. This is an extraction procedure in which coarsely powdered medicinal material, either leaf or stem bark or root bark, is placed in a container; menstruum is poured on top until the medicinal material is completely covered. After that, the container is closed and kept for at least three days. The contents are stirred periodically and, if bottled, must be shaken from time to time to ensure complete extraction. At the end of the extraction, the micelle is separated from the chaga by filtration or decantation. The micelle is then separated from the menstruum by evaporation in an oven or over a water bath. This method is convenient and very suitable for thermolabile plant material [22]. Studies have shown that phenolics and total anthocyanins can be extracted

from fruits under optimized conditions of 50 % ethanol, solids to solvent ratio of 1:20 and particle size of 0.75 mm. The efficiency of the method can be improved by combining it, for example, with microwave and ultrasonic extraction methods, and the combination of these methods brings economic benefits, as it is possible to reduce the process temperature during extraction. However, when the maceration method is combined with other extraction methods, the efficiency is not high enough to obtain valuable compounds. When studying the application of this method, it can be concluded that this method is effective only in combination with other extraction methods [55].

2.7. Supercritical fluid extraction

Supercritical fluid extraction is a technique that uses a supercritical fluid, a substance whose physical properties as both a gas and a liquid exceed the critical point. CO₂ with a critical point above 31.1 °C and 7380 kPa is the most commonly used supercritical fluid in supercritical fluid extraction. It is flammable, relatively non-toxic, chemically stable and inexpensive. Its critical temperature is suitable for the extraction of thermolabile compounds. However, since it is non-polar, it is recommended to add polar modifiers such as ethanol, methanol, ethyl acetate or acetone to extract the polar phenolic compounds. A pressure of 50–600 bar, a temperature of 20–35 °C and a time of 5–180 min are considered to be the parameters that provide the highest yield of phenolic compounds extracted from various samples (e.g., plant materials) by the supercritical method. Although CO₂ is the preferred extraction solvent (for extraction of non-polar compounds), the polarity of supercritical carbon dioxide extraction can be increased by adding a miscible polar compound (e.g., ethanol) as a modifier. Due to the selectivity of the supercritical fluid extraction process, the extracts obtained by this method have a low concentration of undesirable compounds. Additionally, supercritical carbon dioxide becomes gaseous after depressurization and can be easily removed from the flow system [56]. Supercritical fluid extraction has many advantages over traditional extraction methods, such as lower organic solvent consumption during the process, high extract selectivity and separation, and shorter extraction time compared to other extraction methods. The main advantage of this method is the reduced possibility of sample contamination by solvent impurities and the avoidance of decomposition and oxidation of the extracted compounds, as it is performed in a closed system without air and light. However, the initial cost of supercritical fluid extraction equipment is very high, and the cost of using it on an industrial scale often exceeds the technical benefits [49], [56].

Advantages of this method: (a) improved transport properties – the solute diffuses faster through a supercritical solvent than through a liquid solvent; (b) the equilibrium ratio and separation coefficients are usually quite high; and (c) the solvent can be regenerated with gas at reduced pressure, resulting in significant energy savings. Small changes in temperature and pressure at the critical point result in extremely large changes in solvent density and solubility, which is an advantage of supercritical fluid extraction. Carbon dioxide has a low cost, no harmful chemical properties and a low critical temperature [57]. The properties of supercritical fluid can be changed by varying the pressure and temperature, allowing for the selective extraction of actives, giving it an advantage over other extraction processes [58]. Supercritical CO₂ is cheap and readily available in bulk with high purity, ensuring minimal changes in bioactive compounds and maintaining their therapeutic or functional properties, able to dissolve lipophilic substances and easily separate from end products [49]. The disadvantage of supercritical fluid extraction is that the capital cost of supercritical fluid extraction equipment is significantly higher (at least 50 %) than conventional extraction equipment [57].

2.8. Enzyme assisted extraction

Enzyme-assisted extraction is suitable for extracting pectins from waste and by-products by increasing the permeability of cell walls. Enzymes are for the extraction of many phenolic compounds, additional flavonoids and anthocyanidins. Enzyme activity, processing time, substrate ratio, and particle size are all aromatized to achieve maximum efficiency during enzymatic processing [59]. Enzyme-assisted extraction has high efficiency and easy extraction conditions while maintaining extraction properties and stability. This method is widely used in the extraction of biologically active components from plants [60].

One of the advantages of using enzymes is that they can be added to hydrophilic and multi-step lipophilic extractions, especially for by-product valorization. In Europe, for example, postharvest to distribution food losses of grains, fruits, and vegetables range from 20, 41, and 46 %, respectively. Supplementing them with the help of enzymes increases the phenolic content of the lipophilic extracts, which is perfectly applicable in the production of nutritional or pharmaceutical products [61]. However, by-product safety restrictions are increasing and the topic is receiving more attention. In comparison, for hydrophilic extracts, enzymes effectively increase the water-soluble content of new derivatives used in the food industry. In addition, enzymatic extraction methods are characterized by easy reaction conditions, substrate specificity, industrial applicability and many other advantages. These extracts can be used continuously in many fields and, surprisingly, in the development of green synthesis [62].

2.9. Ultrasound-assisted extraction

An extraction method that uses ultrasound to create rapid solvent movement, resulting in increased mass transfer rates that speed up extraction times [63]. This extraction method has become more popular due to its several advantages, such as the short extraction time (10 – 30 minutes) [64], low power consumption (approx. 0–100 W) [65], less damage to the active compound and high extraction efficiency compared to traditional extraction methods [34]. In the ultrasonic treatment process, acoustic vibrations or mechanical waves with a frequency from 20 kHz to 100 MHz are applied to the sample. Ultrasonic extraction is based on cavitation, mechanical and thermal properties and is a very efficient method for the extraction of compounds of interest. These combined properties result in a decrease in particle size, cell wall ruptures, and an increase in reaction rates as mass moves across the cell wall. Ultrasound treatment creates a mechanical effect on the cell wall. This improves the penetration of the solvent into the cell. Thus, the maximum amount of intracellular compounds dissolves in the solvent, which is collected and purified. The ultrasonic method can accelerate the extraction of bioactive compounds. The extraction is carried out in a gaseous or liquid solvent by cavitation, which relies on liquid-liquid or gas-liquid interfaces. During the extraction, mechanical fragmentation of the cell wall occurs, which helps to easily remove the extract from the cell. The ultrasonic method is used for the extraction of bioactive compounds with reduced energy consumption, less amount of solvent addition, shorter processing time. This method is very fast and effective, because the cell wall is ruptured as a result of the ultrasound action. When ultrasound waves pass through a liquid, it causes cycles of compression and expansion. The expansion part forms bubbles or cavities in the liquid. The process of bubble formation, growth and explosive disruption is called cavitation. In a pure liquid system, the bubble maintains its circular structure because the environment around the bubble is homogeneous. When a circular bubble bursts on a solid surface, its shape changes and creates a high-velocity solvent jet against the cell wall and enhances solvent penetration into the cell wall. It improves the interaction between solid and liquid. In addition, in the solid material,

the ultrasound wave causes swelling, wetting and dilation of the pores in the cell wall. This increases diffusion and thus improves mass transfer. However, cavitation properties can also introduce new reaction mechanisms to form different types of free radicals. Sometimes highly reactive free radicals can be released, which can modify other compounds such as proteins as well as speed up the extraction of bioactive compounds [31].

The ultrasound method has various advantages. Technology with the help of ultrasound improves food processing to improve the physicochemical and quality of food products. Today, the ultrasonic extraction method is chosen mainly because high extraction yields of plant bioactive compounds can be obtained with this method. Ultrasound-assisted extraction can also increase the availability of bioactive compounds in food. It is likely that ultrasound assistance is a good alternative method to improve the yield and bioavailability of compounds compared to the heat reflux method [66].

The ultrasonic wave in this method could also improve the physical properties of compounds such as suspension, particle size, viscosity, color, pH, acidity and stability. The stability of bioactive compounds is an important criterion for bioavailability. Studies have observed that sonicated juice had lower oxygen levels, which was a favorable environment for carotenoid retention [66]. Ultrasonic technology is also useful in inhibiting the enzymatic browning process. Studies have shown that sonication with an aqueous extract of purslane can help delay browning of potatoes. This could be due to the “sponge effect” created by the ultrasonic wave with a frequency of 40 kHz during cavitation, although the treatment is only 10 min. Ultrasound can repeatedly squeeze and release the purslane extract into the cells, which is called the “sponge effect”. This phenomenon created an external low-concentration solution to achieve an effective anti-browning concentration in the cells. In addition, cavitation can also change the partial pressure of microbial cells, thereby promoting cell death caused by cell stress. Reducing the microbial load in products would extend shelf life, as microbes are always a major contributor to product spoilage [66]. Disadvantages could be limited recovery, efficiency, time and solvent consumption [67].

2.10. Heat reflux extraction

The process is simple and only in combination with other extraction methods is more effective. The sample is placed in a container of distilled water, then filtered and concentrated using a rotary evaporator [68]. The reflux apparatus allows the solution to be easily heated, but without the loss of solvent that occurs when heating in an open vessel. In a reflux setup, solvent vapors are trapped by a condenser and the concentration of reactants remains constant throughout the process. Heat reflux extraction is a more efficient method compared to percolation and decoction because it requires a shorter extraction time and less solvent. The technology involves heating the matrix for a certain period of time, causing a complex chemical reaction. Since the process uses a reflux extractor as the main reactor, better mass transfer and contact efficiency between the solvent and the treated matrix is achieved. The vapor flows to the flask, thereby controlling the temperature of the reaction. This technology is preferred due to its simplicity and convenient operation. The technology has found application in the extraction of many natural, phytochemical compounds and essential oils [69].

This method has both advantages and disadvantages. Advantages include low investment costs, for example compared to the supercritical CO₂ extraction method, and the method provides a very high extraction efficiency at the end of the process [10]. However, the disadvantages include the high consumption of the solution, which is environmentally

unfriendly, and the high temperature required for the process (compared to other methods and similar to the Soxhlet method) [70].

2.11. Mechanochemical-assisted extraction

Highly efficient, economical and environmentally friendly extraction of target bioactive components from complex matrices of dietary supplements or natural medicines has always been a challenge for both bioactivity determination, batch preparation and, more importantly, quality assessment of natural products. Mechanochemical extraction, which is a green technology, shows a clear superiority in the application of high-energy mechanical force acting on raw materials to separate target components from natural products in an aqueous environment at normal temperature and without using harmful, dangerous and expensive substances. organic solvents. In addition, mechanical chemical extraction in a one-pot extraction provides a rapid process, good reproducibility, and direct solution transfer to instruments such as reverse-phase high-performance liquid chromatography systems for further analysis [71]. This technology is based on the study of the physicochemical and chemical transformation of compounds caused by mechanical force, such as grinding in a ball mill. It consists of mechanically treating a sample (e.g., plant material) under very insensitive mechanical pressure in a ball mill with a solid reagent (usually carbonated salts) prior to solvent extraction. During the process, the cell walls are ruptured, allowing the target compounds to be obtained with improved water solubility. This property allows the process to use water instead of other common solvents, reducing extraction costs and simplifying the purification process. The most commonly used reagents have been solid alkali reagents such as Na_2CO_3 , NaHCO_3 , and NaOH , depending on their alkali strength and the chemical properties of the target compounds. Studies have shown that the extraction process provides a more efficient time and temperature reduction and does not use organic solvents. However, since the technique is quite new, the effect of different extraction parameters is still inconsistent and a complete understanding is lacking, which is essential for the scale-up process and future applications [55]. Of course, this method has both advantages and disadvantages. Mechano-chemical extraction can have a significant impact on the environmentally friendly processing of medicinal plants [72]. Mechanical chemical extraction is considered a good alternative method to traditional methods for the extraction of bioactive compounds from plant and animal by-product raw materials. The main advantages of mechanical chemical extraction are: (1) selectivity and increased extraction yield, (2) low operating temperature, thus allowing the extraction of thermolabile compounds, (3) in most cases, water is used as a solvent instead of conventional. organic solvent, (4) short extraction time [73], (5) simplified process. Thus, it is possible to obtain bioactive compounds from plant and animal materials by mechanochemical extraction method [56]. Studies have proven the increased efficiency and selectivity of mechanical chemical extraction as a new extraction method, the absence of consumption of organic solvents, simplification of manipulations and shorter extraction time. The mechanochemical extraction process can avoid the loss of heat-sensitive compounds due to its relatively low extraction temperature ($\sim 40^\circ\text{C}$). Thus, the mechanical chemical extraction technique has a wide application in the pharmaceutical and food industries in the future. Although the performance of the mechanical chemical extraction technique is impressive, various problems arise when using this method. Not applicable to hydrophobic and neutral compounds [52]. Further research and application of mechanical chemical extraction is important, including the extraction of other plant materials, especially water-insoluble substances and heat-sensitive compounds. In addition, further development of extraction equipment is also required. Available ball mills with different weights can allow

mechanical chemical extraction to be used on a larger scale. The mechanism and kinetics of mechanochemical extraction are still debated and require further investigation. A deeper understanding of the mechanism is essential for the further development of mechanical chemical extraction. For example, the physicochemical and biological changes induced by mechanochemical pretreatment should be further investigated. Although mechanical chemical extraction is not yet widely used in the modern food and pharmaceutical industry, we believe that it will be a competitive tool for the extraction of bioactive substances in the future. Further development of the extraction process and equipment will promote the application of mechanical chemical extraction technology [73].

2.12. Microwave-assisted extraction

Microwave extraction is a method that uses non-ionizing electromagnetic wave radiation with a frequency of 300 MHz to 300 GHz to induce motion of molecules in polar or polarizable materials or solvents by acting on dipoles. The molecular motions heat the sample, which causes moisture to evaporate from the sample, creating pressure that causes the cell wall to rupture and the necessary compounds to be released. During radiation, the solvent molecules in the normal phase are aligned with the electric field. In the rapid electric field changes that occur in microwave extraction, the solvent molecules are unable to rearrange and begin to vibrate, causing the solvent to heat up due to frictional forces. This allows the solvent to easily penetrate the sample matrix and facilitates the extraction of the desired compounds. Solvents should be selected based on their boiling points, dispersion and dielectric properties. Based on these properties, ethanol, acetone, or their combination with water are often used to extract phenolic compounds using microwave-assisted extraction. Since microwave energy is transferred only by dielectric absorption, non-polar solvents with lower dielectric constants can absorb much less energy, which can lead to lower extraction efficiency. Therefore, microwave-assisted extraction is considered a selective method for polar molecules and solvents with high dielectric constants. Microwave extraction has many advantages similar to ultrasonic extraction, including lower solvent usage, shorter extraction time and processing costs, and high extraction efficiency. However, this method is limited to low molecular weight phenolic compounds such as phenolic acids, quercetin, isoflavone and trans-resveratrol, which were shown to be stable under microwave heating conditions up to 100 °C for 20 min. Phenolic compounds with a higher number of hydroxyl substituents, such as tannins, or thermosensitive compounds such as anthocyanins, may not be suitable for microwave extraction [56].

The advantage of microwave extraction is that it is an automated green extraction method that has a short extraction time (can be a few seconds [23]) and low solvent consumption during the process, as well as the ability to obtain several (up to 40) samples at the same time, significantly improving the permeability of the samples [74]. Although the small sample size used in many analytical extraction processes has some advantages and is more environmentally friendly, it also has at least one disadvantage, such as the amount of microwave energy absorbed decreases as the sample size decreases. If the sample is small in size, a large amount of energy is not absorbed but reflected. Reflected energy can damage the magnetron, so when using small samples for analytical work, it is recommended to use microwave systems designed to protect the magnetron from reflected power. Commercially available applicators are not compatible with microextraction, as the minimum amount of solvent required is usually around 10 mL. Sample size is directly related to the amount of solvent required for extraction. The nature of the sample and the dielectric properties of the sample or its components can be very important in microwave extraction. For example, water

added to or naturally present in the sample is a key factor because water molecules have a high dipole moment, resulting in a high heating efficiency for the sample. A related inconvenience is the requirement to control the water content of the matrix to obtain reproducible results. Other possible matrix components (such as ferrous material) may cause buckling due to absorption of microwave energy. The organic carbon content of the matrix is known to hinder extraction due to the many strong analyte-matrix interactions that are difficult to break. In this case, microwave extraction is a very effective technique [75].

2.13. Instant controlled pressure drop extraction

This process firstly involves a short heating stage (10–60 s) including the injection of saturated steam under high pressure (up to 1 MPa) applied to the product initially placed under vacuum. This step involves condensation of the vapor and heating of the product, which increases the moisture content of the product by 0.1 g H₂O/g dry matter. The initial vacuum ensures rapid contact between the vapor and the sample and thus improves heat transfer. Compressed air can sometimes be used as a pressurizing agent, such as for multi-cycle instantaneous controlled pressure drop extraction treatments. After the first heating stage, a sudden pressure drop (0.5 MPa s⁻¹) towards vacuum (3–5 kPa) in just 10–60 ms causes automatic evaporation of water in the product, which creates steam and significant mechanical stress. This allows the product to expand. In addition, automatic water evaporation ensures rapid cooling, which prevents thermal degradation of sensitive compounds and thus ensures the high quality of processed products. The cooling rate can reach an extraordinary 1500–2000 kW m² [47].

Instantaneous controlled pressure drop extraction technology is also currently being used at research and industrial levels. Depending on the application, products can be collected from the processing tank, while extracts and liquids can be collected from the vacuum tank. Furthermore, it is important to emphasize that the processing conditions defined at the laboratory scale can be directly applied at the industrial scale, which becomes an additional advantage of the instantaneous controlled pressure drop technology [76]. Research at laboratory and industrial scales has led to the development of many applications of instantaneous controlled pressure drop technology in food processing. This process is well guaranteed to maintain functional properties, organoleptic quality, effective microbiological/fungal decontamination and reduced energy consumption and shorter drying time. Instant controlled pressure drop extraction treatment is a high temperature/short time process that improves both drying process performance and high quality functional food [77]. The efficiency of obtaining essential oils can be improved by combining this method with other types of methods (for example, the hydrodistillation method) [46]. On the other hand, it also has disadvantages, such as it can be energy-intensive and often has a long processing time, which can cause negative chemical changes in the essential oil [46].

3. CONCLUSIONS

The main purpose of extraction is to separate the components from a mixture using a solvent. The application of the extraction method is important in almost all industries, such as pharmaceuticals, chemical industry, wastewater treatment processes, food and cosmetic production processes, etc. Depending on the properties of the materials (samples) to be extracted, it is important to study in detail and find the best and most efficient extraction methods according to the processed sample (by-product).

Over time, mining methods have evolved and become greener and more environmentally friendly. New mining methods have been sought, as well as improved ones used so far. For extraction, reflux extraction is the most common product separation method. Modern extraction methods, which are also considered green extraction methods, including ultrasonic extraction, microwave-assisted extraction, supercritical fluid extraction, and pressurized fluid extraction, have received increased attention in recent years due to their high extraction yield, selectivity, and stability. target extracts and process safety benefits. Some of these green methods have become common sample preparation methods for analytical purposes.

There is a clear and growing interest in obtaining and isolating natural products and their beneficial uses. These specific applications also include the extraction techniques used for conditioning and the new stationary and mobile phases to be used in these techniques. Consequently, these trends are expected to continue in the near future as they are primarily driven by consumer demands and safety, environmental and regulatory issues.

In conclusion, advanced methods have some advantages over traditional methods in terms of extraction yield and time. However, traditional methods still have their values. Traditional press extraction is more suitable for extracting crude oil or other high quality oils, but it is time consuming. Solvent extraction may have the highest extraction yield, but may result in solvent contamination. Supercritical fluid extraction can be considered a kind of green technique if the green solvent is chosen, but it has higher operating costs due to the complexity of the process. In addition, microwave and ultrasonic extraction can increase the extraction yield, but it is difficult to use for large sample sizes. These extraction methods need more research to be able to obtain larger sized material. In general, each of the methods discussed above can be modified or combined with other extraction methods to improve the efficiency of the process. Each method has its pros and cons, but it is also possible to find and adapt the best extraction technology for each material. As well as continuing to develop the extraction methods used so far, they must be more and more efficient, as well as better in terms of time and cost, in order to continue to focus on environmentally friendly processes, taking into account the problem of environmental pollution.

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Bioresource Value Model: Case of Crop Production

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Abstract – The future of sustainable development is the bioeconomy with both global and local renewable energy solutions. The updated Bioeconomy Strategy and the Green Deal serves as prove of European Commission commitment for transformation towards a sustainable and climate-neutral European Union. This process is characterized with an enormous complexity and should be studied thoroughly for designing transition pathways. Scientifically sound methods can support policymaking in dealing with uncertainty and complexity taking place within definition of transition pathways. This article reviews the existing bioeconomy development models, and presents a novel model, which focus on agriculture – one of the main directions of the national economy. The concept of model is tested within a case study of crop production sector in Latvia. The results of case study show economically viable scenario for added value target set for 2030. In the crop sector, the baseline scenario and three alternative scenarios were analysed. The highest added value and the most advantageous alternative scenario is for fibre powder produced from cereal bran (in the bioeconomy sector, food provides the highest added value).

Keywords – Added value; bioeconomy; biorefinery; crop production; green deal targets; optimization; TIMES

1. INTRODUCTION

Sustainable production and consumption (SPC) can broadly be defined as encompassing any and all issues that seek to improve the way that products and materials are sourced, manufactured, and marketed and the way that products are purchased, used, and disposed of at the end of their useful lives [1]. Economy founded on biomass instead of fossil fuels represents a significant shift in socio-economic, agricultural, energy and technical systems towards sustainability. The concept of a bioeconomy, also called the ‘bio-based economy’ or ‘knowledge-based bio-economy’ (or KBBE), can be understood as an economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources, such as plant and animal sources [2].

Addressing complex agri-environmental issues calls for interdisciplinary bio-economic research that recognizes the complexity of agricultural systems, and their roles in food production, delivering ecosystem services, and contribution to rural economies. This study aims at providing a tool for bioresource value modelling and assessment, which would help to evaluate alternative scenarios of bioeconomy development at national level in crop production sector.

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2. LITERATURE REVIEW

2.1. Bioeconomy and Bioresource Value

The bioeconomy concept is becoming more prominent topic in science and policy lately. In 2012 European Commission within a strategy ‘Innovating for Sustainable Growth: A Bioeconomy for Europe’ defined bioeconomy concept [3]. The strategy defines that bioeconomy is based, first of all, on using renewable biomass, by using not only raw material, but also biomass residues and, second of all, producing wide range of high added value products and energy. Production of high added value products means that at first biomass is used to produce high added value products like pharmaceuticals and chemicals and then residues are used for the production of lower added value products. Therefore, the main aim of bioeconomy is to use bioresource as fully as possible and reduce waste [4].

In Latvia, innovative approaches for the efficient and sustainable exploitation of natural resources are developed and introduced in the bioeconomy industries in order to stimulate the growth of the national economy, providing higher value-added, and promoting exports and employment. This shall be achieved while simultaneously balancing economic interests with ensuring environmental quality and preserving and enhancing biodiversity [5]. The successful development of a bioeconomy based on the production of higher value-added products from bio-resources depends on the direction of policy strategies [6].

Latvia is a small country with a limited domestic market and limited resources. Economic growth and wellbeing in Latvia directly depend on its foreign trade, investment, capability to compete and produce high value-added products [7]. The current relevance of the use of biomass in the energy sector compared to other higher value-added products (e.g. composites, fine chemicals and biomedicines) highlights the need for an interdisciplinary assessment of the added value of bio-resources from various sources such as agriculture in to the circular economy [8].

2.2. Agriculture Sector of Latvia

About one-third of agricultural land in Latvia is used for crop cultivation, and about one-tenth is dedicated to pasture for livestock. Of the crops, grain (mainly rye) is the most important. Cereals account for the largest share of agricultural production (around 30 % of total final agricultural production) [9]. Potatoes, onions, carrots, and sugar beets are the main crops produced for export [10]. The role of two major sectors is becoming stronger with every year – cereal production and milk production [11].

In the last 20 years, the sector of agriculture was affected by sharp political changes: in the 90s of the last century, Latvia’s land management structure changed fundamentally, collapse of collective farm system started, resulting in emerging private farms [12]. In the meanwhile, they dominated in the sector and a proportion of household plots increased. Whereas in 2004, Latvia acceded to the European Union (EU). Upon accession, Latvia transposed its basic legislation and adjusted to EU principles. Therefore, the development of Latvia’s agriculture, to a large extent, is associated with the future of the EU Common Agricultural Policy (CAP). CAP objective is ensuring a stable income for farmers and at the same time facilitating production of high-quality products in accordance with the market demands as well as encouraging farmers to seek new development opportunities by diversifying types of activities [11], [13].

In agriculture, in general and in plant production, in particular one of the major sectors is production of cereals. Providing the country with a sufficient amount of cereals contributes to strengthening of its independence. Production of cereals is particularly import for animal

husbandry as neither branch of animal husbandry can exist without cereals. Particularly important production of cereals is for pig breeding and poultry farming. The year 2013 was the second distinguished year after 2012 for cereal producers. In 2013, the total yield of cereals was 175.8 thousand tonnes less than in 2012, reaching 1948.7 thousand tonnes. Total of 32.6 % of agriculture areas are accounted for cereals cultivation with the yield of least 4 t per ha. Lately, cereals are used not only for animal husbandry and food production but also in production of alternative energy, including heat production [14].

In 2013, oilseed rape sown area increased (9.1 %) however, as compared with a successful 2012, an average productiveness of oilseed rape has dropped. Thanks to enlargement of sown areas, the total yield has stayed on the level of the previous year. Basically, cereal production farms are engaged in growing of oilseed rapes because soil cultivation technologies, cereal sowing and harvesting machinery is similar to that needed for oilseed rape. However, there is a certain risk, as crop rotation on these farms goes between two crops – oilseed rape and wheat, and oilseed rape is being sown on one and the same field every second year or every 2–3 years, at best. This can lead to a situation that in a long run, oilseed rape can be affected by clubroot, resulting in a sharp reduction in yields. It is forecasted that next summer, spring oilseed rape areas could reduce considerably due to the Commission's decision to ban the use of some pesticides and treating oilseed rape with mordant [14].

The entire territory of Latvia is suitable for growing of vegetables but specialization of farms in horticulture is determined by location of markets, mainly closeness to towns and cities [14]. Horticulture farms are mainly situated in Riga neighbourhood and Zemgale region. In 2013, Latvia's vegetable area, as compared with 2012, increased by 5 %. Field areas increased by 5 % but covered areas reduced by 15 %. Although, covered area has reduced, but the total yield of vegetables in covered area increased by 7 % in 2013 as compared with 2012. It is due to introduction of new technologies in production of vegetables in covered areas resulting in higher vegetable yields. 98 % of covered areas are under tomatoes and cucumbers, leaving only 2 % to the rest of covered area species [14].

2.3. Bio-Economic Models

There is a growing interest in interdisciplinary bio-economic modelling, to provide information to policy makers and to help improve management decisions [15]. A large number of bio-economic models has been developed for different farming systems and agro-ecological conditions. Such models may link biophysical and economic models [16], but their individual components are typically developed from a single-disciplinary perspective (e.g. economics or agronomy). Bio-economic models tend to be limited in their level of integration, and often involve limited genuinely interdisciplinary teamwork. There have been increasing calls for bio-economic models that focus more on integrating knowledge at conceptual as well as technical implementation levels [15]. This section gives a review of literature on methods used in bio-economic models and assessment frameworks.

Multi-criteria decision analysis (MCDA) is a valuable tool for decision-making in complex process systems, using a number of parameters that influence embedded processes in the value chain [17]. These parameters can be assessed by different actors in the chain as 'significant factors'. In addition, by including this flexibility in the scope of this assessment, the MCDA ensures systematic investigation and transparency in its decision-making. The overall aim of the MCDA is to provide an opportunity to explore the knowledge and concerns raised by actors in the chain, to weigh them from an objective point of view, to systematically analyse them, to set key criteria and then to take decisions in complex multi-stakeholder process systems [18].

Studies are being carried out to use two-tier MCDAs to rank biological value chains based on a set of selection criteria, emphasizing the importance of respecting the principles of their circular economy. The results of the analysis highlight the importance of these selection criteria to highlight the features of any bio-based value chain / business model [19].

A mapping methodology has been developed to understand the strengths, weaknesses, opportunities and challenges inherent in the biological value chain associated with the synthesis of different bioproducts, and demonstrates the importance of bottom-up processes and material use in downstream activities (mainly post-consumption and end-of-life management). Different biological value chains have been identified in the EU. This list of tentative value chains is based on a review of the literature above, focusing on the biological value chains / products covered by the EU certification schemes and market demand [20]. The list includes organically produced value chains with (but not limited to) a variety of characteristics, including:

- From virgin food-based feedstock to bio-waste cascading;
- 100 % bio-based to partially bio-based, value chains;
- Those with a fully-functional waste management infrastructure to those that lack one;
- Diverse product functionality [21].

A recognized methodology known as GE-McKinsey Matrix [22] uses nine modules or boxes to identify aspects of the potential new bioproducts market. The methodology has been developed and tested on three existing products. The calculations combine economic data and data on technology, as well as data on product competitiveness and market data. The data analysis is based on aggregated data from information sources and is presented in two dimensions – market attractiveness and product competitive advantage. The method provides the results to allow to make recommendations for further evaluation of the production of new products in the current location or in a country where local resources are available [23].

The methodology for the GE-McKinsey Matrix can be modified to include considerations and constraints such as environmental protection, required in the manufacturing process and product sustainability [23]. Instead of the competitive position of the company, it shows the competitive attractiveness of a particular product. After obtaining results, it is possible to gain insight into market opportunities for the product. The GE-McKinsey Matrix is widely used for product portfolio management and in the analysis of competitive scenarios [24]. A similar analysis can be made using the Boston Consulting Group matrix [25], however, the GE-McKinsey Matrix can provide a broader range of factors, while the Boston Consulting Group matrix was found not to be sufficiently flexible and complexity issues are reported [26].

Life cycle analysis (LCA) is a well standardized methodology that can be applied for bioeconomy studies [27]. The LCA selects and analyses a list of key bioeconomic value chains for each pillar to identify existing and potential biomass conversion technologies and assess their environmental performance. The criteria for selecting value chains are: relevance in the global market, representativeness and / or suitability for competition with similar products of fossil origin [28].

Few studies with application of Socio-economic analysis (SEA) [29] for biorefineries have been found in the literature. Socio-economic performance in the production of various bioenergy products is divided into categories, mainly for positive, neutral or negative effects. In the study of [17] a rural biorefinery was assessed for the development of the territorial integration of economic activities in the region based on the socio-economic framework. In addition, a social life cycle assessment (SLCA) is included as one of the criteria for examining the social dimension of a rural biorefinery [30].

A specific bio-economic model called SYNERGY (cross-Scale model using complementarity between livestock and crop farms to enhance regional nitrogen self-

sufficiency) is a static non-linear programming model, which maximizes regional profit under constraints is introduced in study of [31]. It is calibrated to starting conditions using Positive Mathematical Programming. SYNERGY is applied to a particular area called ‘region’ that is divided into several ‘sectors’ to consider a variety of soil and climate conditions. SYNERGY's main originality lies in its ability to represent farm-to-farm exchanges of intermediate products (manure and crops), which occur on a local market (i.e., intra-sector or intra-region). It generates four types of indicators:

1. Structural (e.g., crop areas, numbers of animals);
2. Technical (e.g., protein self-sufficiency, application of N fertilizers);
3. Economic (e.g., regional profit, farm income, farm-to-farm exchanges);
4. Environmental (i.e., N efficiency and potential losses of N).

These outputs are provided for each farm type at the sector and regional levels [32].

Another modelling framework MOSAICA can be used for optimising individual farmer's utilities at the regional scale, considering the expected farm revenue and the risk aversion towards price and yield variations [33]. The inputs of the model are:

- The geographic database of fields that contain information about the biophysical context and the farm structure, e.g., the farm size and the land tenure,
- The database of activities that describe the cropping systems and technical-economic coefficients that can be allocated to fields, and
- The farm typology and the classification algorithm for the eight farm types.

The allocation of cropping systems is modelled through a set of equations that model the choice of cropping systems by farmers at different scales, namely the field, farm, sub-regional and regional scales. Optimization is done on a regional scale, as equations are introduced at this scale to limit the total production of some crops (due to market size or production quotas). The results of the model are estimations of sustainability range of the trimming system [34].

The SEAMLESS-Integrated Framework (SEAMLESS-IF) aims to assess the impact of agricultural and environmental policies on agricultural systems and sustainability indicators [35]. Integrated evaluation requires that the policy issues addressed by SEAMLESS-IF be translated into scenarios assessed using a set of key economic, environmental, social and institutional indicators. To model key aspects of farming systems from the field to the farm scale, SEAMLESS-IF provides an intelligent combination of crop production system model, bioeconomy farm model and indicators. This modelling chain can be used to identify which farm locations and agro-ecological technologies will be preferred in the implementation of the research policies and agro-ecological technologies and to model their impact [36].

The cropping system model *CropSyst* [37] can be used to quantify the relationship between crop production and environmental effects at field scale, as the cropping system component of SEAMLESS-IF [38]. *CropSyst* implements modules capable of simulating crop response to a wide range of weather, soil and management conditions using daily time steps, for periods ranging from one year to a hundred years. *CropSyst* is a multi-year, multi-crop, daily time step cropping system model. It can simulate the soil water budget, soil–plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate. Crops are simulated using a generic crop simulator, in which some processes (e.g. photoperiod response, vernalisation) can be switched on or off using appropriate parameter values. *CropSyst* simulates plant growth as potential growth and under water, nitrogen, and temperature stresses [36].

A bio-economic farm model, ‘MEETA’ (Modelling Energy and Emissions Trade-offs in Agriculture) [39]. The objective of the MEETA model is to capture trade-offs between

different aspects of the farm system – those that are not captured by the LCA analysis [23]. The MEETA model is a linear programming optimisation model that represents multi-year cropping within a single year framework, based on combinable crops common to cereal farms. Output from crops is a product of straw and grain at representative market values; the model maximises the gross margin between total output and variable costs of seeds, fertilisers and sprays, contract costs and fuel costs. Energy inputs and outputs and emissions data are associated with the main inputs and outputs using secondary data and LCA literature. The major constraints in the model are farm size, crop rotations and availability of on-farm machinery for some operations. The model can optimise for either (maximised) farm gross margin, net farm energy or (minimised) GHG emissions, and produces the optimal crop mix, associated machinery and contract use and the farm gross margin, net energy and GHG emissions for each optimal crop mix [40]. The model structure allows trade-offs between energy, emissions and financial performance to be quantified with a specific focus on bioenergy production. The MEETA model focuses on farm level trade-offs and hence the upper model boundary includes everything that is used on farm, up to the point of sale at the farm gate. The following sections provide more detail on the levels of complexity and boundaries for specific parts of the model [40].

Lastly, the Integrated MARKAL-EFOM System (TIMES) model [41] is bottom-up, linear programming tool applied for long-term energy systems planning allowing to analyse effect of different scenarios. It optimises the whole energy system including supply and demand services by minimizing the total cost in the considered modelling period [42]. The Irish TIMES (The Integrated MARKAL-EFOM System) model is an energy system model that was developed by University College Cork (UCC) in collaboration with the Economic and Social Research Institute (ESRI), Energy Engineering Economic Environment Systems Modelling Analysis (E4SMA) and KanORS over the period March 2009–November 2011. The Irish TIMES (The Integrated Markal-EFOM System) is a model that analyses energy usage, emissions, and natural resources and was extracted from the Pan European TIMES (PET) model of Europe, and was then updated and expanded using local and more detailed data and assumptions [42].

TIMES Bioeconomy Value Model (TIMES-BVM) is developed with the aim to model bioresource flows and technologies for bioeconomy development and bioresource value-added growth to 2030. In particular, addressing the development of biorefineries from perspectives of natural boundaries for resource utilization capacity, economic feasibility in terms of cost of technologies and their operation and maintenance, and socio-economic aspect as an added value in terms of salaries and indirect taxes [43].

3. METHODOLOGY

3.1. Goal of the Study

The goal of this study is to develop and test a tool for analysis of agriculture sector bioresource utilization added value for energy and material over longer term and definition of the optimal bioresource utilization scenarios on national level. To achieve the goal of the study following tasks are performed:

1. Definition of hypothesis for agriculture sector bioresource utilization added value on national level;
2. Selection of appropriate modelling approach able to capture the scope necessary for achieving the goal of the study and test hypothesis;
3. Definition on model boundaries and scenarios under analysis;

4. Creating data inventory for the model;
5. Analysis and interpretation of results (see Results chapter).

3.2. Hypothesis and Modelling Approach

There is a certain difference in added value created from resources when they are used for energy production and materials. Historically, the development towards bioeconomy started with high emphasis on bioenergy, and now is moving towards bioresource utilization for more advanced technological and material applications. Therefore, currently a topical issue for policy planners, decision maker and other stakeholders is finding the optimal scenarios for resource utilization with the highest added value. In light of this, the proposed hypothesis for testing the developed tool is defined as achieving agricultural bio-resources utilization added value increase at the national level (by at least 30 % by 2030) by implementing new technologies. In the model, the value added of products was calculated using the total value of the product and dividing it by the volume produced. In the direction of the bioresource utilization for energy purposes one of the most recognized methods is TIMES for energy modelling. In this study TIMES modelling approach is selected and adapted for agriculture sector of Latvia. TIMES Agricultural Bioresource Value Model (ABVM) is developed to model bioresource flows and technologies for bioeconomy development and bioresource value-added growth to 2030. The selected approach is based on optimization of costs attributed to investment and operation of technologies, resource flows and final demand. Historical demand for crop products was taken from the FAOSTAT database, but for 2030 it was calculated based on future population changes. In this way, TIMES allows to evaluate optimal scenarios for bioresource use in energy sector and biorefineries for production of higher added value products. In particular, addressing the development of biorefineries from perspectives of natural boundaries for resource utilization capacity, economic feasibility in terms of cost of technologies and their operation and maintenance, and socio-economic aspect as an added value in terms of salaries and indirect taxes. The proof of model concept and the hypothesis is tested through case study on crop production sector of Latvia.

3.3. Model Boundaries and Scenarios

The model boundaries are defined according to classification of TIMES model components. The components included are commodities and technologies that are linked with flows.

Commodities are defined as bioresource carriers, materials, products. These commodities in the model are outputs and inputs of technology (process). Commodity flows are entering the processes and are turning into other commodities in the process output (for example, production of food). In this case, flows are biomass flows and measured in mass units.

Technologies component in TIMES represents technological processes that is used to transform one type of commodities into another. Processes are divided in: 1) primary production of commodities, e.g., mining (in default) – or as in case of bioresource, it is also harvesting, import processes, and 2) transformation activities like conversion plants, biorefineries, end-use demand (in this case products). The final consumption of commodities is determined in the model by demand per end sector use.

In TIMES ABVM, model boundaries in bioresources cereals, vegetables and oils (quantities of products grown and harvested), food (fresh and cooked), feed and other products (bioethanol and biodiesel) as commodities, which are linked to respective conversion technologies with commodity flows (see Fig. 1).

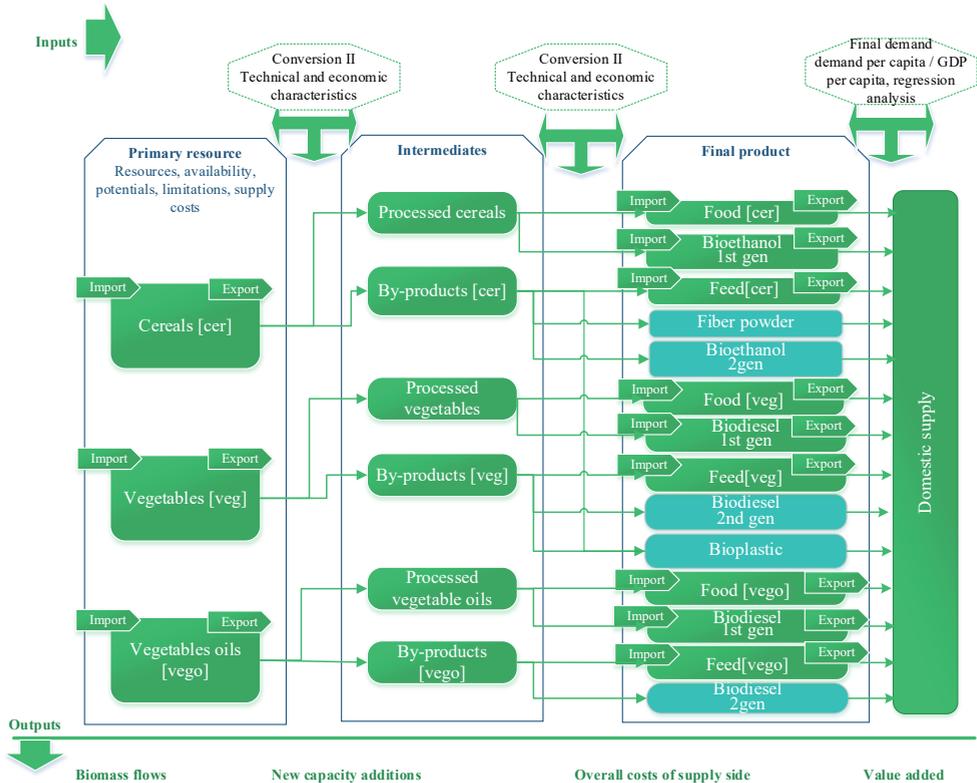


Fig. 1. Defined model boundaries for TIMES ABVM.

The definition of flows linking commodities with technologies are based on the current Latvian crop production sector, where the main extraction of crop products is locally grown products. In the processing of crop products, such as cereals, vegetables and vegetable oils are used to produce food, feed and other products (biofuels). Cereal, vegetable and vegetable oils are primarily used in food production, as well as in the production of first-generation biofuels, and the by-products are used in feed production. Novel foods as well as non-food products were considered as new products in crop products, including the production of fibre powder from grain bran, production of bioplastics from vegetable and cereals by-products, and production of 2nd generation biofuels from grain, vegetable, and vegetable oil by-products.

Based on the available information it is considered that not all crop products in Latvia are processed into food products, some are used in the production of bioethanol and biodiesel. In the process of grain processing, residues are generated, which is not used in food production (milling process). By-products from crop processing are used to produce fodder. Bread production technologies were used in the processing of cereals into food. In the processing of vegetables were considered technologies that are associated with the canning of vegetables and the production of vegetable oils. The production of bioethanol (grains) and biodiesel (vegetables and oils) was considered in other crop products.

To increase the added value of bioresources in the crop sector, four new technologies have been introduced in the model: production of fibre powder, bioplastic production, biofuel production. The total number of scenarios investigated in this study is 5, including:

1. The baseline scenario without any new technology introduction;
2. Separate scenario for each of the new technologies (3 new technologies in total);
3. Aggregated scenario with all new technologies.

Specifically, the scenario for the production of fibre powder from crops is based on the fact that the by-products of grain pre-processing – bran – are used in the production of a new product. The bioplastic production scenario from crops assumption is that by-products of grain pre-processing – bran and vegetable residues – are used in the production of a new product. As well as a new technology scenario for the production of second-generation biofuels (bioethanol and biodiesel). For the production of bioethanol assumption is that by-products of grain processing or bran are used and vegetable oil residues for the production of biodiesel.

3.4. Data Inventory

Data is collected for each commodity included in TIMES ABVM in terms of amount and costs of resources, food, feed and other products production, imports, exports and costs. Most of the data are obtained from the official statistical portal of Latvia [44], as well as the database of the Food and Agriculture Organization of the United Nations was used [45].

The historical input data from 2015 to 2019 is used in TIMES ABVM to define the upper and lower limits for amount of resources harvested, imported and exported. These limits are respected in the optimization of added value for target year 2030, in order not to exceed the expected limits for the crop products grown and minimize the potential impact of changes in imports and exports on the model output. The input data for the model's final product or industry demand is determined by a forecast based on population change for the target year 2030.

Data on respective conversion technologies are included in the model in terms of capacity, efficiency, investment, operation & maintenance (O&M) costs, lifetime and availability, and the added value of the product production process. Technological costs are taken from financial statements and reports of Latvian companies. Data on the technology capacities are obtained from the companies' pollution permits.

The added value of products is calculated from two databases. The total added value for food, feed and biofuels is obtained from the European Commission database [46]. The volumes of food, feed and biofuels produced (thousand tons) from the database of the Central Statistical Bureau of the Republic of Latvia were also considered. Value added for food, feed and biofuels was calculated by dividing total value added and output.

Literature is reviewed on new technologies in agriculture sector is performed for definition of alternative scenario input data. The new technology availability is set to 2025. The new technologies are:

1. The production of fibre powder from grain processing by-products or bran;
2. The production of bioplastics from grain bran and vegetable residues; and
3. The production of second-generation biofuels (bioethanol from grain by-products and biodiesel from vegetable oil by-products).

4. ANALYSIS OF RESULTS

The tool for analysis of agriculture sector bioresource utilization added value TIMES ABVM is developed and tested in case study on Latvian agriculture sector, considering the limitation of the method and availability data. The scenarios of the case study include baseline scenario for agriculture sector and alternative development scenarios with new technologies.

Results of are presented separately for baseline scenario separately for each of the agriculture resource group cereals, vegetable oils and vegetables, and for alternative scenarios together. The Sankey chart is used to visualize the flow of bioresources in light blue and the goods in yellow.

4.1. Baseline Scenario for Cereals

Fig. 2 shows the bioresource flows in the baseline scenario for the 2015 simulation year with fixed input commodity parameters to provide a historical view of the crop sector. The results show that most of the crop products are grown in Latvia and the imported part is smaller. The mass balance of commodity flows results in minor inconsistencies, leading to conclusions that some crop products of unknown origin are consumed by processes to satisfy the demand that do not appear in the statistics. Thus crop products of unknown origin are used in the model to fill the gap between supply and demand in the model, taking into account the efficiency of current crop processing technologies.

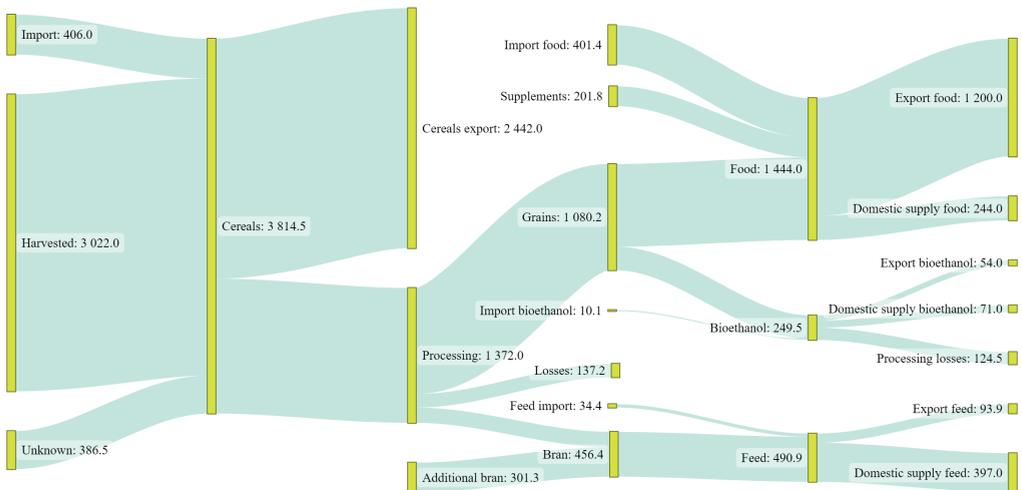


Fig. 2. Sankey diagram for bioresource flows of base scenario in 2015 for cereals, thousand tonnes.

Fig. 2 shows that the main flows of finished cereal products in 2015 are food for domestic supply and export, followed by domestic supply of feed and export of feed. Additives are added to cereal products and make up a large proportion of the final food. In the production of grain food, primary processing produces by-products from which fodder is produced. Part of the cereals is used to produce first-generation bioethanol.

Fig. 3 shows the goods flow results for the 2030 baseline scenario. The main change compared to 2015 is in the production of grain food and feed, as the demand for food has decreased by 20 %, which can be explained by the decrease in the number of inhabitants, however, given the growing world population, grain exports are increasing. Demand for feed has also declined, as total livestock numbers are projected to decline slightly, but demand for bioethanol has increased, which can be explained by an increase in demand for biofuels.

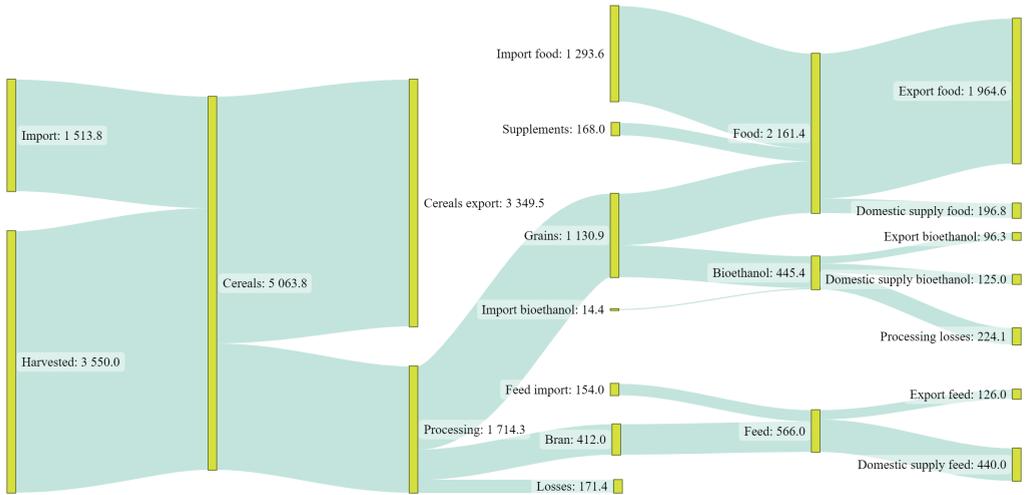


Fig. 3. Sankey diagram for bioresource flows of base scenario in 2030 for cereals, thousand tonnes.

4.2. Baseline Scenario for Vegetable Oils

In Fig. 4, the main flows of finished vegetable oil production in 2015 are for domestic supply and export of biodiesel, followed by domestic supply of feed and export of feed. In the production of vegetable food, primary processing produces by-products from which fodder is produced. Large share of the vegetable oil is used to produce first-generation bioethanol.

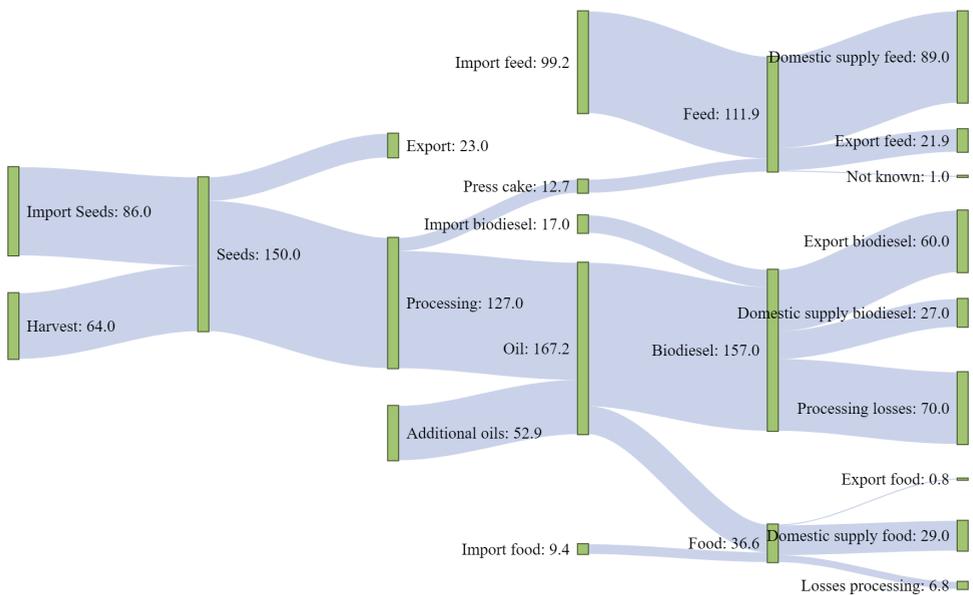


Fig. 4. Sankey diagram for bioresource flows of base scenario in 2015 for vegetable oils, thousand tonnes.

Fig. 5 shows the goods flow results for the 2030 baseline scenario. The main changes compared to 2015 are in the production of vegetable oils for food and feed, as the demand for food has decreased by 17 %, which can be explained by a decrease in the population. Demand for feed has also declined, as total livestock numbers are projected to decline slightly, at the same time demand for biodiesel has increased.

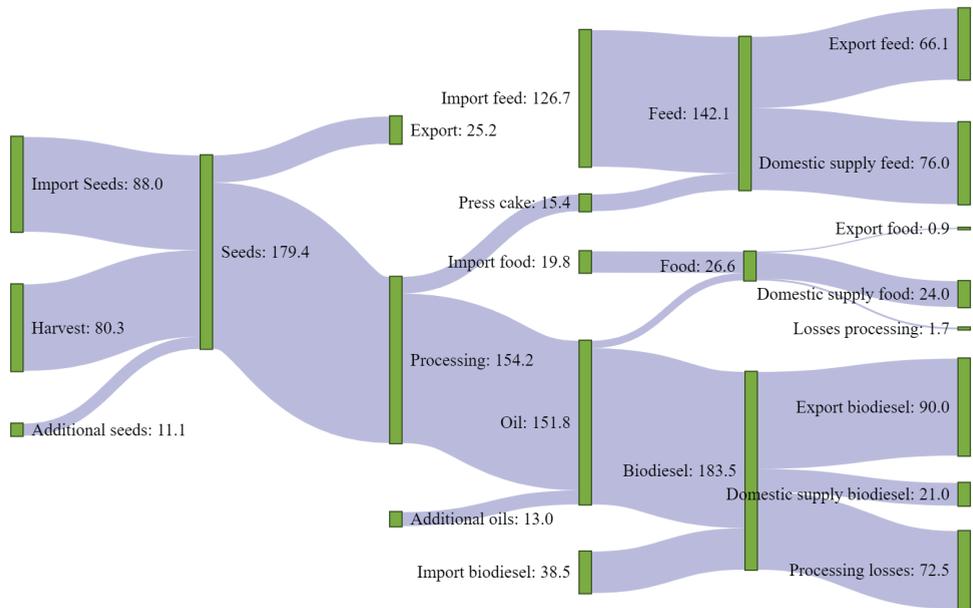


Fig. 5. Sankey diagram for bioresource flows of base scenario in 2030 for vegetable oils, thousand tonnes.

4.3. Baseline Scenario for Vegetables

In Fig. 6, the main flows of finished vegetable production in 2015 are food for domestic supply and export, followed by domestic feed supply and feed export. Additives are added to cereal products and make up a small part of the final food. In the production of grain food, primary processing produces by-products from which fodder is produced.

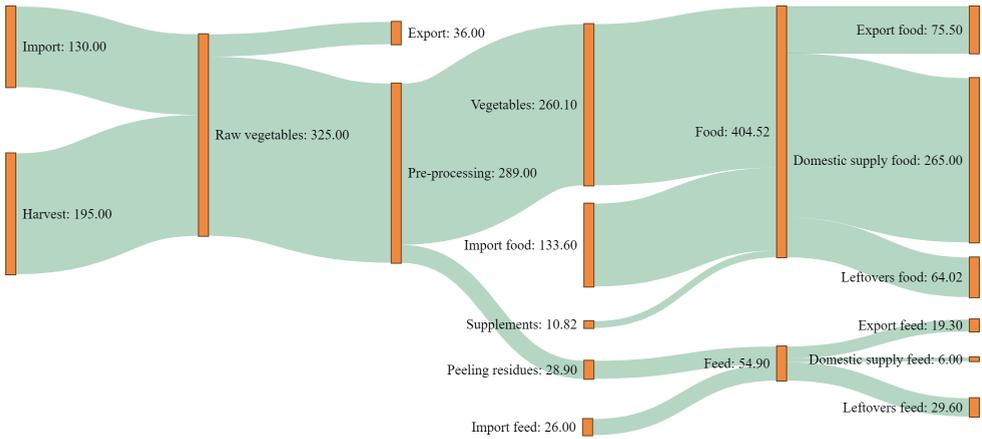


Fig. 6. Sankey diagram for bioresource flows of base scenario in 2015 for vegetables, thousand tonnes.

Fig. 7 shows the flow of goods results for the 2030 baseline scenario. The main changes compared to 2015 are in the production of vegetables for food and feed, as the demand for food has decreased by 22 %, which can be explained by the declining population, but due to the increase in the world's population, vegetable exports are increasing. Demand for fodder has also declined, as the total number of livestock is expected to decline slightly.

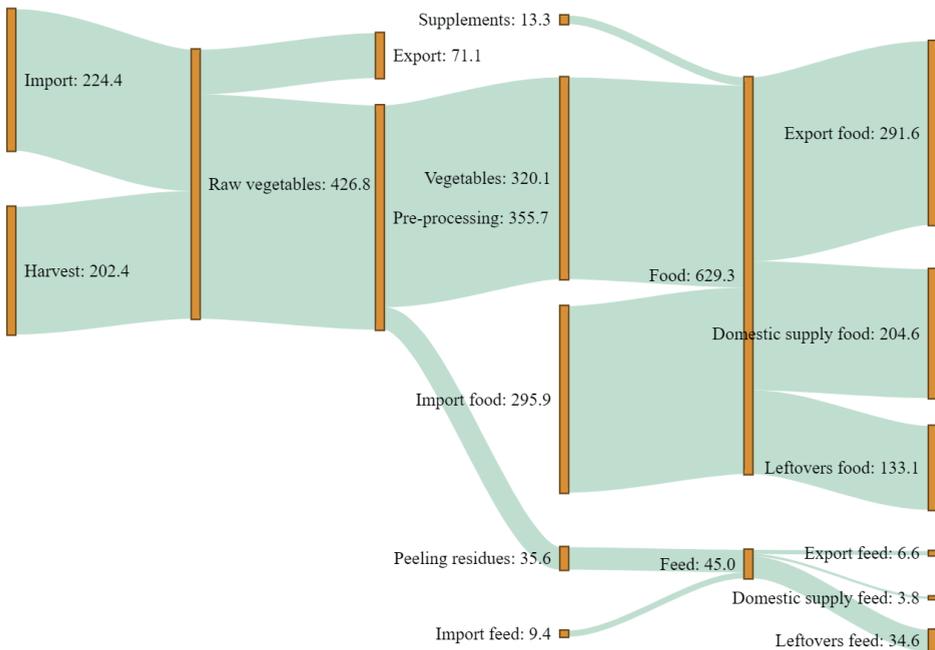


Fig. 7. Sankey diagram for bioresource flows of base scenario in 2030 for vegetables, thousand tonnes.

4.4. Alternative Scenario Analysis

In addition to the baseline scenario, four alternative scenarios are used for the crop case study with TIMES ABVM. The alternative scenario includes new technologies availability after 2025. The results of alternative scenarios are compared with the baseline scenario by added value in 2030, shown in Fig. 8.

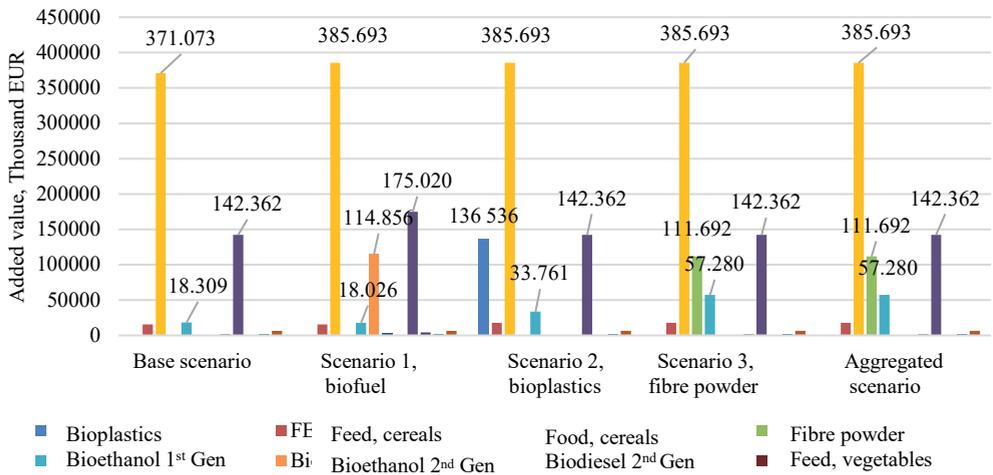


Fig. 8. Scenario analysis for new technologies in agriculture sector in Latvia, year 2030.

Base scenario shows that highest added value is reached from cereals food and vegetable food production. If the added value target is set +30 % from base scenario, in first scenario added value is reached by increasing the food production, other product production and adding new technology that is second generation biofuel production. In the second scenario added value is reached by increasing food production from cereals and bioethanol production from cereals, but most of contribution to the added value target is from bioplastic production as new technology. In third scenario food and other product production from cereals show increase and the use of new technology for fibre powder. Aggregated scenario results show that added value aim can be reached by adding fibre powder production that has higher added value than biofuel or bioplastics and is economically viable.

Cereals account for the largest share of crop production. According to statistical data, the largest amount of cereals grown is exported, as well as the largest share of grain is used in food production (all types of flour products). Vegetables and dase oils make up the smallest part of crop products. Most cereals, vegetables and oils are used for food production and feed and other products (biofuels) account for the smallest share. The model also shows losses and surpluses, which could be explained as discrepancies in the databases. New technologies were introduced in the scenarios. Cereal by-products are used in the production of second-generation biofuels, vegetable residues and by-products in the production of bioplastics. The new technology considered a scenario for the use of grain bran in the production of fibre powder. Similar as in scenario 3, the amount of fibre in the aggregated scenario is rather small, see Fig. 9, only 261 thousand tonnes. However, this amount is sufficient to meet the value-added target, as food has a higher added value in the bioeconomy compared to bioplastics and biofuels.

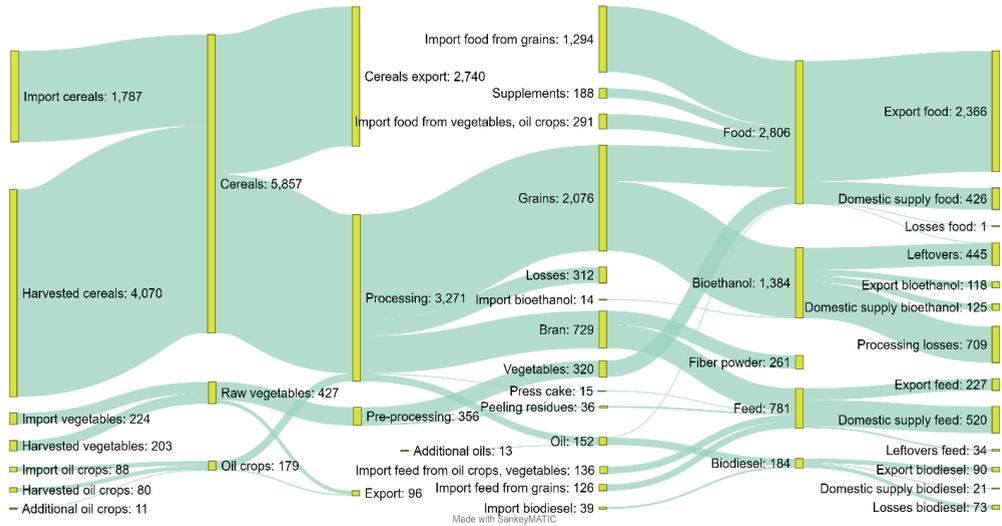


Fig. 9. Best alternative scenario modelling bioresource flow for 2030 crop farming sector, thousand tonnes.

5. CONCLUSIONS

A review of the literature on modelling tools used to optimize the value of bioresources showed that there are many choices among existing tools for bioeconomic analysis. Based on this review, BVM TIMES has been identified as the most appropriate tool to support the decision-making process, where it is important to provide detailed information on technologies and resources on both the demand and supply side. The model helps to find the best supply-demand balance scenarios in a given set of technology cost and resource limits at the national level based on linear optimization. The structure of the developed bioresource optimization model is adapted according to the available statistics from national and EU databases and reflects the multidimensionality of the sustainability pillars using environmental, economic and social criteria.

The study of the crop sector BVM TIMES proved the concept of this model as a tool for optimizing the value added of bioresources. Future studies with the BVM TIMES model should focus on improvements such as the use of new technologies and modelling at regional level.

The forecasts for food and feed demand for 2030 considered the decline in the number of people. As the demand for food decreases, it would be more important to use the amount of existing resources in the production of products with higher added value. Without reducing production and producing high value-added products, the economic situation would be improved.

The agricultural sector can strongly contribute to the development of bioeconomy. Along with food production new pathways for utilization of crops for production of higher added value products are examined in this study.

When collecting the data, it was concluded that the Latvian databases did not provide accurate and complete information, which caused discrepancies in the data. In the absence of information, assumptions were made based on historical trends.

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Development of a Mycelium-Based Thermal Insulation Material

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Abstract – The study explores the potential of mycelium-based materials as sustainable thermal insulation for construction. Mycelium, the vegetative part of fungi, grows on organic substrates such as agricultural byproducts, forming a lightweight, biodegradable composite with insulating properties. The experiments focus on optimizing the material's thermal conductivity and mechanical strength. Mycelium insulation demonstrates thermal conductivity values comparable to traditional materials like mineral wool and expanded polystyrene (EPS), with a range of 0.039 to 0.05 W/m·K. The production process employs renewable resources, is non-toxic, and aligns with circular economy principles by repurposing agricultural waste. Challenges remain in enhancing water resistance and mechanical adaptability. The findings underline mycelium's potential as an eco-friendly alternative in modern sustainable construction, emphasizing its role in reducing carbon footprints and promoting resource efficiency.

Keywords – Agricultural by-product; eco-friendly materials; mycelium; thermal insulation.

1. INTRODUCTION

The demand for sustainable thermal insulation materials and the reduction of environmental pollution are among the greatest challenges of the 21st century. Achieving sustainability in energy and environmental sectors is critical, as energy consumption continues to outpace limited resources, while growing populations and premature material disposal exacerbate environmental concerns [1].

The construction and automotive industries are among the largest energy consumers, with buildings alone accounting for approximately 40 % of global energy use and generating 36 % of total CO₂ emissions. Consequently, improving energy efficiency in buildings has become a priority. High-performance thermal insulation can significantly reduce heat loss during heating and cooling, with studies indicating that proper insulation can cut household energy consumption by up to 65 % [1].

As awareness of the environmental impact of building materials grows, new solutions are being developed to lower carbon emissions, reduce reliance on non-renewable resources, and enhance indoor air quality. This has led to an increasing focus on bio-based insulation materials such as wood fiber, hemp, and straw [2]. Additionally, circular economy

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principles are being applied to promote the reuse and recycling of materials, reducing waste and environmental pollution [3].

One of the most promising bio-based insulation materials is mycelium – the vegetative part of fungi, which acts as a natural binder for organic substrates. This innovative technology allows the production of biodegradable, lightweight, and fire-resistant biocomposites. Mycelium biocomposites (MB) can be molded into various shapes, offering a sustainable alternative to synthetic materials like expanded polystyrene (EPS) while maintaining similar insulation properties and a lower environmental footprint [4].

Besides reducing CO₂ emissions and costs, mycelium-based insulation supports the circular economy, as confirmed by life cycle analysis [5]. However, MB insulation still faces challenges, including high density and water absorption, which hinder its commercial viability. Its performance depends on factors such as substrate composition, fungal strain, and incubation conditions, necessitating further research and design improvements [6].

Despite these challenges, MB materials open new possibilities for designers, including the creation of customized shapes through 3D printing. However, their production remains labor-intensive and requires automation and digital optimization. Advancements in material properties and manufacturing processes are essential to fully realize their potential. Addressing these limitations could make mycelium biocomposites a viable alternative to conventional insulation materials, significantly contributing to sustainability and the circular economy [7], [8].

2. LITERATURE REVIEW

In response to the increasing demand for sustainable materials, mycelium-based products have gained significant attention as an eco-friendly alternative. Their ability to replace traditional synthetic materials makes them particularly suitable for insulation and packaging applications.

Mycelium-based materials can be produced in two ways:

- By utilizing mycelium's natural ability to bind to various substrates, forming a dense and durable structure.
- By cultivating pure mycelium from liquid cultures [9].

The performance of mycelium-based materials is heavily influenced by cultivation methods, similar to how material science and engineering emphasize the relationship between structure, properties, and processing conditions. Key factors such as humidity, temperature, and substrate composition play a crucial role in determining material quality [10].

Research has primarily explored different substrates for mycelium cultivation, including:

- Agricultural waste [11],
- By-products from food processing [12],
- Industrial waste from paper and textile production [13].

Not all fungal species and substrates are equally effective for mycelial growth. The rate of colonization and material density vary depending on substrate type and environmental conditions [10].

The choice of substrate is essential, as it directly impacts mycelial growth and the quality of the resulting green composites. Several chemical factors must be considered when selecting a substrate, including cellulose, hemicellulose, and lignin content, pH level, organic carbon, total nitrogen, and the carbon-to-nitrogen (C:N) ratio. These factors

influence not only the efficiency of mycelial growth but also the properties of the final product [14].

Cellulose, a key component of plant cell walls, serves as an important carbon source for mycelium, providing essential nutrients that support robust growth and the formation of durable composite materials. Hemicellulose, another plant cell wall component, also contributes to mycelial growth and enhances the mechanical properties of the final product. In contrast, lignin, a complex polymer that reinforces plant cell walls, is more challenging for mycelium to break down, making substrates with lower lignin content more suitable for cultivation. Additionally, mycelium thrives best in slightly acidic conditions (pH 5–8), necessitating careful pH adjustments for optimal growth [15].

Organic carbon serves as a primary energy source for mycelium, promoting vigorous growth. Similarly, nitrogen is essential for protein synthesis, enzyme production, and cellular processes. An optimal C:N ratio, typically ranging from 19:1 to 80:1, is crucial for balanced mycelium development. Substrates with a higher C:N ratio may require additional nitrogen supplementation. Overall, selecting an appropriate substrate is a critical step in optimizing the production of high-quality mycelium-based composites [14].

Temperature and humidity also play significant roles in mycelial growth. The ideal temperature is around 24–25 °C [16], [17], while high humidity levels (up to 98 % relative humidity) are required to support mycelial development. Consequently, humidifiers are often used to maintain appropriate growing conditions [17], [18].

Once the mycelium has fully developed, it contains a high water content (over 60 %). To halt further growth and ensure reliable mechanical properties, most of this moisture must be removed. For example, hemp pulp-based substrates retain more water than cotton wool. Additionally, various coatings can influence moisture absorption. The moisture content before inactivation typically ranges between 59 % and 70–80 %, with the final material retaining approximately 10–15 % moisture, as recommended by researchers [17].

To produce mycelium-based materials, it is crucial to focus on developing a robust mycelial network while minimizing energy-intensive fruiting body formation. The mycelium cultivation process consists of four main steps, with three additional steps required for material production [19].

First, the substrate is prepared, providing the necessary environment for fungal growth. The substrate can include cellulose-rich materials such as straw, wood, or hemp, chosen based on the species of mycelium and cultivation goals [20]. For large-scale production, cost-effective and nutrient-rich substrates like straw are preferred. Conversely, laboratory research often employs pure and easily controlled substrates, such as sugar solutions. Following preparation, the substrate undergoes sterilization to eliminate competing microorganisms [21]. Next, the sterilized substrate is inoculated with mushroom spawn, which is typically sourced from specialized facilities that maintain high purity standards. Mycelium then colonizes the substrate, forming a uniform material. Throughout this phase, precise environmental control is necessary, depending on the fungal species and production objectives. Once the substrate is fully colonized, growth is halted to prevent further metabolic activity that could compromise material integrity [22]. This is achieved through heat treatment, which terminates mycelium development. Finally, the material is removed from its mold and may be coated with protective layers to enhance its mechanical strength and aesthetic appeal. The resulting mycelium-based composites offer a sustainable alternative to traditional materials while maintaining high quality and adaptability for various industries [23].

Thermal insulation materials are typically evaluated based on their thermal conductivity coefficient, λ , which ranges from 0.024 to 0.07 W/m·K. The effectiveness of insulation materials – whether homogeneous, simple, or composite – is assessed using parameters such as thermal conductivity, heat transfer rate, thermal diffusivity, and specific heat capacity. For commonly used insulation materials, the thermal conductivity coefficient ranges from 0.030 to 0.040 W/m·K for expanded polystyrene and mineral wool, and from 0.020 to 0.030 W/m·K for polyurethane-based insulation. Mycelium-based insulation materials, with their sustainable composition, offer a promising alternative within this range [24].

3. METHODOLOGY

For the production of mycelium materials, agricultural by-products such as straw and wood chips were used, which served as a substrate for mycelium growth. The experimental process for developing mycelium-based insulation material began with screening nine mold species to identify the most suitable candidate for material production. These included *Rhizopus oryzae*, *Aspergillus versicolor*, *Penicillium chrysogenum*, *Cladosporium cladosporioides*, *Cladosporium herbarum*, *Stachybotrys chartarum*, *Trichoderma viride*, *Mucor mucedo*, and *Mucor plumbeus*. The primary selection criteria were the formation of a dense hyphal network and rapid growth rate. Cultures were initially grown on two nutrient media: Potato Dextrose Agar (PDA) and Malt Extract Agar (MEA). The choice of these materials was determined by their wide availability, low cost and richness of organic composition, which provides the nutrients necessary for mycelium growth. For additional stability and homogeneity of the substrate, a mixture of xanthan, water and ethanol was used as a binder. Although mycelium naturally acts as a binder, creating a cohesive and mechanically stable biocomposite, in some cases it is not enough to ensure uniform substrate distribution and structural homogeneity before mycelium colonization. Therefore, a mixture of xanthan and water is used as a structuring and moisture-retaining agent, which: 1) improves the plasticity of the substrate, 2) prevents the settling or separation of bulk particles, 3) and ensures uniform distribution of the mycelium. Xanthan is not used as a source of mechanical strength of the final material, but as an aid in the early stages of formation. The experimental part was carried out at the Riga Technical University's Institute of Energy Systems and Environment Laboratory, where appropriate conditions and control over the entire process were provided. The substrate preparation stage included the careful creation of a mixture of straw and wood chips, using different proportions according to the experimental plan. Precise dosing allowed to achieve the necessary homogeneity and ensured optimal distribution of nutrients. The prepared mixture was subjected to sterilization in an autoclave (temperature approximately 121 °C, pressure one atm) to destroy unwanted microorganisms and seeds that could interfere with mycelium growth. After sterilization, the substrate was cooled to room temperature to maintain favorable conditions for inoculation.

The sterilized substrate was inoculated with *Trichoderma viride* spores previously grown on potato dextrose agar (PDA) and enriched media. This fungal strain was selected due to its high growth capacity and efficiency in creating a dense mycelium network.



Fig. 1. Mycelium samples with a mass of 20 mg each.

3.1. Mycelium Material Production Process

3.1.1. Inoculation and growth

The inoculated substrate was placed in metal molds with dimensions of 20×20 cm, which provided a shape and structure for the growth process. Optimal growth conditions were maintained in the molds:

- Temperature: 25–30 °C,
- Relative humidity: 60–70 %,
- Substrate pH: ~5.

The growth process lasted 3–5 days, during which the mycelium actively colonized the substrate, forming a dense network that bound the substrate particles into a single material. The mycelium served as a natural binder, creating a mechanically stable structure.



Fig. 2. Mixing mycelial material.

3.1.2. Heat treatment

Once the growth process was complete, the molds with mycelium material were transferred to a heat treatment chamber. The material was subjected to drying at temperatures up to 105 °C to stop further mycelium development, prevent fruiting body formation, and destroy any remaining moisture sources. The heat treatment ensured the mechanical stability of the material, as well as reduced its thermal conductivity.



Fig. 3. Mycelium material after drying.

3.1.3. Testing and analysis of the finished material

After heat treatment, the mycelium material obtained was subjected to thorough testing using standard laboratory methods. The following measurements were taken:

- Thermal conductivity: Determined to assess the insulation properties of the material and compare it with traditional synthetic insulation materials.
- Density: Measured to assess the uniformity of the material and its suitability for various applications.
- Mechanical strength: Tested to determine the compressive and tensile properties of the material, which are essential in various industries, such as construction and design.

The study developed and analyzed a process that ensures efficient production of mycelium materials, from substrate preparation and inoculation to thermal treatment of the final product. The obtained samples were thoroughly tested to evaluate their physical and mechanical properties, which allows evaluating the material's potential in various fields of application. The results discussed below provide an insight into the main characteristics of the material.

4. RESULTS

More than 130 material samples (20×20 cm in size) were produced during the study. Various substrates were used, including straw, wood chips, hemp, hay, and their combinations. The mycelium was mixed with 13 different types of additives in various combinations, such as xanthan gum, glycerol, ethanol, gluten, yeast, molasses, baking soda, nutrient medium, water, starch solution, and sawdust. These combinations were tested to explore the effects of different ingredient ratios and interactions on the growth, structure, and properties of the resulting mycelium-based materials.

Mycelium composite materials were developed in the experiment, the properties of which were analyzed to determine their potential as an environmentally friendly and sustainable thermal insulation material. The study focused on the thermal conductivity, density, mechanical properties and ecological aspects of the materials.

4.1. Thermal Conductivity Analysis

When testing experimental samples of mycelium materials, their thermal conductivity values were in the range of 0.039–0.05 W/m·K. According to the literature, the thermal conductivity of mycelium thermal insulation materials is on average from 0.03 to 0.07 W/m·K [3]. These indicators are comparable to traditional thermal insulation materials, such as mineral wool and expanded polystyrene, which indicates the competitiveness of mycelium materials in the construction industry. Low thermal conductivity allows these materials to be used in the construction of more energy-efficient buildings, reducing energy consumption for heating and cooling.

TABLE 1. MATERIAL PROPERTIES

Material	Thermal conductivity (W/m·K)	Density (kg/m ³)
Plant-based		
Mycelium	0.039–0.05*	72–120*
Hemp	0.039–0.043 [25]	28–42 [25]
Flax	0.034–0.052 [26]	40–100 [26]
Rice husk	0.04–0.073 [27], [28]	97–200 [29]
Wood fiber	0.038–0.042 [30], [31]	50–250 [30], [31]
Inorganic (fibrous & foam)		
Glass wool	0.03–0.045 [32]	10–96 [32]
Rock wool	0.034–0.035 [33]	45–140 [33]
Synthetic foams		
EPS	0.035–0.037 [34], [35]	12–50 [34], [35]
Polyurethane	0.027–0.037 [36], [37]	88–111 [36], [37]
Phenolic foam	0.018–0.023 [38]	35–200 [38]
XPS	0.033–0.04 [39]	28–78 [39]

*The data are obtained experimentally.

4.2. Density Properties

The density of the mycelium materials ranged 72–120 kg/m³, and depended on the type of substrate used and the mycelium growth conditions:

- Higher densities (120 kg/m³) were achieved using substrates with a higher amount of wood chips.
- Lower densities (72 kg/m³) were observed using straw or hay as the main substrate components.

The possibility of varying the density ensures the adaptability of the material to different needs, such as lighter structures or higher mechanical strength.

4.3. Mechanical Properties and Stability

The experimental samples with higher densities showed higher mechanical stability, which is an essential property for the materials to be used in construction. They successfully withstood compressive loads and maintained their integrity after heat treatment and dehydration. At the same time, materials with lower densities offered better thermal insulation, however, their mechanical properties still need to be improved. Further research will focus on finding a balance between these two properties.

4.4. Ecological Aspects

Mycelium materials are biodegradable and are produced using renewable resources, such as agricultural by-products (straw, hay, wood chips). No toxic chemicals were used in the production process, making the materials safe for both humans and the environment. Their production ensures low carbon emissions and promotes the reuse of resources.

5. CONCLUSIONS

Experimentally developed mycelium materials demonstrate low thermal conductivity (0.039–0.05 W/m·K), making them comparable to traditional insulation materials such as mineral wool and expanded polystyrene. This confirms their potential as an alternative thermal insulation solution, particularly in light of the growing demand for environmentally friendly and energy-efficient construction methods. Their low thermal conductivity enhances building energy efficiency by reducing heating and cooling demands, thereby contributing to sustainable development.

The material's density ranges from 80 to 120 kg/m³, allowing for adaptability to various practical applications. A higher density provides greater mechanical stability, making it suitable for load-bearing structures, while a lower density improves thermal insulation and reduces weight—an important factor for lightweight constructions. Mycelium materials exhibit sufficient mechanical strength to withstand compressive loads, even after heat treatment and dehydration, making them a viable option for construction applications where both durability and sustainability are key considerations.

Produced from renewable resources such as agricultural by-products (straw, wood chips, hay), mycelium composites are manufactured without toxic chemicals, offering significant ecological benefits. Their biodegradability ensures natural decomposition, reducing construction waste and environmental impact. Additionally, their low ecological footprint results from resource reuse and minimal emissions during production, making them particularly attractive in sustainable construction.

Despite their promising properties, some challenges remain. The material's sensitivity to moisture necessitates improvements in water resistance, especially for applications in humid environments. Several solutions are being explored to improve water resistance. One of them is the use of biocompatible coatings – for example, layers based on biowax, natural resins or chitin, which reduce water absorption while maintaining the biodegradability of the material. Enhancing the mechanical properties of lower-density variants is also essential, as greater strength in lightweight materials could expand their usability across various industries. Ongoing research into optimizing substrate composition and growth conditions can help strike a balance between thermal insulation, mechanical stability, and density.

Mycelium composites present an innovative and sustainable solution for insulating residential buildings, where an eco-friendly and energy-efficient approach is required. They are also well-suited for lightweight structures, such as temporary buildings or interior panels, due to their low weight and ease of biodegradation after use. In industrial construction, they offer a viable alternative to conventional materials with enhanced sustainability. The wider adoption of mycelium materials in the future could reduce dependence on fossil-based resources, enhance construction sustainability, and support the transition to a circular economy.

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Production of Renewable Insulation Material – New Business Model of Bioeconomy for Clean Energy Transition

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Abstract – Mycelium composites is a new class of renewable materials which can be used for heat insulation of buildings. Use of the composites would help to reduce both operational energy consumption and embodied energy of building insulation materials. In addition, use of the renewable composites could also reduce embodied greenhouse gas (GHG) emissions of the insulation materials. Local production and use of the composites could stimulate residential building insulation process via additional socio-economic benefits, such as positive impact on local economy, created workplaces and reduced import. The research question of this study is to determine a difference between embodied energy and GHG emissions of the mycelium insulation material and synthetic insulation alternatives. System dynamics model is used as the method for assessment of the dynamics of the total embodied energy and GHG emissions if equal amounts of the insulation materials is produced. Time horizon for the modeling is 2021–2050. Data used in the model were taken from scientific publications and laboratory experiments with growth process and properties of the mycelium composites. The model includes several feedback effects, e.g., effect of research and development on efficiency and productivity of the mycelium production process. The results show that embodied energy of the mycelium insulation material is higher than for the synthetic alternatives but the embodied GHG emissions are considerably lower than for the alternatives. The embodied GHG emissions are even lower if the absorption of CO₂ of renewable materials used for the production of the mycelium composites is included.

Keywords – Bioeconomy; energy efficiency; insulation of buildings; mycelium insulation material; sustainability; system dynamics modeling

1. INTRODUCTION

The construction industry has come under considerable pressure over the last decade as the supply of traditional building materials such as cement, brick, timber, cladding and partition materials has struggled to cope with increasing demand. Production of these conventional building materials consumes energy, limited natural resources and pollutes air, land and water. Up to 36 % of the lifetime energy consumption of a typical dwelling can be attributed to harvesting or extraction of primary materials as well as other production processes, transport and construction of a building. Low-energy buildings, although using less energy, have even larger environmental impact in the construction phase (up to 46 % of residential

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energy demand can be attributed to the building construction) due to increased heat insulation, higher density materials and additional technologies used [1].

The material that provides structural performance with minimal environmental impact is mycelium-based biocomposites [2]. Mycelium composites are a new type of novel, economical, and environmentally sustainable materials that have attracted increasing academic and commercial interests over the past decade. Mycelium is the vegetative growth of filamentous fungi that bonds organic matter through a network of hyphal microfilaments in a natural biological process that can be exploited to produce composite materials [1].

Mycelium composites have customizable material properties due to their composition and manufacturing process, and they can replace foam, wood and plastics for such applications as insulation, panels, floors and furniture. The material has low thermal conductivity, high acoustic absorption and fire safety properties that surpass traditional building materials such as synthetic foam. However, there are limitations, such as mechanical properties, water absorption and other properties, which must be assessed when the composite is used in building materials. Nevertheless, the useful material properties, in addition to low cost, ease of manufacture and environmental sustainability suggest that they will play an important role in the future of environmentally friendly construction [1]. Many natural materials have fiber architecture. Examples are many, including silk spider webs, bone, plant stems such as bamboo, connective tissue. The design of these natural materials has inspired researchers to imitate such synthetic architectural materials, although this has proven to be a difficult task in many cases. A new approach to this problem is designed engineering components, obtained by direct growing of a natural material in the desired form. Such components inherit microstructure and properties of the base materials [3]. Compared to synthetic composites, a composite made from mycelium and other natural materials yields a low-density material with high strength and an opportunity for lowered embodied energy. Furthermore, the inclusion of a natural cellulosic textile for reinforcement allows for reuse of an otherwise-waste material and expands the composite's end of life options [4].

Mycelium has the unique ability to form composite materials quickly and easily [4]. From the perspective of a raw fiber resource, fungi can beat lignocellulosic textiles in terms of energy and physical properties [5]. Due to its unique structure and composition, it may be possible to produce large quantities of mycelium-based materials [6]. Mycelium 'acts like a natural, self-assembling glue that digests and binds securely to natural reinforcement materials and agricultural byproducts with essentially no added energy'. Growing mycelium around other natural materials is a sustainable and efficient way to generate various products, as outlined below [4]. In the production of mycelium, it is necessary to completely stop the growth of the fungus before the substrate (such as straw or sawdust) is completely degraded. In this case, the organic fibers or particles of the hypha compound together, thus colonizing the substrates. Fungal growth can be stopped by drying and / or heating the colonized substrate. Heating destroys the fungus, but drying keeps the fungus in the 'winter' state [7].

Some recent studies have shown the competitiveness of foam-like mycelium-based composites compared to conventional materials such as expanded polystyrene (EPS) or other foams, or other bio-based composites such as hemp concrete. In general, mycelium-based materials have proven their potential to replace the use of less environmentally friendly materials, such as bioplastics or wood composites [8]. The composite is an environmentally responsible alternative to expanded polystyrene and other plastics. The material competes directly with petrochemical foams in terms of performance, cost and with low embodied-energy [9]. The whole production process is considered to be an environmentally friendly waste stream due to valorisation, thus preventing the destruction of ecosystems and obtaining resources [10]. Mycelium materials consist entirely of renewable materials and require very

little energy to process. Therefore, they are definitely a part of the circular economy model [11]. Due to its unique structure and composition, we anticipate the production of large quantities of mycelium-based materials. To date, mycelium has been used mainly by a US company using raw biomass glued to mycelium, resulting in foaming structures, but there is still much room for improvement and further development of mycelium-based materials [12].

The value chain of forest bio-products can be divided into several groups of activities. Production, collection, processing, storage, transport, marketing and sales are key activities in the forest product value chain, using value-added bio-based products that reach their target customers [13].

Different applications of building materials can have different areas of problems. The main concern for internal insulation materials is a transfer of moisture between the interfaces of insulation and structural materials, as the largest temperature gradient occurs at the interfaces. Condensed liquid can cause swelling and shrinkage of insulation materials or even significant reduction of insulating properties. [14] Only a few research centers and companies around the world have the knowledge and capacity to produce mycelium-related materials for the building and construction industry. Studies on the use of mycelial composites as structural elements date back to 2009, when *Ganoderma lucidum* and sawdust were used to create the tea house [13].

Fig. 1 shows the product development steps from materials to the energy efficient building. A new material with good technical properties is not yet ready for the market, but suitable products need to be developed. If the products do not fit into existing building systems, new systems are required for proper integration with the entire building. This requires both technical development and improved know-how in the production process, design, installation, analysis of overall performance, etc. However, radical leaps in innovation can significantly accelerate the emergence of new solutions on the market [14].

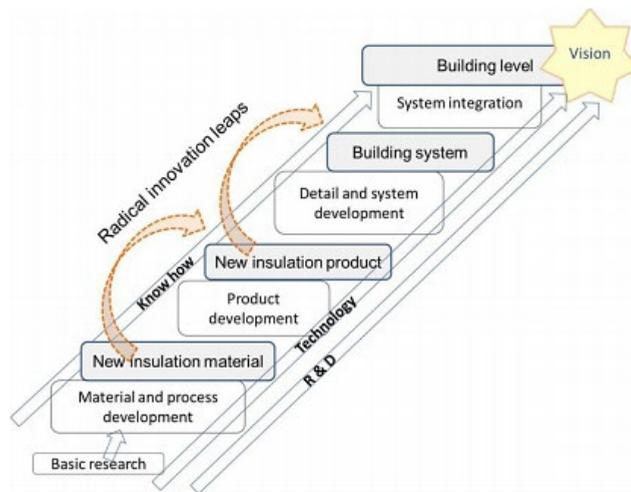


Fig. 1. Product development stages from materials to the level of energy efficient building [14].

As shown in Table 1, plant-based insulation materials (i.e. hemp, flax, rice husk, wood fibers) have competitive thermal conductivity and possibly lower costs compared to inorganic and synthetic insulation materials. From an environmental point of view, plant-based materials have significantly lower embodied energy and carbon than the fossil-based materials [15]. In addition, when designing building envelopes, thermal insulation materials

with a higher specific heat output ($\text{kJ/m}^3\text{K}$), such as plant-based insulation materials, can store the maximum solar radiation that absorbs the building facades and reduce the maximum cooling loads by delaying the maximum indoor temperature. caused by solar radiation during the summer [16].

TABLE 1. PROPERTIES OF CONVENTIONAL INSULATION MATERIALS [15]

Material	Density	Thermal conductivity	Specific heat capacity	Water vapor diffusion resistance factor	Cost	Embodied energy	Embodied carbon
Unit	kg/m^3	$\text{W}\cdot\text{m}^{-1}\text{K}^{-1}$	$\text{J/g}\cdot^\circ\text{C}$	–	USD/m^3	MJ/kg	$\text{kgCO}_{2,\text{eq}}/\text{kg}$
Plant-based							
Hemp	25–100	0.039–0.123	1.7–1.8	1–10	15–19.4	18.71	0.14
Flax	20–100	0.033–0.09	1.6	1–5.28	15.18	39.5	20
Rice husk	130–170	0.048–0.08	1.2–2.7	2	5	1.36	0.6
Wood fiber	50–270	0.038–0.05	1.9–2.1	1–5	26.6–37.8	20.3	0.124
Inorganic (fibrous & foam)							
Glass wool	10–100	0.03–0.05	0.8–1	1–1.3	9.3–14.7	14–30.8	1.24
Rock wool	40–200	0.033–0.04	0.8–1	1–1.3	12–20	16.8	1.05
Synthetic foams							
EPS	18–50	0.029–0.041	1.25	20–100	8.6–17	80.8–127	6.3–7.3
XPS	32–40	0.032–0.037	1.45–1.7	80–170	18–23	72.8–105	7.55
Polyurethane	30–160	0.022–0.035	1.3–1.45	50–100	24.91	74–140.4	5.9
Phenolic foam	40–160	0.018–0.024	1.3–1.4	35	23	13–159	4.15–7.21

The Global Sustainable Development Strategy implies reduction of non-renewable materials by replacing them with bio-based materials. In addition to biological materials, such as bioplastics, bacteria, algae or fungi materials are increasingly being used as innovative bio-based alternatives [6].

Analysis of scientific articles shows that so far only bog-type mushroom materials have been analyzed and used; therefore, within this study the use of mold mushrooms in production of thermal insulation materials was studied. Although molds were considered harmful to human health, not all of them have an adverse effect on the human body, as the experimental mushrooms are used in the production of fertilizer, as well as the growth of mushroom hyphae is stopped and neutralized during the drying process. Drying of the material is necessary because by removing moisture from the material, the spores of the fungus are no longer able to absorb nutrients and multiply, and are therefore neutralized by returning to a previous safe state. Mushroom spores never really ‘die’ because they can always start to multiply again later when new moisture becomes available. Therefore, the mycelium material must be provided with a coating that prevents the formation of moisture in the material, as well as preventing the mold from ‘reviving’ and continuing to grow. Mold can grow in the temperature of $\sim 25\text{--}30^\circ\text{C}$, as well as provide 90–100 % relative humidity in the room. Given these factors, it is possible to avoid the ‘revival’ and the growth of the fungus.

The goal of this study is to compare mold mushroom embodied emission and energy between synthetic materials.

2. METHODOLOGY

The system dynamics approach, which is a mathematical method used to study and manage complex systems that change over time based on causes and feedback loops, was used in the study. This approach was developed in the Massachusetts Institute of Technology by Professor Jay Wright Forrester in 1956 [17]. Stella Architect has been used as a software tool for building stock and flow structure and simulation of system's behavior. The model was used to compare differences between the production of mycelium insulation material and four other synthetic insulation materials: expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane, and phenolic foam. Average values of synthetic insulation materials were taken from the thesis [15]. The comparison is made based on volumes of the produced insulation materials that provide equal heat insulation properties (thus, considering differences in thermal conductivity). The focus of comparison was on the difference in embodied GHG emissions and embodied energy of materials in the cradle-to-gate life-cycle stage and the results are expressed per cubic meter of insulation material as well as in form of cumulative values of embodied GHG emissions and embodied energy. The time period of calculations is set from 2021 to 2050. The time span of 30 years was chosen for simulation because most of EU climate policies are concerned with the time period of up to 2050, when climate neutrality has to be reached. Since the simulation includes not only building up a capacity for mycelium insulation material production but also effects of research and development (R&D) on production efficiency of the material, the time period has to be sufficiently long to reflect these effects.

2.1. Structure of the Model

A causal loop diagram (CLD) was used to describe the structure of the modeled system, and it was created before model construction (Fig. 2). CLD depicts the mechanics of a system without calculations [18]. CLD illustrates the main feedback structure of the system and captures the causes of the dynamics. Three reinforcing and four balancing loops represent the studied system (Fig. 2). Reinforcing loops exhibit exponential growth behavior. Reinforcing loop R1 shows how the production of mycelium insulation material increases the amount of reduced (avoided) GHG emissions since the material substitutes synthetic one with higher embodied GHG emissions. The more emissions are reduced the more carbon allowances can be sold providing revenues. Part of the revenues can be invested in the increase of allocated land for production resulting in increased capacity of production technologies which allow increased use of renewable insulation materials even more. The reinforcing loop R2 describes the feedback, where part of the revenues from sales of carbon allowances is invested in research and development to increase the energy efficiency of production. An increase in energy efficiency increases the amount of reduced emissions even more. It takes time for the research and development process to reduce energy consumption, and this is modeled by assuming that the investment in the research and development reduces the time it takes to move through stages of the research and development process. The production capacity is limited by the availability of the raw material, and the limit to the energy efficiency is a certain maximum value. Reinforcing loop R3 conveys how investment in research and development increases the amount of insulation material produced per area, i.e. production yield. As production yield increases, so does the use of renewable insulation materials increasing the amount of emissions reduced compared to the synthetic insulation materials, even more, thus increasing revenues from sales of carbon allowances. That, in turn, increases potential investment in research and development even more.

Balancing, also known as negative feedback loops, lead to the goal-seeking behavior of a system. The first balancing loop B1 shows how the use of raw material availability interacts with raw material consumption for the production of the mycelium insulation material, i.e. use of renewable insulation materials. The raw material consumption results in the insulation material production and the more insulation material is produced, the less raw materials are left from which to produce. The second balancing loop B2 shows how energy efficiency interacts with the remaining potential for energy efficiency increase. In this study, energy efficiency increase is made by investment in research and development. Revenues from that investment come from sales of carbon allowances. The more energy efficiency is increased, the less it can be increased next turnaround. A similar effect of depletion of potential for production yield improvement can be portrayed by the balancing loop B3 and also for land allocated for production in loop B4.

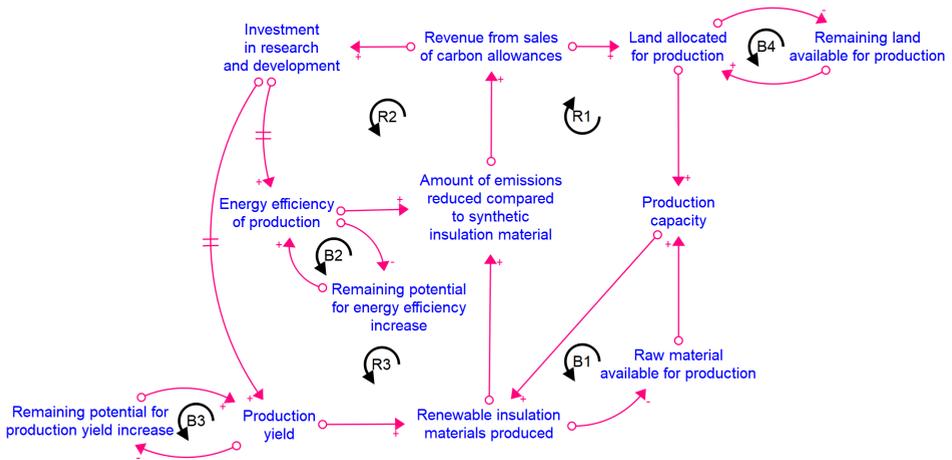


Fig. 2. Causal loop diagram portraying structure of the system dynamics model for mycelium insulation material production.

2.2. Data Collection

For the calculation of embodied emissions of mycelium insulation material, emission factors and emission absorption of materials, as well as data on the consumption of electricity and heat are required. The same applies to embodied energy calculation where instead of emission factors, embodied energy of materials is used. The materials required to produce 1 m³ of mycelium insulation material were taken from laboratory experiments done at Riga Technical University. The mycelium embodied emission and energy data is not included, because a fraction of the material inputs are used for bioreactor feed to grow mold mushrooms. Materials, electricity, and heat required for production, emission factors, emission absorption, and embodied energy input data can be seen in Table 2.

TABLE 2. EMISSION FACTORS AND EMBODIED ENERGY OF PRODUCTION INPUTS PER 1 M³ OF MYCELIUM INSULATION MATERIAL

Input	Input in production, unit/m ³	Emission factor, kgCO _{2eq} /unit	Emission absorption, kgCO _{2eq} /unit	Embodied energy, MJ/unit
Mycelium, kg	0.117	–	0.0025 [19]	–
Distilled water, kg	259.3	0.0008 [20]	0	23 [21]
Molasses, kg	7.5	0.074 [22]	0.1 [23]	1 [23]
Starch, kg	6.4	2.4 [24]	0.174* [25]	0.0014 [25]
Whey powder, kg	7.5	0.082 [26]	0.98 [23]	20 [23]
Carbamide, kg	0.97	1.85 [27]	0.73 [28]	49 [28]
Xanthan, kg	2.3	0.00497 [29]	0.048 [30]	7.6 [31]
Soda, kg	13.6	0.00059 [20]	0.524 [32]	26.9 [32]
Wood Chips, kg	189.3	0.000187 [33]	1.835*	17 [34]
Straw, kg	63.1	0.1036 [35]	1.468* [36]	2.125 [37]
Electricity, kWh	988	0.1019 [38]	0	3.6
Heat, kWh	754	0.0942 [38]	0	3.6

*Value was calculated for this study

2.3. Modelling

Some elements of the model were taken from the already existing model made for bioeconomy sector at Riga Technical University [39] then modified and further developed for this study. The model was adjusted to simulate a factory-like environment for material comparison. Multiple changes were made regarding raw material availability, available area, production, research and development, emissions, as well as new sectors were added named ‘energy’ and ‘functional cubic meters’.

2.3.1. Available Area and Raw Material Availability

To determine the area used for material production, an assumption is made that the total land available for production is 10 000 m². Land initially used is 1000 m² and the remaining 9000 m² are available to allocate for production based on the initial time of land allocation and income from carbon trade. An increase in income from carbon trade decreases the time of land allocation, therefore increasing the land allocation rate and the area allocated for production.

Mycelium insulation production requires 9 raw input materials. The raw materials are restocked annually based on production area and production yield of input materials.

2.3.2. Production Process

Raw material inputs are accumulated in a single stock and summed up to determine the annual potential production rate. The stock acts as a limit to production as it is not possible to produce more material than the accumulated raw material. Production is not only dependent on the accumulated material and potential production but also production capacity in operation. Production capacity in operation is the maximum possible production amount, as

it is not possible to produce more insulation material than technical equipment is capable to produce.

2.3.3. Research and Development

It is assumed that the electricity requirement of production can be reduced by 30 % and heat requirement by 45 %. The initial time to research energy efficiency improvement is set for 5 years and the initial time to develop solutions from labs to implementation phase is 3 years. Initial production yield is set to 90 (m³/m²)/year and it can be increased up to 120 (m³/m²)/year. The initial time to research yield is set to 50 years and the time to implement solutions – to 25 years. There is also the time needed for educating with the new solutions and it is set to 10 years. The time to educate is not influenced by research and development. The research and development time can be influenced by the amount of financial support towards the research and development. Funding for the research and development is obtained from selling avoided CO₂ emissions. That investment into research and development decreases ‘time to research’ and ‘time to development’ by up to two times.

2.3.4. Emissions

Each material used in production causes a certain amount of emissions per ton used. Knowing the amount of material used in the production of the insulation material the emissions from the materials (embodied emissions) were calculated by multiplying the amount of the raw material used by its emission factor. Similarly, the amount of carbon dioxide (CO₂) absorbed is calculated using the absorption factor instead of the emission factor. Annual emissions from each material were summed up to determine the total amount of emissions from material use. For electricity and heat emissions, the annual consumption rate was taken and multiplied by its emission factor for each consumption then summed up to find out the annual emission amount from energy consumption. To find out mycelium insulation material emission factor both annual material use emissions and energy consumption emissions were summed together and divided by the total amount of produced mycelium insulation material.

Emission factors of other synthetic materials were used to calculate the difference in emissions in material production per cubic meter of insulation material. The difference was used to compare the amount of avoided emission by the production of mycelium insulation material instead of other synthetic material. A comparison was also made in cumulative emissions for each insulation material.

2.3.5. Energy

Approach calculation of embodied energy was very similar to the calculation of the embodied emissions. Input material embodied energy was multiplied by the amount of input material, and then electricity and heat consumption are added, and summed energy was divided by the amount of material produced. The difference between the mycelium insulation material and other materials was used to calculate the avoided energy consumption. Cumulative energy consumption during the production process of each material was also determined.

2.3.6. Functional Cubic Meters

Since the considered insulation materials have different thermal conductivity, a correction has to be made to make comparison based on the amount of materials providing the same heat

insulation properties. Therefore, we introduce ‘functional cubic meters’ (fm^3) which is an amount of insulation material required to have the same heat flux value as a material in comparison. The correction is done by calculating ratios of thermal conductivities of the considered insulation materials to the thermal conductivity of the mycelium insulation material (see Table 3.). To calculate functional embodied emissions and functional embodied energy, the ratios were multiplied by embodied emissions and embodied energy of the considered insulation materials. To calculate thermal conductivity of the mycelium material, thermal conductivity values of the raw material components were taken from Table 1. and calculated to an average value.

TABLE 3. INSULATION MATERIAL THERMAL CONDUCTIVITY VALUES AND THERMAL CONDUCTIVITY TO MYCELIUM THERMAL CONDUCTIVITY RATIO

Material	Thermal conductivity, W/(mK)	Ratio to mycelium thermal conductivity, unitless
Mycelium insulation	0.04	1
EPS	0.035	0.875
XPS	0.0345	0.863
Polyurethane	0.0285	0.713
Phenolic foam	0.021	0.525

3. RESULTS AND DISCUSSION

3.1. Embodied Emissions and Embodied Energy

The initial embodied emission value of the mycelium heat insulation material is $213 \text{ kgCO}_2\text{eq/m}^3$, and as research and development decrease the amount of electricity and heat required to produce 1 m^3 of material the embodied emissions are reduced to $159 \text{ kgCO}_2\text{eq/m}^3$. Material use initially contributes to 19 % of production emissions or $40 \text{ kgCO}_2\text{eq/m}^3$, heat use 33 % or $71 \text{ kgCO}_2\text{eq/m}^3$ and electricity 48 % or $101 \text{ kgCO}_2\text{eq/m}^3$. In 2050, emissions from the material use stay the same only having a higher share of 27 %, emissions from heat have lowered to 26 % or $39 \text{ kgCO}_2\text{eq/m}^3$, and emissions from electricity 47 % or $70 \text{ kgCO}_2\text{eq/m}^3$. The mycelium insulation material has lower embodied emission values than other examined materials (see Table 4). When counting in CO_2 absorption, mycelium insulation material embodied emission value initially is $-244 \text{ kgCO}_2\text{eq/m}^3$ and with the decrease of energy requirement, embodied emissions are reduced to $-298 \text{ kgCO}_2\text{eq/m}^3$. When the values of embodied emissions are compared on the basis of ‘functional m^3 ’ then differences between the mycelium and synthetic materials are smaller (see Table 4) due to lower thermal conductivity of the synthetic materials.

Decrease in electricity and heat requirement also reduces embodied energy of the mycelium insulation. The initial embodied energy of mycelium insulation material is $16\,176 \text{ MJ/m}^3$ and in 2050. with the decrease of heat and electricity requirements, the value of embodied energy is reduced to $14\,071 \text{ MJ/m}^3$. Most of the embodied energy comes from material use. Initially, materials result in 61 % of all embodied emissions, but as heat and electricity requirement decreases material embodied energy share goes up to 71 %. All synthetic materials have lower per 1 m^3 of insulation material embodied energy values than the mycelium insulation. The compared material embodied emission and embodied energy values stay constant during the production period.

TABLE 4. THE INITIAL EMBODIED EMISSION AND ENERGY VALUES PER 1 M³ AND FUNCTIONAL 1 M³ OF MYCELIUM INSULATION AND SYNTHETIC INSULATION MATERIALS

Material	Embodied emissions, kgCO ₂ eq/m ³	Embodied emissions, kgCO ₂ eq/fm ³	Embodied energy, MJ/m ³	Embodied energy, MJ/fm ³
Mycelium insulation	213	213	16176	16176
Mycelium insulation (including CO ₂ absorption)	-244	-244		
EPS	231.2	202	3532	3091
XPS	271.8	234	3200	2760
Polyurethane	560.5	399	10184	7256
Phenolic foam	1136	596	8600	4515

3.2. Accumulated GHG Emissions

The mycelium insulation material has the lowest emissions per cubic meter of material (Fig. 3), therefore the cumulative emission value during the production process is the lowest. Mycelium insulation cumulatively emits 3.58 MtCO₂eq. If CO₂ absorption is included, then it is estimated that the mycelium insulation material absorbs 6.26 MtCO₂eq. Emissions of the synthetic materials are: EPS 4.3 MtCO₂eq, XPS 4.98 MtCO₂eq, polyurethane 8.48 MtCO₂eq and phenolic foam 12.7 MtCO₂eq. Correction of amounts of the materials due to differences in thermal conductivity was done as described above. The same applies to cumulative energy consumption.

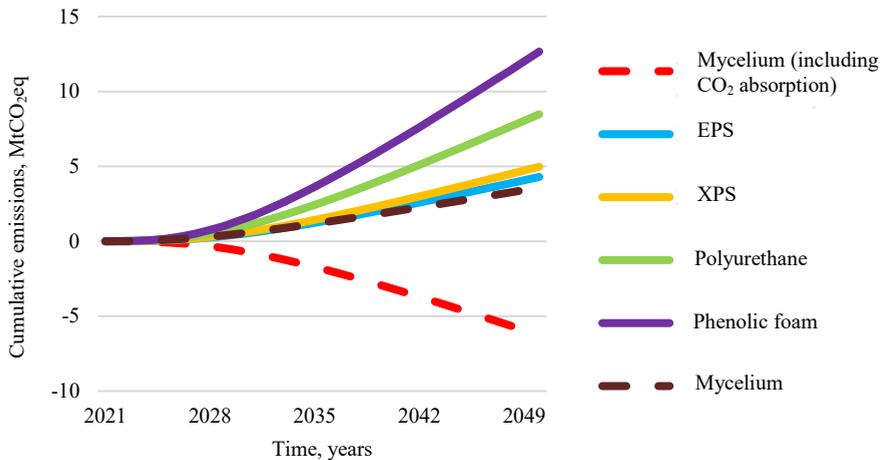


Fig. 3. Cumulative GHG emissions from insulation material production.

3.3. Accumulated Energy Consumption

Results of the embodied energy show that the mycelium insulation material has the highest embodied energy per cubic meter of material (Fig. 4). Therefore, the mycelium insulation cumulative energy consumption value is the highest equal to 337 PJ. The cumulative energy

consumptions of the synthetic materials are – EPS 65.6 PJ, XPS 58.6 PJ, polyurethane 154.1 PJ, and phenolic foam 95.9 PJ.

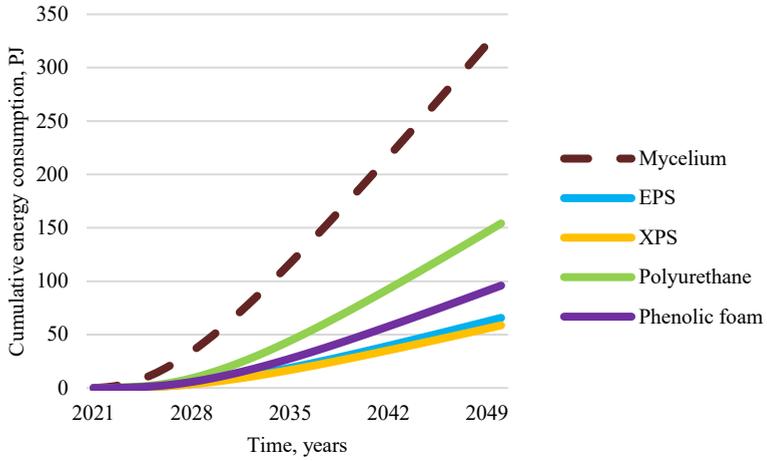


Fig. 4. Cumulative energy consumption from insulation material production.

3.4. Feed-back Effects on Avoided Emissions

When feed-back effects of using revenues from displaced carbon emissions for funding R&D and land allocation for production of the renewable insulation material (see Fig. 3) are included amount of cumulative avoided emissions when use of synthetic materials is compared with use of the mycelium insulation materials reach nearly 19 MtCO₂eq (see Fig. 5).

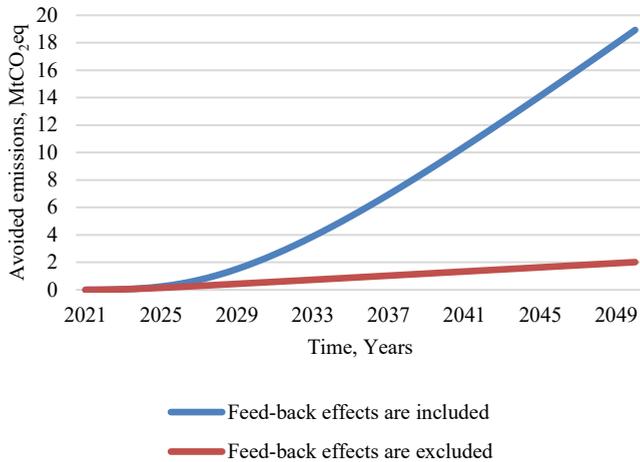


Fig. 5. Cumulative avoided GHG emissions when the emissions of the mycelium material is compared with the emissions resulting from phenolic foam, with feed-back effects included and excluded.

If the feed-back effects are excluded the avoided cumulative emissions are only circa 2 MtCO₂eq. When the feed-back effects are included, revenues from sales of carbon allowances are invested in R&D, which increases production yield of the land used and energy efficiency of production (both of power and heat use). Revenues also allow to allocate more land for production. All these effects are absent when no feed-backs are considered. Comparison in Fig. 5 is obtained by comparing the emissions resulting from the mycelium material production with the emissions resulting from production of the phenolic foam insulation.

4. CONCLUSIONS

Comparing the mycelium insulation with other synthetic materials in terms of embodied GHG emissions shows that the mycelium insulation production is less emitting, mainly due to CO₂ absorption by the materials involved in production. Therefore, switching from synthetic insulation material production to mycelium insulation production would result in lower annual GHG emissions and lower emissions accumulated in the atmosphere. The way insulation material is produced impacts embodied emissions in cradle-to-gate life cycle analysis, but the average synthetic material embodied emission value is higher than the mycelium insulation material. Therefore, more studies should be concluded regarding comparison of organic insulation materials with synthetic in terms of different types of production. When CO₂ absorption is included in calculations, results show that the mycelium insulation can sequester up to 298 kgCO₂/m³, meaning that the mycelium insulation material is carbon negative. As cumulative emission results show, production of the mycelium insulation would be more favored towards reduction of GHG emissions in insulation material production. Namely, producing mycelium insulation instead of phenolic foam would result in 18.9 MtCO₂eq emissions avoided in the considered time span.

Most of the embodied energy comes from material use for production. As of cumulative energy consumption results, mycelium insulation is the most energy-consuming. Mycelium insulation material is not competitive with synthetic materials in terms of energy consumption during the cradle-to-gate life cycle, therefore research towards alternative material use and energy requirement to reduce energy requirement in production should be concluded. Likewise, to study emissions more production variations should be examined.

Feed-back effects play an important role in stimulating production process. Revenue flow from avoided emissions increases production rate of renewable insulation material creating positive feed-back loop. Therefore, feed-back effects associated with avoided emissions by substituting renewable for synthetic materials in production of heat insulation materials have to be considered.

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