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**Ilze Luksta**

# SUSTAINABLE DEVELOPMENT OF THE BIOECONOMY. AGRICULTURE TOWARDS CLIMATE NEUTRALITY

Summary of the Doctoral Thesis

RTU Press
Riga 2025

**RIGA TECHNICAL UNIVERSITY**
Faculty of Natural Sciences and Technology
Institute of Energy Systems and Environment

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# SUSTAINABLE DEVELOPMENT OF THE BIOECONOMY. AGRICULTURE TOWARDS CLIMATE NEUTRALITY

**Summary of the Doctoral Thesis**

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# DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 26 June 2025, at 14.00 at the Faculty of Natural Sciences and Technology of Riga Technical University, 12/1 Āzenes Street, Room 607.

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## DECLARATION OF ACADEMIC INTEGRITY

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

Ilze Luksta ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, 3 chapters, Conclusions, 35 figures, 22 tables, and 14 appendices; the total number of pages is 197, including appendices. The Bibliography contains 127 titles.

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# 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 $CO_2$ 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.

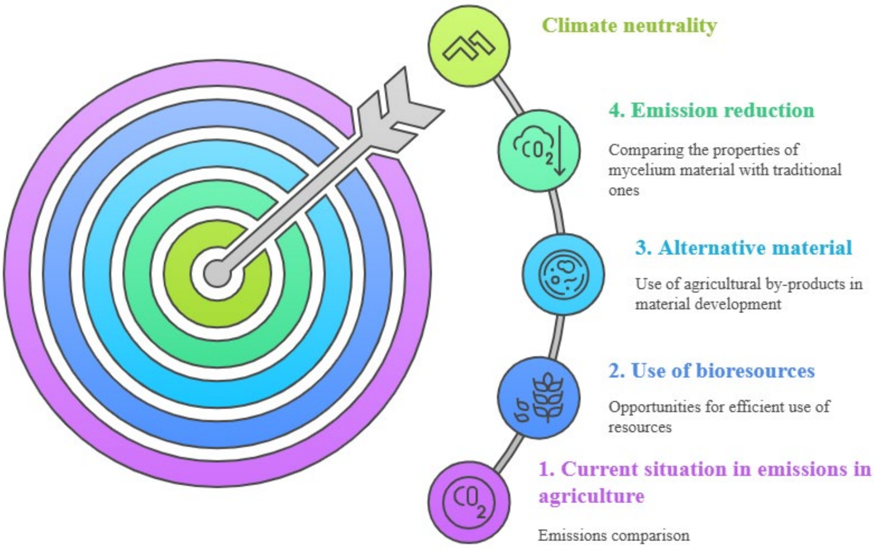


Fig. 1. Structure of the Doctoral Thesis.

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/rtuect-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, **CONECT 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, **CONECT 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, **CONECT 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, **CONECT 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, **CONECT 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ 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. 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.

## 1.1. 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 [1], the total population [2], and the country's GDP per capita [3] 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.

$$\text{Emissions per population, t } CO_2 \text{ eq} = \text{emissions / population} \qquad (1.1)$$

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.

$$\text{Emissions per GDP, t } CO_2 \text{ eq/million EUR} = \text{emissions / GDP} \qquad (1.2)$$

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.

$$\text{Emissions per GDP per Capita, kt } CO_2 \text{ eq/EUR} = \text{emissions / population} \quad (1.3)$$

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 [4].

The EU has introduced various policy initiatives to reduce emissions from agriculture and promote more sustainable practices. Examples are the Common Agricultural Policy [5] and the Green Deal [6], 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.

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.

## 1.2. 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. 1.1).

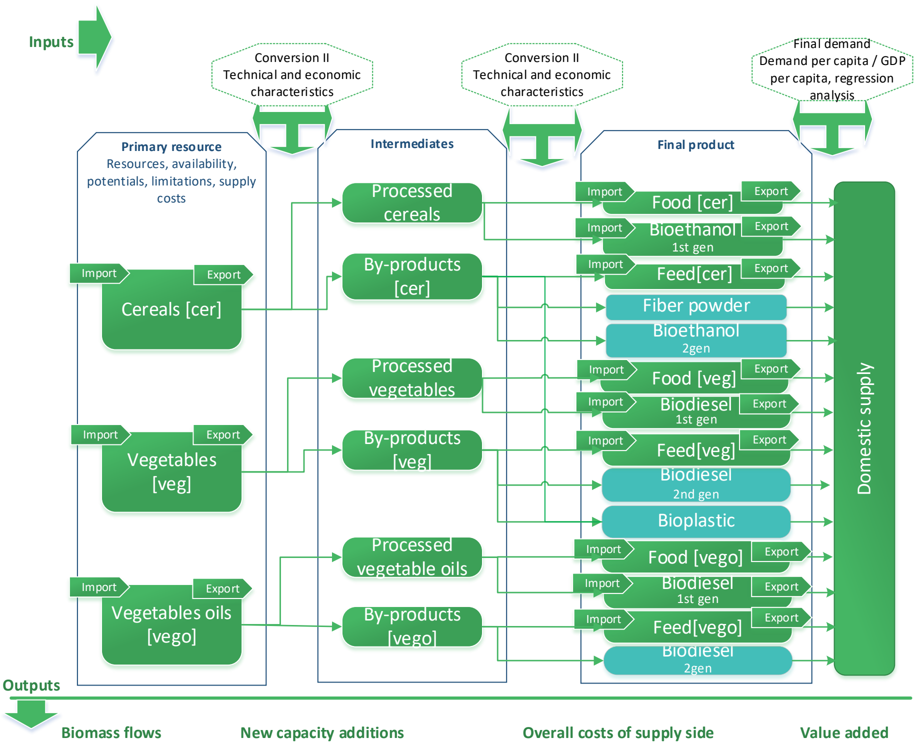


Fig. 1.1. Defined model boundaries for TIMES.

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 [7], as well as the database of the Food and Agriculture Organization of the United Nations [8].

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.

Data on respective conversion technologies are included in the model in terms of capacity,efficiency, investment, operation & maintenance costs, lifetime and availability, andthe 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 [9]. 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.

## 1.3. 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 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 destructose 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.

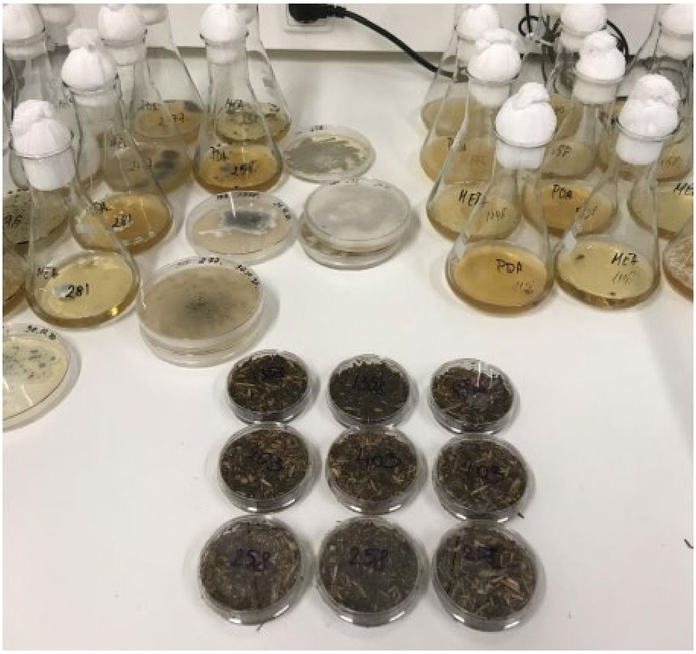


Fig. 1.2. Mycelium samples (weight of each sample: 20 mg).

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 ºC) 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.

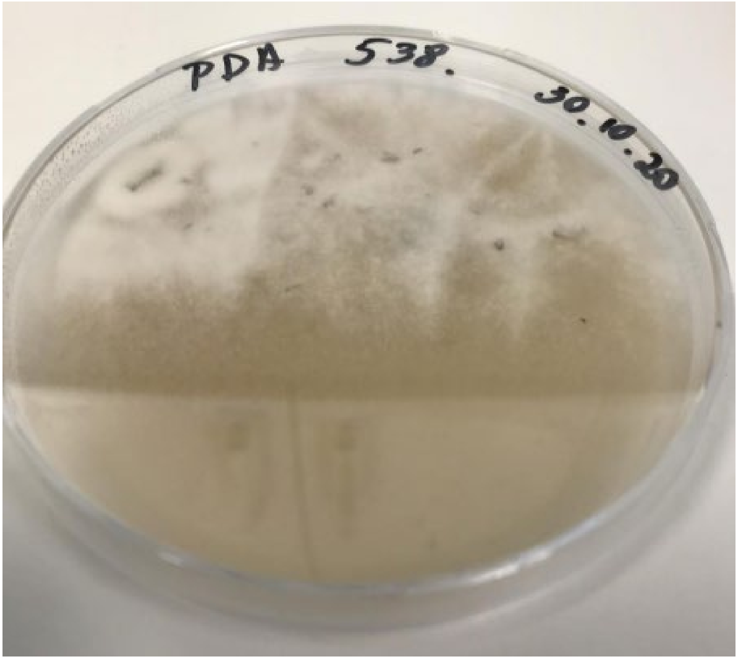


Fig. 1.3. *Trichoderma viride* spores grown on solid PDA medium.

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.

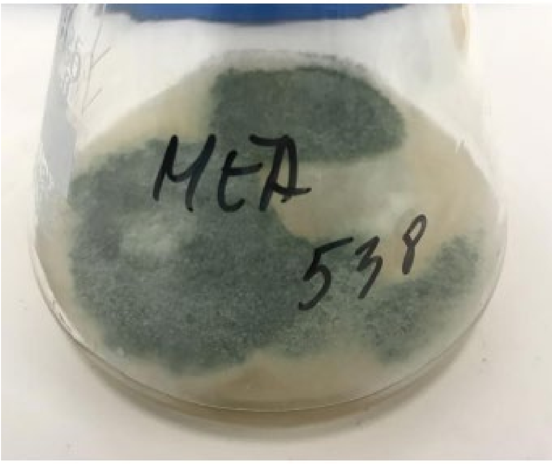


Fig. 1.4. *Trichoderma viride* spores grown on liquid MEA medium.

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. 1.5. 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. 1.6. 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 1.2

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 1.2 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.

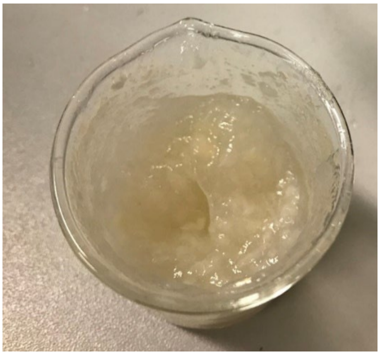

Fig. 1.7. Mixture of xanthan, water and ethanol.

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. 1.8. 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. 1.9. Pouring the mycelium material into the mold.

Figure 1.9 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. 1.10. 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. 1.11. Mycelium samples (S7, S9, S11, S12, S13, S14).


Fig. 1.12. Mycelium samples (S15, S16, S17, S18, S19).

In Figs. 1.12 and 1.11, 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 1.3

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 suggested in the equations were tested to improve the thermal conductivity of the mycelium material.

Taking into account the obtained results in the samples containing wood chips, wood chips were no longer used in subsequent 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).

Initially, the sample numbers were simplified (for example, from S1 to S19), however, as the experiments continued, the sample numbers were specified (for example, by indicating the substrate proportions or, if a particular experiment was focused on differences in the amount of binders, by indicating the percentage of binders added).

Table 1.4

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 |

## 1.4. 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 [10]. 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: expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane and phenolic foam. The average values of the synthetic insulation materials were taken from the literature [11]. 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. 1.13). The CLD represents the system's mechanics without involving numerical calculations [12]. 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. 1.13). 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 take time, and this is modelled 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).

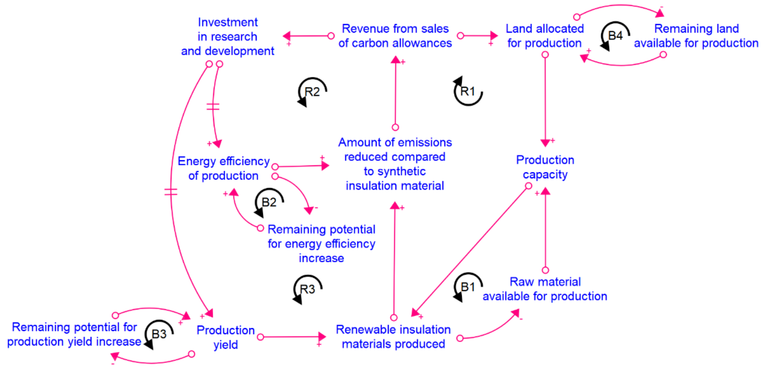


Fig. 1.13. Causal loop diagram portraying the structure of the system dynamics model for mycelium insulation material production.

## 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 1.5.

Table 1.5

Emission Factors and Embodied Energy of Production Inputs per 1 $m^3$ 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 1.5 (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.

### Modelling

Some elements of the model were taken from the already existing model made for the bioeconomy sector at Riga Technical University [33], 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”.

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 $CO_2$ 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 $CO_2$ 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" ($fm^3$) 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 1.6). 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 1.6

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 |

# 2. 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.

## 2.1. 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.

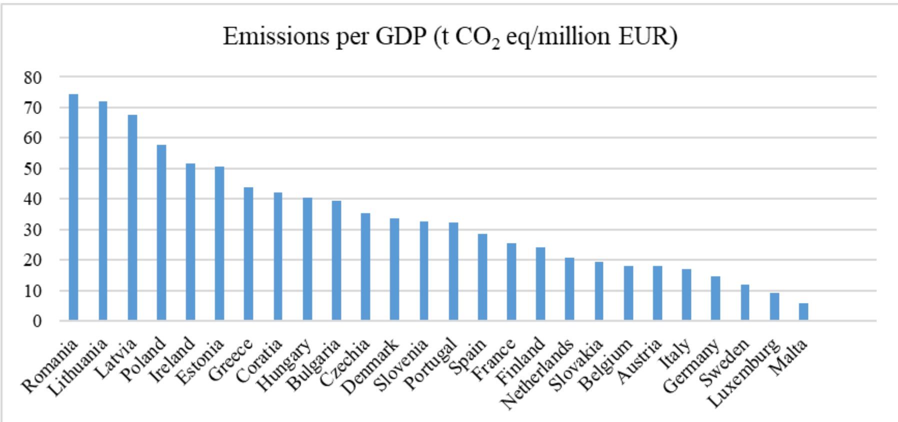


Fig. 2.1. Emissions in agriculture per GDP.

Figure 2.2 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.

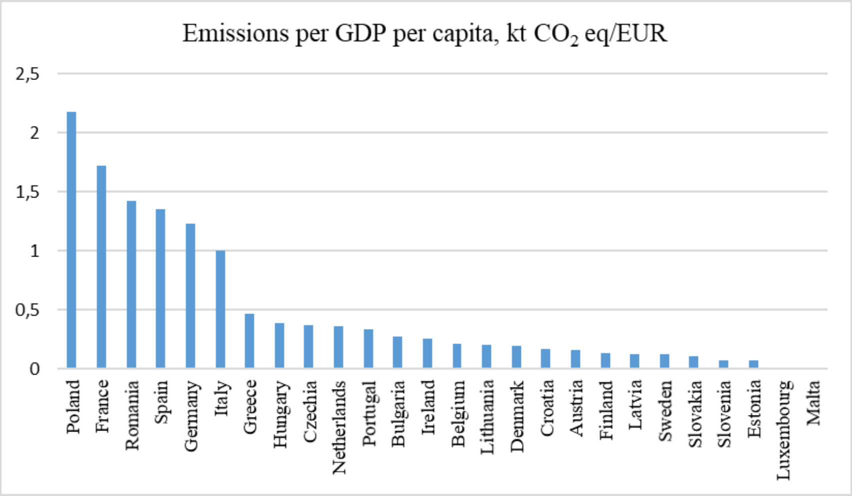


Fig. 2.2. Emissions in agriculture per GDP per capita.

Figure 2.3 shows data on the amount of GHG in the agricultural sector per capita in different countries, expressed in kt $CO_2$ 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.

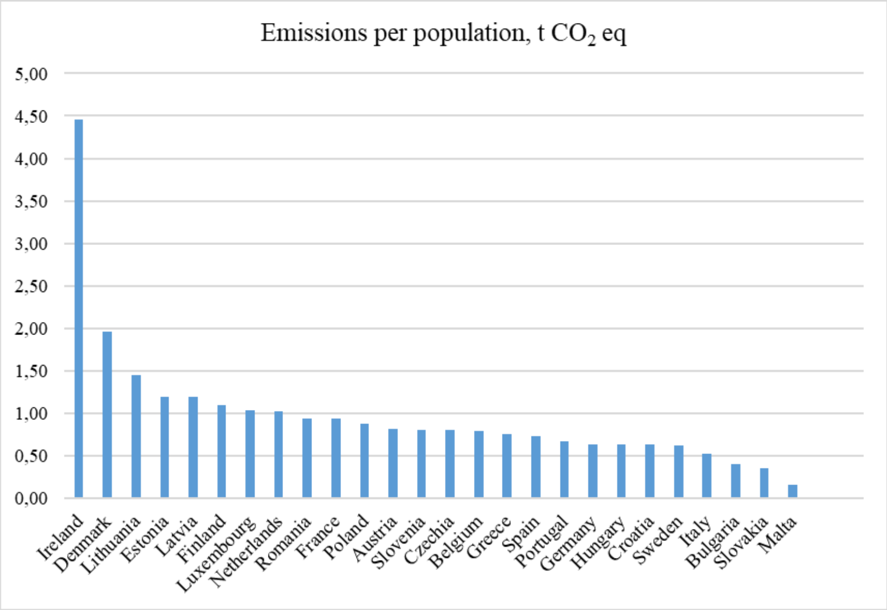


Fig. 2.3. Emissions in agriculture per population.

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 [34]. 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 [35]. 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-$CO_2$ GHG emissions from agriculture, indicating the need for innovative strategies and targeted measures [36]. 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 the European level, including the exchange of best practices, knowledge sharing and coherent policy frameworks, can foster collective action and progress towards common goals [37].

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.

## 2.2. 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 modelling 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 2.4 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.

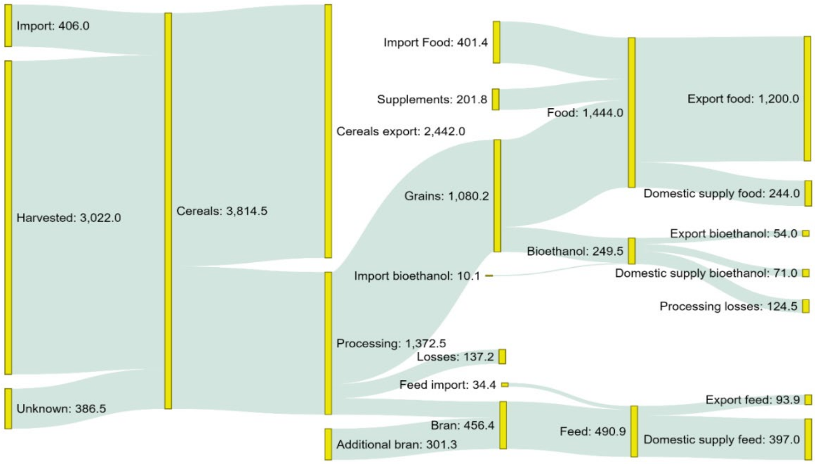


Fig. 2.4. Sankey diagram for bioresource flows of the base scenario in 2015 for cereals, thousand tonnes.

Figure 2.4 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 2.5 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.

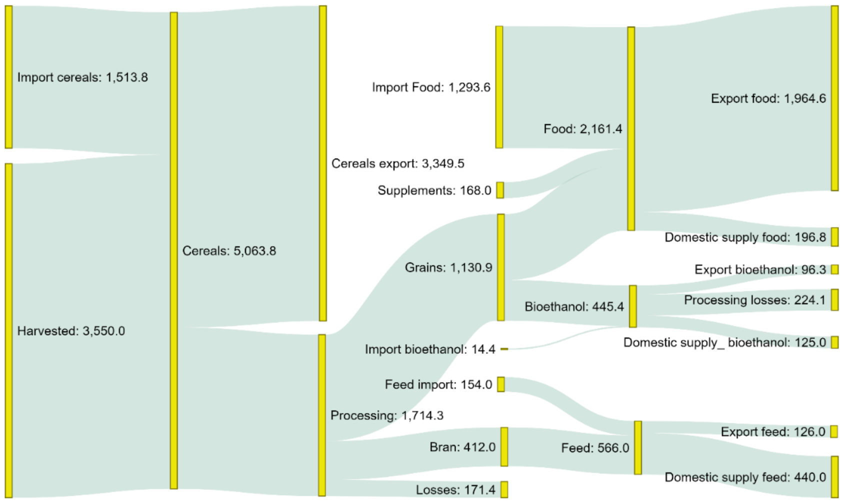


Fig. 2.5. Sankey diagram for bioresource flows of the base scenario in 2030 for cereals, thousand tonnes.

### Baseline scenario for vegetable oils

In Fig. 2.6, the main finished vegetable oil production streams in 2015 are biodiesel for domestic consumption and export, followed by feed for domestic consumption and export. The primary processing of vegetable oils produces by-products that are used to produce animal feed. A large proportion of vegetable oils is used to produce first-generation bioethanol.

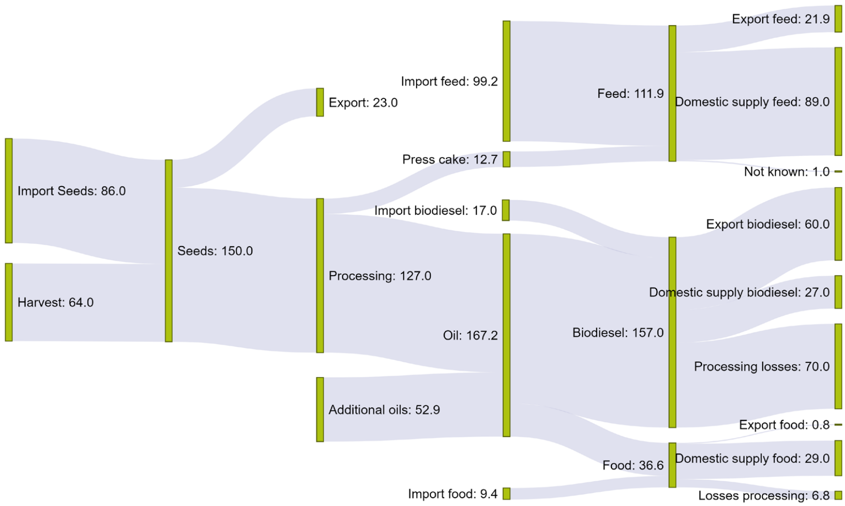


Fig. 2.6. Sankey diagram for bioresource flows of the base scenario in 2015 for vegetable oils, thousand tonnes.

Figure 2.7 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.

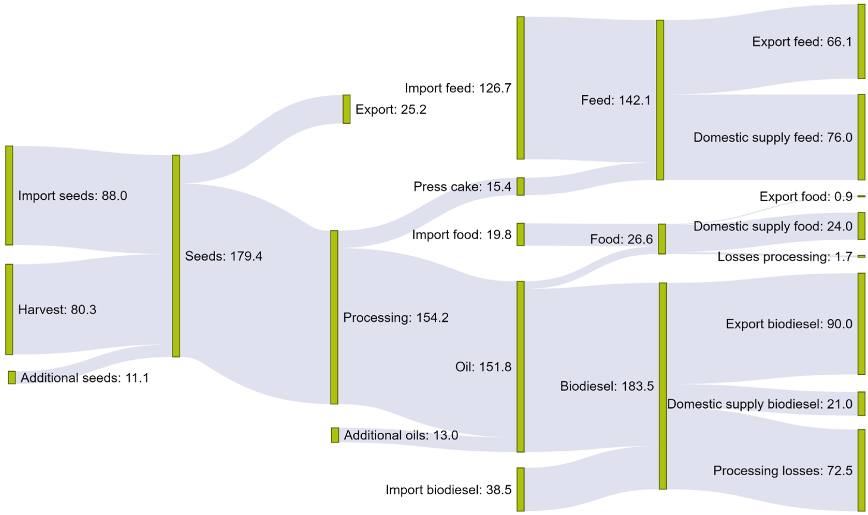


Fig. 2.7. Sankey diagram for bioresource flows of the base scenario in 2030 for vegetable oils, thousand tonnes.

**Baseline scenario for vegetables**

In Fig. 2.8, 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. 2.8. Sankey diagram for bioresource flows of the base scenario in 2015 for vegetables, thousand tonnes.

Figure 2.9 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.

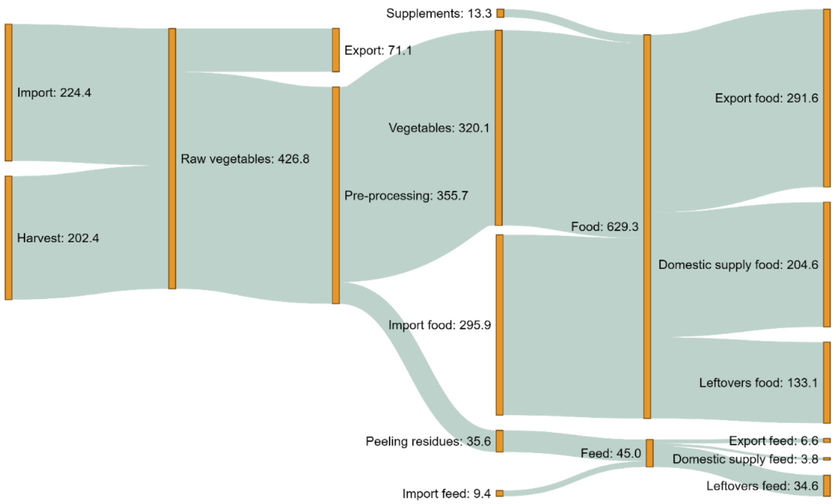


Fig. 2.9. Sankey diagram for bioresource flows of the base scenario in 2030 for vegetables, thousand tonnes.

## Alternative scenario analysis

In addition to the baseline scenario, four alternative scenarios were used for the TIMES crop case study. The alternative scenarios include 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. 2.10).

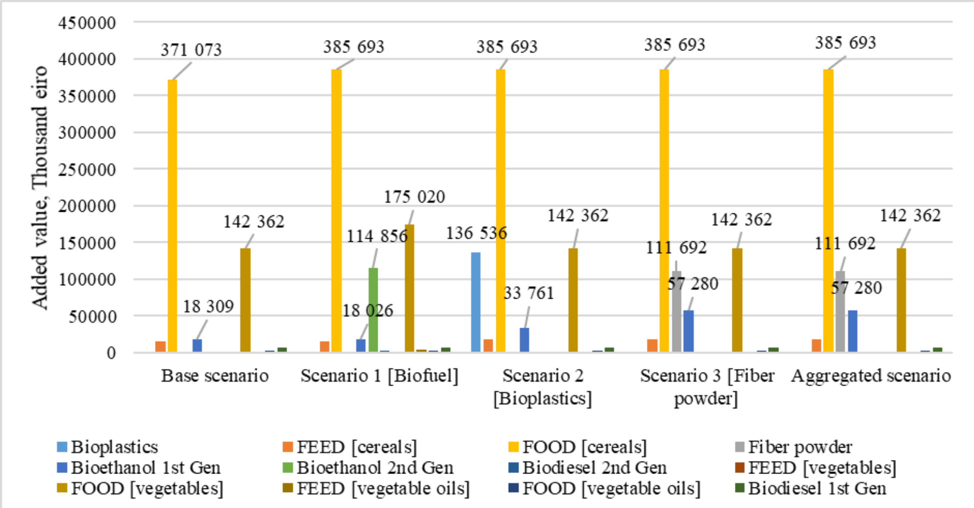


Fig. 2.10. Scenario analysis for new technologies in the agriculture sector in Latvia, year 2030.

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:

- it uses existing by-products, reducing waste;
- it offers high added value, especially in the food sector;
- it requires relatively lower investment and operating costs.

This scenario meets the goals of the bioeconomy, promoting sustainable resource use and economic growth.

Cereals make up the largest share of crop production. According to statistical data, the largest volume of cereals grown is exported, and most of the grains are used in food production (all types of flour products). Vegetables and vegetable oils make up the smallest share of crop production. Most cereals, vegetables and oils are used for food production, but a smaller part is allocated for animal feed and other products (biofuels). The model also shows losses in processing processes and surpluses, which can be explained by database inconsistencies. New technologies were introduced in the scenarios. Cereal by-products are used in the production of second-generation biofuels, plant residues and by-products in the production of bioplastics. The scenario also considers the use of grain bran in the production of fiber powder as a new technology. Similar to scenario 3, the amount of fiber in the summarized scenario is also quite small (Fig. 2.11) – only 261 thousand tons. However, this amount is sufficient to achieve the value-added goal, since food has a higher added value in the bioeconomy compared to bioplastics and biofuels.

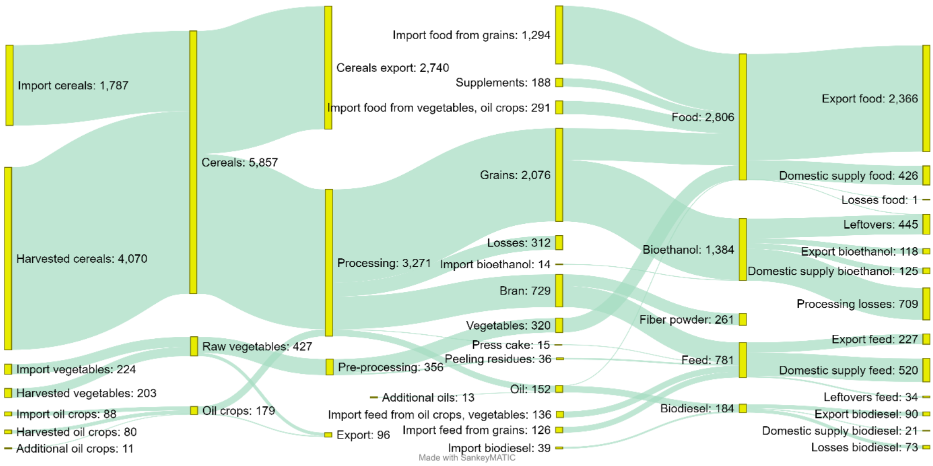


Fig. 2.11. Best alternative scenario modelling bioresource flow for the 2030 crop farming sector, thousand tonnes.

Summarizing the results of the TIMES model in the context of Latvian agriculture, it can be concluded that the efficient use of bioresources allows for the creation of more environmentally friendly development scenarios. However, in order to achieve real emission reductions in practice, the development and application of innovative materials also play a significant role.

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.

## 2.3. 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 in the chapter 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 2.1

Thermal Conductivity Results of 17 Mycelium Material Samples

| No. | $\lambda_1$, W/(mK) | $\lambda_2$, W/(mK) | $\lambda_3$, W/(mK) | $\Lambda_{avg}$, 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 2.1 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 2.2

Density of 17 Samples of Mycelial Material

| **No.** | **$\rho_1$, kg/m$^3$** | **$\rho_2$, kg/m$^3$** | **$\rho_3$, kg/m$^3$** | **$P_{avg}$, 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 2.2 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 2.3

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

| | Wood chips | Straw | Water | Xanthan | Sodium carbonate | Mycelium | Medium | $\Lambda_{avg}$, 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 2.3. 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 2.4

Density of Variants of Mycelium Samples

| No. | $\rho_1$, kg/m$^3$ | $\rho_2$, kg/m$^3$ | $\rho_3$, kg/m$^3$ | $\rho_{vid}$, 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 2.5

Thermal Conductivity Results of Mycelium Samples

| No. | $\lambda_1$, W/(mK) | $\lambda_2$, W/(mK) | $\lambda_{avg}$, 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 2.5. 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 2.6

Density of Mycelium Samples

| No. | $\rho_1$, W/(mK) | $\rho_2$, W/(mK) | $\rho_{avg}$, 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 |

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

Table 2.7

Properties of Hay and Straw Materials

| No. | $\lambda_{avg}$, 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.

## 2.4. System dynamics model results

### Embodied emissions and embodied energy

The initial embodied emission value of the mycelium heat insulation material is 213 kg$CO_2$eq/m$^3$, and as R&D decrease the amount of electricity and heat required to produce 1 m$^3$ of material, the embodied emissions are reduced to 159 kg$CO_2$eq/m$^3$. Material use initially contributes to 19 % of production emissions or 40 kg$CO_2$eq/m$^3$, heat use 33 % or 71 kg$CO_2$eq/m$^3$ and electricity 48 % or 101 kg$CO_2$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 kg$CO_2$eq/m$^3$, and emissions from electricity 47 % or 70 kg$CO_2$eq/m$^3$. The mycelium insulation material has lower embodied emission values than other examined materials (Table 2.8). When counting in $CO_2$ absorption, mycelium insulation material embodied emission value initially is –244 kg$CO_2$eq/m$^3$, and with the decrease of energy requirement, embodied emissions are reduced to –298 kg$CO_2$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 (Table 2.8) due to the lower thermal conductivity of the synthetic materials.

Table 2.8

The Initial Embodied Emission and Energy Values per 1 $m^3$ and Functional 1 $m^3$ of Mycelium Insulation and Synthetic Insulation Materials

| Material | Embodied emissions, $kgCO_2eq/m^3$ | Embodied emissions, $kgCO_2eq/fm^3$ | 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 $MJ/m^3$, and in 2050, with the decrease of heat and electricity requirements, the value of embodied energy is reduced to 14,071 $MJ/m^3$. 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, the 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.

**Accumulated GHG emissions**

The mycelium insulation material has the lowest emissions per cubic meter of material (Fig. 2.12); therefore, the cumulative emission value during the production process is the lowest. Mycelium insulation cumulatively emits 3.58 $MtCO_2eq$. If $CO_2$ absorption is included, then it is estimated that the mycelium insulation material absorbs 6.26 $MtCO_2eq$. Emissions of the synthetic materials are: EPS – 4.3 $MtCO_2eq$, XPS – 4.98 $MtCO_2eq$, polyurethane – 8.48 $MtCO_2eq$, and phenolic foam – 12.7 $MtCO_2eq$. 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.

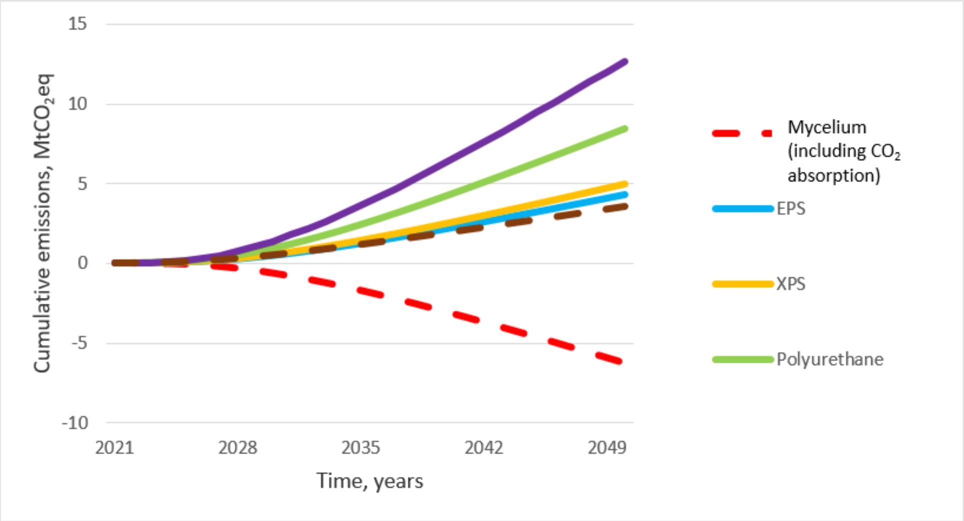


Fig. 2.12. Cumulative GHG emissions from insulation material production.

**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. 2.13). 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.

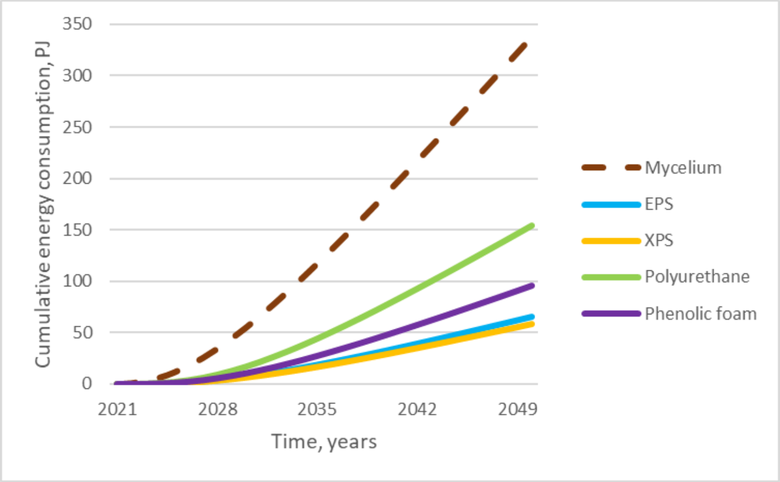


Fig. 2.13. Cumulative energy consumption from insulation material production.

### 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. 2.14), then the cumulative avoided emissions, comparing the use of synthetic materials with the use of mycelium insulation materials, reach almost 19 $MtCO_2eq$ (Fig. 2.14). If the feedback loop is not taken into account, the cumulative avoided emissions are only about 2 $MtCO_2eq$.

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.

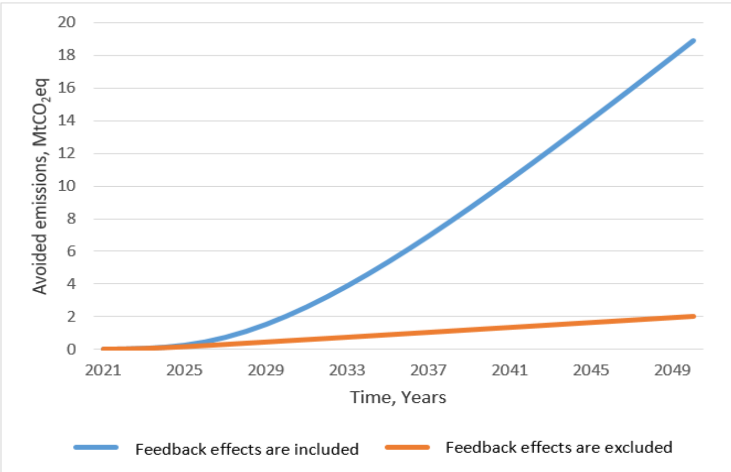


Fig. 2.14. Cumulative avoided GHG emissions when the emissions of the mycelium material are compared with the emissions resulting from phenolic foam, with feedback effects included and excluded.

The results shown in Fig. 2.14 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/m$^3$ to 120 kg/m$^3$. 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 $CO_2$ is absorbed during the production process. Calculations show that mycelium insulation can sequester up to 298 kg$CO_2$/m$^3$, making it a carbon-negative material. Compared to phenolic foam, the use of mycelium insulation could reduce GHG emissions by 18.9 Mt$CO_2$eq 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.

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