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SUSTAINABLE BIOMASS POTENTIAL FOR HEAT PRODUCTION

Summary of the Doctoral Thesis



RIGA TECHNICAL UNIVERSITY

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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 Sciences (PhD), the present Doctoral Thesis has been submitted for defence at the open meeting of the RTU Promotion Council on 26 November 2026 at 14:00 at the Faculty of Natural Sciences and Technologies 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 (PhD) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Oskars Švedovs (signature)

Date:

The Doctoral Thesis has been written in English. It consists of an Introduction, three chapters, Conclusions, 101 figures and 31 tables; the total number of pages is 154. The Bibliography contains 442 titles.

TABLE OF CONTENTS

Introduction	5
1. Literature analysis summary	9
2. Methodology summary	11
2.1. BIBLIOMETRIC ANALYSIS.....	13
2.2. MATERIAL FLOW ANALYSIS.....	14
2.3. BIOMASS QUALITY ANALYSIS.....	14
2.4. FUEL COMBUSTION TESTS.....	15
2.5. ANALYSIS OF ASH CHEMICAL COMPOSITION AND STRUCTURE	19
2.6. REGRESSION ANALYSIS.....	20
2.7. MULTI-CRITERIA DECISION ANALYSIS.....	20
2.8. LIFE CYCLE ASSESSMENT.....	22
2.9. SUSTAINABILITY ASSESSMENT	24
3. Results summary	26
3.1. EXPERIMENTAL RESEARCH RESULTS.....	26
3.1.1. Fuel quality analysis results.....	26
3.1.2. Combustion tests results	28
3.1.3. Ash analysis results.....	30
3.1.4. Regression analysis results	31
3.2. MULTI-CRITERIA DECISION ANALYSIS RESULTS.....	32
3.3. LIFE CYCLE IMPACT ASSESSMENT RESULTS	34
3.4. SUSTAINABILITY ASSESSMENT RESULTS	35
Conclusions	38

INTRODUCTION

Relevance of the Doctoral Thesis

Solid biofuel continues to play a significant role in heat production, while the pressure to reduce fossil fuel use and broaden the local energy resource base is increasing. Global bioenergy consumption data show that biomass use in energy increased from 13 000 TWh/year to 15 000 TWh/year in 2014–2023, with solid biomass clearly dominating this structure. At the same time, a further 15 000 TWh/year of unused biomass potential is identified globally. Therefore, the development of bioenergy is not only a question of increasing consumption but also of determining which biomass flows can be justified for energy use while maintaining the principles of resource efficiency and sustainability. In the structure of unused biomass potential, wood accounts for 74 %, while non-wood biomass accounts for 26 %. This distribution shows that wood will remain an important bioenergy resource, yet non-wood biomass is not an insignificant flow. It is a quantitatively important part of the resource base, but its assessment in the solid biofuel market has so far been less systematic than that of wood fuel. This is particularly important in the pellet and wood chip sector, where quality, logistics and combustion-related assumptions have largely been developed based on wood fuel properties. The scale of the pellet market further strengthens this problem. In 2024, global pellet production reached 48.3 million t, while consumption exceeded 45 million t for the first time. This volume shows that pellets have become established as a standardised solid biofuel with an international market. At the same time, the feedstock base for pellet production is mainly based on forestry and wood-processing residues, the availability of which is affected by the scale of the wood industry, export flows, the cascade use principle and competition with other products. Therefore, the further development of the pellet sector is not only a question of production capacity, but also of diversifying the feedstock base. In Latvia, this issue is relevant because biomass already plays an important role in the heat supply resource structure, while agriculture, food and beverage production, land management and other sectors generate biomass flows that are not fully utilised. These flows can supplement the local solid biofuel base if their use can be substantiated in terms of quality, combustion performance and sustainability. Market requirements for traceability also strengthen this need: in 2025, 22.8 million t of biomass, including pellets, were sold with a Sustainable Biomass Program certificate. Together with the requirements of the Renewable Energy Directive (RED II), this means that the use of alternative biomass cannot be justified only by volume or availability. An approach is required that links resource origin, fuel quality, combustion results, life cycle impact, GHG emission savings and practical implementation conditions in one system.

The aim and tasks of the Doctoral Thesis

The main aim of the Thesis is to develop a methodology for determining the sustainability of alternative biomass and to assess its potential for heat production by ensuring a unified and repeatable approach for comparing the studied fuel samples concerning resource availability,

fuel quality, combustion process, emissions, ash properties, life cycle impact and sustainability criteria.

To achieve the aim, the following tasks were set.

- Select alternative biomass types for the study and assess their availability, considering the practical feasibility of resources, use-related limitations and potential for fuel production.
- Prepare the studied fuel samples and determine the parameters characterising their quality to obtain mutually comparable data on the suitability of alternative biomass pellets and wood chip mixtures for heat production.
- Perform combustion tests of the fuel samples, determining the parameters characterising the combustion process, emission formation patterns and the chemical and structural composition of the obtained ash.
- Carry out a comprehensive assessment of the studied fuel samples, including technical, social, environmental and sustainability criteria, to substantiate the potential of alternative biomass use for heat production.

Scientific novelty of the Doctoral Thesis

The novelty of the Thesis lies in the developed methodology, which combines the experimental investigation of alternative biomass, life cycle impact assessment, multi-criteria decision-making methods and sustainability assessment within one framework, covering the assessment of alternative biomass potential across the full supply and use chain from collection to combustion. The repeatability and integration of the methodology are particularly important in a situation where both the fuel market and regulatory requirements are moving towards verifiable traceability, emission control and comparable sustainability argumentation.

Hypothesis of the Doctoral Thesis

The quality and combustion-related indicators of alternative biomass fuel may fail to meet the existing requirements for solid biofuel use; however, such fuel may be comparable to wood in terms of sustainability.

Practical significance of the Doctoral Thesis

The developed methodology is applicable in the energy sector for assessing the sustainability of alternative biomass fuels by providing a structured and comparable approach for evaluating different biomass resources. The methodology can serve as a decision-support instrument for heat production companies, fuel producers and policy makers when selecting technically, environmentally and economically justified fuel solutions. The methodology can also be used to improve the sustainability certification process for alternative biomass fuels because it integrates fuel quality, combustion process, emissions and life cycle impact assessment into one system. It therefore supports an objective comparison of alternative pellets with conventional wood fuel and promotes the sustainable use of local biomass resources for heat production.

Structure of the Doctoral Thesis

The Thesis has a linear structure consisting of three parts: theoretical, experimental and analytical. In the theoretical part, the research direction is selected on the basis of bibliometric analysis, and the availability of the biomass types selected in the study is examined. In the experimental part, fuel tests are carried out for the selected biomass samples to determine quality, and combustion tests are performed to determine combustion-related parameters and emissions, together with chemical analysis of the ash collected during combustion tests. In the analytical part, the experimentally obtained data are analysed statistically using a regression approach to identify relationships between variables; multi-criteria analysis is carried out based on experimental and survey data; life cycle assessment is performed to evaluate the environmental impact of biomass pellet production and use; and a sustainability assessment of biomass pellets is carried out to verify compliance with existing legally approved requirements. The structure and the selected biomass types (pellet samples in the residential heating context and wood chip mixtures in the district heating context) are shown in Fig. 1.

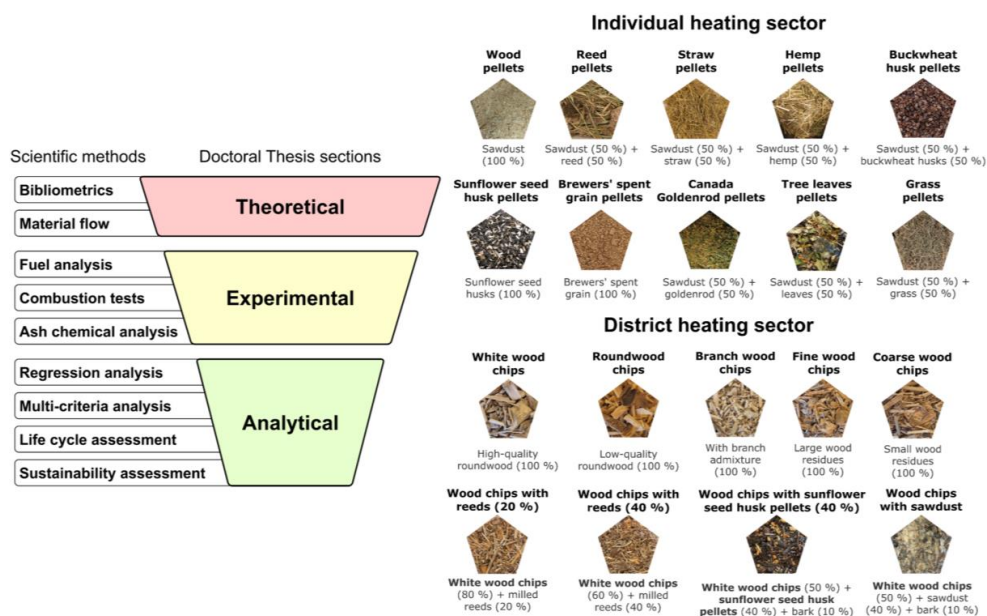


Fig. 1. Structure of the Thesis (left) and prepared biomass samples (right).

Scientific approbation of the Doctoral Thesis

The results of the Doctoral Thesis have been presented at 4 international scientific conferences.

- **Svedovs, O.,** Džikevičs, M., and Kirsanovs, V. Bibliometric Analysis of the Alternative Biomass Types and Biomass Combustion Technologies, International Scientific Conference of Environmental and Climate Technologies (CONNECT 2023), Latvia, Riga.
- Kirsanovs, V., Kokorevičs, K., **Svedovs, O.,** Siktars, H., Sturmane, A., Priedniece, V., Džikevičs, M., and Vīgants, E. Biomass diversification for heat production: From theory

to practice, International Scientific Conference of Environmental and Climate Technologies (CONNECT 2024), Latvia, Riga.

- Kirsanovs, V., Kass, K., Siktars, H., **Svedovs, O.**, Cerneja, J., Mikelsone, E., Priedniece, V., Mika, T., Vigants, G., and Vigants, E. Biomass for district heating: The tango between sustainable biomass criteria and heat production vitality, International Scientific Conference of Environmental and Climate Technologies (CONNECT 2025), Latvia, Riga.
- Kirsanovs, V., Dilshad, M., Siktars, H., **Svedovs, O.**, and Mika, T. Alternative biomass for pellet production: To be or not to be? International Scientific Conference of Environmental and Climate Technologies (CONNECT 2026), Latvia, Riga.

The results of the Doctoral Thesis are reflected in 6 international scientific publications.

- **Svedovs, O.**, Vigants, E., Siktars, H., Kirsanovs, V., and Blumberga, D. (2025). A Bibliometric and Literature-Based Overview of Biomass Pre-treatment and Conversion Technologies Modelling with Aspen Software. *Environmental and Climate Technologies*, 29(1), 880–898. Available: <https://doi.org/10.2478/rtuect-2025-0059>
- Dzikevics, M., Stūrmane, A., **Svedovs, O.**, Kirsanovs, V., Kalnbalkite, A., Ibile, D., and Blumberga, D. (2025). Sankey-Based Material Flow Analysis of Residual Biomass for Combustion: A Case Study of Latvia. *Environmental and Climate Technologies*, 29(1), 483–499. Available: <https://doi.org/10.2478/rtuect-2025-0033>
- **Svedovs, O.**, Sturmane, A., Feofilovs, M., Kirsanovs, V., and Romagnoli, F. (2026). Comparative Cradle-to-Grave Life Cycle Assessment of Wood and Alternative Biomass Pellet Feedstocks for Decentralized Heating Using Experimental Data. *Biomass and Bioenergy*, 208, Scientific paper 108880. Available: <https://doi.org/10.1016/j.biombioe.2025.108880>
- **Svedovs, O.**, Siktars, H., Cerneja, J., Kass, K., Mika, T., Priedniece, V., Vigants, E., and Kirsanovs, V. (2026). Empirical Model for Predicting the Combustion Performance of Low-Quality Biomass Pellets Based on Experimental Data. *Environmental and Climate Technologies*, 30(1), 232–250. Available: <https://doi.org/10.2478/rtuect-2026-0016>
- Kirsanovs, V., Siktars, H., Kass, K., **Svedovs, O.**, Cerneja, J., Priedniece, V., Vigants, G., and Vigants, E. (2026). Biomass Diversification for District Heating: Trade-Off Between Biomass Sustainability and Heat Production Efficiency. *Environmental and Climate Technologies*, 30(1), 307–325. Available: <https://doi.org/10.2478/rtuect-2026-0020>
- **Svedovs, O.**, Karklina, A., Bass, D., Kirsanovs, V., Vigants, E., Kusnere, Z., Kalnbalkite, A., and Kubule, A. (2026). Prioritization of Alternative Biomass Pellets for Heat Production Using Multi-Criteria Ranking and Greenhouse Gas Savings Assessment. *Biomass and Bioenergy*, 217, Scientific paper 110018. Available: <https://doi.org/10.1016/j.biombioe.2026.110018>

1. LITERATURE ANALYSIS SUMMARY

Biomass use is first considered in the context of the carbon cycle, greenhouse gases (GHG) and anthropogenic emissions. This perspective shows that fuel choice is related not only to energy production but also to the impact on GHG emissions. Unlike fossil fuels, biomass participates in a shorter carbon cycle; however, this does not mean that any use of biomass is sustainable. Biomass sustainability is determined by the origin of the feedstock, competition with other uses, processing requirements, transport, combustion efficiency and emissions throughout the life cycle.

The literature analysis shows that the role of biomass in heat supply is increasing both in the EU and in Latvia, particularly in district heating systems and in the residential heating sector. In Latvia, this trend is driven by the availability of local biomass resources, fluctuations in fossil fuel prices and the need to reduce dependence on imported energy resources. At the same time, the principles of bioeconomy and cascade use indicate that lower value-added biomass flows, residues and by-products should primarily be used in energy if they do not have a justified higher-value application. Therefore, the relevance of alternative biomass is not related only to additional fuel volumes, but also to more efficient integration of resources into the local bioeconomy. The practical suitability of biomass for fuel production and use is determined by a set of properties. The lower heating value characterises the energy value, but in practice moisture content, ash content, material homogeneity, ash melting behaviour, emission profile and the operating regime of the combustion unit are equally important. Therefore, in the assessment of alternative pellets and wood chip mixtures, fuel quality, combustion test efficiency and emissions, as well as ash properties and potential ash management, must be analysed simultaneously.

The results of the bibliometric analysis (see methodology in Section 2.1) in the keyword co-occurrence network show the main research directions in biomass energy and their interconnections (see Fig. 1.1). Around the keyword “biomass”, several thematic clusters are formed: sustainability, renewable energy, life cycle assessment and environmental impact; thermal conversion technologies, including pyrolysis, gasification, carbonisation and torrefaction; and research on lignocellulosic biomass, cellulose and lignin. This structure shows that biomass research is no longer related only to the technological use of fuel or conversion efficiency, but increasingly also includes questions of resource origin, environmental impact and sustainability. A similar trend is found in other bibliometric studies of bioenergy, where the number of publications has increased after 2000, and the importance of environmental and systemic analysis has grown. This supports the approach selected in the Doctoral Thesis: to assess alternative biomass not only by quality and combustion results, but also by life cycle impact, practical applicability and sustainability potential.

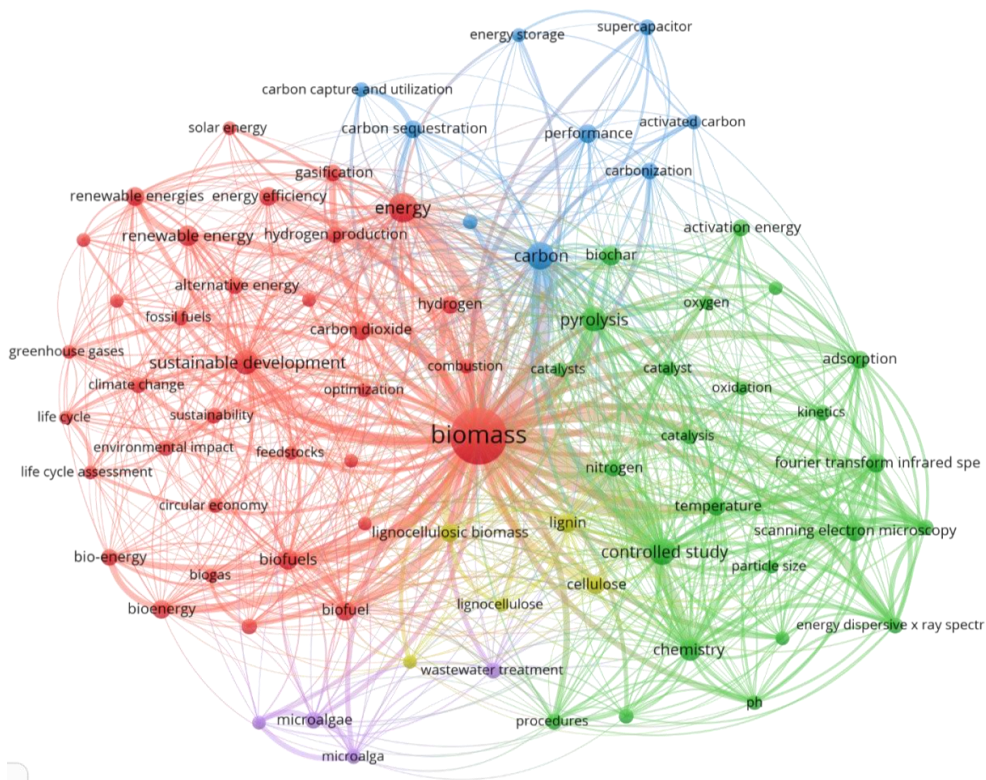


Fig. 1.1. Keywords related to biomass in the energy context from scientific publications.

The analysis of the regulatory framework confirms that the introduction of alternative biomass is determined not only by resource availability and price. Fuel quality requirements, emission limit values, ecodesign conditions and sustainability criteria are also important. RED II links biomass use with verifiable feedstock origin and GHG emission savings, while ecodesign requirements for small-scale boilers limit the use of alternative pellets for which compliance with emission limit values cannot be demonstrated. Therefore, the introduction of alternative biomass fuels is simultaneously a technological, environmental and regulatory issue.

Existing studies provide an important basis for assessing alternative biomass fuels, but they often cover only part of the required assessment. One group of studies focuses on pellet quality and its improvement by analysing the effect of feedstock on moisture content, ash content, mechanical durability, bulk density and other indicators. Another group assesses pellet combustion, boiler efficiency and emissions in small-scale units; however, these studies usually do not simultaneously analyse life cycle impact, sustainability criteria and the practical factors needed for decision-making. Life cycle assessment studies provide a broader view of environmental impact, but their results depend strongly on system boundaries, the functional unit, biogenic carbon accounting, transport assumptions and the databases used. This justifies the need for an integrated approach in which alternative biomass is assessed simultaneously by quality, combustion results, environmental impact and sustainability.

2. METHODOLOGY SUMMARY

This chapter describes the methodology developed and applied in the study. The choice of feedstocks was based on a preliminary study aimed at identifying biomass flows that are available under Latvian conditions and are suitable for the study. The preliminary study is not interpreted as a separate results part of the Doctoral Thesis but as a selection stage before the full application of the methodology. Actual feedstock availability was defined as the initial selection criterion because the literature includes examples of pellet feedstocks that may be technically usable for solid biofuel production but do not correspond to the regional resource context of Latvia.

To assess biomass availability not only as a theoretical resource but as a specific economic flow, material flow analysis (MFA) was carried out for some feedstocks (see methodology in Section 2.2). MFA made it possible to determine how the respective biomass is distributed among existing uses and what part could potentially be directed to fuel production. This approach was applied to wood, reeds, straw, brewers' spent grain and leaves. The calculations showed that the potential amount usable in energy is 110 880 TJ/year for wood, 963 TJ/year for reeds, 5 542 TJ/year for straw, 57 TJ/year for brewers' spent grain and 12 TJ/year for leaves. The example of the straw flow (see Fig. 2.1) demonstrates the relevance of this approach: from 17 000 TJ/year of collected straw, 5 882 TJ/year were identified as usable straw, of which 5 542 TJ/year could be used for energy.

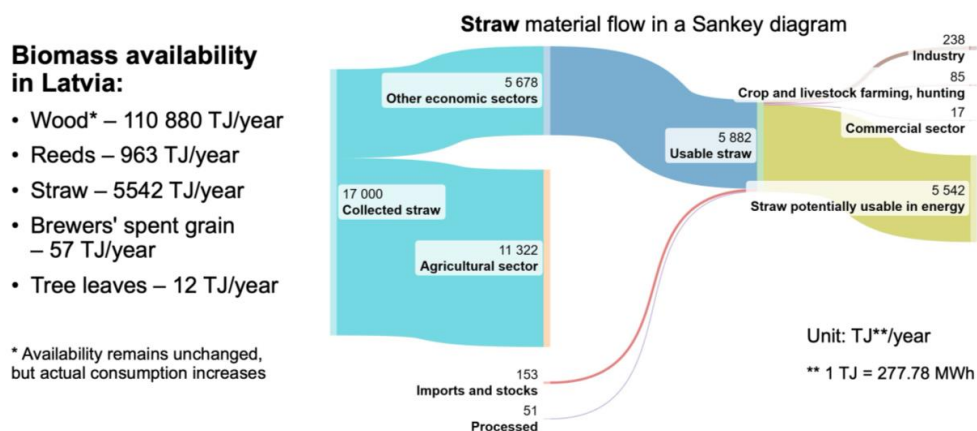


Fig. 2.1. Material flow analysis results and visualisation example.

After the availability assessment, additional selection criteria were considered: initial feedstock quality, particle size, practical preparation feasibility and, in the case of pellets, the mechanical durability of the obtained product. Initial quality was assessed qualitatively by considering visually identifiable contamination, material heterogeneity, unpleasant odour and signs of biological degradation. These criteria enabled early exclusion of feedstocks whose use at laboratory scale would not be technically justified or reproducible.

The selection of pellet samples was carried out in the residential or individual heating (IH) context, where fuel homogeneity, mechanical durability, stable feeding and suitability for a small-scale pellet boiler are important. The study included samples representing several biomass groups: wood fuel, agricultural residues, food industry by-products, as well as biomass that is of low value or problematic from a management perspective. Wood, reeds, straw, hemp, buckwheat husks, sunflower seed husks, brewers' spent grain, Canadian goldenrod, tree leaves and grass were selected for pellet production. Initial pelletization trials were carried out at laboratory scale. The practical selection criterion was the ability of pellets to retain shape and mechanical durability after pressing and cooling without pronounced fragmentation. Feedstocks producing friable and unstable pellets were excluded from further study. For some alternative biomass types, co-pelletization with 50 % wood sawdust by mass was used to improve pellet mechanical durability and ensure more stable combustion tests. The target value for pellet mechanical durability was set at least 90 %. Biomass preparation before pelletization included drying or moistening, particle-size reduction and material homogenisation. Wetter feedstocks required additional drying, while drier feedstocks required moisture stabilisation before pressing. Practical pelletization trials showed that, in addition to feedstock type, moisture, particle size, die selection and repeatability of pressing were important. For the purposes of the Doctoral Thesis, pellets were produced at laboratory scale in quantities sufficient for quality analysis and combustion tests under stable operating conditions.

The selection of wood chip samples and mixtures was carried out in the district heating (DH) context. The purpose of this part of the study was not to test pelletization suitability, but to assess a situation in which a boiler operator replaces or supplements part of traditional wood chips with other biomass flows. Therefore, wood chip flows of different origin and fraction size were compared, and wood chip mixtures were prepared. The actual origin of the wood chips is not disclosed due to commercial confidentiality considerations of the district heating plant operator; however, the samples were selected to represent fuel quality scenarios encountered in practice in district heating boiler houses.

The composition of the pellet samples and wood chip mixtures used in the study is summarised in Table 2.1. The table presents both the pellet samples used in the IH part and the wood chip samples and mixtures used in the DH part, thereby ensuring consistency of the designations used in further calculations and interpretation of results.

Table 2.1

Composition of the studied pellet samples and wood chip mixtures (% by mass)

Designation	Fuel composition
W	Sawdust from the wood industry (100 %)
R	Sawdust from the wood industry (50 %) and reed stem biomass (50 %)
S	Sawdust from the wood industry (50 %) and wheat straw stem biomass (50 %)
H	Sawdust from the wood industry (50 %) and hemp stem biomass (50 %)
BH	Sawdust from the wood industry (50 %) and buckwheat husk biomass (50 %)
SH	Sunflower seed husk biomass (100 %)
BSG	Brewers' spent grain biomass (100 %)
CG	Sawdust from the wood industry (50 %) and Canada goldenrod stem biomass (50 %)

Designation	Fuel composition
L	Sawdust from the wood industry (50 %) and fallen deciduous tree leaves (50 %)
G	Sawdust from the wood industry (50 %) and cut grass (50 %)
WC1	Wood chips from high-quality roundwood (100 %)
WC2	Wood chips from low-quality roundwood (100 %)
WC3	Wood chips from forest harvesting with branch admixture (100 %)
WR1	Wood chips from the wood industry (small fraction) (100 %)
WR2	Wood chips from the wood industry (large fraction) (100 %)
WM1	Wood chips from high-quality roundwood (80 %) and R pellets (20 %)
WM2	Wood chips from high-quality roundwood (60 %) and R pellets (40 %)
WM3	Wood chips from high-quality roundwood (50 %), bark admixture (10 %) and SH pellets (40 %)
WM4	Wood chips from high-quality roundwood (50 %), bark admixture (10 %) and sawdust from the wood industry (40 %)

2.1. Bibliometric analysis

Bibliometric analysis was used to identify the main scientific directions in biomass energy research and to substantiate the position of the Doctoral Thesis within this research field. It enables systematic analysis of a set of publications using bibliographic data, including year of publication, authors, institutions, citations, journals, keywords and abstracts. In the Doctoral Thesis, bibliometric analysis was used not as a self-contained literature description, but as an instrument for verifying the scientific relevance of the research direction. The analysis was performed sequentially. First, the research topic was defined, and search queries were developed using keywords characterising biomass, its conversion technologies, combustion, pellets, sustainability and life cycle assessment. The selection of keywords considered that different terms may be used in the literature for the same research topic; therefore, the queries were designed to cover the main directions while reducing the risk of including irrelevant records. Data were obtained from the Scopus database because it provides broad coverage of scientific publications and allows export of data required for bibliometric analysis. Searches were carried out in publication titles, abstracts and keywords. Publications from 2000 to 2025 were included, covering the fields of energy, engineering and environmental science. The data were exported in CSV format, including information on authors, year of publication, citation count, source, abstract and keywords. Publication counts, citations, authors, countries, institutions and journals were analysed using Scopus Analyser and Citation Overview tools, while further data processing and summary preparation were carried out in Microsoft Office Excel 365. Thematic links were identified using VOSviewer, in which co-authorship and keyword co-occurrence analyses were performed. Co-authorship analysis made it possible to characterise the collaboration structure among researchers and institutions, while keyword co-occurrence analysis enabled the identification of the main thematic clusters and their interrelations. Network and overlay visualisations were used in result interpretation. Network visualisation shows which topics and keywords form stronger interconnections, while overlay visualisation allows assessment of how research directions have changed over time. This approach provided a structured basis for the literature analysis and demonstrated that the

research direction selected in the Doctoral Thesis corresponds to current trends in biomass energy research.

2.2. Material flow analysis (MFA)

MFA was used in the Doctoral Thesis to assess the availability of alternative biomass and justify the inclusion of selected biomass flows in the subsequent experimental study. The analysis was based on the collection of available statistical data and literature sources on the formation and use of the respective biomass flows in the economy. In the Latvian context, the main data source was the database of the Official Statistics Portal (OSP) of the Central Statistical Bureau (CSB), where information was sought on biomass production, collection, consumption, processing, import, export and use pathways. Depending on the specific biomass type, data on agricultural crop areas and yields, wood and wood industry flows, food and beverage production by-products, and waste or residue management flows were used. The aim of MFA was to determine what share of the total biomass flow is already used for food, animal feed, industry, energy or other purposes, and what share remains unused or is used for lower-value purposes and could potentially be directed to fuel production. In the Doctoral Thesis, MFA was not used as a full mass-balance closure method because for several biomass types, the available data are not detailed enough to describe all flows and stocks precisely. Therefore, MFA was used as an instrument for assessing and justifying biomass availability. If sufficiently detailed data on a specific biomass flow were not available in the CSB OSP, justified assumptions were made based on literature sources, descriptions of similar biomass flows or data from neighbouring countries. This was necessary, for example, when statistics report total production or consumption volumes but do not separate usable residues, by-products or the share potentially usable in energy. Assumptions were used only at the stages where they were necessary to construct the flow structure, and the results were interpreted as potential estimates rather than as a full national mass balance. To enable comparison among different biomass types, flow quantities were converted into energy equivalents. This made it possible to assess not only material mass but also its potential contribution to heat production. This approach was applied to wood, reeds, straw, brewers' spent grain and leaves, for which the available data allowed determining the share of the flow potentially usable for energy. MFA results were visualised using Sankey diagrams prepared with the SankeyMATIC tool. This form of representation is suitable for biomass availability analysis because the width of flow arrows is proportional to the respective flow volume and shows where biomass is used, accumulates or remains potentially available for fuel production. Thus, MFA provided a basis for selecting and comparing alternative biomass resources before quality, combustion and sustainability assessment.

2.3. Biomass quality analysis

Fuel quality analysis was carried out to obtain comparable data on the suitability of the studied pellet and wood chip samples for heat production. The selected indicators characterise both the energy value of the fuel and its behaviour during storage, feeding, pelletization and combustion. Moisture content (*MC*) affects fuel heating value and combustion stability, ash

content (*AC*) characterises the amount of inorganic residue, volatile matter (*VM*) and fixed carbon (*FC*) describe the course of combustion, while elemental composition (*CHNSO*) links the chemical structure of the fuel with the risk of emission formation. In addition, the gross (Q_a^d) and net (Q_z^d) calorific values, ash melting temperature (*AMP*), bulk density (*BD*) and mechanical durability (*DU*) were determined, because these indicators characterise practical fuel usability, feeding stability and operational risks. The analyses were carried out in the Environmental Monitoring Laboratory for IH pellet samples and DH wood chip samples using the respective LVS EN ISO standards; the summary of methods and equipment is provided in Table 2.2.

Table 2.2

Parameters, methods and equipment used in the experimental fuel study

Activity/parameter	Methodological basis	Equipment
Sample preparation	LVS EN ISO 14780:2017	Vibrotechnik PM120 cutting mill
<i>MC</i>	LVS EN ISO 18134-2:2017	Precisa XB 120A scales
	LVS EN ISO 18134-3:2015	Ecocell 55 scales
<i>AC</i>	LVS EN ISO 18122:2016	Precisa XB 120A scales
		Nabertherm L3/11/P320 muffle furnace
		Desiccator
<i>VM</i>	LVS EN ISO 18123:2023	SNOL 7.2/1300 muffle furnace
		Precisa XB 120A scales
		SNOL 7.2/1300 muffle furnace
		Temperature control set (FLUKE 1528 CHUBE-4 datalogger, FLUKE PT-100 probe, K-type thermocouple)
<i>FC</i>	Calculated as	Desiccator
	$FC = 100 - VM - AC$	-
<i>CHNSO</i>	LVS EN ISO 16948:2015	Costech ESC 4010 elemental analyser RADWAG AS120.R2 PLUS scales
	LVS EN ISO 16994:2016	
	LVS EN ISO 16993:2016	
Q_a^d, Q_z^d	LVS EN ISO 18125:2017	IKA-Werke C 2000 calorimeter
		IKA-Werke C 21 pellet press
		IKA C 248 oxygen filling station
		IKA C 5010 calorimetric bomb
<i>AMP</i>	LVS EN ISO 21404:2020	Carbolite CAF DIGITAL ash fusion analyser
<i>BD</i>	LVS EN ISO 17828:2016	5 l metal container with handles
<i>DU</i>	LVS EN ISO 17831-1:2016	Motovario HA 42 motor
		Retsch AS 400 sieve shaker
		KERN 572-57 scales

2.4. Fuel combustion tests

Fuel combustion tests were performed at two scales: under IH conditions using a pellet boiler and under DH conditions using a wood chip boiler with moving grates. This division was selected to compare the use of alternative biomass in a small-scale heating boiler and in a

practically operated medium-scale boiler house within one methodological framework. The tests determined the effect of fuel on flue gas emissions, boiler efficiency and the properties of ash produced after combustion.

In both stands, flue gas temperature (FT), oxygen content in flue gas (O_2), carbon monoxide concentration (CO), nitrogen oxide concentration (NO_x), and particulate matter concentration (PM) were measured, and the excess air coefficient (α) was calculated. Gaseous emissions were determined using a Testo 350 flue gas analyser, while PM was measured using a Testo 380 analyser. CO and NO_x values were converted to normal conditions and referenced to 10 % O_2 to ensure comparability among tests. For PM , the conversion was performed by the Testo 380 instrument using operator-entered parameters. In IH tests, fuel consumption during the test period (B), draught in the chimney (P), water volumetric flow (WVF), mean return-water temperature ($\bar{T}_{in}$), and mean supply-water temperature ($\bar{T}_{out}$) were also determined. These parameters were used to calculate the energy input with the fuel (Q_{IN}), useful heat output (Q_{OUT}) and IH boiler efficiency (E_{ISA}). In DH tests, boiler efficiency (E_{CSA}) was determined from heat loss calculations. A summary of the measured and calculated parameters, methodological basis and equipment is provided in Table 2.3.

Table 2.3

Summary of parameters studied within IH and DH combustion tests

Designation	Parameter	Application	Methodological basis	Equipment/ data source
FT	Flue gas temperature	IH/DH	EN 14789:2017	Testo 350, K-type thermocouple
O_2	Oxygen content in flue gas	IH/DH	EN 14789:2017	Testo 350
CO	Carbon monoxide concentration	IH/DH	EN 15058:2017; conversion to normal conditions and 10 % O_2	Testo 350
NO_x	Nitrogen oxide concentration	IH/DH	ISO 10849:2022; conversion to normal conditions and 10 % O_2	Testo 350
PM	Particulate matter concentration	IH/DH	VDI 4206-2:2015; instrument conversion using operator-entered parameters	Testo 380
α	Excess air coefficient	IH/DH	Calculated from O_2	Calculated from Testo 350 data DINI ARGEO
B	Fuel consumption during the test period	IH	LVS EN 45501:2015	DFW06 weighing platform, stopwatch
P	Draught in the flue	IH	Test regime control	DPT FLOW 2000 pressure sensor
WVF	Water volume flow	IH	For efficiency calculation according to LVS EN 303-5:2021	Kamstrup MULTICAL 602
$\bar{T}_{in}$	Mean return-water temperature	IH	For efficiency calculation according to LVS EN 303-5:2021	Campbell Scientific TC 108, K-type thermocouples

Designation	Parameter	Application	Methodological basis	Equipment/ data source
$\bar{T}_{out}$	Mean supply-water temperature	IH	For efficiency calculation according to LVS EN 303-5:2021	Campbell Scientific TC 108, K-type thermocouples
Q_{IN}	Energy input with fuel	IH	Calculation from B and Q_z^d	Calculation
Q_{OUT}	Useful heat output	IH	Calculation from W_{FV} , $\bar{T}_{out}$ and $\bar{T}_{in}$	Calculation
E_{ISA}	IH boiler efficiency	IH	LVS EN 303-5:2021, direct balance method	Calculation
q_A	Heat losses with sensible heat of combustion products	DH	LVS EN 303-5:2021	Calculation
q_U	Losses due to incomplete oxidation	DH	LVS EN 303-5:2021	Calculation
q_S	Losses by radiation, convection and conduction	DH	LVS EN 303-5:2021	Calculation
q_B	Losses in unburned combustible matter remaining in ash	DH	LVS EN 303-5:2021	Calculation
E_{CSA}	DH boiler efficiency	DH	LVS EN 303-5:2021, indirect balance method	Calculation from heat losses

IH combustion tests were carried out in the RTU IESE Combustion Process Research Laboratory using a 25 kW GRANDEG GD BIO pellet boiler. All pellet samples were burned with the same boiler configuration, based on the manufacturer's settings for wood pellet combustion. This approach ensured comparable combustion conditions and allowed the behaviour of alternative pellets to be assessed without adjusting the combustion regime individually for each sample. Pellet feeding was performed using the boiler screw conveyor, while the boiler was placed on a DINI ARGEO DFW06 weighing platform to determine B . P was controlled in the flue using a DPT FLOW 2000 pressure sensor and maintained at approximately -10 Pa. Heat production was calculated using W_{FV} measured with a Kamstrup MULTICAL 602 heat meter and the temperature difference between $\bar{T}_{out}$ and $\bar{T}_{in}$ measured with K-type thermocouples connected to a Campbell Scientific TC 108 data logger. E_{ISA} was determined using the direct balance method according to LVS EN 303-5:2021 by comparing energy input with the fuel and useful heat output. After each test, ash was collected, labelled and stored for further analysis of chemical composition and crystalline phases. The schematic diagram of the IH stand is shown in Fig. 2.2.

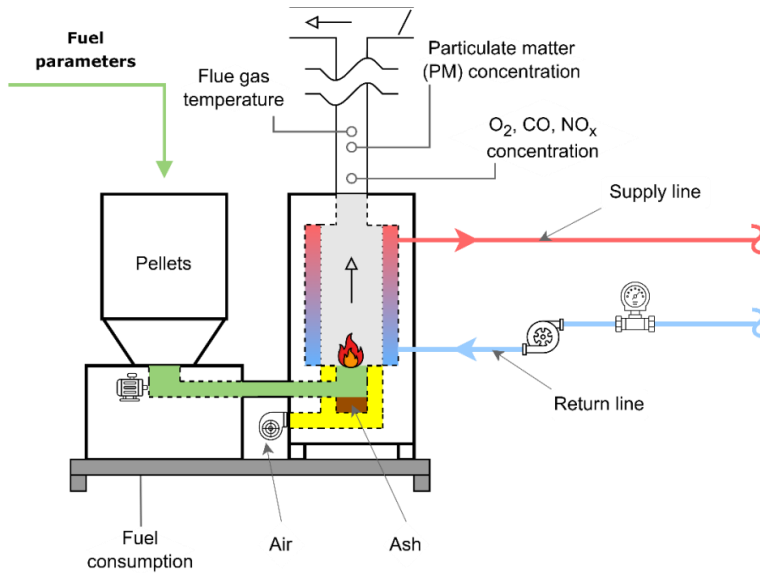


Fig. 2.2. Principal scheme of the combustion research stand used for pellet samples.

DH combustion tests were carried out in the Ādaži boiler house using a KAPAK2000N boiler with a nominal heat output of 2 MW. Previously prepared wood chip samples and wood chip mixtures were tested, and their quality had been analysed before combustion. All samples were burned at the boiler's default settings to assess fuel behaviour in a practically operated boiler rather than under a laboratory-optimised regime. During the experiment, the boiler's automatic feeding chain from the storage bunker was restricted, and the prepared samples were fed to the feeding hopper in a controlled manner. Mixtures were prepared in the required proportions before the test; if the prepared quantity was insufficient for the full test cycle, an additional amount was prepared during the test. The boiler operating regime was monitored using data available from the control system, including boiler output, furnace temperature, air supply and fuel feed information. E_{CSA} was calculated using the indirect, or reverse, balance method according to LVS EN 303-5:2021. Heat losses with sensible heat of combustion products (q_A), losses due to incomplete oxidation (q_U), losses by radiation, convection and conduction (q_S) and losses in unburned combustible matter remaining in ash (q_B) were included. The indirect method was selected because the direct balance method was not suitable for a practically operated 2 MW boiler with the available measurement set. The DH boiler corresponds to a medium-scale solid fuel combustion plant; therefore, emission values were further compared with the requirements of Cabinet Regulation No. 17. The chemical composition of the ash collected after DH tests was determined to assess ash flow properties and potential management options. The principal scheme of the DH part of the study is shown in Fig. 2.3.

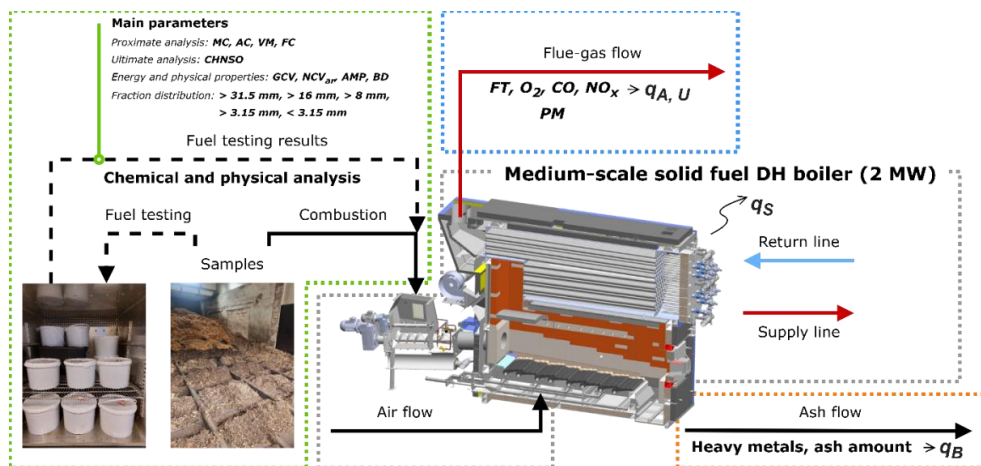


Fig. 2.3. Scheme of the DH experimental system.

2.5. Analysis of ash chemical composition and structure

An analysis of ash chemical composition and structure was performed to assess the properties of ash obtained after combustion, potential operational risks and further utilisation options. The ash oxide composition was used to construct ternary composition diagrams, or Vassilev diagrams. This approach allows ash to be classified according to the dominant oxide complex and enables an initial assessment of possible use in cement production, glass-ceramic materials or agronomic reuse, while also indicating a possible risk of slagging during combustion. Ash chemical composition was determined by inductively coupled plasma optical emission spectrometry (ICP-OES). ICP-OES analysis was performed for both IH pellet ash samples and DH wood chip mixture ash samples, because a comparable characterisation of oxide composition was needed for interpreting both parts of the study. The analysis was carried out using a Thermo Scientific iCAP 7400 ICP-OES instrument. Before measurement, ash samples were digested in closed vessels using a MARS 6 microwave digestion system with EasyPrep Teflon vessels. To ensure more complete digestion of silicate-containing ash, a mixture of nitric acid and hydrofluoric acid with hydrogen peroxide was used; after digestion, the solutions were treated with boric acid to bind residual fluorides. Measurement quality control included reagent blanks, calibration check solutions and parallel digestion samples.

To determine crystalline phases in pellet ash, X-ray diffraction (XRD) analysis was additionally carried out using a Bruker D8 Advance diffractometer in Bragg-Brentano reflection geometry. XRD analysis was applied only to IH pellet ash samples because, in the pellet part of the study, ash properties were assessed in more detail in relation to the different composition of alternative biomass, combustion in a small-scale boiler and potential further use of ash. In the DH ash part, the main task was to determine oxide composition and compare the chemical profile of wood chip mixture ash; therefore, XRD analysis was not applied in this part of the study. Before XRD analysis, ash was finely ground and placed in the sample holder as a homogeneous layer. Measurements were performed in the range of 10–80° 2 θ . Crystalline

phases were identified using the Open Crystallography Database, while semi-quantitative phase analysis was performed by Rietveld refinement in Profex v5.5.2 using the BGMN algorithm.

2.6. Regression analysis

Regression analysis was used in the Doctoral Thesis to determine relationships between independent variables describing fuel quality and dependent variables obtained from combustion tests. This approach enabled the identification of parameters that most strongly explain changes in emissions and boiler efficiency and the development of empirical prediction models for comparing the studied fuel samples. Simple and multiple linear regression were used. Simple linear regression was applied when changes in the dependent variable were sufficiently described by one dominant factor, whereas multiple regression was used when the result was influenced by several fuel quality parameters simultaneously. Model quality was evaluated using the coefficient of determination, which indicates the share of the variance in the dependent variable explained by the independent variables included in the regression model. Regression analysis was performed using Microsoft Office Excel 365 and Statgraphics Centurion 19. Microsoft Office Excel 365 was used for initial data processing and results compilation, whereas Statgraphics Centurion 19 was used for correlation assessment, development of multiple regression models and selection of the most significant variables. Stepwise variable selection was used in multiple regression, retaining in the model the fuel quality parameters with the most important effect on the dependent variable. The analysis assumed that a linear relationship exists between dependent and independent variables, that observations are mutually independent and that there is no pronounced correlation among the independent variables.

2.7. Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) was used in the Doctoral Thesis for the technical-social assessment of pellets studied within the IH framework. The approach was not applied to DH wood chip mixtures because the MCDA matrix was developed specifically for comparing pellets in the context of a small-scale heating boiler, where not only fuel quality and combustion results are important but also the user's willingness to accept an alternative fuel and adapt the combustion process. The choice of alternative biomass pellets is not an unambiguous technical task: a pellet with a higher heating value is not necessarily the most suitable if it also has higher emissions, lower mechanical durability, more complex feedstock acquisition or a greater adaptation burden for the user. MCDA was therefore selected as a method that allows criteria with different units, directions of influence, and practical significance to be combined in one decision matrix.

Criteria were selected based on two principles: the criterion had to be related to practical use of pellets in an IH boiler and had to be determinable from the data obtained in the Doctoral Thesis or from respondent assessment. The experimentally obtained data (technical criteria) form the quantitative criterion set, which includes fuel quality and combustion indicators. The qualitative criterion set (social criteria) consists of socio-economic and socio-technical criteria. The values of qualitative criteria and the criteria weights were obtained from a Google Forms

survey involving 11 respondents aged 20–60. Qualitative criteria (except “Energy density”) were evaluated on a three-level scale, where “1” means the most favourable assessment, “2” an intermediate assessment and “3” the least favourable assessment in the context of the respective criterion. The criteria are summarised in Table 2.4.

Table 2.4

Criteria included in the MCDA matrix

Criterion group	Criterion subgroup	Criterion	Designation	Positive (+) / negative (–)
Technical	Biomass quality	Q_z^d	C1	+
		AC	C2	–
		DU	C3	+
		AMP	C4	+
	Combustion parameters	CO	C5	–
		NO_x	C6	–
		PM	C7	–
		E_{ISA}	C8	+
Social	Socio-economic	Energy density (energy per unit volume or mass)	C9	+
		Specific feedstock costs (cost per unit of feedstock)	C10	–
		Production costs (pellet production and technology adaptation costs)	C11	–
	Socio-technical	Resource availability (stable and accessible feedstock supply)	C12	–
		Complexity of resource acquisition (difficulty of obtaining and processing feedstock)	C13	–
		Public acceptance (user willingness to use the pellets)	C14	–
		Willingness to adapt the combustion process (readiness to adjust boiler operation or design)	C15	–

The analytic hierarchy process (AHP) approach was used to determine criteria weights because it enables respondent assessment to be converted into quantitative weights. The weighted sum model (WSM) in combination with AHP was used as the main approach because it provides a transparent compromise assessment and allows direct tracing of how criteria weights affect the overall result of the alternatives. Multi-objective optimisation by ratio analysis (MULTIMOORA) in combination with AHP was used as a verification approach because it compares alternatives using the ratio system, the reference point approach and the full multiplicative form. This makes it possible to check whether a high rank is stable or whether it is formed only because weak indicators in one criterion group are compensated by better indicators in another.

2.8. Life cycle assessment

Life cycle assessment (LCA) was used in the Doctoral Thesis to determine the environmental impact of the pellet samples studied within the IH framework throughout their preparation, production and use chain. The LCA approach was tested specifically on pellet samples because, for this part of the study, a full and mutually comparable fuel production chain was developed, from feedstock collection and transport to mechanical preparation, pelletization, combustion and inclusion of the ash flow in the model. DH wood chip mixtures were assessed in the Doctoral Thesis as a practical combustion case in a district heating boiler, where the main task was to determine the effect of mixtures on boiler operation, emissions and compliance with regulatory limit values. Therefore, the LCA methodology in this research was applied to IH pellet samples, for which it was possible to define the functional unit, system boundaries and all production and use stages consistently.

The assessment was performed in accordance with the ISO 14040 and ISO 14044 LCA framework, which provides for defining the goal and scope, creating the inventory, carrying out impact assessment and interpreting the results. The functional unit was defined as 1 MWh of heat obtained from pellet combustion. This functional unit was selected because, in an energy context, comparison of pellets is more justified based on produced heat rather than mass, since the studied samples differ in net calorific value, moisture content and boiler efficiency. The system boundaries were defined as cradle-to-grave, including feedstock collection, transport to the production facility, mechanical preparation, drying, milling, pelletization, transport of pellets to the consumer and combustion in the IH boiler. The processes were structured using “A”, “B” and “C” designations: “A” processes describe the wood flow, “B” processes describe the alternative biomass flow, and “C” processes describe the production and use of wood and alternative biomass mixture pellets. The process designations and their meanings are summarised in Table 2.5. Figure 2.4 shows how wood, alternative biomass and mixture pellet processes are connected within one cradle-to-grave system boundary.

Table 2.5

Division of pellet life cycle into stages and processes

Life cycle stage	Wood flow (A)	Alternative biomass flow (B)	Wood and alternative biomass mixture flow (C)
Collection stage	Roundwood collection (includes growing phase) (A1)	Biomass collection (B1) Hemp primary shredding (B1a)	
	Wood transportation to production facility (A2)	Biomass transportation to production facility (B2)	
Production stage		Biomass drying (B3)	
	Wood chipping (A3)	Leaves and grass sieving (B3a)	
	Wood drying (A4)	Biomass shredding (B4)	
	Wood milling (A5)	Biomass milling (B5)	
	Wood pellet production (A6)	Biomass pellet production (B6)	Wood and biomass pellet production (C1)

Life cycle stage	Wood flow (A)	Alternative biomass flow (B)	Wood and alternative biomass mixture flow (C)
Combustion stage	Wood pellet transportation to distributor and customer (A7)	Biomass pellet transportation to distributor and customer (B7)	Wood and biomass pellet transportation to distributor and customer (C2)
	Wood pellet combustion (A8)	Biomass pellet combustion (B8)	Wood and biomass pellet combustion (C3)

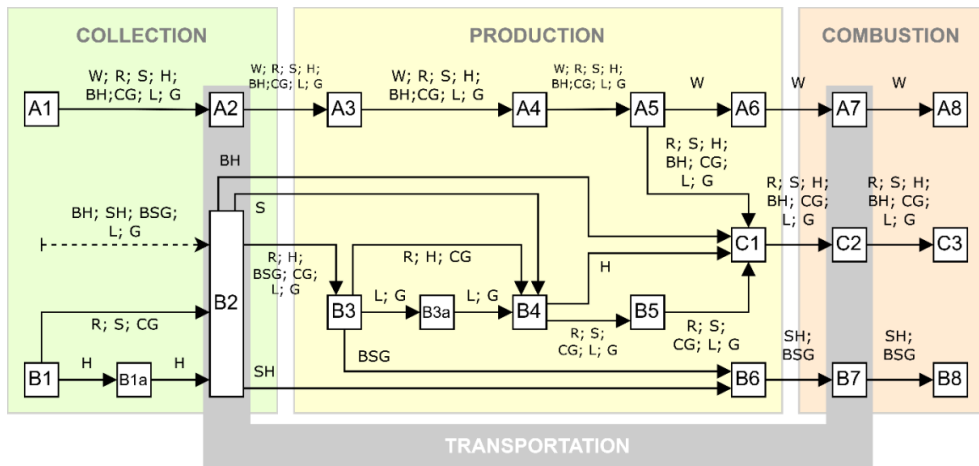


Fig. 2.1. Flow scheme of the production-chain processes and system boundaries of the studied biomass pellet types (see designations in Tables 2.1 and 2.5).

The LCA inventory is based on laboratory and experimental data obtained within the Doctoral Thesis. The calculations used data on feedstock mass, moisture content, electricity and heat consumption in preparation and pelletization processes, transport distances, pellet quality, boiler efficiency, flue gas emissions and ash quantity. Thus, the LCA model is not based only on literature assumptions but is linked as far as possible to the specific pellet samples prepared and tested in the Doctoral Thesis. Where direct data for background processes were not available, corresponding processes available in the Ecoinvent 3 databases were used, maintaining a consistent modelling approach for all samples.

LCA calculations were performed in SimaPro 10.2 using the ReCiPe 2016 Endpoint (H) V1.09/World (2010) H/A method. Results are expressed in points (Pt), where a higher value indicates a greater overall environmental impact. The ReCiPe endpoint approach combines impacts on human health, ecosystem quality and resource availability into one comparable indicator suitable for comparing alternatives at the decision-making level. In interpreting the results, LCA stages were grouped into three parts: collection, production and combustion. This division makes it possible to determine whether the total impact of a sample is driven more by feedstock acquisition and transport, energy-intensive preparation and pelletization processes, or emissions during combustion. Therefore, LCA was used in the Doctoral Thesis not only to

calculate total environmental impact but also to identify the stages in which the greatest improvement potential arises in the production and use chain of alternative biomass pellets.

2.9. Sustainability assessment

The sustainability assessment in the Doctoral Thesis is directly based on LCA inventory data, using the same system boundaries and the same pellet life cycle stages: collection, production, transportation and combustion. Unlike life cycle impact assessment, where the result is expressed in points and characterises the overall environmental impact, the sustainability assessment focuses on one indicator that is important in the regulatory framework: specific GHG emission savings compared with the fossil fuel comparator. This approach allows the results for the studied alternative biomass pellets to be interpreted in accordance with current EU legal requirements for GHG emission reductions from solid biofuels in heat production. The approach used in the Doctoral Thesis complements the RED II methodological logic; the author developed a calculation sequence in which each variable required to determine GHG emission reduction is, as far as possible, obtained from the research data. The calculation therefore characterises not a typical or legally assumed supply chain but a specific use scenario for laboratory-prepared and experimentally tested pellet samples. The summary of the equations used in the calculation is provided in Table 2.6, while Table 2.7 presents explanations of the symbols used in the equations. This structure enables specific GHG emissions to be assessed at two levels. The first level characterises emission formation in pellet life cycle stages before energy transformation while maintaining the link with LCA inventory processes. At the second level, emissions are related to the obtained useful heat using the experimentally determined IH boiler efficiency. GHG emission savings are determined by comparing the specific GHG emissions obtained after energy transformation with the fossil fuel comparator; for pellet boilers installed and operating from 2021, at least 70 % GHG savings must be achieved, while from 2026 at least 80 % savings are required. RED II default values for different pellet types are used for comparison in the Doctoral Thesis.

Table 2.6

Equations for calculating specific GHG emissions and emission savings

Calculation part	Equation	Meaning
Collection	$e_{ec} = \frac{S_b \cdot B_{dd} \cdot Q_{dd} \cdot E_{dd}}{m_p \cdot Q_z^d}$	Specific GHG emissions from field work or feedstock collection, related to pellet energy content
Production	$e_p = \frac{(\sum_{i=1}^n Q_{el,i} \cdot 3,6) \cdot (E_{el} \cdot 277,78)}{m_p \cdot Q_z^d} + \frac{(\sum_{i=1}^n Q_{h,i} \cdot 3,6) \cdot (E_h \cdot 277,78)}{m_p \cdot Q_z^d}$	Specific GHG emissions from electricity and heat consumption in biomass preparation and pellet production processes
Transport	$e_{td} = \frac{\sum_{i=1}^n W_{x,i} \cdot E_w}{m_p \cdot Q_z^d}$	GHG emissions from freight turnover in feedstock or pellet transport stages

Calculation part	Equation	Meaning
Combustion	$e_u = \frac{m_{em\ NO_x} \cdot 0,025 \cdot E_{N_2O}}{m_p \cdot Q_z^d}$	N ₂ O share included in the combustion stage, calculated from the NO _x mass in flue gas
Total emissions before energy transformation	$E_x = e_{ec} + e_p + e_{td} + e_u$	Sum of specific GHG emissions from pellet life cycle stages before relating them to boiler efficiency
Total emissions after energy transformation	$EC_x = \frac{E_x}{E_{ISA_x}/100}$	Specific GHG emissions after relating to experimentally determined IH boiler efficiency
GHG emission savings	$S = \frac{EC_f - EC_x}{EC_f} \cdot 100$	Emission savings against the fossil fuel comparator; $EC_f = 80\text{ gCO}_{2ekv}/\text{MJ}$

Table 2.7

Symbols and units used in the sustainability assessment equations

Symbol	Explanation	Unit
e_{ec}	specific GHG emissions from feedstock collection or acquisition	gCO _{2ekv} /MJ
S_b	field area to be treated for biomass collection	ha
B_{dd}	specific diesel consumption for field treatment	l/ha
Q_{dd}	diesel fuel heating value	MJ/l
E_{dd}	diesel fuel emission factor	gCO _{2ekv} /MJ
m_p	pellet mass required to reach the functional unit	kg
Q_z^d	net calorific value of pellets	MJ/kg
e_p	specific GHG emissions from processing and production processes	gCO _{2ekv} /MJ
$Q_{el,i}$	electricity consumption of unit i	kWh
E_{el}	electricity emission factor	tCO ₂ /MWh
$Q_{h,i}$	heat consumption of unit i	kWh
E_h	heat emission factor	tCO ₂ /MWh
e_{td}	specific GHG emissions from transport	gCO _{2ekv} /MJ
$W_{x,i}$	freight turnover in the transport stage	t·km
E_w	truck emission factor	gCO ₂ /(t·km)
e_u	specific GHG emissions from fuel use	gCO _{2ekv} /MJ
$m_{em\ NO_x}$	NO _x mass in flue gas when combusting m_p	g
E_{N_2O}	N ₂ O emission factor	gCO _{2ekv} /g
E_{ISA_x}	IH boiler efficiency for pellets x	%
E_x	total specific GHG emissions before energy transformation	gCO _{2ekv} /MJ
EC_x	total specific GHG emissions after energy transformation	gCO _{2ekv} /MJ
EC_f	fossil fuel comparator for heat production	gCO _{2ekv} /MJ
S	GHG emission savings	%

3. RESULTS SUMMARY

3.1. Experimental research results

3.1.1. Fuel quality analysis results

The basic quality indicators of the pellets and wood chip mixtures are summarised in Table 3.1. For pellet samples, *MC* was 5.09–12.88 %, while for wood chip mixtures it was substantially higher, 17.93–52.05 %. This difference reflects the preparation and use context of the two fuel groups: pellets are pressed and pre-conditioned fuels, whereas wood chip mixtures represent the moisture variability typical of DH systems. *AC* for pellet samples was 0.72–6.51 % and for wood chip samples and mixtures – 1.02–6.20 %. The lowest *AC* values were determined for wood-based samples (W pellets and WC1 wood chips), while the highest values were obtained for L pellets and the WM3 mixture. In pellets, increased *AC* is related to the share of non-wood biomass, whereas in wood chip mixtures *AC* is affected by wood chip quality and the share of admixtures. *VM* was similar in both fuel groups: 71.8–84.4 % for pellets and 73.7–83.1 % for wood chip mixtures. *FC* was 13.6–25.7 % for pellets and 15.9–20.1 % for wood chip mixtures. The wider *FC* range in the pellet group reflects the greater diversity of feedstocks, while the wood chip group remains closer because it is based mainly on different wood flows and their mixtures.

Table 3.1

Moisture, ash, volatile matter and fixed carbon content of pellets and wood chip mixtures

Sample	<i>MC</i> , wt%	<i>AC</i> , wt%	<i>VM</i> , wt%	<i>FC</i> , wt%
W	5.09	0.72	84.4	14.9
R	7.05	3.73	82.7	13.6
S	9.39	4.22	74.4	21.4
H	10.55	6.00	73.6	20.4
BH	11.52	1.39	72.9	25.7
SH	9.10	3.40	76.6	20.0
BSG	9.70	3.96	80.3	15.7
CG	12.88	3.76	74.5	21.7
L	9.18	6.51	71.8	21.7
G	12.02	6.32	71.9	21.8
WC1	47.91	1.02	83.1	15.9
WC2	52.05	1.49	82.3	16.2
WC3	17.93	2.22	81.1	16.7
WR1	41.15	3.71	78.8	17.5
WR2	35.24	4.51	77.6	17.9
WM1	37.70	2.77	80.8	16.4
WM2	33.94	3.44	80.2	16.4
WM3	50.92	6.20	73.7	20.1
WM4	51.27	3.33	78.9	17.8

The elemental composition and calorific values of pellets and wood chip mixtures are summarised in Table 3.2. *C* content was 46.02–51.10 % for pellet samples and 50.06–53.25 % for wood chip mixtures. In the wood chip group, *C*, *H* and *O* values are closer to one another, which corresponds to the dominant share of wood flows in these samples. In the pellet group, differences in elemental composition are more pronounced because the samples were produced from biomass of different origin. BSG pellets stand out with the highest *C* content (51.10 %) and the lowest *O* content (32.97 %). *N* content varied more widely in the pellet samples than in the wood chip samples. The lowest *N* value was determined for W pellets (0.28 %), while the highest was obtained for BSG pellets (4.66 %). Higher *N* content in fuel can contribute to increased NO_x formation during combustion. In the wood chip samples and mixtures, *N* content was 1.00–2.05 %, with the highest value for WR2. *S* content was low in most samples, except for BSG pellets, where it reached 0.44 %. Q_z^d on a wet basis was 16.3–18.7 MJ/kg for pellets and 7.6–14.8 MJ/kg for wood chip mixtures. This difference is mainly related to the substantially higher *MC* in the wood chip group. On a dry basis, Q_z^d was similar in both fuel groups: 18.3–19.9 MJ/kg for pellets and 18.0–19.3 MJ/kg for wood chip mixtures.

Table 3.2

Elemental composition and calorific values of pellets and wood chip mixtures

Sample	<i>CHNSO</i>					Q_z^d , MJ/kg		Q_a^d , MJ/kg
	<i>C</i> , %	<i>H</i> , %	<i>N</i> , %	<i>S</i> , %	<i>O</i> , %	Wet bases	Dry basis	
W	47.77	6.17	0.28	0.00	45.08	18.7	19.9	21.2
R	46.02	5.68	1.06	0.08	43.44	17.3	18.8	20.4
S	46.02	5.65	0.35	0.06	43.69	16.3	18.3	19.7
H	46.31	6.10	0.36	0.05	41.18	16.4	18.6	19.9
BH	47.40	5.69	0.64	0.07	44.82	16.8	19.3	20.5
SH	50.50	5.90	1.10	0.05	39.05	17.0	18.9	20.3
BSG	51.10	6.87	4.66	0.44	32.97	17.6	19.8	21.3
CG	48.08	6.20	1.15	0.11	40.71	16.4	19.2	20.6
L	47.41	5.87	0.86	0.08	39.28	17.0	18.9	20.2
G	46.04	6.06	1.86	0.11	39.62	16.3	18.9	20.3
WC1	53.22	5.31	1.03	0.01	40.43	8.8	19.1	20.5
WC2	52.21	5.32	1.21	0.01	41.25	7.6	18.6	19.9
WC3	52.08	5.32	1.52	0.01	41.07	14.8	18.6	19.9
WR1	52.47	5.51	1.60	0.01	40.41	9.6	18.1	19.4
WR2	53.25	5.25	2.05	0.01	39.44	10.9	18.2	19.5
WM1	50.59	5.20	1.66	0.01	42.54	10.4	18.2	19.5
WM2	52.01	5.16	1.54	0.01	41.28	11.2	18.1	19.5
WM3	50.06	4.72	1.47	0.01	43.74	7.6	18.0	19.3
WM4	52.02	5.05	1.00	0.01	41.92	8.1	19.3	20.6

The physical and mechanical indicators of pellets and wood chip mixtures are summarised in Table 3.3. For pellet samples, *AMP* was 1020–1480 °C, while for wood chip mixtures it was 1133–1353 °C. The lowest *AMP* was determined for S pellets and the highest for BSG pellets. In the wood chip group, the lowest *AMP* was obtained for WM3 and the highest

for WC3. Lower *AMP* values indicate a higher risk of ash slag formation during combustion; therefore, this indicator is important when assessing fuel suitability for long-term boiler operation. *BD* was 390–640 kg/m³ for pellet samples and 109–240 kg/m³ for wood chip mixtures. This difference is expected because pellets are pressed fuel, while wood chips are a loose material with an uneven fraction. In the pellet group, the highest *BD* was determined for W pellets and the lowest for CG pellets. In the wood chip group, the highest *BD* was determined for WC2 and the lowest for WM2. *DU* was determined only for pellet samples. *DU* values were 91.7–97.8 %, and all samples exceeded the internal 90 % threshold defined in the Doctoral Thesis. The highest *DU* values were obtained for SH, BH and W pellets, while the lowest were obtained for CG, BSG and H pellets. This shows that mechanically durable alternative biomass pellets could be produced at laboratory scale, although some samples did not reach the durability level required for higher-quality market pellets; according to the B-class requirements of LVS EN ISO 17225-6:2021, mechanical durability must be at least 96 %.

Table 3.3

Bulk density, mechanical durability and ash melting temperature of pellets and wood chip mixtures

Sample	<i>AMP</i> , °C	<i>BD</i> , kg/m ³	<i>DU</i> , %
W	1295	640	96.9
R	1096	580	94.9
S	1020	520	92.9
H	1422	453	92.4
BH	1079	540	97.3
SH	1125	498	97.8
BSG	1480	570	92.1
CG	1102	390	91.7
L	1208	500	95.8
G	1128	520	96.0
WC1	1251	226	-
WC2	1265	240	-
WC3	1353	184	-
WR1	1198	174	-
WR2	1192	215	-
WM1	1179	133	-
WM2	1187	109	-
WM3	1133	216	-
WM4	1225	189	-

3.1.2. Combustion test results

The combustion test results for IH pellets and DH wood chip mixtures are summarised in Table 3.4. E_{ISA} was 66.3–80.4 %, with the highest values obtained for W and BSG pellets and the lowest for SH pellets. W pellets also showed the lowest *CO*, *NO_x* and *PM*. *CO* in IH tests varied widely, from 52 mg/Nm³ for W pellets to 29 237 mg/Nm³ for SH pellets. High *CO* values were also obtained for S, G, L, CG and BSG pellets. α in IH tests was 1.6–2.1; however, high

CO were also observed at α values of approximately 2.0–2.1, for example for S and G pellets. This indicates that incomplete oxidation of alternative pellets was not determined only by excess air; fuel properties, feeding and combustion conditions were also important. NO_x in IH tests was 140–948 mg/Nm³. The lowest value was determined for W pellets and the highest for BSG pellets. In the BSG case, the highest NO_x level corresponds to the increased *N* content in the fuel; therefore, emission formation for this sample is related not only to the combustion regime but also to elemental composition. *PM* in IH tests was 21–211 mg/Nm³, with the lowest value for W pellets and the highest for G pellets.

E_{CSA} was 73.5–88.2 %, with the highest efficiency obtained for WC3 and the lowest for WM3. α in DH tests was 1.8–2.3. The highest α values were obtained for WC1 and WC2, while the lowest values were obtained for WM2 and WM3. *CO* in DH tests was 288–8017 mg/Nm³. NO_x in DH tests was 139–416 mg/Nm³. The lowest values were determined for WC2 and WM4, and the highest for WR2 and WR1. In WR2, the highest NO_x level corresponds to the highest *N* content in the wood chip group. *PM* in DH tests was 52–180 mg/Nm³. The lowest *PM* value was determined for WC3 and the highest for WM3. WM3 and WM4 are characterised by high *CO* and *PM* values, indicating a less uniform combustion process for these mixtures. *CO* and *PM* results do not show a simple relationship with α : WR1 and WR2 at α values of 2.1 and 1.9 had the lowest *CO* values (288 mg/Nm³ and 301 mg/Nm³, respectively), whereas WM3 and WM4 reached *CO* concentrations of 8017 mg/Nm³ and 4541 mg/Nm³ at α values of 1.8 and 2.0, respectively. This means that, under DH conditions, excess air is not the only determining factor; wood chip moisture, ash content and mixture homogeneity also affect feeding and combustion on the grate.

Table 3.4

Combustion test results for pellets and wood chip mixtures

Sample	<i>FT</i> , °C	E_{ISA} or E_{CSA} , %	O_2 , %	α , -	<i>CO</i> , mg/Nm ³	NO_x , mg/Nm ³	<i>PM</i> , mg/Nm ³
W	125	80.4	10.4	2.0	52	140	21
R	121	72.7	9.0	1.8	3421	677	143
S	109	68.0	10.8	2.1	20416	192	176
H	108	77.3	11.0	2.1	646	189	161
BH	97	78.4	10.6	2.0	4464	321	58
SH	81	66.3	9.7	1.9	29237	353	104
BSG	110	80.4	8.21	1.6	7288	948	177
CG	104	74.1	11.2	2.1	7648	525	139
L	100	70.5	10.5	2.0	9827	369	139
G	94	72.4	10.6	2.0	14750	780	211
WC1	128	80.9	10.4	2.3	1526	156	59
WC2	123	79.7	9.6	2.3	2405	139	81
WC3	149	88.2	9.0	2.2	2453	224	52
WR1	123	84.1	10.5	2.1	288	340	102
WR2	132	85.4	9.9	1.9	301	416	153
WM1	136	83.2	11.1	2.0	542	329	109
WM2	144	82.0	11.6	1.8	752	321	112
WM3	120	73.5	11.8	1.8	8017	273	180
WM4	122	75.7	11.8	2.0	4541	142	172

The IH test results were compared with the ecodesign requirements of Regulation (EU) 2015/1189 for an automatically operated solid biofuel boiler of this capacity. According to these requirements, for a boiler with nominal heat output > 20 kW, E_{ISA} must be $> 77\%$, while the emission limits are $CO < 500$ mg/Nm³, $NO_x < 200$ mg/Nm³ and $PM < 40$ mg/Nm³. Because all samples were tested in the same 25 kW pellet boiler under unchanged combustion conditions, the comparison shows the performance of one boiler using different pellet samples rather than the compliance of different units. Full compliance with both efficiency and emission requirements was achieved only by W pellets. The E_{ISA} requirement was also met by H, BH and BSG pellets, but their use was limited by emission indicators. In addition to W pellets, the NO_x limit was met by S and H pellets, whereas the CO and PM limits were exceeded by all alternative biomass pellet samples.

The DH test results were compared with the requirements of Cabinet Regulation No. 17, considering that the experiment was carried out in a 2 MW solid fuel boiler corresponding to a medium-scale combustion plant. Until 31 December 2029, existing 1–10 MW solid fuel plants are subject to the limits $CO < 2000$ mg/Nm³, $NO_x < 600$ mg/Nm³ and $PM < 1000$ mg/Nm³. In this comparison, all tested samples met the NO_x and PM limits, while the CO limit was exceeded by WC2, WC3, WM3, and WM4. Thus, under the current requirements, CO is the main non-compliance indicator in DH tests and reflects the share of incomplete oxidation under the specific boiler operating regime. From 1 January 2030, stricter limits become relevant for 1–5 MW solid fuel plants: $CO < 1000$ mg/Nm³, $NO_x < 650$ mg/Nm³ and $PM < 50$ mg/Nm³. At this level, all samples meet the NO_x limit; WR1, WR2, WM1 and WM2 meet the CO limit, but none of the tested samples meets the PM limit; WC3, with 52 mg/Nm³, is closest to the limit.

3.1.3. Ash analysis results

Ash chemical analysis is necessary because further use of ash cannot be justified only by its quantity or origin. To assess ash as a potentially usable material rather than only as a waste stream, its chemical composition and possible use-related restrictions must be known. This approach is also important in the regulatory context, because Cabinet Regulation No. 302 defines criteria for by-product status and end-of-waste status. In this research, the Vassilev diagram was used as an initial ash classification tool. It allows the chemical profile of a specific ash sample to be used to determine whether the material is more suitable for further assessment as a building material (S domain), liming material (C domain) or in the agronomic direction (K domain). This approach does not mean that a specific use is automatically confirmed, but it narrows the direction for further testing.

According to Fig. 3.1, W, L, WC1, WC2, WM4, and WR1 ash should be assessed for liming; H, BH, SH, CG, BSG, and G ash for fertilisation; and S, R, WR2, WM1, WM2, and WM3 ash for use as a cement additive. This classification shows that ash from alternative biomass and wood chip mixtures should not be evaluated in the same way as ordinary wood ash. Each sample requires a separate quality assessment, especially considering pollutant content, leaching risk and the intended use.

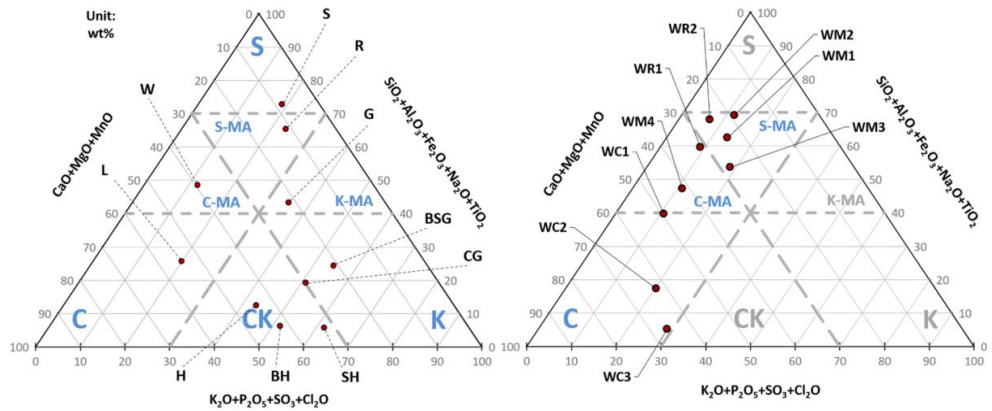


Fig. 3.1. Ash classification of pellets (left) and wood chip mixtures (right) according to the Vassilev diagram.

3.1.4. Regression analysis results

As an example of the results, multiple regression analysis was included for the IH pellet sample data. Its purpose was to test whether emission indicators and boiler efficiency could be described using fuel quality and combustion parameters. This approach identifies which parameters are most closely related to changes in the dependent variables within the specific data set and provides a basis for the preliminary assessment of similar samples before a full combustion test. For further interpretation, only empirical models with a coefficient of determination (R^2) above 0.7 were selected. Only the most relevant variables were retained in the models to obtain equations that are as simple as possible while retaining sufficient explanatory power. The obtained models are summarised in Table 3.5. The highest R^2 values were obtained for PM and E_{ISA} models ($R^2 = 0.89$), as well as for the NO_x model ($R^2 = 0.87$), while the CO model showed lower agreement ($R^2 = 0.73$).

Table 3.5

Empirical models of combustion-related variables

Dependent variable	Empirical model	R^2
CO	$-15802.7 + 6450.17 \cdot \alpha + 4458.88 \cdot C - 17485.48 \cdot Q_z^d + 1410.59 \cdot DU$	0.73
NO_x	$5465.43 - 662.68 \cdot \alpha + 195.27 \cdot N - 71.64 \cdot C - 1.05 \cdot BD$	0.87
PM	$1393.91 - 112.38 \cdot \alpha + 22.72 \cdot AC - 0.11 \cdot AMP - 10.58 \cdot DU$	0.89
E_{ISA}	$-197.4 + 2.24 \cdot MC + 0.024 \cdot AMP + 1.81 \cdot DU + 0.473 \cdot FT$	0.89

The models were checked by comparing calculated and experimentally obtained values (see Fig. 3.2). The equations describe relationships only within the IH pellet sample set studied in this Thesis and within the corresponding measurement range. Therefore, they are not applicable as universal models for all biomass pellet types; broader application would require additional experimental data.

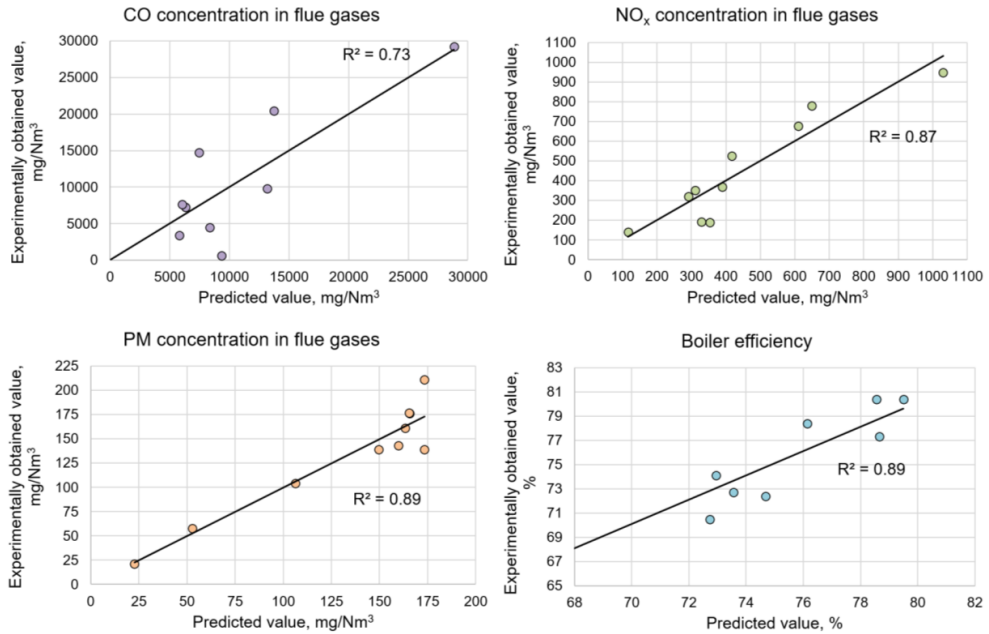


Fig. 3.2. Validation of empirical models.

3.2. Multi-criteria decision analysis results

MCDA was performed for IH pellet samples using quantitative criteria from the experimental study (C1–C8) and qualitative criteria from the expert and user survey (C9–C15). The decision matrix includes 15 criteria (Table 3.6). The values of criteria C10–C15 were obtained by calculating the arithmetic mean of all respondent answers, while the weights were obtained by relating the arithmetic mean values to the total number of criteria and normalising the total to 1.

Table 3.6

MCDA decision matrix for the technical-social assessment of pellets

Criterion	Unit	Weights	Alternative (pellet type)									
			W	R	S	H	BH	SH	BSG	CG	L	G
C1	MJ/kg	0.08	18.7	17.3	16.3	16.4	16.8	17.0	17.6	16.4	17.0	16.3
C2	%	0.07	0.72	3.73	4.22	6.00	1.39	3.40	3.96	3.76	6.51	6.32
C3	%	0.06	96.9	94.9	92.9	92.4	97.3	97.8	92.1	91.7	95.8	96.0
C4	$^{\circ}\text{C}$	0.07	1295	1096	1020	1422	1079	1125	1480	1102	1208	1128
C5	mg/Nm^3	0.07	52	3421	20416	646	4464	29237	7288	7648	9827	14750
C6	mg/Nm^3	0.05	140	677	192	189	321	353	948	525	369	780
C7	mg/Nm^3	0.06	21	143	176	161	58	104	177	139	139	211
C8	%	0.08	80.4	72.7	68.0	77.3	78.4	66.3	80.4	74.1	70.5	72.4
C9	-	0.06	3	1	1	2	1	1	2	2	2	1
C10	-	0.07	2.33	2.30	1.40	2.00	1.80	2.33	2.67	1.9	1.60	1.60
C11	-	0.07	1.50	2.00	2.30	1.78	2.22	1.89	1.25	2.00	2.30	2.44

Criterion	Unit	Weights	Alternative (pellet type)									
			W	R	S	H	BH	SH	BSG	CG	L	G
C12	-	0.07	1.18	1.64	2.64	2.27	2.09	2.09	1.18	1.91	2.36	1.91
C13	-	0.07	1.55	1.55	2.82	2.09	1.82	2.09	1.27	2.18	2.09	2.00
C14	-	0.06	1.45	1.73	1.82	1.64	2.09	1.73	1.00	1.55	1.91	1.82
C15	-	0.06	1.73	2.27	2.55	2.18	2.64	2.45	1.27	2.00	2.27	2.36

The WSM-AHP results (see Fig. 3.3) show that W pellets received the highest overall score (0.84), followed by BSG (0.65), BH (0.49), and H (0.47). The first position of W pellets is related to balanced performance across all criterion groups, especially quality and combustion indicators. The second position of BSG pellets is mainly determined by the contribution of socio-technical criteria, whereas the positions of BH and H pellets are influenced more by combustion indicators. R, CG, and L form the middle group, while the lowest values were obtained for SH, G, and S pellets.

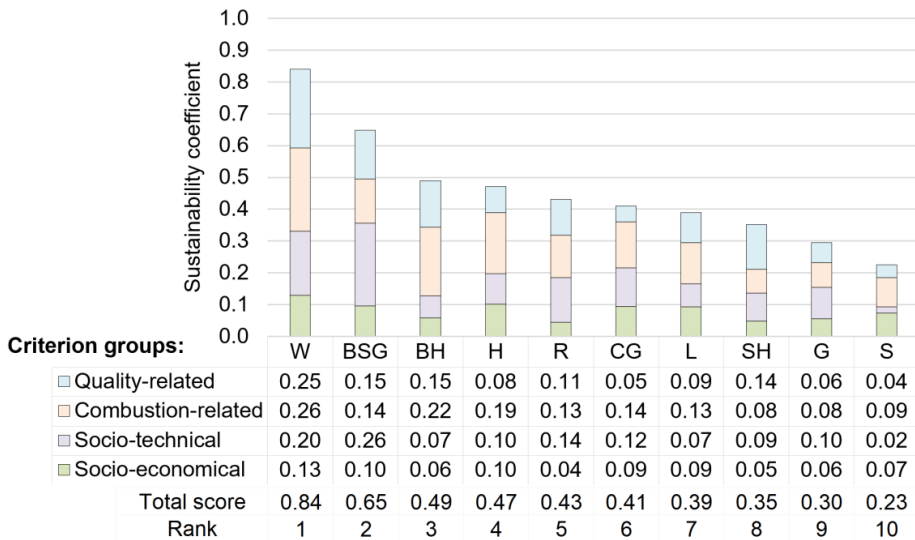


Fig. 3.3. WSM-AHP results of the technical-social assessment of pellets.

The MULTIMOORA-AHP results (see Fig. 3.4) confirm the stable first position of W pellets, as they rank first in all three sub-methods. BH pellets obtain 24 Borda points and remain in third place in all sub-methods; therefore, they can be considered the most stable alternative after W pellets. BSG, H, and CG pellets obtain similar total evaluations, but their positions change depending on the calculation approach: BSG ranks higher in the ratio system, H in the full multiplicative form, and CG in the reference point approach.

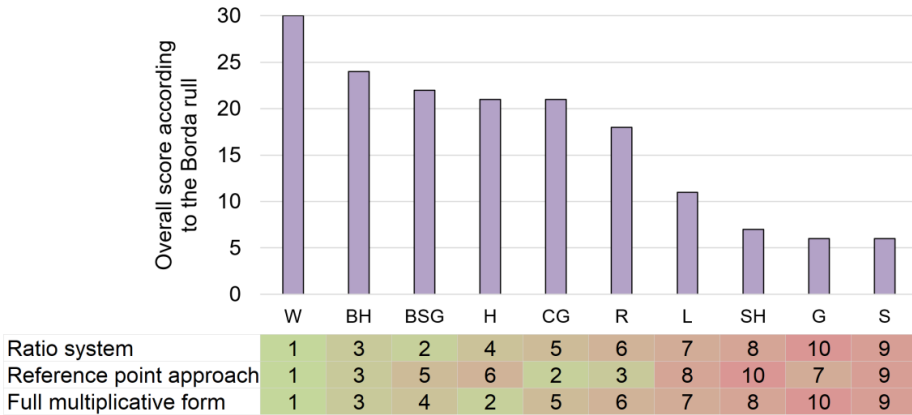


Fig. 3.4. MULTIMOORA-AHP results of the technical-social assessment of pellets.

Comparison of the two MCDA approaches shows that W pellets are the reference option in both cases. The main difference between the methods is the interpretation of BH and BSG positions. WSM-AHP assigns a higher rank to BSG pellets because the weighted-sum approach allows socio-technical advantages to compensate for weaker results in other groups. MULTIMOORA-AHP, in contrast, highlights the stability of BH pellets because this sample maintains the same position in all sub-methods. Therefore, BH pellets can be considered the most stable alternative biomass option after W pellets, while BSG, H, and CG pellets are promising alternatives under specific priorities. The lower positions of S, G, and SH pellets indicate that practical use of these samples would require improvements in several criterion groups, not only in one indicator.

3.3. Life cycle impact assessment results

The life cycle impact results by process are summarised in Table 3.7. In the collection stage, the highest impact was determined for W pellets (2.90 Pt), because this stage is dominated by wood feedstock collection. The lowest collection-stage impact was determined for SH pellets (0.29 Pt), where the model mainly includes alternative biomass transport to the production facility. In the production stage, the highest impact was determined for G pellets (4.66 Pt), followed by L pellets (4.11 Pt); in both cases, mechanical preparation of biomass contributes substantially. The lowest production-stage impact was obtained for SH pellets (1.30 Pt). In the combustion stage, the highest impact was determined for BSG pellets (5.22 Pt) and G pellets (5.04 Pt), while the lowest was determined for W pellets (1.21 Pt). In the overall impact, the lowest values were obtained for SH, BH, H, and S pellets, which show lower impact than W pellets. This shows that some alternative biomass pellets can be competitive from the life cycle impact perspective if no substantial additional burdens arise in their production and combustion stages. The highest overall impact was determined for G and L pellets, where the result is strongly increased by the production stage, as well as for BSG and G pellets due to the combustion-stage impact.

Table 3.7

Life cycle assessment results in ecopoints (Pt)

Sample	Collection				Production			Combustion		
	A1	B1 (+B1a)	A2	B2	A3/ B4	A4/B3 (+B3a)	A5/ B5	A6/B6/ C1	A7/B7/ C2	A8/B8/ C3
W	2.49	-	0.41	-	1.02	0.41	0.66	1.00	0.21	1.00
R	1.34	0.64	0.22	0.13	0.55	0.24	0.72	0.98	0.25	3.60
S	1.45	0.04	0.24	0.13	0.59	0.23	0.93	0.66	0.28	1.53
H	1.23	0.44	0.20	0.33	0.51	0.41	0.33	0.72	0.25	1.53
BH	1.15	-	0.19	0.10	0.48	0.19	0.31	1.10	0.24	1.91
SH	-	-	-	0.29	-	-	-	1.30	0.28	2.46
BSG	-	-	-	0.83	-	1.15	-	0.40	0.22	5.00
CG	1.20	0.02	0.20	0.25	0.50	0.49	0.80	0.62	0.26	3.44
L	1.34	-	0.22	0.33	0.55	0.77	1.90	0.89	0.26	3.15
G	1.26	-	0.21	0.75	0.52	1.39	1.80	0.95	0.20	4.84

In Fig. 3.5, the LCA results are summarised in the ReCiPe areas of protection: human health, ecosystem quality and resource availability. SH pellets show the lowest impact in all three areas, while G pellets show the highest impact. In the human health and ecosystem quality areas, L and BSG pellets are also among the higher-impact samples, while in the resource availability area higher impacts are characteristic of L and G pellets. Lower total impact is not distributed evenly across all impact areas; for some samples, the result is driven more by resource consumption in the production stage, while for others it is driven by combustion-stage emissions.

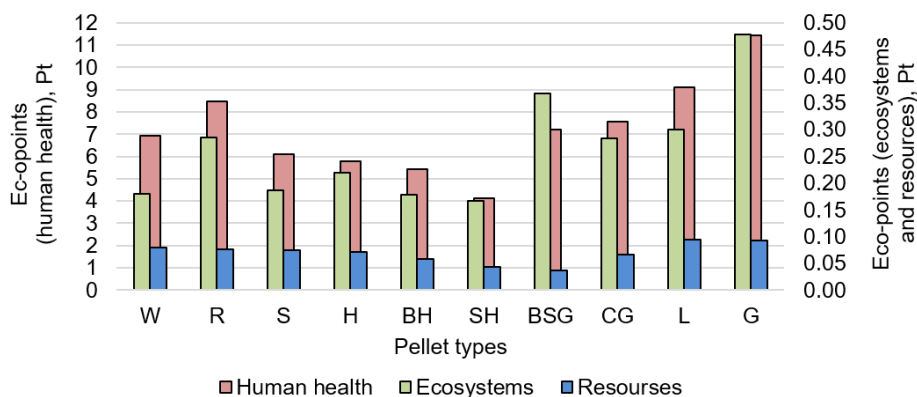


Fig. 3.5. Life cycle impact of pellets on human health, ecosystems and resources.

3.4. Sustainability assessment results

The sustainability assessment calculated the specific GHG emissions of the studied pellets and their savings compared with the RED II fossil comparator of 80 gCO_{2eq}/MJ. The calculation is based on the LCA inventory data obtained in the Doctoral Thesis, the IH boiler

efficiency determined in combustion tests, and the author's supplemented RED II calculation approach. The results make it possible to assess whether the specific pellet samples can meet the RED II emission-saving thresholds for heat production.

Specific GHG emissions before energy transformation, divided by life cycle stage, are shown on the left side of Fig. 3.6. The lowest total value was obtained for SH pellets – 3.00 gCO_{2eq}/MJ, while the highest was obtained for G pellets – 12.99 gCO_{2eq}/MJ. In all samples, a substantial share of emissions is formed in the production stage, while differences among samples are determined by energy consumption in preparation processes, transport and combustion emissions. The comparison with RED II default values (right side of Fig. 3.6) shows that the highest specific GHG emissions occur in pellet scenarios where process heat for production is generated from natural gas. As the share of renewable energy in heat and electricity supply increases, the default values decrease substantially. The W pellet result is close to the RED II value for pellets from wood industry residues in the more modern production scenario, although the distribution of emissions by stage differs. A similar difference is observed between S pellets and RED II straw pellets: the total value calculated in the Doctoral Thesis is lower, but the contribution of individual stages is not identical to the RED II default distribution.

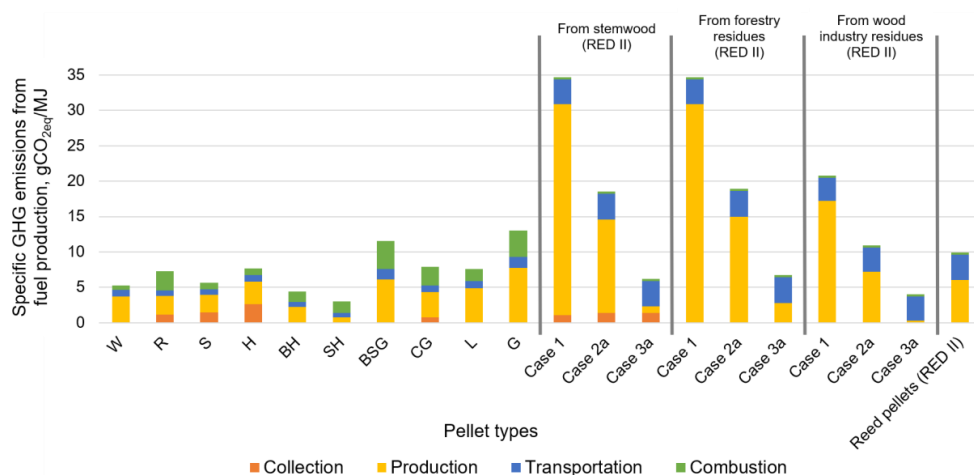


Fig. 3.6. Specific GHG emissions from pellet life cycle stages before energy transformation for the studied pellets and RED II pellet types.

Case 1 – heat from natural gas and electricity from the grid;

Case 2a – heat from a wood chip boiler and electricity from the grid;

Case 3a – heat and electricity from cogeneration.

After relating specific GHG emissions to the experimentally determined IH boiler efficiency, emission savings against the RED II fossil comparator were calculated. The results are shown on the left side of Fig. 3.7. In the RED II context, solid biofuel must comply with GHG emission-saving thresholds: at least 70 % for installations put into operation up to 2026 and at least 80 % for installations put into operation after 2026. Among the studied pellets, the

highest GHG emission savings were obtained for SH pellets (94 %), while the lowest were obtained for G pellets (78 %). G pellets exceed the 70 % threshold but do not reach the 80 % threshold. Therefore, their use in new installations would require higher combustion efficiency or lower combustion-related emissions in practical operation. All other studied pellet samples meet both RED II thresholds, showing that alternative biomass pellets can comply with the current sustainability requirements for heat production.

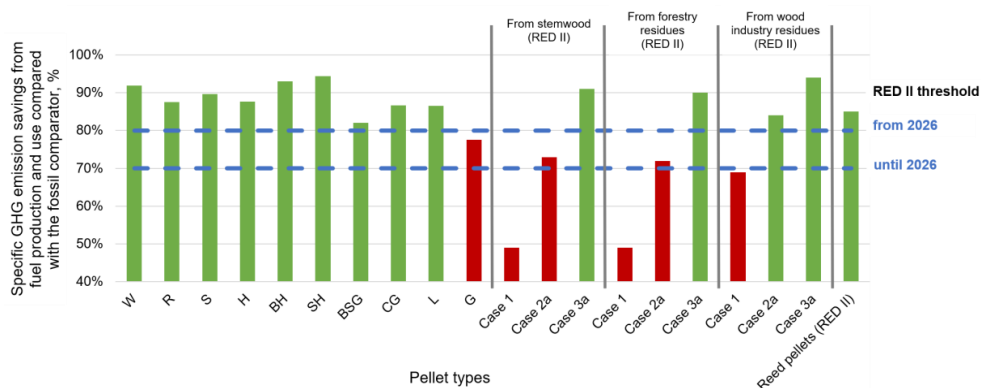


Fig. 3.7. GHG emission savings for pellets and compliance with RED II thresholds.

Case 1 – heat from natural gas and electricity from the grid;

Case 2a – heat from a wood chip boiler and electricity from the grid;

Case 3a – heat and electricity from cogeneration.

The comparison with RED II default values (right side of Fig. 3.7) shows that emission savings strongly depend on the energy source used in production. Pellets produced with process heat from natural gas have lower savings, and some scenarios do not meet the 70 % or 80 % thresholds. In contrast, scenarios using heat from a wood chip boiler or cogeneration achieve higher default savings. This confirms that pellet sustainability is determined not only by feedstock type but also by production energy supply and combustion efficiency. The results of the Doctoral Thesis show that, when based on specific laboratory and combustion test data, most alternative biomass pellets provide sufficient GHG emission savings and can therefore be assessed as sustainable fuels for heat production.

CONCLUSIONS

1. The multidimensional methodology developed within the Doctoral Thesis provides a scientific and structured approach for assessing the sustainability potential of biomass in the context of heat production and can be used to support decision-making by stakeholders involved in the solid biofuel life cycle.
2. The hypothesis was confirmed: alternative pellets do not meet the requirements regarding emission limits generated during combustion; however, they achieve substantial specific GHG emission savings, thereby demonstrating their sustainability potential.
3. The pellet quality analysis and comparison with the LVS EN ISO 17225-6:2021 B-class requirements show that the limiting indicators for the studied samples are *BD* and *DU*. Only W pellets met all B-class criteria, while the alternative pellets mainly failed due to these two indicators.
4. The combustion results for samples show that the emission level is determined by fuel properties and combustion conditions. In the IH models, the significant parameters were *C*, *N*, *AC*, *AMP*, *BD*, *DU*, and *FT*, whereas in the DH tests, emission changes were associated with *MC*, *AC*, and *N* content and wood chip particle size distribution.
5. Ash analysis shows that operational risk is determined not only by *AC* but also by the physicochemical properties of ash. Changing the status of the ash flow from waste to by-product requires demonstrable justification based on chemical composition and crystalline phases. The Vassilev diagram approach allows ash to be grouped according to the dominant oxide complex and the initial definition of possible use directions.
6. The cradle-to-grave LCA shows that the total impact is mainly determined by the production and combustion stages, while the collection stage is strongly influenced by the system boundaries. The lowest total impact was determined for SH, BH, and H pellets (4.33 Pt, 5.67 Pt, and 5.95 Pt, respectively, per 1 MWh of produced heat), while the highest impact was obtained for G pellets. Impact reduction should prioritise lowering energy consumption in the production stage, ensuring drier input material and reducing the NO_x level in flue gas.
7. The MCDA results show that the WSM-AHP and MULTIMOORA-AHP approaches provide a consistent but methodologically differently interpretable ranking. WSM-AHP reflects the compromise among criteria, whereas MULTIMOORA-AHP more clearly highlights alternatives with markedly weak indicators. The highest-ranked pellets in the WSM-AHP approach were W, BSG, and BH, whereas in the MULTIMOORA-AHP approach they were W, BH, and BSG; BH and BSG are the strongest alternatives after W pellets.
8. The sustainability assessment shows that the studied pellets generally provide high GHG emission savings against the fossil fuel comparator. The highest saving was achieved by SH pellets (94 %), while the lowest was obtained for G pellets (78 %). The sensitivity of the result is determined by the energy structure of the production stage and the efficiency of the combustion unit; the priorities are process energy efficiency, decarbonisation of energy sources and reduced NO_x formation.



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In 2024, he completed an academic staff mobility programme at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences, where he enhanced his knowledge of mathematical modelling and optimisation of combustion processes. His master's thesis won first place in the master's thesis category of the 2022 Student Thesis Competition organised by AS Latvenergo.

His research interests include the use of alternative biomass for energy production, biomass fuel quality and combustion, technical modelling of systems, flue gas treatment, life cycle assessment, and the application of multi-criteria analysis methods in sustainability assessment.