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The Impact of Material on Environmental Indicators: An LCA Analysis of 30 Variants of Pitched Roofs

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Abstract

This study presents a comprehensive life cycle assessment (LCA) of 30 variants of pitched roofs compositions, focusing on global, regional, and local environmental indicators. The aim of this study was to quantify the environmental footprint of roof structures, comparing traditional technical solutions with modern systems using bio-based materials. The results show that the integration of solid wood elements and bio-based insulations significantly increases carbon sequestration potential, with the best identified composition showing a significantly negative GWP-total. A dynamic analysis of the optimal variant over time horizons of 50, 100 and 150 years, confirming the stability of environmental benefits in the long term, is presented. In order to achieve a global character, the best composition is modified and optimized for mild, cold and warm climate zones. The work provides important background for decarbonization of the construction sector and the design of adaptive, low-emission building envelope structures.

Keywords: life cycle assessment; pitched roof; carbon sequestration; dynamic analysis; climate zones; decarbonization

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1. Introduction

The construction sector is one of the main sources of environmental burden, as it contributes significantly to the consumption of primary raw materials, energy resources, and greenhouse gas emissions throughout the entire life cycle of buildings. In response to global environmental challenges and the goals of transitioning to a circular economy, there is a growing need for systematic assessment of building structures in terms of their environmental impact throughout their life cycle [1–3]. Life cycle assessment (LCA) methodology is a proven tool that allows these impacts to be quantified based on uniform and transparent rules and enables alternative construction solutions to be compared objectively [4–6].

In recent years, research has shifted its focus from partial assessments such as "Cradle-to-Gate" to a broader "Cradle-to-Cradle" approach, which takes into account not only the

phases of production, construction, and use but also the end of life and the potential for reuse of materials in subsequent life cycles [1,7,8]. Between these two system boundaries, the "Cradle-to-Grave" approach (modules A–C) encompasses the product, construction, operation and end-of-life phase. In this context, Module D, representing potential environmental benefits and loads beyond the boundaries of the assessed system, takes on particular importance. This approach allows building structures to be assessed not only in terms of their direct impacts but also in terms of their ability to contribute to closing material cycles [3,9–11].

Roof structures incorporating bio-based materials represent a promising direction for sustainable construction, as these materials are renewable, with the ability to sequester biogenic carbon, and in many cases require less energy to process than conventional industrial products [6,12,13]. Pitched roofs are a widely used type of roof construction in both residential and public buildings, although their application is highly dependent on climatic and regional conditions [14,15]. Within this type of construction, there is a wide range of compositions that differ in material choices, layer thickness, thermal parameters, component life, and potential for disassembly or recycling, with these differences being particularly significant in solutions using bio-based materials [8,16,17].

The variability in composition is reflected in different environmental profiles throughout the life cycle, but this is not always systematically analyzed at the level of individual roof envelopes in existing LCA studies. Furthermore, the multidimensional nature of environmental impacts further complicates the comparison of alternative roof structures and the identification of more environmentally friendly options. For this reason, the growing complexity of environmental assessment has led to the integration of multi-criteria decision analysis (MCDA) methods into building sustainability research [18]. These methods allow for systematic aggregation and comparison of multiple environmental indicators and support more transparent and balanced decision-making in the selection of optimal design solutions. In the context of roof structures with diverse material bases, methods such as TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and WSA (Weighted Sum Approach) allow for the evaluation of variants based on their overall environmental performance, taking into account compromises between global, regional, and local impact indicators [19,20].

Despite these methodological advancements, existing research still tends to focus primarily on the evaluation of entire buildings or on comparisons between basic construction systems, while detailed comparisons of multiple alternative pitched roof compositions within a unified methodological framework remain limited [17,21]. Furthermore, assessments are often based on a static approach with a fixed reference period of study, without systematical examination of the impact of different time horizons and maintenance scenarios on the resulting environmental balance [22–24]. Considering the long-term durability of roof assemblies, the lifespan of individual layers and end-of-life processes may substantially alter the overall environmental impact profile, particularly in structures incorporating bio-based materials. Therefore, analyzing environmental impacts over extended time horizons represents an important step toward a more accurate understanding of cumulative emissions throughout the life cycle of roof structures [25].

The aim of this study is to perform a comprehensive analysis of the environmental impacts of 30 variants of pitched roof compositions, including both conventional and bio-based material solutions, using the LCA methodology within the Cradle-to-Grave and module D framework. The assessment includes all available environmental impact indicators to quantify the contribution of the material base of individual components to the overall environmental impacts. The work includes an analysis of trends in global warming potential over different time horizons (50, 100, and 150 years), considering the lifespan of

the structure, the frequency of layer replacement, and end-of-life processes. The study also focuses on identifying key sources of environmental impact in individual life cycle phases and structural layers, comparing alternative compositions using multi-criteria decision-making methods, and assessing the impact of design parameters, including changes in the thickness of insulation layers in different climatic conditions, on the overall environmental profile. The results provide a basis for assessing the decarbonization potential of roof structures and support informed decision-making in the design of low-emission and material-optimized solutions.

2. Materials and Methods

2.1. Goal and Scope

The aim of the study is to comprehensively assess the proposed pitched roof compositions during their life cycle and demonstrate the environmental benefits of using bio-based thermal insulation materials. For the purposes of the research, 30 pitched roof variants (PR1–PR30) were designed, which were adapted to the climatic conditions of Slovakia (moderate climate zone). To ensure the comparability of results, a functional unit (FU) with an area of 1 m^2 was defined, assuming a design life of 50 years for the structure. Detailed numerical results from this analysis are available in the supporting documents in Supplementary Material S1. Environmental impacts were assessed within the boundaries of the "Cradle-to-Cradle" system. The OneClickLCA (OCL) software (Version: 0.51.0, Database version: 7.6) tool was used to calculate individual impact categories, and the entire process was conducted in strict accordance with the methodological requirements of the standards. The life cycle stages A1 to C and module D are shown in Figure 1.

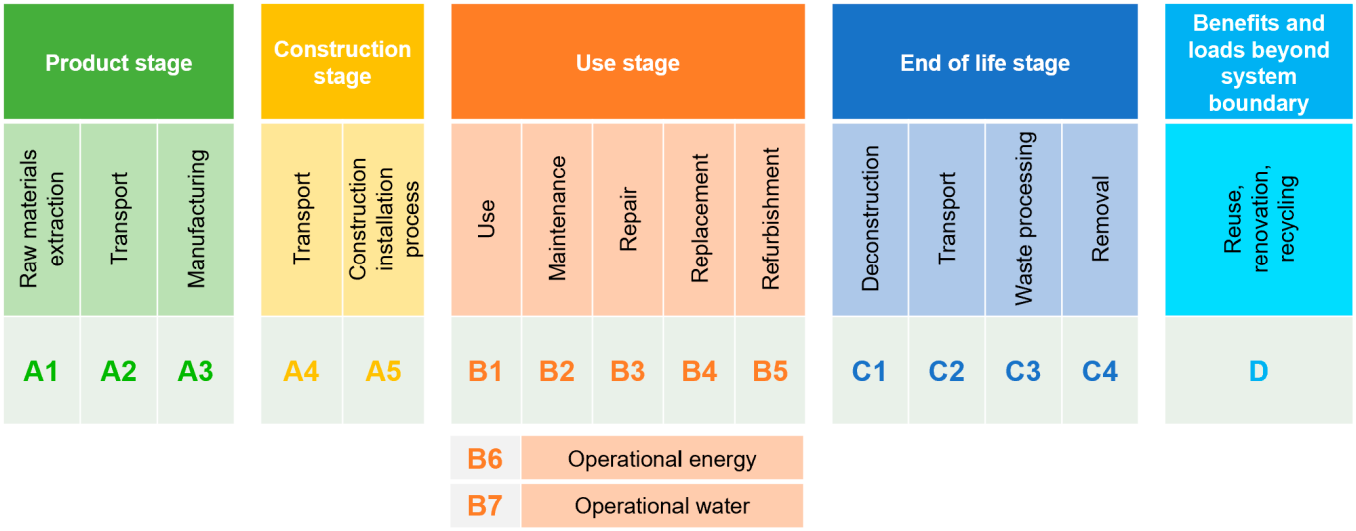


Figure 1. System boundaries and evaluated life cycle stages.

Within the framework of LCA, several approaches to defining the system boundaries are distinguished, which significantly influences the interpretation of the results. The basic model is the "Cradle-to-Gate", which represents a partial assessment ending after the finished product leaves the factory gate (modules A1–A3), without considering the transport to the customer or the use phase. The more comprehensive "Cradle-to-Grave" system boundary covers the entire life cycle, including product at the gate, transportation, construction, operation and waste management processes such as recovery processes (modules A–C). The highest level of sustainability is represented by the "Cradle-to-Cradle" system boundary, which forms the basis of the circular economy. In contrast to previous models that allowed for the generation of waste or loss of material quality (downcycling),

the "Cradle-to-Cradle" model designs products so that their components can be reused in a closed loop. The evaluation methodology was coordinated with the "Cradle-to-Cradle" principles. This approach, widely recognized in sustainable building certifications, allows for the integration of module D, which quantifies the environmental benefits and loads resulting from the recycling and recovery potential of the analyzed roof structures.

2.1.1. Software

The OCL software (version: 0.29.1, database: 7.6) was used to assess environmental indicators in accordance with the ISO 14040 [26], ISO 14044 [27] and EN 15804+A2/AC [28] standards. The analysis was based on data from Ecoinvent 3.8, OneClickLCA, GaBi and EPD databases, with a detailed overview of the data used for individual materials provided in Supplementary Material S1. To ensure the highest possible temporal, geographical and technological representativeness of the data, it was necessary to use multiple databases. Primary data were obtained from Environmental Product Declarations (EPDs) in accordance with the EN 15804+A2/AC standard to reflect specific local production conditions. Where specific EPDs were not available, secondary data from established databases (e.g., Ecoinvent, GaBi, OneClickLCA) were used as a supplement. To ensure compatibility, all the datasets were harmonized to the same functional unit and time frame. The OCL software is in line with the European Level(s) framework for assessing the sustainability of buildings throughout their life cycle. The Level(s) Life Cycle Assessment Tool was applied in the assessment, using data from the PEF 3.0 (Product Environmental Footprint) methodology according to the EN 15804+A2/AC standard. The PEF methodology [29], developed by the European Commission, is a standardized approach to measuring the environmental footprint of products and is based on ISO standards (ISO 14040, ISO 14025, ISO 14067 and ISO 14020) [26,30–32]. Both PEF and EPD are considered robust tools for quantifying environmental impacts. While in the EPD the quality of data and verification depends on the internal rules of the program operators, the PEF methodology requires a strict assessment of data quality based on established criteria.

2.1.2. Multi-Criteria Assessment Methods

Multi-criteria assessment (MCA) methods enable a comprehensive comparison of proposed alternatives based on multiple environmental indicators simultaneously. This approach allows for the consideration of various aspects and preferences in the decision-making process, thereby helping to identify the optimal solution with respect to the established criteria. The main contribution of MCA in this study is the use of multiple methodological approaches to validate the results obtained. The key methods used to evaluate the data in the MCA7 tool (Version 2.6.) were TOPSIS and WSA. The principle of the TOPSIS method consists in identifying a compromise solution that has the smallest geometric distance from the point representing the ideal positive solution while simultaneously being as far as possible from the point representing the negative ideal. It provides an objective comparison of alternatives and minimizes the distance from the ideal reference point. The WSA method was used to validate the results of the TOPSIS method. The selection of these methods was based on their complementary nature. The TOPSIS method was chosen because it can effectively rank alternatives based on their distance from the ideal solution. It is particularly useful in environmental assessment because it seeks an alternative that simultaneously has the best values for positive indicators and the lowest values for negative impacts [33]. To verify the stability of the results, we subsequently used the WSA method. This method is based on the principle of a weighted sum and is valued for its transparency and simplicity [34,35]. The combination of both approaches made it possible

to eliminate the subjective mistakes of individual methods and increase the reliability of identifying the most suitable roof structure composition in terms of sustainability.

MCA was performed using the MCA7 tool to select the optimal pitched roof composition. The analysis considered 13 life cycle indicators, which were assigned a weight of importance: GWP-total, GWP-fossil, GWP-biogenic, GWP-LULUC (Land Use and Land Use Change), ODP (Ozone Depletion Potential), AP (Acidification Potential), EP-AF (Eutrophication Potential of Aquatic Freshwater), EP-AM (Eutrophication Potential of Aquatic Marine), EP-T (Eutrophication Potential Terrestrial), POCP (Formation Potential of Tropospheric Ozone), ADP-E (Abiotic Depletion Potential for Non-Fossil Resources), ADP-FF (Abiotic Depletion Potential for Fossil Resources) and WU (Water Deprived).

Environmental impact indicators are divided into global, regional, and local indicators according to their scope of action. Global indicators (GWP, ODP, ADP-E) affect areas larger than 100 km^2, and the nature of the emission site has no impact on the scope of their impact. Regional indicators (AP, EP, POCP) affect an area of 10 to 100 km^2 (subcontinent or vicinity of the source), where the resulting effect is significantly influenced by geographical location, such as proximity to the coast or inland. Local impacts (ADP-FF, WD) occur in the immediate vicinity of the source within 10 km^2, where they directly affect water quality and biodiversity. A comprehensive assessment may also include other factors such as environmental toxicity, human toxicity, soil degradation, or changes in landscape quality [27,36]. Although the conclusions prioritize global impacts given their key role in international climate and carbon neutrality goals, regional and local impacts remain significant for assessing the overall environmental footprint and biodiversity of specific construction sites.

Indicators with global environmental impact (GWP, ODP, ADP-E) were assigned a total significance weight of 75%, while within this group the GWP-biogenic indicator received a weight of 25%. This value was chosen because the study is focused on assessing bio-based materials that could store carbon while utilizing their full environmental potential. Indicators with regional impact (AP, EP, POCP) were assigned a weight of 20%, and indicators with local impact (ADP-FF, WU) were assigned a weight of 5%. The total sum of the weights is equal to 1 (100%). The results of the analysis are presented in detail in Supplementary Material S2.

2.1.3. Dynamic Analysis

To assess the impact of the lifespan of the pitched roofs, a dynamic analysis of the PR9 composition was performed. The lifespan of the PR9 pitched roof composition was set at 50, 100 and 150 years. Modules A through C were included in the analysis. Module D was excluded from the dynamic timeline because its benefits are traditionally calculated as a one-time credit at the end of the primary life cycle and their timing is highly dependent on future deconstruction technologies, making them less suitable for year-to-year dynamic modeling.

2.1.4. Sensitivity Analysis of Scenario

Quantification of the impact of changing input variables on the model results was carried out through statistical sensitivity analysis. This study applied a scenario analysis approach, where the basic pitched roof model (PR9) was adapted to different climate zones, represented by countries with available data on thermal requirements (Slovakia, Finland, Italy, Brazil). The scenarios included alternative adaptation models for cold and two subtropical climate zones. The selected countries represent different climate zones with the occurrence of pitched roofs and the availability of information regarding the requirements for thermal and technical properties of the envelope. The thickness of the thermal insulation was considered as the main sensitivity factor in the environmental

assessment. The PR9 pitched roof composition was designed to achieve universal applicability with minimal modifications, while considering the thermal insulation suitable for the given zones. The thickness of the thermal insulation was based on the thermal requirements (resistance and heat transfer coefficient of the roof structure) of the studied area: cold climate zone (Finland), subtropical zone 1 (Italy) and subtropical zone 2 (Brazil) (Supplementary Material S3). To ensure the consistency of the sensitivity analysis focused on the thickness of the thermal insulation, the geographical production parameters and energy mix (A1–A3) were fixed throughout the model at average values for Central Europe. Although the insulation thickness varied depending on the climatic requirements of different locations, the environmental impacts per unit of material remained constant. This approach was chosen deliberately to eliminate the influence of variability in the energy grids of individual countries and to isolate the net impact of material volume and the thermal-technical properties of the structure on the overall LCA results. For the purposes of the sensitivity analysis, the transport distances listed in Supplementary Material S1 were set to a constant value across all climate zones. This decision was made to distinguish the environmental impact of material volume (insulation thickness) and thermal performance from the logistical variables. By maintaining a uniform transport distance, the study ensures that the observed variations in LCA results can be directly attributed to roof composition.

2.2. Life Cycle Inventory Analysis

Life cycle inventory (LCI) analysis was used to calculate the carbon footprint and other environmental indicators throughout the life cycle of the pitched roof variants. The compositions of the wooden pitched roofs were designed according to the thermal-technical requirements for heat transfer coefficient (U) and thermal resistance (R) in accordance with the STN 73 0540-2+Z1+Z2 standard [37].

Variants of Wooden Pitched Roof Compositions

The design of the structures was based on various types of load-bearing systems. The basic load-bearing layer consisted of wooden truss systems (KVH beams), I-beam systems, CLT (Cross Laminated Timber) panels, or solid pegged wooden systems. These load-bearing systems, which formed the basis for the pitched roof variants, were supplemented with various thermal insulation materials. The main goal of the design of these structures was to use bio-based materials with high carbon sequestration potential. Conventional mineral wool was chosen as the thermal insulation material in some variants (PR15 and PR26) of the composition. Other progressive variants used a wide range of bio-based insulations such as hemp, sheep's wool, wood fiber insulation, straw, rice straw, and cellulose. Other layers of the wooden pitched roof structures consisted of vapor barrier layers (e.g., OSB 3 boards with taped joints), while exterior protection was provided by diffusion-open wood fiber boards (DHF), waterproofing membranes and final roofing (clay tiles, concrete tiles or sheet metal roofing). All materials used, their thickness, database and transport to the construction site in km are listed in Supplementary Material S1.

All 30 variants of wooden pitched roof structures were designed to meet strict thermal requirements. To achieve relevant results when comparing environmental impacts, the target value for the heat transfer coefficient U_N was set at 0.15 W/(m^2·K), which corresponds to the recommended value for passive and ultra-low-energy houses according to the STN 73 0540-2+Z1+Z2 standard [37]. The heat transfer coefficient values were 0.08–0.09 W/(m^2·K) for the composition variants. Examples of proposed wooden pitched roof compositions are shown in Figure 2.

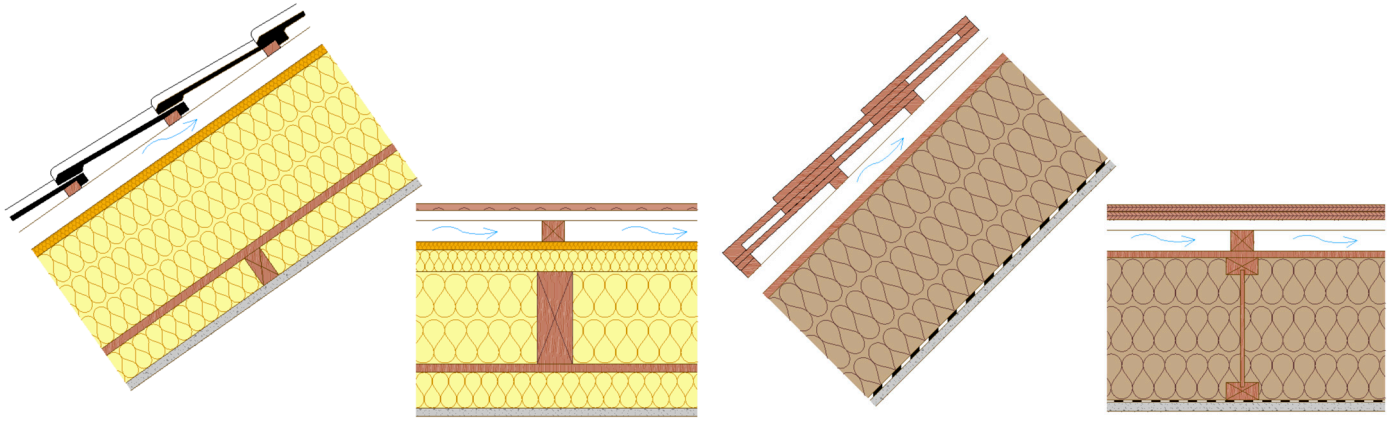


Figure 2. Schematic representation of selected wooden pitched roof compositions (PR15 and PR13).

2.3. Life Cycle Impact Assessment

In the life cycle impact assessment (LCIA), all inventory data collected for the 30 proposed wooden pitched roof compositions were evaluated. The selected LCA approach assessed several categories of environmental impacts in accordance with EN 15804+A2 [28]. Table 1 shows an overview of the impact categories assessed. The impact categories were divided into global, regional, and local.

Table 1. Parameters describing basic environmental impacts [38].

Impacts Categories	Abbreviation	Unit
Global Warming Potential total	GWP-total	kg CO_{2e}
Global Warming Potential fossil	GWP-fossil	kg CO_{2e}
Global Warming Potential biogenic	GWP-biogenic	kg $CO_{2e\ bio}$
Global Warming Potential, LULUC (Land Use and Land Use Change)	GWP-LULUC	kg CO_{2e}
Depletion potential of the stratospheric ozone layer	ODP	kg $CFC11_e$
Acidification potential	AP	mol $H+_{eq.}$
Eutrophication potential of aquatic freshwater	EP-AF	kg Pe
Eutrophication potential of aquatic marine	EP-AM	kg $N_{eq.}$
Eutrophication potential of terrestrial	EP-T	mol $N_{eq.}$
Formation potential of tropospheric ozone	POCP	kg $NMVOC_{eq.}$
Abiotic depletion potential for non-fossil resources	ADP-E	kg Sb_e
Abiotic depletion potential for fossil resources	ADP-FF	MJ
Water use m^3 deprived	WD	m^3

3. Results

3.1. LCA Results

3.1.1. LCA Results for Global Indicators

The life cycle assessment included an analysis of environmental impacts using global, regional, and local categories. Figures 3–5 illustrate the contribution of each life cycle stage to the global warming potential (GWP) indicators for 30 selected variants of pitched roof compositions (PR1–PR30). The focus is on GWP-fossil, GWP-biogenic and GWP-LULUC, which together define the GWP-total impacts of the structures. In addition to climate impacts, ODP and ADP-E are also analyzed to identify critical points in the material composition. A comprehensive comparison of these parameters makes it possible to identify environmentally optimal compositions that achieve negative CO_{2e} emissions thanks to the integration of biogenic materials.

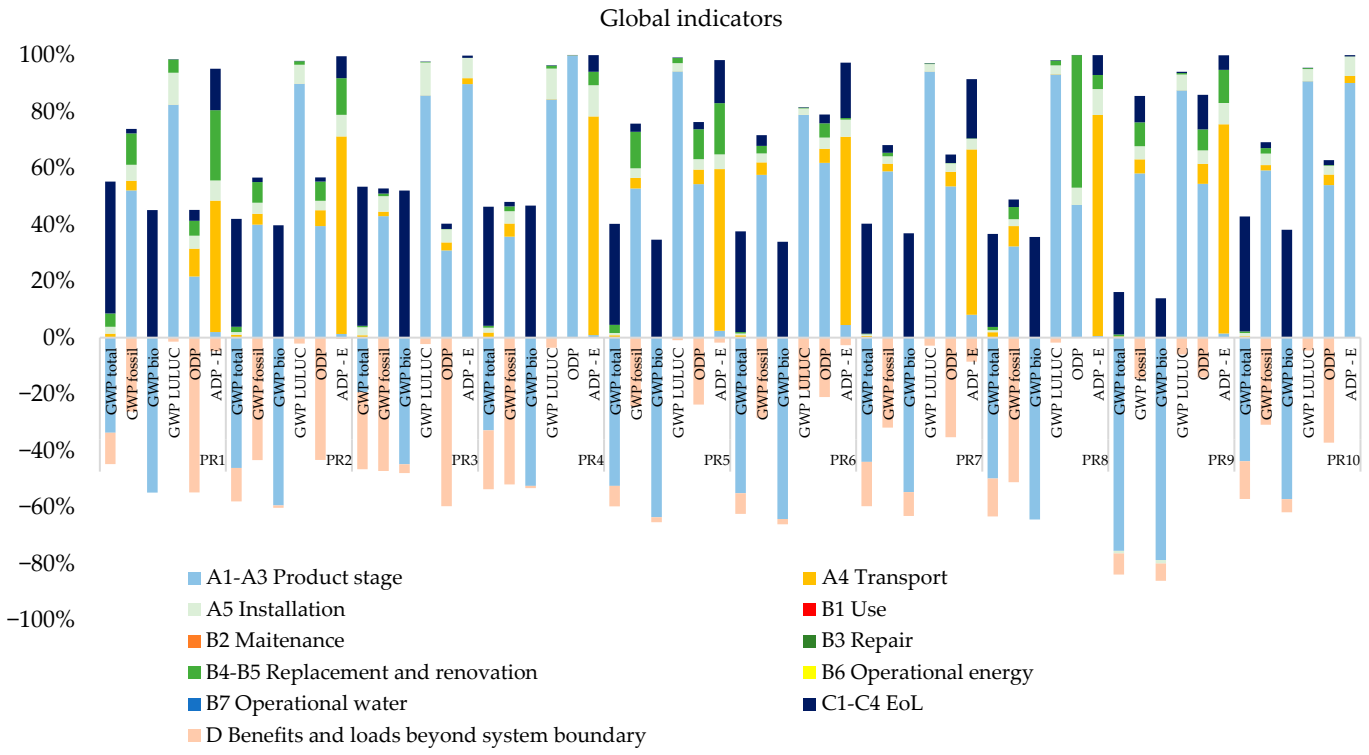


Figure 3. Calculated values of global indicators for the analyzed roof compositions PR1 through PR10.

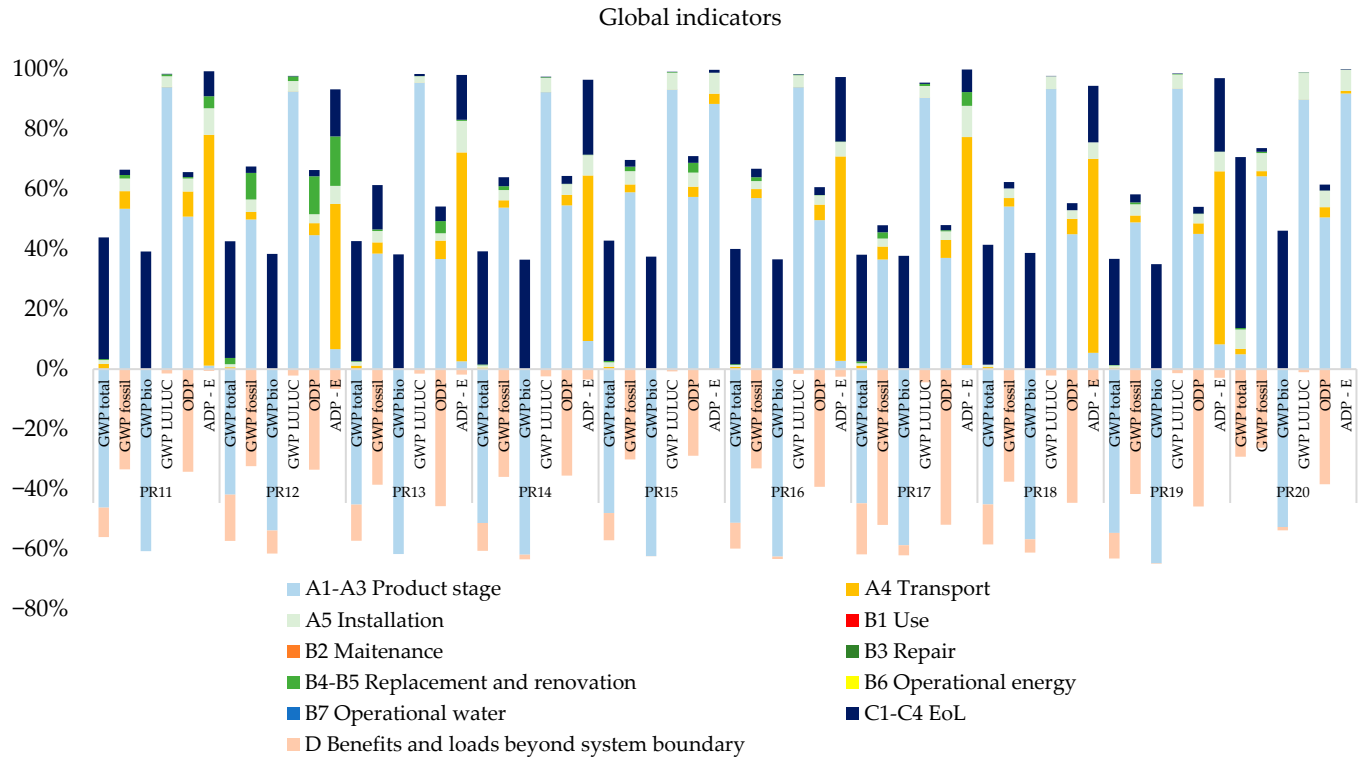


Figure 4. Calculated values of global indicators for the analyzed roof compositions PR11 through PR20.

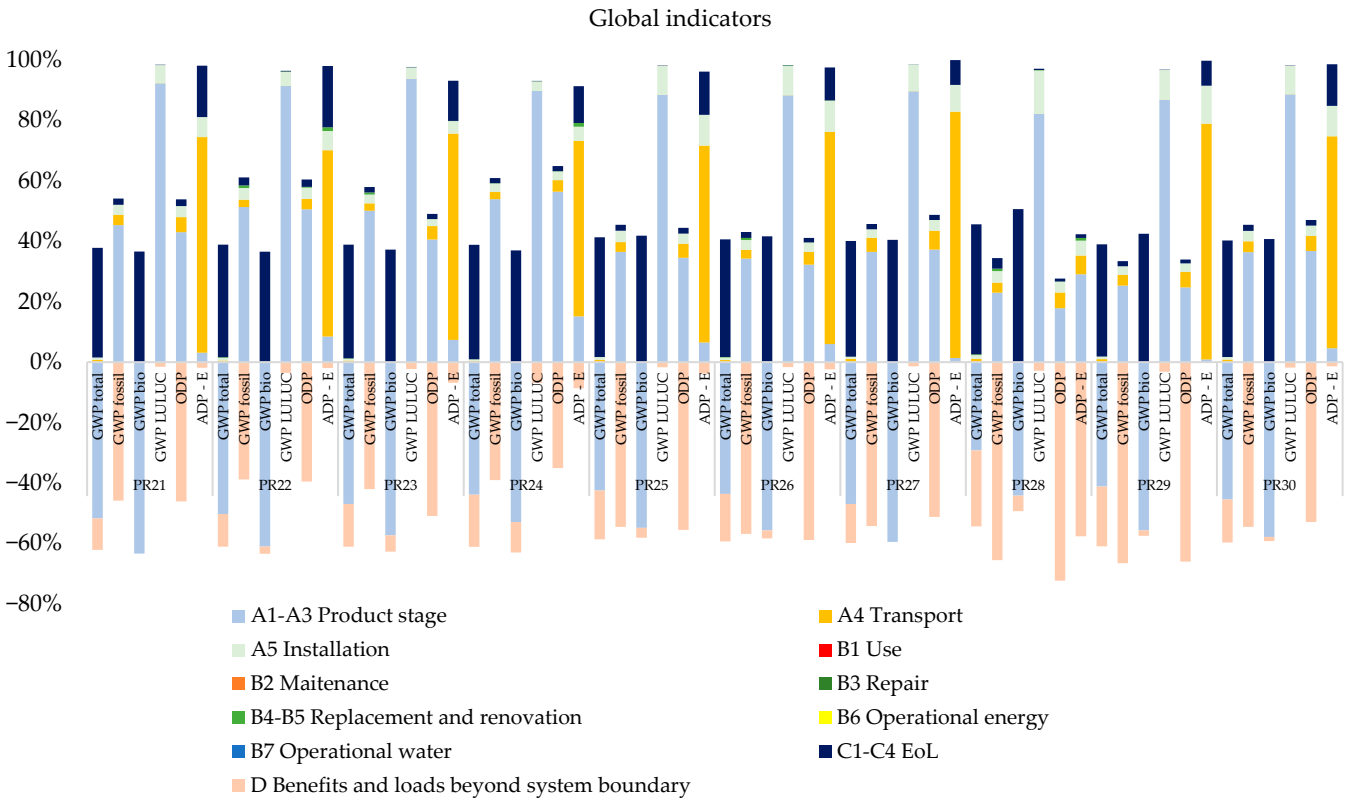


Figure 5. Calculated values of global indicators for the analyzed roof compositions PR21 through PR30.

An environmental analysis of 30 material variants for pitched roofs has shown that the choice of insulation material and support system has a significant impact on the structure. The global warming potential (GWP-total) indicator is dominated by progressive compositions using biomass, which significantly outperform conventional solutions thanks to carbon sequestration. In contrast, the ozone depletion potential (ODP) indicator reflects the technological complexity of processing bio-based materials and their additives. In the abiotic depletion potential (ADP-E) category, the key role of materials from primary sources was confirmed, where the elimination of metal elements in favor of all-wood systems leads to the most balanced results in terms of global assessment.

The life cycle analysis of the investigated roofs highlights significant differences in the GWP, with the biogenic carbon balance playing a key role. Most of the compositions assessed (PR2, PR5-PR11, PR13-PR19, PR21-PR27, PR29, PR30) show negative values for the GWP-total indicator, which suggests that these structures can sequester more CO_{2e} emissions than are released during their production. The most significant environmental benefit is shown by compositions that contain structural wood elements (CLT/finger-jointed timber) in combination with blown or board insulation made of bio-based fibers (cork, wood fiber insulation, cellulose, wool, rice straw). Compared to conventional mineral fiber-based solutions, these bio-based variants achieve a considerably higher rate of biogenic carbon storage, thereby contributing more effectively to decarbonization goals in the construction industry. The lowest environmental impact is achieved by variant PR9 (−17.49 kg CO_{2e}), which is a direct result of very high sequestration in the biogenic component. In terms of environmental impact, the composition represents a reference model for sustainable construction. A key factor in this positive result is the product phase (A1–A3), in which there is a large sequestration of biogenic carbon in the amount of −23.37 kg CO_{2e}, indicating the use of bio-based renewable materials. Although the end-of-life processes (C1–C4) lead to the release of part of the stored emissions (4.37 kg

CO_{2e}), the overall balance remains negative. The low GWP-fossil (2.11 kg CO_{2e}) combined with the benefits beyond the system boundary in phase D (−2.18 kg CO_{2e}) confirms the high potential for material recycling and energy efficiency. Although this composition has the highest load in the GWP-LULUC category (0.016 kg CO_{2e}), this impact is negligible in the context of total carbon storage, making PR9 the most effective solution for low-emission pitched roof construction. Material analysis of the PR9 composition in phases A1–A3 confirms that its remarkable environmental profile is the result of the synergy of several biogenic materials with high carbon sequestration potential. Expanded cork insulation plays a leading role, which, in terms of total volume, sequesters up to −932.8 kg CO_{2e} in the biogenic component, thereby more than compensating for its GWP-fossil. Wooden I-profiles (−201.08 kg $CO_{2e\,bio}$) and interior wood cladding (−20.21 kg $CO_{2e\,bio}$) also contribute significantly to the negative balance, which, together with structural timber, create a stable carbon store in the structure. Although clay roof tiles in GWP-fossil produce 8.71 kg CO_{2e} because of energy-intensive drying, the overall balance of the production phase remains negative due to the biogenic predominance. Conversely, the least favorable in terms of global warming and the depletion of abiotic resources is the PR20 composition, which, with a value of 3.44 kg CO_{2e} (GWP-total) and the highest fossil share (3.81 kg CO_{2e}), represents the greatest environmental load. The high value in phase A1–A3 of composition PR20 in category ADP-E (0.069 kg Sb_e) indicates that this composition contains components with a high proportion of minerals and metals. Unlike the PR9 variant, which stores carbon intensively, PR20 has only minimal storage (−0.38 kg CO_{2e}) in its biogenic component. This means that the proportion of bio-based materials (wood, fiber-based insulation) in this composition is low and, therefore, the emissions generated during production are not offset. In terms of the GWP-LULUC indicator (0.014 kg CO_{2e}), PR20 also has an average negative impact on land use. In combination with other parameters, this variant is defined as the most environmentally demanding, with limited potential for sustainable recycling or reuse at the end of its life cycle. The dominant factor in terms of materials is the use of titanium–zinc roofing, which generates a large GWP-fossil of 136.85 kg CO_{2e} and is the main source of excessive extraction of mineral resources. Although the composition includes biogenic components such as CLT panels (−82.5 kg $CO_{2e\,bio}$) and OSB boards (−23.06 kg $CO_{2e\,bio}$), their carbon storage potential is almost eliminated by emissions from the production of metal elements and plasterboard. In contrast to the PR9 variant, where bio-based insulation materials create a significant carbon deficit, in the case of PR20, even the use of sheep's wool cannot compensate for the fossil contribution of industrial materials, resulting in the highest overall contribution to global warming in the entire set. When comparing the material composition of PR3 with the previous variants, it is clear that this is a combined solution that attempts to strike a balance between biogenic accumulation and industrial functionality. A significant element in terms of carbon capture are the multiple layers of structural timber (a total of approx. −47 kg $CO_{2e\,bio}$) and OSB boards (approx. −30 kg $CO_{2e\,bio}$), which are complemented by MDF wood fiberboard with a contribution of −14. 74 kg CO_{2e} in the GWP-biogenic indicator. Contrary to the best composition of PR9, however, there is no mass insulation such as cork, and the cellulose insulation and sheep's wool insulation used have only a slight impact on the overall balance. Once again, titanium–zinc roofing represents a significant environmental burden, reaching 24.87 kg CO_{2e} in GWP-fossil and significantly increasing the GWP-total of the composition. When comparing the results, it can be concluded that the PR3 composition achieves a negative biogenic balance thanks to its wooden load-bearing elements, but its overall potential is lower due to energy-intensive metal and gypsum elements. The results show that conventional compositions with a high proportion of industrially manufactured materials and mineral insulation have the highest GWP-fossil values. Conversely, compositions based

on solid wood and bio-based fibers show lower fossil emission values in the product phase (A1–A3), which indicates lower energy intensity of primary processing of biomaterials compared to the energy-intensive production of mineral insulation. The GWP-biogenic indicator is key to assessing the sustainability of timber buildings, as it quantifies the amount of CO_2 removed from the atmosphere and stored in biomass during the growth of trees and plants. The results show that all compositions have a negative GWP-biogenic value in phases A1–A3 and reveal significant differences in the ability of pitched roof compositions to store carbon, which is key to achieving a negative carbon balance. The most significant carbon sequestration capacity is found in variants combining solid pegged panels with layers of bio-based insulation (cork insulation, wood wool insulation, sheep's wool, cellulose, rice straw). These compositions act as temporary carbon storage reservoirs, with the storage rate directly correlating with the density and thickness of the bio-based materials used. The PR9 composition has a dominant position, with a value of −19.61 kg $CO_{2e\ bio}$, which is several times higher than other solutions and thus significantly reduces the GWP-total of the structure. The PR19 (−3.03 kg $CO_{2e\ bio}$) and PR21 (−3.04 kg $CO_{2e\ bio}$) compositions also show significant carbon storage potential. On the contrary, variants PR3 (0.31 kg $CO_{2e\ bio}$) and PR28 (0.49 kg $CO_{2e\ bio}$) show positive values, indicating the absence of larger amounts of biogenic materials. Although the PR20 composition is the least favorable overall, it shows only minimal carbon sequestration (−0.38 kg $CO_{2e\ bio}$), which, combined with its high GWP-fossil, confirms the unsuitability of its material composition from the perspective of climate goals. The carbon sequestration capacity of PR19 (−3.027 kg $CO_{2e\ bio}$) is more than four times higher than that of PR1 (−0.71 kg $CO_{2e\ bio}$), which is a direct result of the integration of solid wood elements and cellulose and sheep's wool-based insulation. The high biogenic sequestration rate observed for the PR9 variant is in line with the LCA studies of Sierra-Pérez et al. [39], which highlight the negative emission balance of cork products. Conversely, the critical ADP and GWP-fossil values for the PR20 variant reflect the energy intensity of the metallurgical processes described by Zabalza Bribián [40]. The results indicate that, to achieve carbon neutrality in the pitched roof section, it is necessary to optimize the material composition towards biogenic raw materials that can effectively compensate for the necessary emissions from fossil fuels and transport. Within the GWP-LULUC indicator, all the analyzed compositions (PR1–PR30) show positive values, reflecting greenhouse gas emissions released as a result of land management and changes in land cover during the extraction of raw materials. The most significant load in this category is represented by variant PR9, which reaches a value of 0.0165 kg CO_{2e}, which is the highest. High values are also found in compositions PR20 (0.014 kg CO_{2e}) and the group of variants PR25–PR30, where values exceed 0.010 kg CO_{2e}. Conversely, the lowest environmental impact on land use is shared by variants PR1 and PR13, both with an identical minimum value of 0.0047 kg CO_{2e}. Although the absolute GWP-LULUC values are low compared to the fossil component, their variability between the best and worst variants is more than threefold, confirming the importance of selecting raw materials with regard to sustainable forestry or agricultural production.

Analysis of the ODP indicator (expressed in kg CFC11e) identifies three significant levels of environmental impact in the data set, which are likely related to the use of specific insulation materials or chemical additives. Critical values are reached mainly by two variants: PR8 (2.36×10^{-3} kg CFC11e) and PR4 (6.66×10^{-4} kg CFC11e), which exceed the average of the other compositions. These values indicate the presence of components whose manufacturing process and chemical composition have a negative impact on stratospheric ozone. The lowest impact on the ozone layer was recorded for variants PR1 (1.12×10^{-7} kg CFC11e), closely followed by variants PR3 and PR23. An interesting finding is that variant PR20, which ranked highest in the GWP categories as the

most hazardous, shows an average value for ODP (3.75×10^{-7} kg CFC11e), confirming that environmental optimization requires monitoring of multiple parallel indicators. The ADP-E indicator, which focuses on the consumption of non-renewable metals and minerals, shows a higher dependence on surface treatments and fasteners. Compositions using metal roofing and complex anchoring systems show increased consumption of rare raw materials. The PR20 composition has the highest impact, with a value of 0.069 kg Sbe. This value is more than five times higher than the second worst variant and indicates the use of specific components such as metals or rare minerals. The PR15 (0.013 kg Sbe), PR3 (0.0130 kg Sbe), and PR10 (0.0129 kg Sbe) variants also belong to the group with a higher impact. Conversely, the most favorable values are achieved by variants that minimize metal elements—specifically, systems with solid wood and kiln firing of tiles. The most resource-efficient compositions are PR14, PR23, and PR24, which achieve a minimum value of 0.0005 kg Sbe. An interesting finding is that variant PR9, which achieved the best results in the GWP category thanks to carbon sequestration, shows an average value (0.0012 kg Sbe) in the ADP-E category, which proves that biogenic materials can effectively reduce GWP-total without placing an excessive load on mineral resources. The analysis shows that phases A4 and A5 play a significant role in this indicator, which underlines the need for material optimization not only in the main layers but also in the additional assembly components.

3.1.2. LCA Results for Regional Indicators

In terms of regional indicators, the analyzed pitched roof compositions show significant variability, with the most critical impacts on the surrounding landscape and ecosystems associated with the PR20 variant. This variant is the best in the AP category, with a value of 0.215 kg SO_{2e}, and in POCP (0.011 kg $NMVOC_e$), which is a direct result of the industrial processing of titanium–zinc roofing. At the opposite end of the spectrum is the PR6 composition, which, with a minimum AP value (0.0041 kg SO_{2e}), represents the composition with the lowest values for regional biodiversity. While variants using biogenic materials such as cork and wood, such as composition PR9, show low toxicity and are environmentally friendly to aquatic ecosystems, industrially oriented compositions with a high proportion of metals and synthetic components increase the regional environmental load. This confirms a direct correlation between the GWP-total and the negative impact on the quality of environmental components within individual construction solutions. The results in the POCP category, which indicates the rate of smog formation in the ground layer of the atmosphere, show a direct dependence on the proportion of metal elements in the composition. The highest load among all compositions is represented by variant PR20, which reaches a value of 0.022 kg $NMVOC_e$ in product phases A1–A3. This unfavorable result is mainly due to the production of titanium–zinc roofing, which releases a significant amount of volatile organic compounds. On the contrary, the best solutions include variant PR13, with a value of 0.004 kg $NMVOC_e$, and variant PR18, with a value of 0.005 kg $NMVOC_e$, which represents up to four-times lower air pollution compared to the worst compositions. Although biogenic compositions such as PR9 show excellent results in global warming, their POCP index (0.021 kg $NMVOC_e$) remains relatively high, indicating that bio-based insulations and wood panels still have a measurable regional emission in the industrial processing process. In the eutrophication (EP) category, which assesses the degree of excessive nutrient enrichment in the environment, it shows the most unfavorable results in all three subcategories (freshwater, seawater, and soil), with its values in product phases A1–A3 being higher than in other compositions, reaching up to 0.007 kg P_e for EP-AF and 0.084 kg N_e for EP-AM. Conversely, the lowest values in terms of regional

impact on aquatic and soil biotopes can be attributed to variants PR2 and PR18, which achieve the lowest EP-AM (0.017 kg N_e) and EP-T (0.115 kg mole N_e).

This large difference is mainly due to the industrial intensity of titanium–zinc roofing production in the PR20 composition, while variants using clay tiles in combination with biogenic insulation materials minimize nitrogen and phosphorus emissions, thereby contributing to the stability of regional ecosystems. The authors of the study Schulte et al. [41] state that, although bio-insulations excel in saving fossil resources, categories such as eutrophication (EP) and water consumption (WD) may be higher than mineral insulations due to the agricultural and processing phase. Figures 6 and 7 illustrate regional indicators' results.

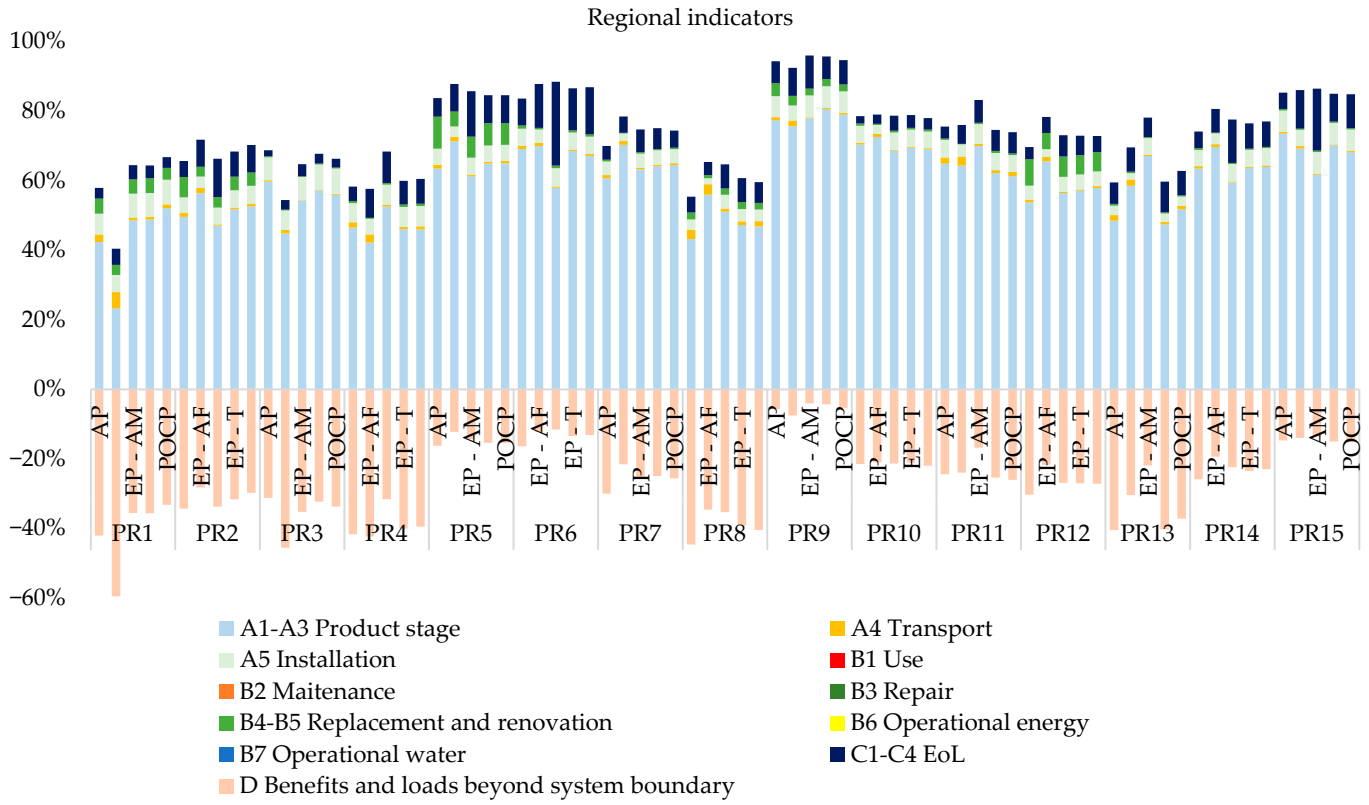


Figure 6. Regional category indicators for the analyzed roof compositions PR1 through PR15.

3.1.3. LCA Results for Local Indicators

Within the analysis, the ADP-FF and WD indicators show significant results that define the environmental profile of individual compositions. The highest emissions in terms of fossil fuel consumption are caused by variant PR20, whose value of 91.33 MJ is more than four times higher than the most economical composition PR16 (18.49 MJ), confirming the high energy intensity of titanium–zinc roofing production. In the WD category, however, the highest emissions are achieved by the PR9 variant with a value of 11.05 m^3, which proves that the processing of bio-based expanded cork can be more burdensome for water resources than industrial metal production (PR20—7.24 m^3). Conversely, the lowest impact on the regional water balance is shown by variants PR23 (0.39 m^3) and PR28 (0.40 m^3), which, together with their low fossil emissions, represent the most sustainable construction solutions in terms of these indicators. Aggarwal et al. in study [16] confirms the high variability in the ADP-FF category, where metal systems have the highest GWP due to energy-intensive primary production. Figure 8 illustrates the impacts of life cycle stages on local indicators.

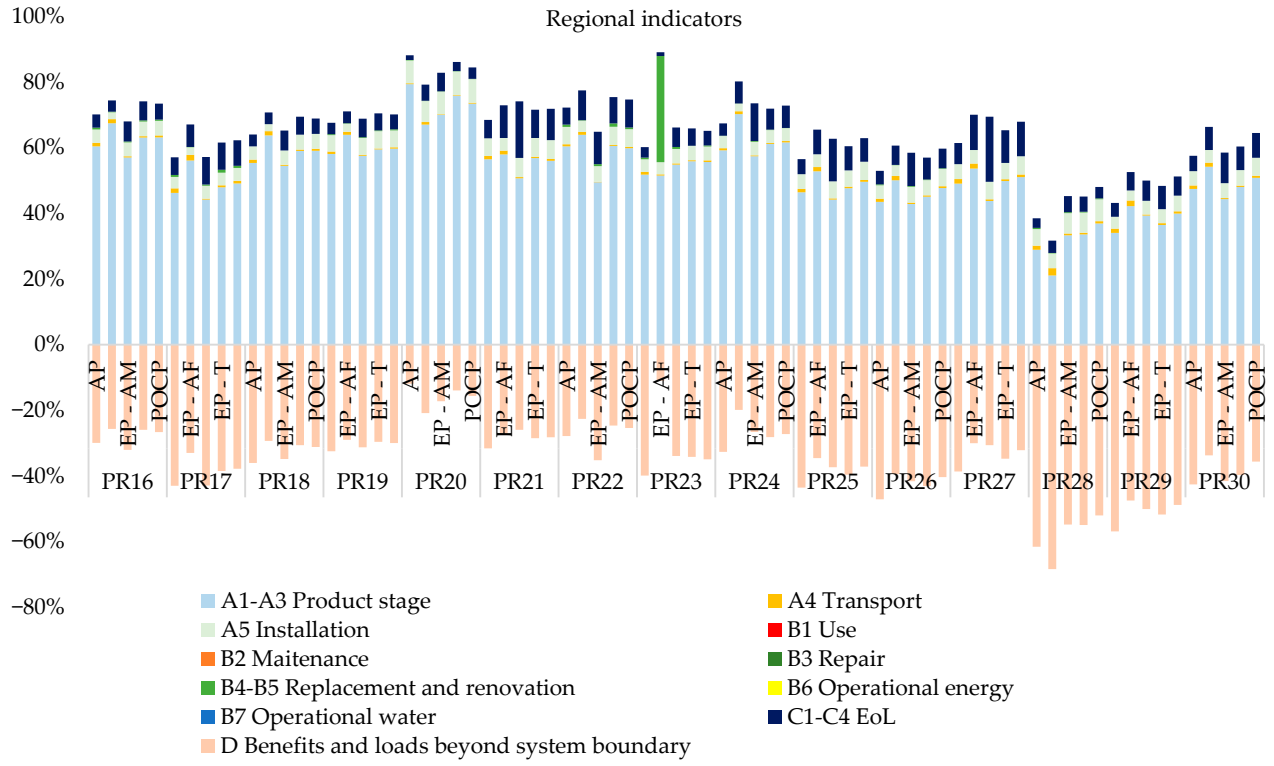


Figure 7. Regional category indicators for the analyzed roof compositions PR16 through PR30.

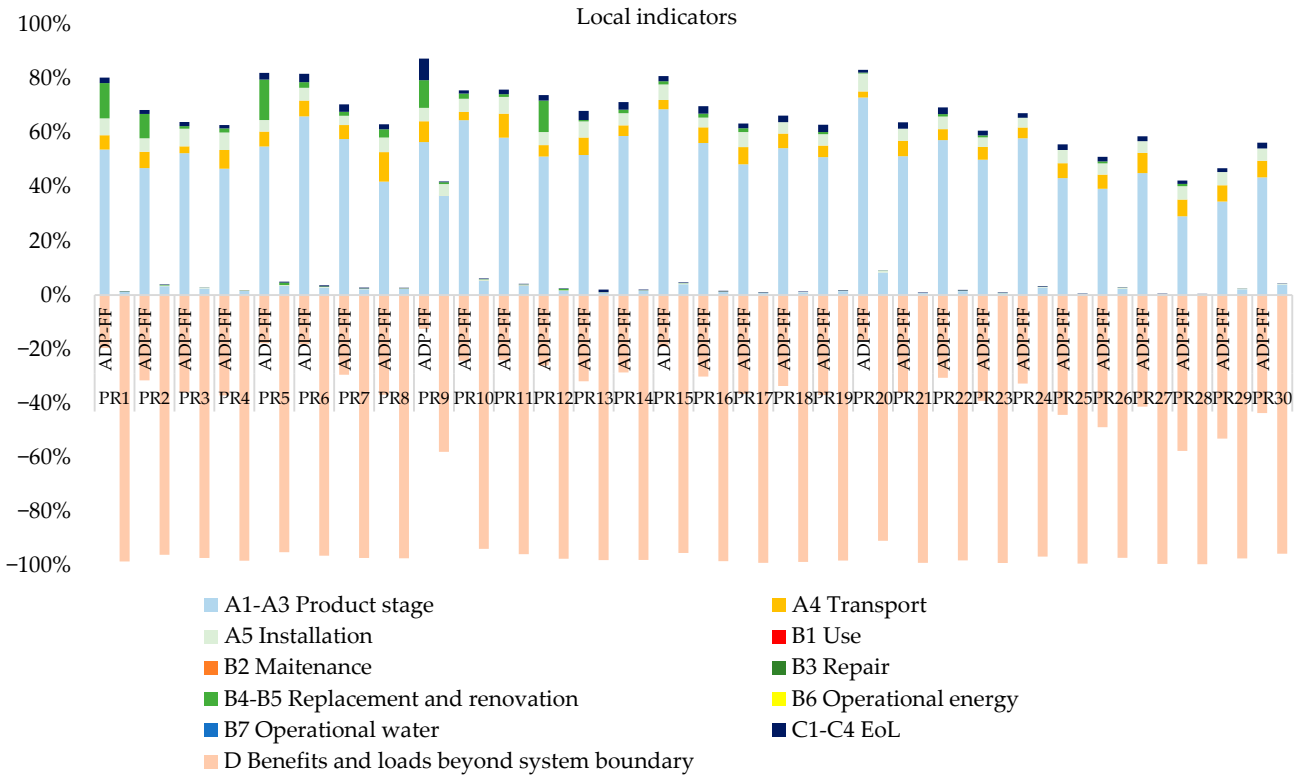


Figure 8. Calculated values of local environmental impacts for the entire set of analyzed compositions (PR1–PR30).

3.2. Multi-Criteria Analysis

Figure 9, with the MCA results, shows that both methods agree on the extreme values (the best and worst variants) but differ in the order of the mean values. The TOPSIS method

clearly identifies PR9 as the best variant (score 0.886), followed by PR19. The WSA method ranks PR19 in first place and PR9 in second place. Both methods agree that the absolute worst variant is PR20, which achieves the lowest score in both methods (TOPSIS: 0.0904; WSA: 0.1542). The PR19 composition achieved the best overall score (0.6817) in the WSA method. WSA is more sensitive to data normalization and, in this case, better reflected the balance of the PR19 variant across all regional indicators. The worst rating of PR20 confirms that its high energy consumption and water pollution outweighed its advantages. The TOPSIS method highlights variant PR9 as the best because it is geometrically closest to the ideal solution and furthest from the anti-ideal solution. This variant is best in the global warming category, although, according to detailed LCA data, it has high water consumption. TOPSIS was able to compensate for this disadvantage with other positive parameters. Conversely, the PR20 composition is the worst due to its extreme impacts in the ADP-FF (91.33 MJ) and AP (0.0409 mol H+ eq.) categories, which, in TOPSIS, were shown to be the furthest from the ideal. From the perspective of MCA analysis, variant PR9 is the most sustainable, and variant PR20 has several times higher impacts than other variants. The combination of LCA and TOPSIS is an effective tool for selecting building materials. While LCA comprehensively assesses environmental impacts throughout the life cycle, TOPSIS then seeks the optimal solution by balancing ecological, economic, and technical criteria [42]. This integration not only identifies problematic materials but also strategically prioritizes interventions to reduce the GWP-total of a project [43]. The result is more effective decision-making that improves the overall sustainability and operational performance of buildings. The combination of LCA and TOPSIS creates an effective decision support system that helps identify key steps to reduce the environmental impact of a building throughout its life cycle [42].

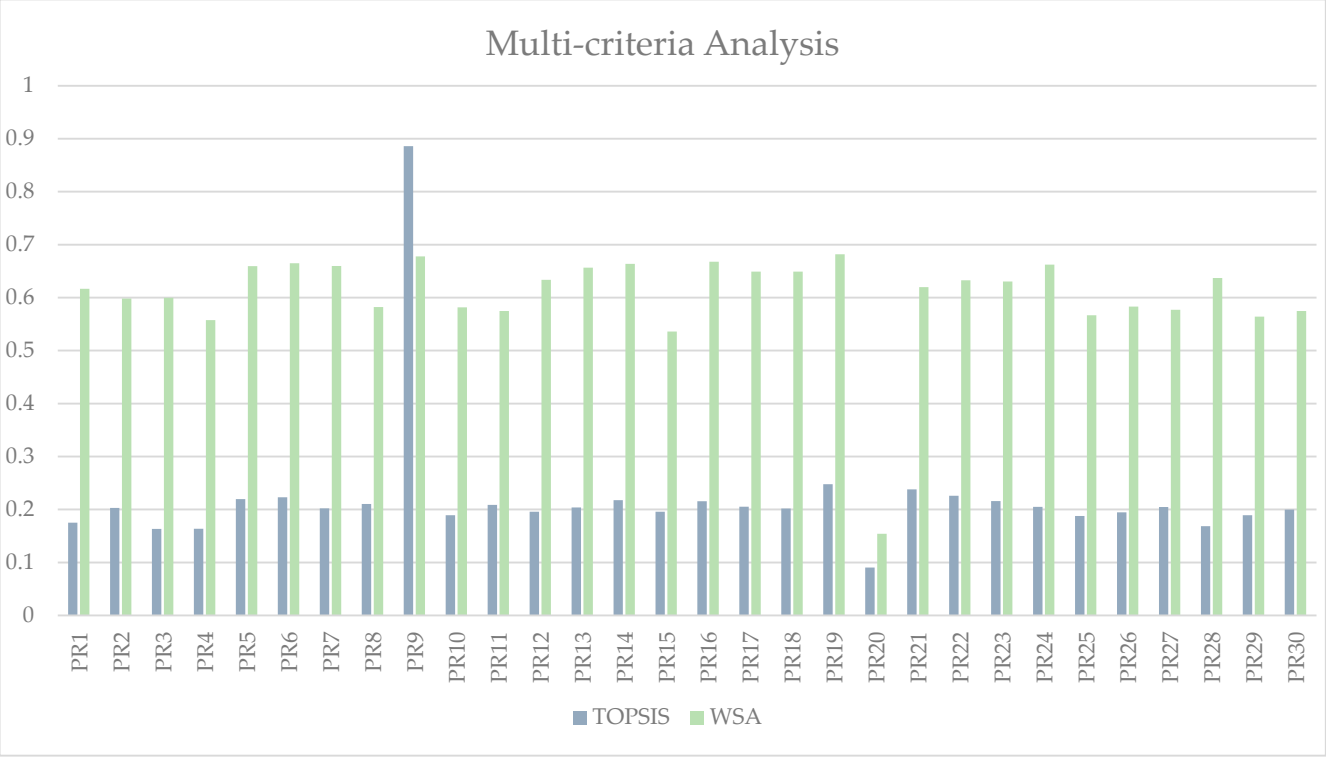


Figure 9. Comparative ranking of roof variants based on TOPSIS and WSA multi-criteria analysis.

3.3. Dynamic Life Cycle Analysis and Long-Term Comparison of Variants

Based on the application of the TOPSIS method, variants PR9 (best) and PR20 (worst) were identified for detailed analysis of the impact of time on environmental sustainability.

While static LCA analysis (50 years) primarily considers the initial impacts of materials, dynamic analysis (100 and 150 years) reveals key differences resulting from the frequency of maintenance and the lifespan of individual layers (Figure 10).

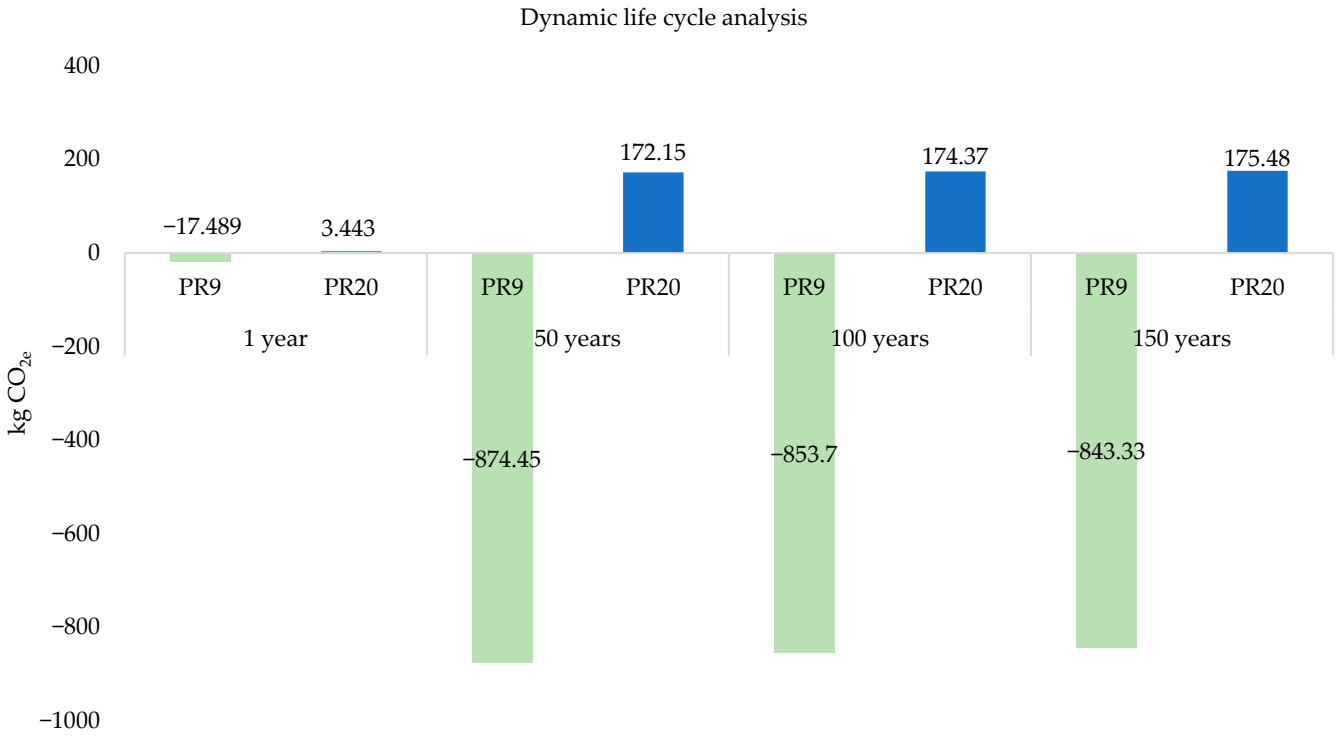


Figure 10. Comparison of GWP-total over 1, 50, 100, and 150-year periods.

The assessment of the environmental impacts of pitched roof composition over time horizons of 50, 100, and 150 years demonstrates a fundamental difference between the initial GWP and long-term sustainability. Dynamic analysis reveals key differences resulting from maintenance frequency and lifespan, where the PR20 variant shows a stable positive GWP-total that increases slightly over time from 172.15 kg CO_{2e} (50 years) to 175.48 kg CO_{2e} (150 years). Conversely, the PR9 variant, using a combination of cork insulation and clay tiles, demonstrates excellent results throughout the analyzed period and remains highly carbon negative even as the time horizon increases. In terms of life cycle phases, the standard 50-year lifetime is dominated by impacts associated with material production (phases A1–A3), where bio-based materials such as cork benefit from carbon sequestration. The composition of the PR9 pitched roof shows a negative value of −1096.24 kg CO_{2e} in phases A1–A3, meaning that the materials used (especially cork and wood) stored more emissions during their growth than were consumed in their processing. On the other hand, for the PR20 variant, the greatest load is represented by the C1–C4 phases and the need to replace materials, which are only partially offset by the potential for recycling zinc roofing in phase D. Although PR20 has high recyclability, high end-of-life emissions and the need for maintenance over time make it less environmentally advantageous than PR9. As the assessment extends to 100 and 150 years, the importance of the maintenance (B2–B3) and end-of-life (C1–C4) phases increases, placing emphasis on the durability of the structure and the ability of materials to be recycled or biodegraded without a negative environmental impact.

The PR9 pitched roof variant, which uses a combination of cork insulation and fired roofing tiles, shows excellent results throughout the entire period analyzed. Clay roof tiles are characterized by a long lifespan, often exceeding 80–100 years, and at the end of their lifespan they are fully recyclable as construction waste. This combination minimizes the

need for frequent replacements, resulting in cumulative CO_{2e} emissions over a 150-year horizon that increase significantly more slowly compared to variants requiring frequent roofing replacement. Conversely, although the PR20 option has a higher initial environmental impact (mainly due to the production of zinc roofing), it demonstrates the benefits of the circular economy in the long term. After considering emission credits for the high recyclability of metal elements, the impact of PR20 over a 150-year horizon is partially offset, although the total cumulative impact may still exceed options with more bio-based maintenance and recyclable roofing, such as PR9. The results confirm that the optimal decision depends on the defined time horizon of the project, but for long-term sustainability, materials with high carbon sequestration capacity and long service life dominate. In this case, the TOPSIS methodology clearly confirms PR9 as the optimal solution for sustainable construction, with a significant ability to offset emissions compared to PR20 over the entire 150-year period.

3.4. Sensitivity Analysis

To determine the extent of the impact of climate zone change on the total GWP and to verify the robustness of the proposed model, a sensitivity analysis was performed. The sensitivity analysis examined the impact of climate change on the environmental profile of the best variant of the PR9 pitched roof. As part of this analysis, the composition of the PR9 pitched roof (temperate zone) was adjusted for the needs of the cold and two subtropical zones, which primarily includes changing the thickness of the cork insulation to achieve the desired heat transfer coefficient in the given locations. Given the variability of climate conditions, a sensitivity analysis was performed to examine how the thickness of the insulation layer changes the resulting GWP. Table 2 documents the impact of climate zone on the total GWP, depending on the thickness of the insulation used.

Table 2. Comparison of environmental impacts (kg CO_{2e}) in four climate zones and percentage difference between moderate and cold/subtropical zones.

Climate Zone	Thickness mm	Cork Insulation (A1–A3)	Assembly PR9 (A1–A3)	Assembly PR9 (A–D)
Moderate climate (U = 0.1 W/m^2·K)	400	−17.94	−21.92	−17.49
Cold climate (U = 0.09 W/m^2·K)	450	−18.35	−22.36	−17.85
Difference %	–	2.27	1.99	2.09
Subtropic climate 1 (U = 0.25 W/m^2·K)	160	−6.53	−10.51	−7.10
Difference %	–	−63.64	−52.08	−59.41
Subtropic climate 2 (U = 0.5 W/m^2·K)	80	−3.26	−7.24	−4.13
Difference %	–	−82	−67	−76

The sensitivity analysis showed that the GWP-total of the PR9 pitched roof structure is highly sensitive to changes in the thickness of the cork thermal insulation layer, depending on the climate zone. The results confirm a direct linear relationship between the insulation thickness and the total GWP, indicating that any reduction in the insulation thickness reduces the volume of biogenic carbon sequestered in the production phase (A1–A3). This decrease in carbon sequestration capacity subsequently leads to an increase in the total emissions of the structure. The most significant drop in carbon sequestration, up to 82%, occurs when the insulation thickness is reduced from 400 mm to 80 mm in subtropical conditions. While increasing the thickness to 450 mm for the cold zone brings an additional reduction in total emissions of 2.09% compared to the reference moderate zone, an excessive reduction in the thickness in subtropical zone 2 leads to an increase in total emissions of up

to 76% compared to the original scenario. This increase is a direct consequence of the loss of the cork layer's ability to compensate for the emissions of other components of the pitched roof, which fundamentally changes the overall environmental profile of the composition.

4. Discussion

The results of the LCA analysis of 30 variants of pitched roofs showed that the choice of thermal insulation material is a critical factor in determining the overall environmental profile of the structure. The main role of insulation in buildings is to reduce heat flows and energy consumption, which is also confirmed by Villasmil et al. [44] and Schiavoni et al. [45]. The key technical property of all the materials considered in our study was low thermal conductivity ($\lambda < 0.1$ W/m·K), which is in accordance with the standard for insulation materials defined by the author Berardi in his study [46]. While commonly used thermal insulations such as mineral wool (PR1) show a similar level of environmental load in LCA studies, the use of natural biomaterials in our research opened space for a significant reduction in global impacts. This trend is also confirmed by an extensive review of 47 publications [47]. Compared to polystyrene thermal insulations, which, according to Llantoya et al. [48], have the greatest negative impact on the environment, mineral wool (PR1) appears to be an acceptable conventional standard but does not achieve the advantages of progressive natural formulations. There is also agreement with the literature in the identification of the main sources of load. In a conventional pitched roof with mineral wool (PR1), the energy-intensive production process (melting of the raw material) dominates. In contrast, in progressive natural variants, the influence of additives and binders comes to the fore, which negatively affect the ODP and the AP values, as documented by Füchsl et al. [47]. The results in this study suggest that the environmental benefit of natural thermal insulation may be partially reduced due to less advanced production technology, such as crushing or agglomeration [39]. This explains the presence of emissions in the GWP-fossil also for natural thermal insulation materials in this study. The inclusion of biogenic carbon sequestration in this study proved to be crucial for an objective assessment, as confirmed by Demertzi et al. [49] on the example of cork insulation. If GWP-biogenic were considered neutral, our progressive wood-based compositions would lose their main benefit in the GWP category. It is the negative GWP-total values for variants PR19 to PR30 that document the ability of these structures to function as temporary carbon storage. The environmental payback, i.e., the time required to compensate for the initial impact of the system [50], is theoretically instantaneous for natural materials due to sequestration within the A1–A3 product phase. In line with the research of Cozzarini et al. [51], it was confirmed that the environmental benefits are not fixed but closely related to the local energy mix. Therefore, in this study we adjusted the best identified composition for different temperature zones. This approach considered the variability of energy needs in a global context. Our findings also highlight the need to prioritize local distribution of raw materials [39], thus minimizing the impact of transport on global indicators and maximizing the net benefit of sequestration. Although natural thermal insulation materials show a high potential for sequestration, LCA results indicate that natural origin is not the only condition for success. The GWP-total is strongly influenced by the technological complexity of processing and logistics. The dynamic analysis for 50, 100 and 150 years in this study follows the concept of long-term sustainability, where the goal is not only to reduce emissions immediately during construction but to retain carbon in the structure throughout its life cycle. The sustainability of a building material throughout its entire life cycle is determined not only by the resulting LCA value but above all by the interplay of four key factors: low carbon intensity of production using renewable raw materials (phases A1–A3); high durability and minimized maintenance (phase B),

which prevent premature replacement; circularity potential (module D), enabling reuse or high-quality recycling after disassembly; and, last but not least, local availability combined with chemical safety, which excludes the use of toxic substances that degrade the material upon its return to the natural or technical cycle [52].

5. Study Limitations and Future Research

Despite the comprehensive approach of this LCA study, certain limitations must be acknowledged. First, the environmental assessment was based on EPD data and databases provided by the software, which may vary across different manufacturers and regions, potentially affecting the absolute accuracy of the results. Second, the study focused primarily on the product and construction phases, while the maintenance and end-of-life phases were modeled using standardized scenarios. Future research should focus on a more detailed analysis of the operational energy performance of these 30 roof variants in different climate zones to integrate the LCA results with a life cycle energy perspective. Furthermore, investigating the long-term durability of bio-based insulation materials under realistic environmental conditions represents an important direction for future studies to further validate the sustainability of wooden roof structures.

6. Conclusions

This study presented a life cycle assessment (LCA) of 30 variants of pitched roof compositions with different structural systems and insulation materials. The results confirmed that the material composition of roof assemblies significantly influences their environmental performance. Roof variants incorporating bio-based materials, particularly cork insulation and wooden structural elements, achieved considerably lower environmental impacts compared to conventional solutions based on mineral or industrial materials.

Among the evaluated variants, the PR9 composition showed the most favorable environmental profile, achieving the lowest value of global warming potential (GWP-total) due to the high carbon sequestration capacity of biogenic materials. In contrast, the PR20 variant demonstrated the highest environmental burden, mainly due to the use of energy-intensive titanium–zinc roofing and a lower share of renewable materials.

In addition to global climate goals, the study demonstrated significant variability in regional and local indicators that directly affect biodiversity and ecosystem quality in the proximity of emission sources. In the category of regional impacts (AP, EP, POCP), variant PR20 appeared to be the most critical, which is a direct consequence of the industrial processing of titanium–zinc roofing. Conversely, advanced formulations utilizing bio-based materials (e.g., PR9 with cork insulation) show low toxicity and are more environmentally friendly to aquatic ecosystems. For local indicators (ADP-FF, WU), the analysis confirmed that, while biogenic materials effectively reduce the total global warming potential (GWP-total), their technological processing and the additives used may, in some cases, increase the local environmental impact, highlighting the need for a multi-criteria assessment in the design of sustainable roof constructions.

The results of the multi-criteria analysis (TOPSIS and WSA) confirmed the findings of the LCA assessment and consistently identified PR9 and PR19 as the most sustainable roof compositions, while PR20 was evaluated as the least environmentally favorable option. Dynamic life cycle analysis further showed that bio-based roof systems can maintain their environmental advantage even over longer time horizons, particularly when durable materials with long service life are used.

The findings highlight the significant potential of bio-based materials to reduce the GWP-total of roof structures and support the decarbonization of the construction sector. The results provide useful guidance for the design of environmentally optimized building

envelopes and emphasize the importance of considering environmental impacts throughout the entire life cycle of building components.

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Abbreviations

The following abbreviations are used in this manuscript:

ADP-E	Abiotic depletion potential of elements
ADP-FF	Abiotic depletion potential of fossil fuels
AP	Acidification Potential
CDA	Concordance discordance analysis
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide equivalent
EP	Eutrophication potential
EP-T	Eutrophication potential terrestrial
EP-AF	Eutrophication potential of aquatic freshwater
EP-AM	Eutrophication potential of aquamarine
EoL	End of Life
EPD	Environmental product declarations
FU	Functional unit
GHG	Greenhouse gas
GWP-bio	Global warming potential biogenic
GWP-fossil	Global warming potential fossil
GWP-LULUC	Global warming potential land use and land use change
GWP-total	Global warming potential total
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MCA	Multi-criterial analysis
OCL	OneClickLCA
ODP	Ozone depletion potential
PE	Polyethylene
PEF	Environmental footprint of the product
PR	Pitched roof
POCP	Photochemical ozone creation potential
R	Thermal resistance
R_N	Thermal resistance standard
TOPSIS	Technique for order preference by similarity to ideal solution
U	Heat transfer coefficient

U_N	Heat transfer coefficient standard
WD	Water deprivation

References

1. Dsilva, J.; Zarmukhambetova, S.; Locke, J. Assessment of building materials in the construction sector: A case study using life cycle assessment approach to achieve the circular economy. *Heliyon* **2023**, *9*, e20510. [CrossRef]
2. Cao, R.; Hao, Y.; Li, Y.; Liao, W. Emerging trends in lifecycle assessment of building construction for greenhouse gas control: Implications for capacity building. *Discov. Appl. Sci.* **2025**, *7*, 398. [CrossRef]
3. Moustafa, Z.; Asif, M.; Wuni, I.Y. Circular economy in the building sector: A systematic review of environmental, economic, and social dimensions. *Sustain. Futures* **2025**, *9*, 100690. [CrossRef]
4. Joensuu, T.; Leino, R.; Heinonen, J.; Saari, A. Developing buildings' life cycle assessment in circular economy—Comparing methods for assessing carbon footprint of reusable components. *Sustain. Cities Soc.* **2022**, *77*, 103499. [CrossRef]
5. Gay, I.C.; Hvam, L.; Haug, A.; Huang, G.Q.; Larsson, R. A digital tool for life cycle assessment in construction projects. *Dev. Built Environ.* **2024**, *20*, 100535. [CrossRef]
6. Barbhuiya, S.; Das, B.B. Life cycle assessment of construction materials: Methodologies, applications and future directions for sustainable decision-making. *Case Stud. Constr. Mater.* **2023**, *19*, e02326. [CrossRef]
7. Katebi, A.; Tushmanlo, H.S.; Asadollahfardi, G. Environmental life cycle assessment and economic comparison of different roof systems. *J. Build. Eng.* **2023**, *76*, 107316. [CrossRef]
8. Maxineasa, S.G.; Entuc, I.S.; Taranu, N.; Florenta, I.; Secu, A. Environmental performances of different timber structures for pitched roofs. *J. Clean. Prod.* **2018**, *175*, 164–175. [CrossRef]
9. Finamore, M.; Oltean-Dumbrava, C. Circular economy in construction—Findings from a literature review. *Heliyon* **2024**, *10*, e34915. [CrossRef]
10. Karakosta, C.; Papathanasiou, J. Decarbonizing the construction sector: Strategies and pathways for greenhouse gas emissions reduction. *Energies* **2025**, *18*, 1285. [CrossRef]
11. Andersen, S.C.; Hollberg, A.; Browne, X.; Wallbaum, H.; Birgisdóttir, H.; Larsen, O.P.; Birkved, M. Environmental impacts of circularity in the built environment: How do system boundaries affect decision support? *Dev. Built Environ.* **2024**, *18*, 100398. [CrossRef]
12. Bourbia, S.; Kazeoui, H.; Belarbi, R. A review on recent research on bio-based building materials and their applications. *Mater. Renew. Sustain. Energy* **2023**, *12*, 117–139. [CrossRef]
13. Cuce, P.M. Sustainable insulation technologies for low-carbon buildings: From past to present. *Sustainability* **2025**, *17*, 5176. [CrossRef]
14. Askar, A.H.; Omle, I.; Kovács, E. The role of roof angle and geographic location on the thermal performance of buildings. *Int. J. Thermofluids* **2025**, *27*, 101192. [CrossRef]
15. Chen, C.; Hou, H.; Shi, Y.; Zhao, P.; Li, Y.; Wang, Y.; Hu, T. Impact of different building roof types on hydrological processes at the urban community scale. *Hydrology* **2025**, *12*, 154. [CrossRef]
16. Aggarwal, C.; Molleti, S.; Ghobadi, M. A comprehensive review of life cycle assessment (LCA) studies in roofing industry: Current trends and future directions. *Smart Cities* **2024**, *7*, 2781–2801. [CrossRef]
17. Mihalakakou, G.; Souliotis, M.; Papadaki, M.; Menounou, P.; Dimopoulos, P.; Kolokotsa, D.; Papaefthimiou, S. Green roofs as a nature-based solution for improving urban sustainability: Progress and perspectives. *Renew. Sustain. Energy Rev.* **2023**, *180*, 113306. [CrossRef]
18. Theilig, K.; Lourenço, B.; Reitberger, R.; Lang, W. Life cycle assessment and multi-criteria decision-making for sustainable building parts: Criteria, methods, and application. *Int. J. Life Cycle Assess.* **2024**, *29*, 1965–1991. [CrossRef]
19. Scolaro, T.P.; Ghisi, E. Life cycle integrated multi-criteria decision model for roof assessment. *Energy Build.* **2025**, *336*, 115628. [CrossRef]
20. Sackey, S.; Kim, B.S. Environmental and economic performance of asphalt shingle and clay tile roofing sheets using life cycle assessment approach and TOPSIS. *J. Constr. Eng. Manag.* **2018**, *144*, 04018104. [CrossRef]
21. Mouton, L.; Allacker, K.; Röck, M. Bio-based building material solutions for environmental benefits over conventional construction products—Life cycle assessment of regenerative design strategies. *Energy Build.* **2023**, *282*, 112767. [CrossRef]
22. Van de Moortel, E.; Allacker, K.; De Troyer, F.; Schoofs, E.; Stijnen, L. Dynamic versus static life cycle assessment of energy renovation for residential buildings. *Sustainability* **2022**, *14*, 6838. [CrossRef]
23. Lira, J.S.; da Silva, E.A. A systematic literature review of dynamic life cycle assessment in buildings: Challenges and guidelines. *J. Build. Eng.* **2025**, *111*, 113503. [CrossRef]
24. Cascione, V.; Roberts, M.; Allen, S.; Charbel, C.; Maskell, D.; Dams, B.; Emmitt, S. Evaluating environmental impacts of bio-based insulation materials through scenario-based and dynamic life cycle assessment. *Int. J. Life Cycle Assess.* **2025**, *30*, 601–620. [CrossRef]

25. Zong, C.; Banihashemi, F.; Lang, W. Dynamic life cycle impact assessment (DLCIA) in a sustainable building planning process. *Sci. Rep.* **2025**, *15*, 32680. [CrossRef]
26. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006.
27. *ISO 14044:2006*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006.
28. *EN 15804:2012+A2:2019/AC:2021*; Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. European Committee for Standardization: Brussels, Belgium, 2021.
29. European Commission. Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations. *Off. J. Eur. Union* **2021**, *471*, 1–396.
30. *ISO 14025:2006*; Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures. International Organization for Standardization: Geneva, Switzerland, 2006.
31. *ISO 14067:2018*; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. International Organization for Standardization: Geneva, Switzerland, 2018.
32. *ISO 14020:2022*; Environmental Statements and Programmes for Products—Principles and General Requirements. International Organization for Standardization: Geneva, Switzerland, 2022.
33. Youssef, A.E. An integrated MCDM approach for cloud service selection based on TOPSIS and BWM. *IEEE Access* **2020**, *8*, 71851–71865. [CrossRef]
34. Zavadskas, E.K.; Turskis, Z. Multiple decision making (MCDM) methods in economics: An overview. *Technol. Econ. Dev. Econ.* **2011**, *17*, 397–427. [CrossRef]
35. Sahabuddin, M.; Khan, I. Multi-criteria decision analysis methods for energy sector's sustainability assessment: Robustness analysis through criteria weight change. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101380. [CrossRef]
36. Hauschild, M.Z.; Rosenbaum, R.K.; Olsen, S.I. *Life Cycle Assessment: Theory and Practice*; Springer: Cham, Switzerland, 2018.
37. *STN 73 0540-2:2019*; Tepelná Ochrana Budov. Tepelnotechnické Vlastnosti Stavebných Konštrukcií a Budov. Časť 2: Funkčné Požiadavky. Úrad Pre Normalizáciu, Metrológiu a Skúšobníctvo SR: Bratislava, Slovakia, 2019.
38. Vilčeková, S.; Budajová, J.; Harčárová, K.; Mésároš, P.; Burdová, E.K.; Zimermann, R. The impact of green roofs' composition on its overall life cycle. *J. Environ. Manag.* **2024**, *369*, 122363. [CrossRef]
39. Sierra-Pérez, J.; Boschmonart-Rives, J.; Dias, A.C.; Gabarrell, X. Environmental implications of the use of agglomerated cork as thermal insulation in buildings. *J. Clean. Prod.* **2016**, *126*, 97–107. [CrossRef]
40. Zabalza Bribián, I.; Capilla, A.V.; Aranda Usón, A. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Build. Environ.* **2011**, *46*, 1133–1140. [CrossRef]
41. Schulte, M.; Lewandowski, I.; Pude, R.; Wagner, M. Comparative life cycle assessment of bio-based insulation materials: Environmental and economic performances. *GCB Bioenergy* **2021**, *13*, 979–998. [CrossRef]
42. Yardimci, Y.; Kurucay, E. LCA-TOPSIS integration for minimizing material waste in the construction sector: A BIM-based decision-making approach. *Buildings* **2024**, *14*, 3919. [CrossRef]
43. Yadav, J.; Singh, V.P.; Kumar, A. Life Cycle Assessment of Sustainable Building Materials. In *Sustainable Technologies for Energy Efficient Buildings*; CRC Press: Boca Raton, FL, USA, 2024; pp. 64–101.
44. Villasmil, W.; Fischer, L.J.; Worlitschek, J. A review and evaluation of thermal insulation materials and methods for thermal energy storage systems. *Renew. Sustain. Energy Rev.* **2019**, *103*, 71–84. [CrossRef]
45. Schiavoni, S.; Bianchi, F.; Asdrubali, F. Insulation materials for the building sector: A review and comparative analysis. *Renew. Sustain. Energy Rev.* **2016**, *62*, 988–1011. [CrossRef]
46. Berardi, U. The impact of aging and environmental conditions on the effective thermal conductivity of several foam materials. *Energy* **2019**, *182*, 777–794. [CrossRef]
47. Füchsl, S.; Rheude, F.; Röder, H. Life cycle assessment (LCA) of thermal insulation materials: A critical review. *Clean. Mater.* **2022**, *5*, 100119. [CrossRef]
48. Llantoy, N.; Chàfer, M.; Cabeza, L.F. A comparative life cycle assessment of different insulation materials for buildings in the continental Mediterranean climate. *Energy Build.* **2020**, *225*, 110323. [CrossRef]
49. Demertzi, M.; Sierra-Pérez, J.; Paulo, J.A.; Arroja, L.; Dias, A.C. Environmental performance of expanded cork slab and granules through life cycle assessment. *J. Clean. Prod.* **2017**, *145*, 294–302. [CrossRef]
50. De Gracia, A.; Navarro, L.; Castell, A.; Boer, D.; Cabeza, L.F. Life cycle assessment of a ventilated facade with PCM in its air chamber. *Sol. Energy* **2014**, *104*, 115–123. [CrossRef]

51. Cozzarini, L.; Marsich, L.; Ferluga, A.; Schmid, C. Life cycle analysis of a novel thermal insulator obtained from recycled glass waste. *Dev. Built Environ.* **2020**, *3*, 100014. [CrossRef]
52. Schöggl, A.P.J.P. Evaluating Lifetime Extension Strategies to Close the Loop: Comparing the Material Circularity and Environmental Life Cycle Performance of Traction Batteries. Ph.D. Thesis, University of Graz, Graz, Austria, 2025.

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