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Research paper

OPTIMIZING BUILDING SUSTAINABILITY: A LIFE-CYCLE CO_2 EMISSIONS ASSESSMENT OF NOVEL AND CONVENTIONAL INSULATION WALL MATERIALS

Hamed Afsoosbiria[1,2], Hesam Afsoosbiria[3], Agnieszka Machowska[4]

Abstract

The growing concern over climate change has intensified the need to control greenhouse gas emissions, particularly in the building sector. A significant portion of a building's environmental impact arises during its operational phase, primarily due to energy consumption for heating and cooling. Insulation wall materials play a crucial role in enhancing energy efficiency by reducing heat transfer, thereby lowering energy demand and long-term carbon emissions. However, the selection of insulation materials is often driven by technical performance, with limited consideration of their full life-cycle impact.

This study adopts a Life Cycle Assessment (LCA) approach to evaluate the environmental performance of various insulation materials, comparing their embodied carbon, thermal properties, and overall contribution to sustainability. By analyzing both conventional and emerging solutions, the research aims to provide quantitative insights that assist in selecting materials that balance energy efficiency, durability, and environmental impact. The findings will contribute to informed decision-making in sustainable construction, supporting efforts to minimize the carbon footprint of buildings while maintaining optimal thermal performance.

Key words: *Sustainable Construction, Environmental Impact, Life Cycle Assessment (LCA), Low-Carbon Buildings, Thermal Envelope.*

[1] MSc. Eng. Hamed Afsoosbiria, Doctoral study, VSB-TU Ostrava, Faculty of Civil Engineering, e-mail: hamed.afsoosbiria@vsb.cz, Czech Republic, ORCID: 0000-0002-7210-6379.

[2] Faculty of Civil Engineering, Warsaw University of Technology, 00-637 Warsaw, Poland; hamed.afsoosbiria.stud@pw.edu.pl, Poland, ORCID: 0000-0002-7210-6379.

[3] MSc. Eng. Hesam Afsoosbiria, Doctoral study, Warsaw University of Technology, Faculty of Environmental Engineering, e-mail: hesam.afsoosbiria.dokt@pw.edu.pl, Poland, ORCID: 0000-0002-9408-6073.

[4] DSc, PhD. Eng. Agnieszka Machowska, university professor, Warsaw University of Technology, Faculty of Environmental Engineering, e-mail: agnieszka.machowska@pw.edu.pl, Poland, ORCID: 0000-0002-3573-6822.

1. INTRODUCTION

The building sector is regarded as one of the largest energy consumers worldwide. Consequently, insulation plays a crucial role in reducing the energy consumption of this sector [1]. The energy consumption of a building strongly depends on the characteristics of its envelope [2]. The envelope is recognized as a key component in enhancing thermal efficiency, as it accounts for between 50% and 60% of the total heat transfer [3]. The thermal performance of external walls illustrates a key factor in increasing the energy efficiency of the building sector and reducing greenhouse gas emissions. Thermal insulation is definitely one of the most effective methods to reduce energy consumption due to both winter heating and summer cooling [2]. The choice of suitable insulation materials is one of the fundamental methods for reducing a building's energy consumption. The thermal performance of insulating materials can directly influence the shape of the building's energy consumption and effectively minimize heat transfer from building envelopes, both internally and externally, helping in the provision of more desired indoor thermal comfort for residents [4]. Materials for building insulation, with proposed solutions, can be categorized as either traditional or state-of-the-art. The most widely used, conventionally available low-thermal-conductive building insulation materials are cellulose, cork, EPS, polyurethane, and XPS [5]. Insulation materials in the construction industry are essential to enhancing the thermal performance of buildings, reducing energy demands, and carbon emissions. In transitioning to a low-carbon economy, building renovations can significantly enhance energy Europe, deep renovation of the EU's existing stock (110 million buildings) and new construction could result in 80% of cumulative energy savings by 2050. The EU's need for insulation materials has increased to reduce energy consumption, and this trend is expected to continue [6]. As new constructions are characterized by reduced operational energy use, more attention should be paid to the Global Warming Potential (GWP) of building materials and systems.

Life Cycle Assessment (LCA) is one of the most effective strategies for monitoring environmental consequences throughout the life cycle and calculating carbon footprints. It is a tool that is increasingly being used in various areas of the construction sector to evaluate impacts on ecosystems, natural resources, and human health by using a standardized approach to model, assess, and quantify the impacts of a product or process over a complete time horizon extended to the useful life of products [7]. By analyzing both novel and conventional options, this study intends to provide quantitative insights that will help in the choice of materials that balance energy efficiency, durability, and environmental impact. The findings will assist in influencing decision-making in sustainable design, supporting attempts to reduce buildings' carbon footprint while maintaining optimal thermal performance.

2. INSULATION BUILDING MATERIALS AND THEIR CONTRIBUTION TO SUSTAINABILITY

Thermal insulation systems and materials are designed to lessen heat flow transmission. The thermal insulation performance of individual or combined homogeneous materials is generally determined by thermal conductivity and thermal transmittance [8]. The insulation of the external envelopes constructs the main stage in ensuring the energy efficiency of a building. There are many alternatives available for insulation materials [9]. The performance of thermal insulation of the building's vertical walls can be considered as an investment for economic objectives. This investment, however, has a notable impact on the environment. On the one hand, there must be some costs incurred, associated with production, transport, and location of thermal insulation. On the other hand, during the use of the building phase, there is a depletion in energy demand for heating [10,11]. The most important parameters that state the thermal performance of an insulation material are the thermal conductivity λ (W/mK) for the steady state and the thermal diffusivity D for the unsteady state [2]. A material is mainly considered a thermal insulator if its conductivity is lower than 0.07 W/mK [8]. Thermal conduction, also known as U-Value, and the development of requirements for the U-Value [W/(m^2·K)] of walls from 1962 to 2024 is shown in Figure 1 [12]. The choice of insulation materials is important both for the construction of new buildings and retrofitting, i.e., throughout the operational phase of the building. There exists a variety of insulation materials exhibiting different properties [13].

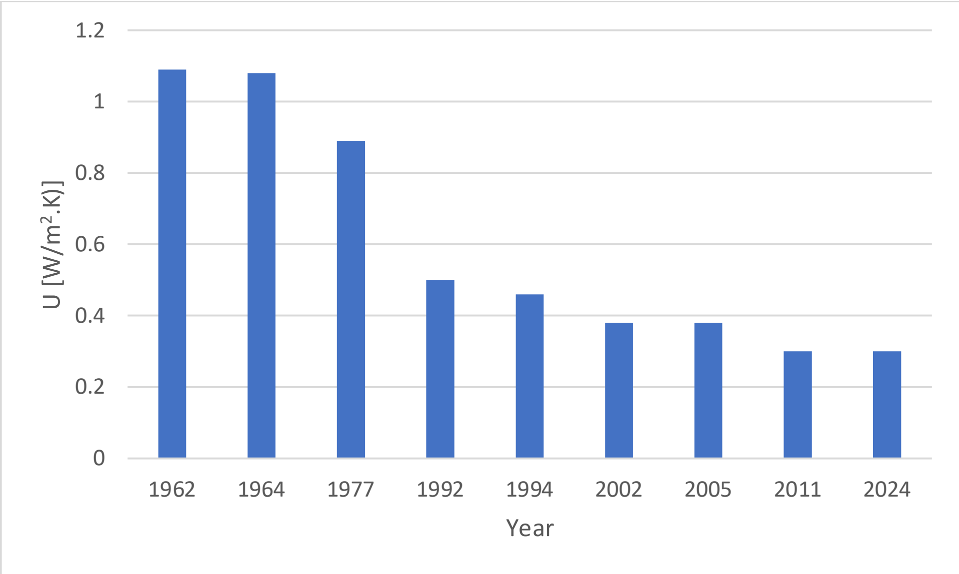

Figure 1. Development of requirements for the heat transfer coefficient of walls (bar chart elaborated based on [12]).

In recent decades, the sustainable development of the planet has been negatively influenced by several factors, including the building industry. Further, demands for energy savings have increased [14]. Accordingly, the European Union's significant objectives for 2030 and 2050 imply that energy measures, climate neutrality, CO_2 decline, and emphasis on the Green Deal [15] strongly emphasize the construction industry [14]. As there is a growing awareness of the environmental impact of building materials. This has given rise to the development of more sustainable building products that attempt to decrease embodied carbon emissions, lessen reliance on non-renewable resources, and improve indoor environmental quality [16]. The building sector is considered one of the key consumers of energy, where the major usage accounts for the heating and cooling of the building. Energy consumption could be reduced using novel insulation strategies, and the building would be energy-efficient in this scenario as it would need less heating in winter and less cooling in summer to maintain the desired internal temperature [1,17]. A well-insulated home will assist in reducing energy use and, in turn, the consumption of fossil fuels and the production of carbon emissions. Enhancing a home's energy efficiency, through better insulation, for example, can lessen its carbon footprint.

2.1. Classification of Wall Insulation Building Materials

Insulation has a critical function in improving environmental sustainability. It is an essential element in reducing the consumption of energy, limiting carbon dioxide release, and supporting the overall goal of creating a more sustainable future for our planet. These materials can be categorized based on their function, specifically directed at insulation materials for walls in the EU. This categorization eases a comparative analysis of novel (innovative) and common (traditional) materials, allowing a more effective evaluation of their performance and properties. Table 1 presents different Thermal Insulation groups for residential buildings and their features. Here, the insulation material is divided into 4 types, namely Bio-Based (Organic), Mineral-Based (Inorganic), Petrochemical (Organic Chemistry), and Advanced materials. In addition, 18 kinds of wall insulation materials are assessed.

Table 1. Characteristics of different types of insulation materials

Thermal Insulation Category	Type	Thermal Conductivity (W/m. K)	Density kg/m^3	EC (kgCO_2e/kg)
Bio-Based (Organic)	WW	0.070	180	0.98
	WF	0.038	160	0.124
	HF	0.038– 0.060	20– 90	0.14
	C	0.04– 0.050	80– 115	1.156
Mineral-Based (Inorganic)	GW	0.031– 0.037	13– 100	1.533
	RW	0.029– 0.042	40– 200	1.050 *
	F	0.030– 0.050	10– 100	1.350 *
	P	0.040– 0.055	139– 166	0.520
	V	0.04– 0.064	64– 130	0.520
	FG	0.038– 0.045	100–120	1.565
Petrochemical (Organic Chemistry)	EPS	0.031– 0.038	15– 35	4.205– 7.3
	XPS	0.032– 0.037	32– 40	5.84–7.55
	PUR	0.022– 0.046	30– 100	4.260
	PIR	0.018– 0.028	30– 45	3.089 *
	PF	0.018– 0.024	40– 160	4.15–7.21
Advanced materials	VIP	0.0035– 0.008	160– 230	8.551
	A	0.015– 0.028	150– 220	4.200
	CR	0.044	60	0.367

Sources: created based on [2, 4, 5, 18- 35].

WW: Wood Wool, **WF**: Wood Fiberboard, **HF**: Hemp Fiber, **C**: Cork, **GW**: Glass Wool, **RW**: Rock Wool, **F**: Fiberglass, **P**: Perlite, **V**: Vermiculite, **FG**: Foam Glass, **EPS**: Expanded Polystyrene, **XPS**: Extruded Polystyrene, **PUR**: Polyurethane foam, **PIR**: Polyisocyanurate, **PF**: Phenolic Foam, **VIP**: Vacuum Insulation Panels, **A**: Aerogel. **CR**: Cellulose-recycled. **EC**: Embodied Carbon, ***:** only Carbon.

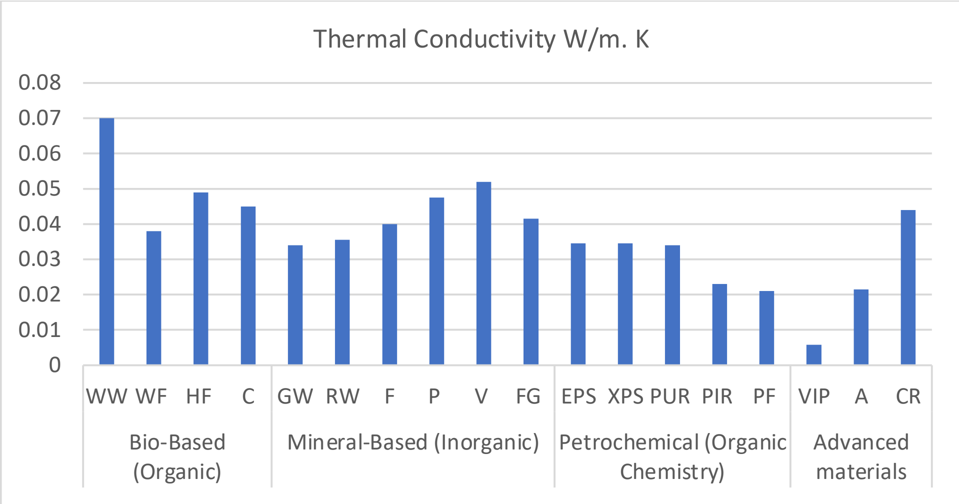

Figure 2. Comparative thermal conductivity overview of various thermal insulation materials

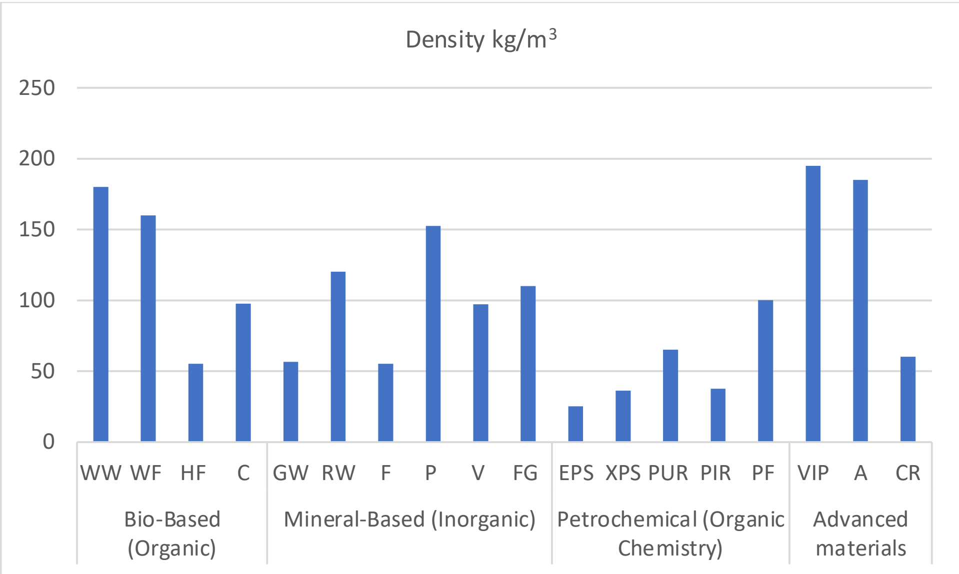

Figure 3. Comparative density overview of various thermal insulation materials

Bar charts in Figures 2 and 3 provide a comparative investigation of numerous thermal insulation materials classified into Bio-Based (Organic), Mineral-Based (Inorganic), Petrochemical (Organic Chemistry), and Advanced Materials. Each material is specified by its thermal conductivity (W/m·K) and density (kg/m³), which are key properties for evaluating insulation performance. Furthermore, many sources and databases [2, 4, 5, 18- 35] have been used to prepare Table 1, and given that numerous ranges are provided for different materials and these ranges seem logical, the average values of each material have been used to prepare the bar charts.

Lower values of thermal conductivity (λ) indicate less heat transfer. In this regard, Vacuum Insulation Panels (VIP), as an advanced material with λ = 0.0035–0.008 W/m·K, are the best performers, followed by Aerogel (A), Phenolic Foam (PF), and Polyisocyanurate (PIR), with λ = 0.015–0.028 W/m·K. Advanced and petrochemical insulation materials offer highly effective solutions with the potential to greatly enhance the thermal insulation performance of building walls.

In terms of density, the petrochemical categories indicate a lower average density. For instance, EPS has a density of 25 kg/m³, XPS has 36 kg/m³, and PIR has 37.5 kg/m³. Additionally, some bio-based and mineral-based categories, like GW and F, have an average density of 55 kg/m³. However, it is important to note that mineral-based (inorganic) insulation materials exhibit higher heat conductivity compared to petrochemical (organic) options. Generally, petrochemical insulation materials have lower mean heat conductivity and density compared to bio-based and mineral-based materials. However, the average heat conductivity of advanced insulation materials may be lower than that of petrochemical insulation, although they tend to have higher density than petrochemical materials. In addition, further investigation into the required thickness of materials is needed to meet building energy efficiency requirements for specific project conditions and regional contexts. For instance, reference [

12] suggests different walls using aerogel and EPS that based on wall design, walls using aerogel had lower thickness compared to walls designed using EPS, and also both walls had approximately the same weight, so it is important to consider all aspects for designing energy-efficient walls.

3. LIFE-CYCLE CO_2 EMISSIONS ASSESSMENT

Life cycle assessment (LCA) is a tool used to estimate the potential environmental impacts and resources consumed throughout a product's life cycle (cradle to grave or cradle to gate), i.e., from raw material acquisition, through production, use phases, and waste management, to the recycling phase [36]. The method to do this assessment is defined in the ISO standards 14040 [37] and 14044 [38]. The life cycle center is required to assist decision-making when choosing the finest technology to hand and reduce the environmental impact of the buildings throughout their design or refurbishment [18]. Life cycle assessment should cover the definition of goal and scope, inventory analysis, impact evaluation, and explanation of results, as painted in Figure 4 [37].

This research applies a Cradle-to-Gate (A1–A3) Life Cycle Assessment (LCA) methodology to assess the embodied carbon (EC) impact of several insulation materials, following ISO 14040 and ISO 14044 standards. Python is used to efficiently examine, rank, and visualize the results.

A comparative bar chart in Figure 5 shows the Environmental Impact of thermal insulation materials based on type and embodied carbon (kg CO_2e/kg) for each category. In addition, the Python output for the Cradle-to-Gate (A1–A3) LCA approach to analyzing insulation materials' environmental impact is shown in Figure 6.

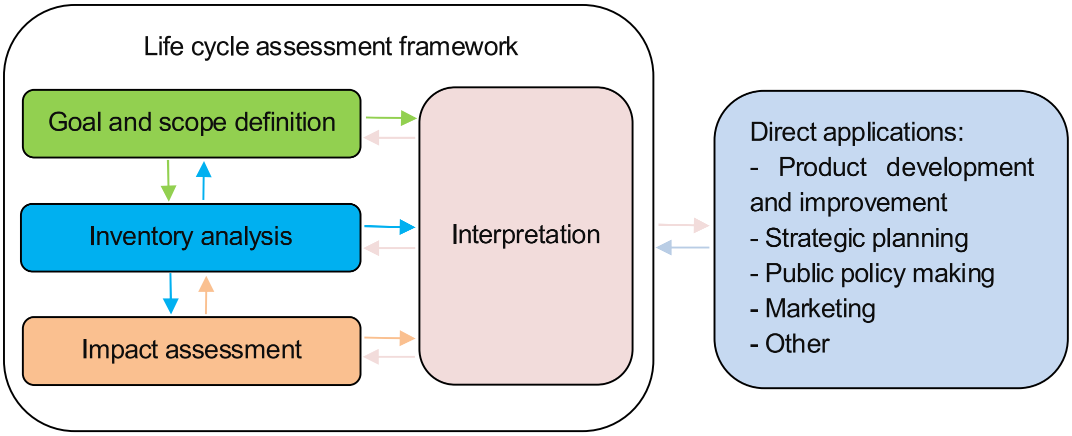

Figure 4. Phases of a Life Cycle Assessment (figure elaborated based on [37]).

Thermal insulation plays a vital function in decreasing a building's operational energy demand, but the embodied carbon (EC) related to insulation materials is increasingly urgent for evaluating their full life-cycle environmental consequence. Figure 5 shows the average EC (kg CO_2e/kg) values for commonly used insulation wall materials and highlights their role in sustainable construction.

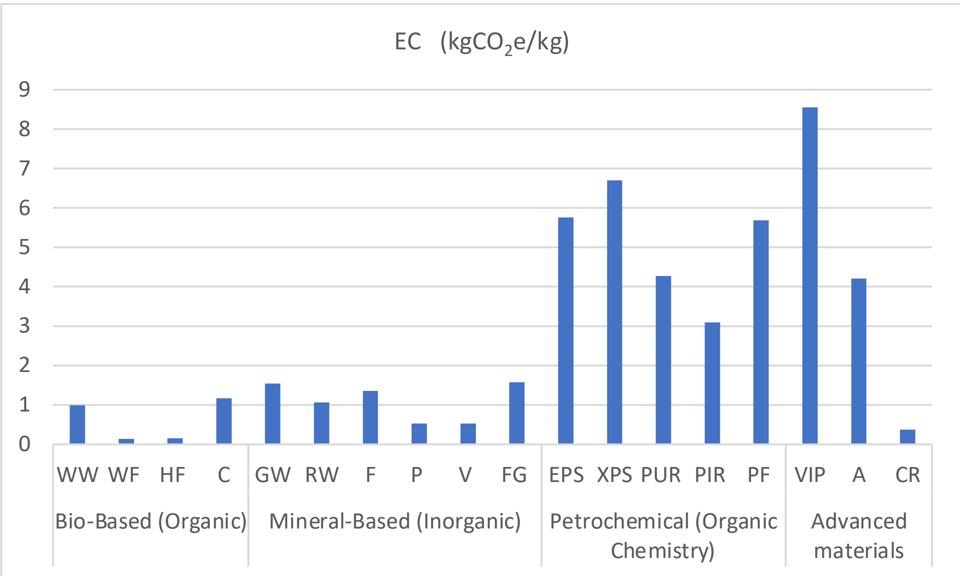

Figure 5. Embodied Carbon (kg CO_2e/kg) of various thermal insulation materials based on different categories.

In a time where the buildings in Europe are in charge of 40% of total energy consumption and 36% of greenhouse gas (GHG) emissions [39], improving insulation and optimizing wall and roof thickness not only reduce energy consumption by up to 40% [12], but also selecting suitable insulation with low embodied carbon is an effective step toward climate-resilient, regenerative buildings. Although most advanced and petrochemical insulation materials offer lower thermal conductivity than the other groups, except CR (Cellulose-recycled), which has low Embodied Carbon, the rest of the advanced and petrochemical categories leave a larger carbon footprint.

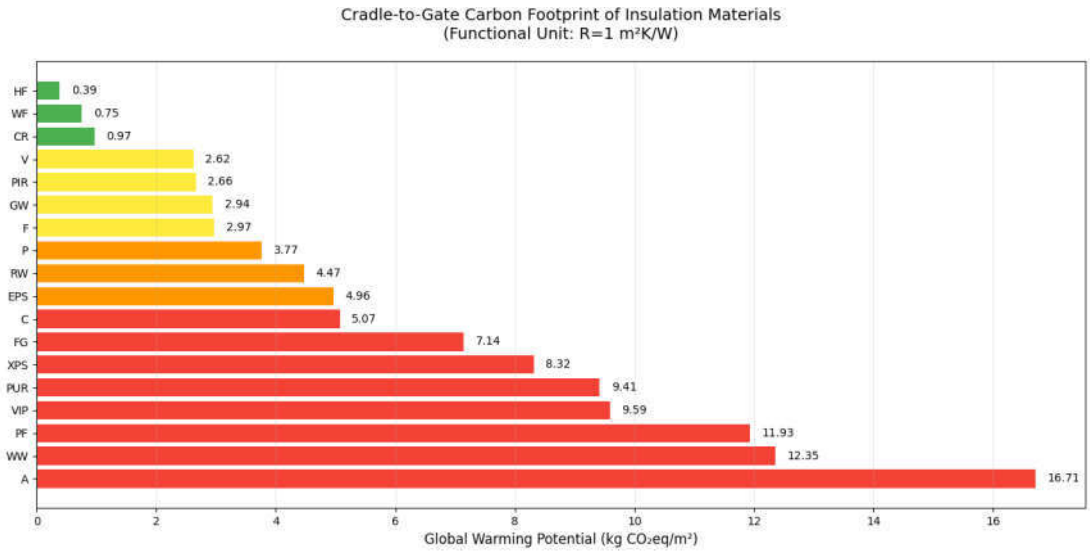

Figure 6. Cradle-to-Gate (A1–A3) Life Cycle Assessment (LCA) approach for comparative analysis of the environmental impacts of various insulation materials using Python.

To ensure a fair comparison, the thickness of each insulation material was calculated based on achieving a thermal resistance of R = 1 m²K/W using $d = R \times \lambda$. This thickness was then used to calculate the material mass per square meter and, subsequently, the GWP (kg CO_2e/m²), based on the embodied carbon per unit mass of each material [2]. Figure 6 shows the comparative analysis of Global Warming Potential (kg CO_2eq/m²) for various insulation materials in the building envelope per unit area (m²) to achieve the requirements of thermal resistance (R=1 m²K/W). The graph visualizes GWP (kg CO_2eq/m²) values, clearly indicating that HF (Hemp Fiber), WF (Wood Fiberboard) from bio-based categories have lower carbon with GWP of 0.39 and 0.75 (kg CO_2eq/m²) respectively, and CR (Cellulose-recycled) from advanced groups has GWP of 0.97 (kg CO_2eq/m²), which means these materials offer GWP less than 1 kg CO_2eq/m² and are shown with green colors which have low carbon on environment. Furthermore, in this study, the medium carbon footprint is categorized between 2-3 kg CO_2eq/m², denoted by a yellow color, where V, PIR, GW, and F are placed in this group. Moreover, insulation materials like P, RW, and EPS are specified with orange colors, indicating a high carbon footprint of 3-5 kg CO_2eq/m². Finally, the insulation materials with the worst environmental impact, characterized by a very high carbon footprint (more than 5 kg CO_2eq/m²), are highlighted in red. 8 types of insulation material are placed in this group which 5 out of 8 are from advanced or petrochemical classification, and it shows that using high-tech for manufacturing these materials offers extreme thermal performance, but their manufacturing processes are energy-intensive, involving high GHG emissions.

4. CONCLUSIONS

European building stock was largely constructed in the 20th century and is characterized by high energy demands. The selection of appropriate insulation materials is one of the essential ways for reducing a building's energy consumption. In this study, by investigating different insulation options for the wall provide quantitative insights that will assist in the choice of materials that balance energy efficiency and environmental impact. The findings will assist in influencing decision-making in sustainable design, supporting attempts to reduce buildings' carbon footprint while maintaining optimal thermal performance.

The results show that the Vacuum Insulation Panels, as an advanced material with λ = 0.0035–0.008 W/m·K, are the best performers, followed by Aerogel, Phenolic Foam, and Polyisocyanurate, with λ = 0.015–0.028 W/m·K. Advanced and petrochemical insulation materials suggest highly effective solutions with the potential to greatly enhance the thermal insulation performance of building walls.

In terms of density, the petrochemical (Organic Chemistry) classification indicates a lower average density. However, the average heat conductivity of advanced insulation materials may be lower than that of petrochemical insulation, although they tend to have higher density than petrochemical materials.

Comparative analysis of the environmental impacts of various insulation materials shows that Hemp Fiber, Wood Fiberboard from bio-based categories have lower carbon with GWP of 0.39 and 0.75 (kg CO_2eq/m²) respectively, and Cellulose-recycled from advanced groups has GWP of 0.97 (kgCO_2eq/m²). The insulation materials, such as Cork, Foam Glass, Extruded Polystyrene, Polyurethane foam, Vacuum Insulation, Phenolic Foam, Wood Wool, and Aerogel, have a GWP of more than 5 (kg CO_2eq/m²).

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