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Investigating the ecological efficiency of widely utilized bio-sourced insulation materials in the building lifecycle

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Abstract

Because of rising pollutant emissions, potential global warming results, and rising energy demands, environmentally friendly and renewable building insulation materials are increasing in popularity. The changes in fossil-based energy resource prices, climate variation, and ecological menaces have resulted in important requisitions for bio-sourced and renewable materials, with building products accounting for an important volume. The building sector has important social, environmental, and financial effects. C-footprint of 15 insulating materials was investigated to compare the ecological efficiency of a building over its entire lifecycle. The values calculated were crosschecked with the thermal insulation's real impact. The benchmark was made with the ecological effect evaluation rating by accounting for each material's density and also variances in thermal conductivity degree. This research characterizes how to choose the most environment-friendly construction insulating material from the present alternatives based on a series of qualitative and quantitative parameters. It is suggested that the analytic hierarchy process be used to evaluate options and select the best option. The article presents the findings of a search for the most environmentally friendly bio-sourced thermal insulating material for buildings.

1. Introduction

The essence of construction has remained largely unchanged over the centuries. Modern structures must comply with established functions, appear aesthetic, and remain one of the most material and energy-intensive industries. The need to decrease the amount of consumed energy prompted the idea of assessing building energy efficiency. This concept incorporates both economic (higher fuel prices) and ecological considerations, such as environmental protection from adverse usage effects. From an environmental standpoint, it is critical to develop and implement novel, efficient products and industries with optimized generation operation characteristics to reduce material consumption and energy demand raw. These technologies should promote the efficient use of energy from renewable resources [1, 2]. Because the aforementioned trends are compatible with the principles of sustainable development [3, 4], the concept of the sustainable building was developed. Maintainable improvement is significant for the users' life quality in buildings, too. The innovative resolutions and contemporary construction industries can have a significant impact on the comfort of apartments and offices, and thus the health of the occupants. Because of the high energy and material usage in the structure industry, the use of environmental assessment methods appears to be justified. Most countries around the world are aware of the problem of energy consumption in the construction industry [5]. There is significant financial potency that could be utilized to decrease global greenhouse gas emissions over the future several decades [6]. Due to high heating demands, energy requisition and the associated ecological effects in the utilization stage of buildings remain highly relevant [7]. This is especially true in the event of uninsulated or poorly insulated constructions. As a result, thermal isolation is becoming more and more important in the global policy-making standard. When the life-cycle evaluation of a building and its utilization tier are considered, the energy conservations exceed the insulation materials' effects [8]. All the same, there is still a significant opportunity to reduce environmental impacts. Diverse isolation products made from sustainable feedstocks have been introduced to the market in this context. Renewable isolation materials support resource protection besides their essentially essential thermal storage capacities and good thermal conductivities. This is because they warehouse CO_2 in the course of their time of life and can replace fossil-based sources in potential.

Making the decisions to achieve different targets during the design process is a crucial step, especially when a lot of variables is needed to be taken into consideration during the process. The multi-criteria decision-making methods provide the tools to make the process easier and more efficient. Environmental bio-sourced material selection also known as sustainable material selection is significant during the manufacturing-design operation, which aims to ensure production efficiency while reducing the overall cycle-life effect on human and environmental health. As a result, it has been the theme of numerous research papers [9-11]. Using extended fuzzy-AHP methods, Akadiri et al.

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represented a new model for construction material selection [12]. Bhatt and Maniya used the precedence selection index methodology to find a suitable product that fulfills the requirements of the planning engineers [13]. Chatterjee et al. investigated a novel interconnected multi-attributes decision-support methodology for selecting the optimal material alternative that unites the complicated commensurate evaluation methodology and the mixed information methodology's assessment [14]. All the same, when choosing a proper bio-sourced material for planning purposes, design engineers should consider multiple attributes or criteria, such as physical property, cost, and ecological efficiency, rather than focusing on a single criterion. Each material performs differently for diverse features, and no sole material can compensate for all the respective features. As a result, selecting green materials should be overviewed as a complicated multi-attributes decision-support issue. A reasonable and systematic strategy is needed to address this issue.

Material selection is critical in the development and design of products, as well as in the competitiveness and success of the manufacturers. Incorrect material selection can cause assembly damage or failure, as well as significantly lower product performance, affecting an organization's productivity, profitability, and reputation [15, 16]. Many studies and investigations have been performed in the literature in diverse frameworks to choose material alternatives for real engineering processes based on various backgrounds/requirements such as market demand, green manufacturing, eco-innovation, etc. [17-21]. To deal with climate change, it is worth noting that maintainability as a thought has more and more entered the manufacturing and design sectors for products [22, 24]. It is critical to conduct material selection research against the backdrop of long-term development [25, 26]. The material alternative selection is a multi-objective issue with combination restrictions that can be noted as a complicated multi-attributes decision-support issue [27]. The criteria and objectives in the material selection operation are frequently at odds, and exchanges between determinative attributes are required. An efficient and systematic strategy is needed to perform the true decision and alleviate the material selection process. Many arithmetical techniques have been applied and developed in the material selection field. Anojkumar et al., for instance, created a mixed multi-attributes decision-support methodology by combining 4 MCDM methodologies to resolve the pipe material selection difficulty in the sugar industry [24]. Liu et al. proposed a range of two-tuple lingual ITL-VIKOR (VIKOR) methodology for resolving the material selection issue in the presence of uncertain and incomplete information [15]. Zahraa et al. used the multi-selection method to select a façade system based on sustainability criteria. The researchers compared various cladding systems, including single and double brickwork, aluminum panels, and ceramic cladding. The researchers were able to select the sustainable façade cladding that best fits the context of the area by using the AHP multi-decision-making tool and the Delphi technique [28]. Mark et al. published an analysis of multiple-attributes decision-support methodologies in which they discussed the benefits, drawbacks, and applications of widespread multiple-attributes decision-support techniques that can be utilized in the selection of construction materials in the industry [29]. Based on quantitative environmental impact analysis, Maria et al. used multi-criteria decision-making techniques to choose between two alternative construction materials and the multi-attribute utility method to choose between precast concrete and cast-in-situ. They debated three sets of main attributes and sub-sets of attributes, and the results revealed that precast elements are more environmentally friendly than cast-in-situ elements [30]. Liu et al. suggested a mixed decision-support strategy integrating deduced collection operators into VIKOR in a multi-attribute decision-support issue involving material selection, and the conclusions are crosschecked for various kinds of normalized interval collection systems [31]. For the ecologically sensitive material selection problem, Huang et al. introduced an indefiniteness analysis methodology and a novel multi-attribute decision-support model. By addressing the materials selection challenge, the TOPSIS methodology was used, and indefiniteness analyses were applied for modeling efficiency and flexibility [32].

According to the review of literature, most of the investigators focused on material selection methodologies using multi-attribute decision-support strategies. Even though present methodologies supply a wealth of beneficial equipment for material selection, the majority of them continue to disregard several areas such as technical features, which play an important role in the evaluation operation for bio-sourced material options; some common methods are not suitable for assessing all types of material alternatives because of the range of their measurement scale [33]. As a result, this research suggests an AHP strategy for selecting optimal ecological materials for sustainability based on product requirements, as well as developing a novel hierarchical design that includes physical and environmental features. A life-cycle evaluation of selected materials was conducted to obtain a perception of the sustainability of these materials and to be able to assess them concerning their effect on climate change. To provide a more comprehensive picture, the investigated impacts were cross-checked to the ecological effects of commonly used traditional isolation materials derived from fossil-based and renewable resources.

This research aims to determine the most eco-friendly bio-sourced insulation materials in addition to providing a relative comparison of the evaluation criteria.

2. Methodology

The Analytic Hierarchy Method Saaty's [34] AHP method is a popular and favored applied methodology for multiple-attribute decision-support to resolve problems concerned with prioritization attributes [35]. This sorting operation has drawn the attention of many investigators in various areas because it is a straightforward aspect of doing decisions based on a few attributes while diminishing incoherence in alternatives [36]. The AHP methodology focuses on doing matched benchmarks within a hierarchy based on a basic scale rate [37]. Furthermore, the AHP process identifies preferences in decision making, to strive for a multi-direction scaling question and convert it to a uni-way scale [37].

In addition, sensitivity evaluation is the AHP methodology's critical stage because it allows decision makers to think about the variation in their weighting coefficients and determine the important focus points of the inputs [38]. In addition to embodied quantitative criteria, one of the primary benefits of the AHP methodology over other multi-attributes decision-support methodologies is that it includes a decision on conceptual qualitative criteria. This technic employs 3 bases: judging experts' assessments through a binary benchmark of options, improving the model's construction and criteria, and utilizing the Eigenvector methodology to determine the criteria's weightiness. A complicated decision-support question is formulated as a structure in the first step, and this complicated decision-support question is then converted into interdependent factors' an easy hierarchy including options and criteria. This structure had 3 degrees; options below, criteria thought in the middle, and the primary target above [39, 40]. The second stage involves a benchmark of attributes and options. The issue is split first, and the structure is created; next, the relative significance of the criteria is defined by using the prioritizing operation within each of the levels. The binary benchmark using a scale of notional significance ends below degree and starts at the middle degree. The criteria' multi-binary benchmarks are performed here on from 1 to 9 point-scale (Table 1).

Table 1. The attribute's significance (i over j)

Relative significance (aij)	Description (i over j)
8,6,4,2	Intermediate values
9	Extremely significance
7	Very strong significance
5	Strong significance
3	Moderate significance
1	Equal significance

In the end, a mathematical computation was performed to standardize the matrix, and then nominal weights for each of the attributes were calculated. An accuracy evaluation technique [41] is utilized to assess the experts' accuracy in addition to the overall structure.

3. Results and Discussion

In buildings, insulation materials are especially important in achieving energy effectiveness goals. The proper thermal insulating material selection is one of the simplest and most popular strategies for effectually decreasing construction energy requisition. The insulating material selection is impacted by factors other than the construction's thermal performance. The selection of materials can also influence aspects like environmental impact and life quality. Nowadays, the insulating materials' range is fairly broad, and each of the materials has unique properties. Several materials are more ecologically friendly than others, while others have more efficient thermal insulating features and are more technically favorable. In Table 2, the ecological and physical properties of widely utilized bio-sourced insulation materials in the building's full lifecycle are given [42].

Five different criteria are used to evaluate the insulation material alternatives. These criteria are Insulation's per superficies needed weightiness, thermal conductivity, density, the most widely utilized materials' C-footprint per mass for external walls of buildings, and insulation's per superficies unit C-footprints. Table 2 below provides the values of the insulation material alternatives for the selected criteria.

Table 2. Characteristics of the insulation material alternatives

Insulation materials	Insulation's per	Thermal	Density	The most widely	Insulation's per

	superficies (1m²) needed weightiness at U=0.2W/m²K	conductivity		utilized materials' C-footprints per mass for external walls of buildings	superficies unit (1m²) C-footprints at U=0.2W/m²K
	(kg/m²)	mW/(m K)	(kg/m³)	[(kgCO_2)eq/kg]	[(kgCO_2)eq/ m²]
VIP	4,83	6	170	11,08	53,5
Foam glass	48,29	60	170	1,16	56,0
Cellulose-recycled	12,50	44	60	0,37	4,6
Aerogel	11,27	17	140	4,20	47,3
PU polyurethane	5,33	25	45	4,83	25,7
Cork	37,88	50	160	1,15	43,6
XPS	5,76	38	32	5,86	33,7
EPS with reflective additives	2,42	32	16	3,50	8,5
EPS	2,80	37	16	3,38	9,5
Wood fiber wool (high density)	161,92	90	380	0,06	9,9
Wood fiber wool (less density)	28,41	50	120	0,06	
Glass-wool (high density)	14,39	38	80	1,30	18,7
Glass-wool (less density)	3,75	36	22	1,46	5,5
Rock-wool (high density)	33,02	45	155	0,90	29,7
Rock-wool (less density)	13,26	40	70	1,08	14,3

Evaluation of the insulation materials based on the selected criteria requires a relative comparison of the criteria to reflect the relative importance of each criterion with respect to each other. On a scale between 1 and 9 is used when using pairwise comparison of the criteria. Table 3 below is constructed based on the aggregated evaluations of a group of experts in the field.

Table 3. Pairwise Comparison of Criteria

	Insulation's per superficies (1m²) needed weightiness at U=0.2W/m²K	Thermal conductivity	Density	The most widely utilized materials' C-footprints per mass for external walls of buildings	Insulation's per superficies unit (1m²) C-footprints at U=0.2W/m²K
Insulation's per superficies (1m²) needed weightiness at U=0.2W/m²K	1	0.14	0.20	2	2
Thermal conductivity	0.14	1	3	2	2
Density	0.20	3	1	3	3
The most widely utilized materials' C-footprints per mass for external walls of buildings	2	2	3	1	1
Insulation's per superficies unit (1m²) C-footprints at U=0.2W/m²K	2	2	3	1	1

The decision matrix provided in Table 2 results in the following relative weights for the selected criteria as they are shown in Figure 1 below. As the figure indicates, Thermal conductivity is concluded to have the most significant impact on the attractiveness of insulation materials.

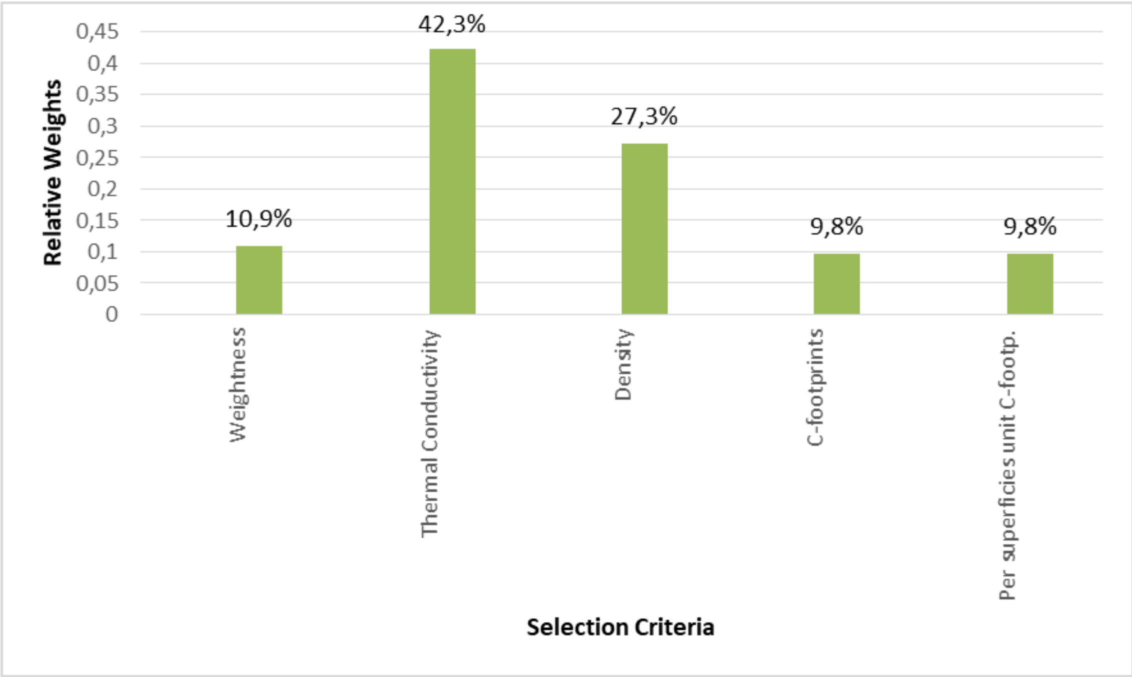

Figure 1. Relative Weights of the Criteria

As Table 4 below indicates, lower values are better for every criterion to make an insulation material more competitive among the other alternatives.

Table 4. Direction of values

Insulation's per superficies (1m^2) needed weightiness at U=0.2W/m^{2}K	low
Thermal conductivity	low
Density	low
The most widely utilized materials' C-footprints per mass for external walls of buildings	low
Insulation's per superficies unit (1m^2) C-footprints at U=0.2W/m^{2}K	low

Since the values of different characteristics used in Table 1 have a wide range of scales, these values need to be normalized for comparison purposes. Normalized values in Table 5 below are calculated using Eq.1:

$$n_{ij} = x_{ij} / \Sigma_{j=1} x_j \qquad for\ \forall i = 1, \ldots, m \qquad Eq.\ (1)$$

where;

x_{ij} = *Value of* j^{th} *material for the* i^{th} *criterion*

n_{ij} = *Normalized value of* j^{th} *material for the* i^{th} *criterion*

Table 5. Normalized values

Insulation materials	Insulation's per superficies (1m^2) needed weightiness at U=0.2W/m^{2}K	Thermal conductivity	Density	The most widely utilized materials' C-footprints per mass for external walls of buildings	Insulation's per superficies unit (1m^2) C-footprints at U=0.2W/m^{2}K
	(kg/m^2)	mW/(m K)	(kg/m^3)	[(kgCO_2)eq/kg]	[(kgCO_2)eq/ m^2]
VIP	0,013	0,125	0,032	0,029	0,014
Foam glass	0,010	0,099	0,072	0,028	0,041

Cellulose-recycled	0,104	0,104	0,037	0,086	0,028
Aerogel	0,274	0,029	0,009	0,104	0,120
PU polyurethane	0,130	0,137	0,011	0,115	0,063
Cork	0,013	0,125	0,032	0,029	0,014
XPS	0,010	0,099	0,072	0,028	0,041
EPS with reflective additives	0,104	0,104	0,037	0,086	0,028
EPS	0,274	0,029	0,009	0,104	0,120
Wood fiber wool (high density)	0,130	0,137	0,011	0,115	0,063
Wood fiber wool (less density)	0,013	0,125	0,032	0,029	0,014
Glass-wool (high density)	0,010	0,099	0,072	0,028	0,041
Glass-wool (less density)	0,104	0,104	0,037	0,086	0,028
Rock-wool (high density)	0,274	0,029	0,009	0,104	0,120
Rock-wool (less density)	0,130	0,137	0,011	0,115	0,063

As a final step, the values in Table 5 should be multiplied by the relative weight of each criterion to reflect the contribution of each criterion to the overall attractiveness of each insulation material. To produce the weighted scores of the alternatives shown in Table 6, these normalized values above are multiplied by the relative weight values of each criterion that were provided in Figure 1 using Eq.2:

$$y_{ij} = n_{ij} * w_i \qquad \text{for } \forall j = 1, \ldots, n \qquad \text{Eq. (2)}$$

where;

y_{ij} = *Weighted value of* j^{th} *material for the* i^{th} *criterion*

w_i = *Weight of the* i^{th} *criterion*

Table 6. Weighted scores of insulation materials

Insulation materials	Insulation's per superficies ($1m^2$) needed weightiness at $U=0.2W/m^2K$	Thermal conductivity	Density	The most widely utilized materials' C-footprints per mass for external walls of buildings	Insulation's per superficies unit ($1m^2$) C-footprints at $U=0.2W/m^2K$
	(kg/m^2)	mW/(m K)	(kg/m^3)	[($kgCO_2$)eq/kg]	[($kgCO_2$)eq/ m^2]
VIP	0,001	0,014	0,004	0,003	0,002
Foam glass	0,004	0,042	0,031	0,012	0,017
Cellulose-recycled	0,028	0,028	0,010	0,023	0,008
Aerogel	0,027	0,003	0,001	0,010	0,012
PU polyurethane	0,013	0,013	0,001	0,011	0,006
Cork	0,001	0,014	0,004	0,003	0,002
XPS	0,004	0,042	0,031	0,012	0,017
EPS with reflective additives	0,028	0,028	0,010	0,023	0,008
EPS	0,027	0,003	0,001	0,010	0,012
Wood fiber wool (high density)	0,013	0,013	0,001	0,011	0,006
Wood fiber wool (less density)	0,001	0,014	0,004	0,003	0,002
Glass-wool (high density)	0,004	0,042	0,031	0,012	0,017
Glass-wool (less density)	0,028	0,028	0,010	0,023	0,008
Rock-wool (high density)	0,027	0,003	0,001	0,010	0,012
Rock-wool (less density)	0,013	0,013	0,001	0,011	0,006

Total	0,073	0,100	0,046	0,060	0,044

Figure 2 below illustrates the comparison of insulation material alternatives based on the selected criteria and their relative weights. Since the lower values are expected for every criterion is expected, lower overall scores are more attractive. Thus, *Glass-wool (less density)* with an overall score of 0*.0346* has the best score among the other alternative.

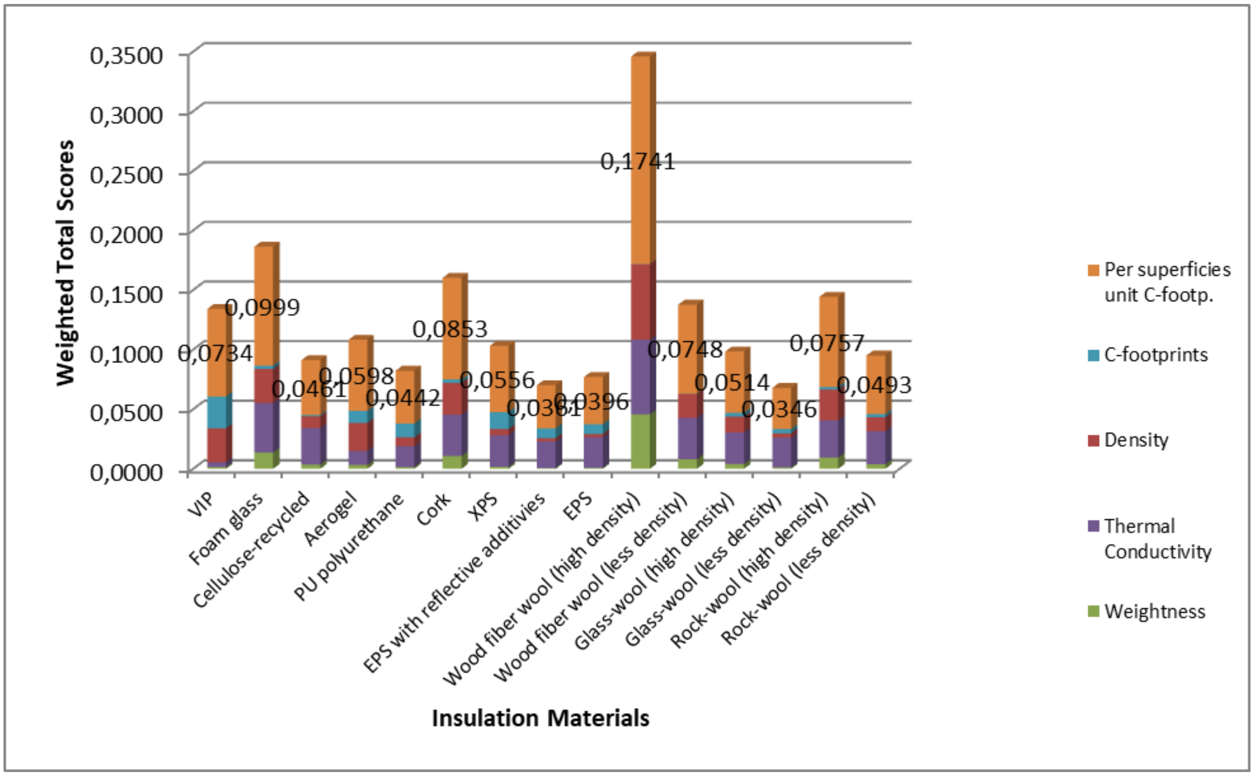

Figure 2. Comparative results of the insulation materials

4. Conclusions

Most of the energy in buildings is used to meet the needs of heating, ventilation, and air conditioning [43]. Significant energy savings in buildings can be achieved by choosing appropriate building design solutions. Heat consumption is effectively reduced by improving the insulation properties of buildings; therefore, increasing the energy efficiency of buildings has become an important aspect of national energy strategies in many countries [44]. A lot of initiatives focus on the construction sector and there are many objectives aimed at promoting technological innovation, developing energy performance [45], reducing ecological effects [46], and improving quality of life attributes [47].

Though the reviewed studies could improve sustainable building envelope planning by utilizing more natural bio-sourced insulation materials, environmental constraints limit their applicability. Researchers are primarily concerned with the energy efficiency of selected façade materials. Green efficiency and the origin of building materials, on the other hand, have been thought to depend on disciplines limited. Furthermore, earlier respective optimization strategies do not provide a complete picture. Therefore, integrating the origin and performance evaluation criteria of multiple disciplines is critical to achieving an environmentally friendly green building façade.

This paper proposes a method of selecting the most environment-friendly insulation material among the existing alternatives based on a series of qualitative and quantitative parameters. It is suggested that the analytic hierarchy process be used to evaluate options and select the best one. The method allows both qualitative and quantitative information to be incorporated in the decision process, with both subjective and objective criteria about a decision problem. Decision makers make their evaluations not always with certain values. Thus, in the decision-making process, not only the solutions based on numerical data are sought, but also the ideas and thoughts of the people who make the decision. While making pairwise comparisons, judgments are converted into numbers with a simple numerical scale. With its flexibility, simplicity, and ease of use, AHP can easily be applied to all kinds of personal, institutional, national analysis of complex decision problems.

Using AHP methodology, this study presents the findings for the most environmentally friendly bio-sourced thermal insulating material for constructions. Considering the fact that the buildings industry alone accounts for approximately 76% of electricity use [48], it is essential to increase energy efficiency in buildings. Using efficient insulation materials significantly helps conserving the energy inside the buildings and avoiding over-consumption. Another contribution of this study is the assessment of bio-sourced thermal insulation materials and taking their C-footprints over their lifecycles into account.

The proposed methodology not only determines the most eco-friendly bio-sourced insulation materials but also provides a relative comparison of the evaluation criteria. The subsequent steps along the lines of this research include additional evaluation criteria to form a hierarchy of criteria for a more comprehensive evaluation of the available alternatives.

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