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Integrated CRITIC-TOPSIS and Monte Carlo Sensitivity Analysis for Optimal Various Natural Fibre Selection in Sustainable Building Insulation Composites to Support the Sustainable Development Goals (SDGs)

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ABSTRACT

The selection of sustainable insulation materials is crucial for supporting environmentally responsible building construction in alignment with the Sustainable Development Goals (SDGs). This study proposes an integrated multi-criteria decision-making approach by combining the CRITIC method for objective criteria weighting, the TOPSIS method for ranking alternatives, and Monte Carlo sensitivity analysis to assess ranking stability under uncertainty. Twelve natural fibres were evaluated based on mechanical strength, physical characteristics, and moisture resistance. The CRITIC-TOPSIS integration effectively identified the most suitable fibre alternatives for insulation purposes. Sensitivity analysis validated the robustness of the model, ensuring consistent ranking outcomes across multiple simulations. This integrated approach offers a reliable and transparent framework for optimal material selection in sustainable construction practices. The study contributes to advancing sustainable building technologies while supporting SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production).

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1. INTRODUCTION

The construction sector has demonstrated increased interest in natural fibre-reinforced composites as alternatives to conventional building materials [1]. Natural fibre materials provide several benefits, such as enhanced mechanical qualities, less environmental impact, and improved sustainability [2, 3]. A comprehensive study assessed the feasibility and efficacy of various natural fibres, including jute, hemp, flax, and bamboo, in reinforcing polymeric matrices for building purposes [4].

Selecting appropriate materials and optimising their combinations are crucial in developing natural fibres reinforced composites to meet specific application requirements [5]. Key aspects in this selection process include these composites' mechanical capabilities, thermal characteristics, and environmental impacts. This study delineates a comprehensive material selection methodology employing the CRITIC and TOPSIS methodologies to identify the optimal natural fibres amalgamation for standard commercial insulation in building construction applications.

A thorough examination of the current literature was conducted to identify pertinent natural fibres evaluated for construction applications. The review emphasised the advantages of natural fibres, including their environmentally benign characteristics, enhanced mechanical properties, and superior thermal performance compared to conventional synthetic fibres. Extensive research has demonstrated that natural fibres improve construction materials' mechanical and thermal properties, positioning them as a viable alternative to traditional options [6- 8].

Research indicates that natural fibres have several advantages over synthetic fibres, such as reduced cost, decreased environmental impact, and improved thermal insulation properties [9]. Incorporating natural fibres into construction materials can promote the development of sustainable and energy-efficient building solutions, aligning with the growing emphasis on eco-friendly construction practices [10, 11].

The material selection utilises a multi-criteria decision-making approach to evaluate mechanical properties, thermal conductivity, cost, and environmental impacts. The CRITIC technique evaluates the importance of each criterion, while the TOPSIS method ranks various material combinations based on their performance relative to the selected criteria [12]. A sensitivity study is performed to evaluate the robustness of the chosen material combination and the impact of the criteria weights on the final ranking. The MCDM technique is crucial for selecting composite material components, offering a systematic framework for decision makers to assess a constrained set of possibilities [13- 15].

The literature has demonstrated the application of several mathematical strategies to address the issue of material selection. To the best of our knowledge, a limited body of work addresses material selection for sustainable composites in building construction. To address this research gap, using the beneficial features of both CRITIC and TOPSIS, the current study has combined these two methodologies to establish a decision-making model for the selection of sustainable natural fibres in insulation building construction materials. Diverse MCDM models to assess the effectiveness of various alternatives and identify the optimal solution among multiple options. **Table 1** outlines MCDM studies related to material selection in construction issues discovered in the literature.

Table 1 shows MCDM that was applied in the construction area, it can be concluded that it demonstrates a rich exploration of MCDM methodologies in material selection, notably omits the application of CRITIC-TOPSIS within the context of building construction. This absence is evident as the reviewed studies utilise a range of established and specialised MCDM methods, including Analytical Hierarchy (AHP), TOPSIS (without CRITIC), System optimisation, Criteria classes, TODIM-SWARA, LHPP-FAHP, MIVES and MADAMOS. Despite the diverse focus areas, encompassing composite materials, insulation, and sustainable building practices, none of the referenced works leverage the unique advantages of CRITIC-TOPSIS. This methodology, with its ability to objectively determine criterion weights based on contrast intensity and conflict, presents a potentially powerful tool for addressing the complex, multi-faceted challenges inherent in building material selection. The lack of its application within this specific domain, therefore, highlights a significant research gap. While various MCDM methods are employed to assess material properties, sustainability, and performance, the objective weighting and comprehensive ranking capabilities of CRITIC-TOPSIS remain unexplored in the context of building construction. This absence undergoes the novelty and potential contribution of research that seeks to bridge this gap, offering a more robust and transparent framework for informed DM in the selection of construction materials.

Table 1. MCDM study in the field of material selection in the construction area.

Ref.	**MCDM Method**								**Others**		
	AHP	**CRITIC**	**TOPSIS**	**TODIM**	**SWARA**	**MIVES**	**MADAMOS**	**MOORA**	**LFPP**	**FAHP**	**MCS**
[16]				√	√						
[17]	√							√			
[18]			√								
[19]	√									√	
[20]	√										
[21]									√	√	
[22]						√					
[23]							√				
[24]	√										
This Study		√	√								√

Note: AHP: analytical hierarchy process; CRITIC: CRiteria Importance Through Intercriteria Correlation; TOPSIS: Technique for Order Preference by Similarity to Ideal Solution; TODIM: an acronym in Portuguese for Interactive and Multi-criteria Decision Making; SWARA: Step-wise Weight Assessment Ratio Analysis; LFPP: Logarithmic Fuzzy Preference Programming; MOORA: Multi-Objective Optimisation by Ratio Analysis; FAHP: Fuzzy Analytic Hierarchy Process;

This comprehensive material selection process identifies the optimal natural fibre reinforcement for common commercial building insulation materials, thereby facilitating the development of sustainable and high-performance construction solutions [25]. This study integrates a comprehensive literature review on natural fibres reinforced composites, the implementation of the CRITIC-TOPSIS decision-making (DM) framework, and sensitivity analysis to validate the selected materials. The findings provide valuable insights for researchers, designers, and construction professionals in the selection of potential natural fibre reinforced composites for building insulation applications. The findings contribute to sustainable material selection, supporting global efforts towards sustainable development goals (SDGs), such as SDG 9 (Industry, Innovation, and Infrastructure) [26], SDG 11 (Sustainable Cities and Communities) [27], and SDG 12 (Responsible Consumption and Production) [28], ultimately promoting eco-friendly building practices.

3. METHODS

This study's essential method is outlined in four phases to improve clarity. The phases are delineated in the following sections, as depicted in **Figure 1**. Phase 1 involves delineating selection criteria, creating a material database, and specifying structural hierarchy. Weight assessment utilising the CRITIC methodology and material prioritisation through the TOPSIS method was performed in phase 2. This study employed a materials selection process incorporating the MCDM method, explicitly utilising the CRITIC and TOPSIS methods.

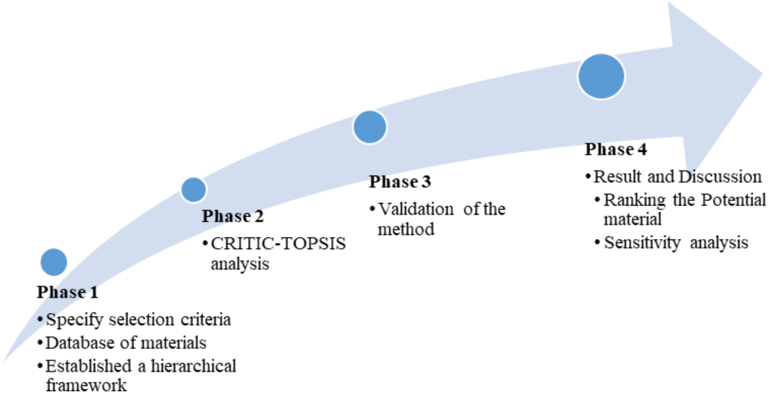

Figure 1. Research framework for this study.

The CRITIC-TOPSIS methodology was validated through phase 3. The results discussion in step 4 includes criterion review and the implementation of a sensitivity analysis. A sensitivity analysis is conducted to evaluate the chosen material combinations' resilience and the criteria weights on the ultimate ranking [29]. The results of this comprehensive materials selection process and the subsequent discourse are outlined in the following sections. These provide essential insights for researchers, designers, and construction professionals regarding selecting appropriate natural fibre reinforced composites for insulation and building construction.

The CRITIC method is employed to evaluate the significance of each criterion by examining the conflicts between them and the information each criterion provides. The CRITIC method establishes criterion weights by examining the standard deviation of criterion values and the interrelationships among the criteria [30, 31]. The TOPSIS method is utilised to evaluate and rank potential material combinations according to their performance relative to specified criteria. The TOPSIS method assesses and ranks prospective material combinations based on their performance against defined criteria. The TOPSIS method evaluates and ranks potential material combinations according to their performance against established criteria. The TOPSIS method is a widely utilised technique in MCDM that identifies the optimal choice by assessing the minimal distance to the ideal solution and the maximal distance from the anti-ideal solution [32, 33].

The researchers utilised a multi-criteria decision-making approach, applying the CRITIC and TOPSIS methods to systematically assess and rank different combinations of natural fibre-reinforced composites for insulation building construction.

Figure 2 illustrates the specific steps involved in the CRITIC-TOPSIS MCDM process. It focuses on assigning weights to the criteria using the CRITIC-TOPSIS, and these weights are used to rank the alternatives via the TOPSIS method. In contrast, other flowcharts shown in **Figure 2** are more generalised MCDM processes rather whereas **Figure 3** provides a detailed look at a specific MCDM implementation, for Phase 1 and Phase 2.

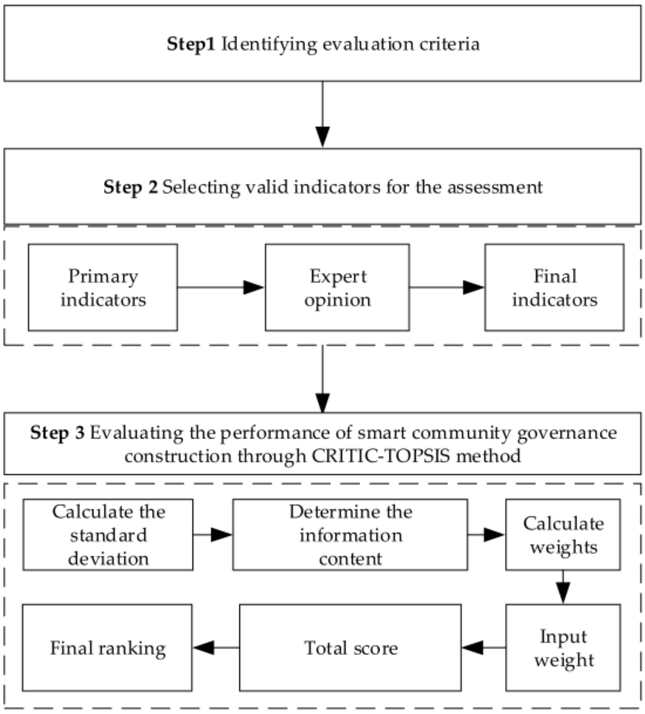

Figure 2. Framework model structure from other researchers [34].

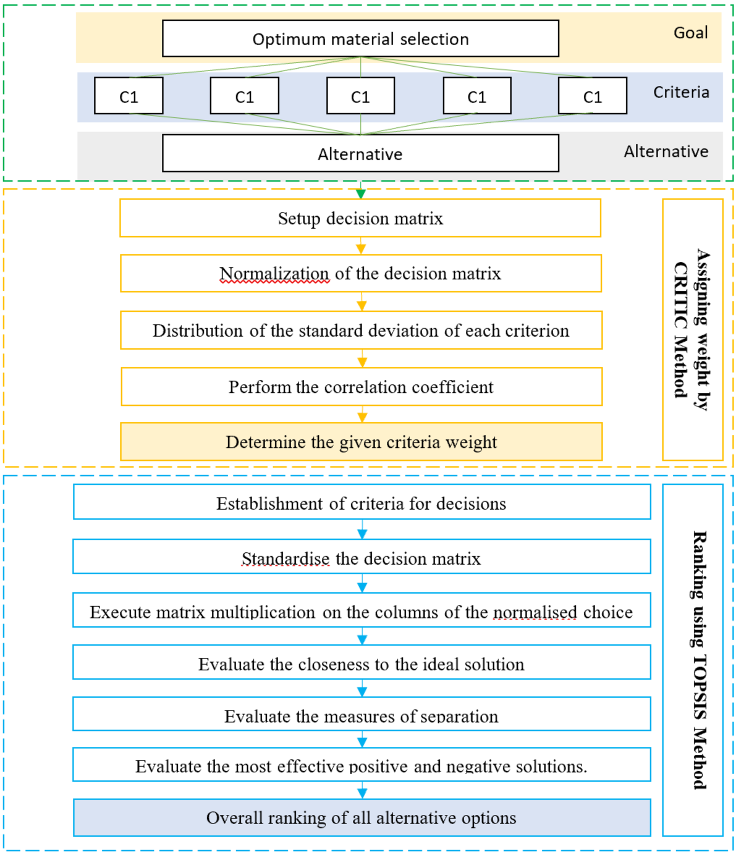

Figure 3. Framework model structure for phase 1 and phase 2 of this study [35].

2.1. Phase 1: Specify Selection Criteria

The study focused on developing a model for MCDM tailored to the material specifications of insulation building construction (see **Table 2**). Insulation is an energy-efficient technique widely utilised in residential, commercial, and industrial structures. Thermal insulation consists of materials or composites with elevated thermal resistance intended to diminish the rate of heat transfer. Insulation in structures facilitates the maintenance of a comfortable internal temperature while minimising heat dissipation to the external environment [36-38].

Nonetheless, its high cost may limit its applicability in certain contexts where other suitable and cost-effective solutions can meet the requirements [39]. Similarly, the use of waste materials for building insulation plays a vital role in promoting sustainability in construction materials [40]. Recycled waste materials, such as textiles, paper, and glass wool, can be repurposed to create eco-friendly and economical insulating materials [41]. These materials offer enhanced insulation properties while contributing to waste reduction and resource conservation [42].

Table 2. A proposed database of natural fibre alternatives from 2018 to 2023 [44-47].

Fibre	Weight			Strength			Moisture Resistance		
	Density (g/cm^3)	Diam. (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)	Moisture Content (%)	Hemi-cellulose (%)
Kenaf	1.2	12 to 36	1.4 to 11	295 to 930	22 to 60	2.7 to 6.9	53.5	6.2 to 12	21
Ijuk	1.22 to 1.45	221	-	122 to 304.2	2.11 to 5.9	8.9 to 29.9	9.94 to 13.3	43.75 to 52.3	5.5 to 8.67
Hemp	1.47	10 to 51	5 to 55	580 to 1110	45	1.6 to 4.5	43	8	17.9 to 22.4
Abaca	1.5	10 to 30	4.6 to 5.2	430 to 813	41	2.9	56 to 63	14	21
Banana	1.35	12 to 30	0.4 to 0.9	721.5 to 910	27 to 32	5 to 6	62 to 64	10 to 11	6 to 19
Coir	1.2	7 to 30	0.3 to 3	175	6	15 to 25	45.6	10	0.3
Flax	1.38	5 to 38	10 to 65	700 to 1000	60 to 70	1.2 to 3	70 to 80	7	18.6 to 20.6
Sisal	1.2	7 to 47	0.8 to 8	507 to 855	9 to 22	1.9 to 3	60 to 77	11	11
Jute	1.23	5 to 25	0.8 to 6	325 to 770	37.5 to 55	1.5 to 3.1	59 to 71.5	12	13.6 to 20.4
Bamboo	0.6 to 1.1	25 to 88	1.5 to 4	270 to 862	17 to 89	1.3 to 8	26 to 43	11 to 17	11.4
Pineapple	1.5	8 to 41	3 to 8	1020 to 1800	60 to 82	1 to 3	80.5	14	16 to 19
Ramie	1.44	18 to 80	40 to 250	915	61.4 to 128	2 to 4	71.09	12 to 17	14 to 16

2.2. Material Database

Consequently, twelve alternatives of natural fibres were found (**Figure 4**). The criteria were classified according to the mechanical properties of materials utilised in insulation for building construction, alongside the design and production characteristics. The principal criteria for material selection were identified as "weight" and "strength," focusing on evaluating natural fibres' mechanical properties and barrier functions. The additional principal criterion outlined pertained to "moisture resistance." The important criterion for determining “strength” is the insulation of building construction. The restricted water resistance of natural fibre-reinforced composites (NFRC) has hindered their extensive application. This resulted from the fibres' inherent capacity to absorb moisture [43]. Moisture resistance is crucial when installing in the building, as it is often done in a humid environment. Hence, the "weight" of natural fibre was determined to be a key factor, as it has the potential to impact the overall weight of safety features.

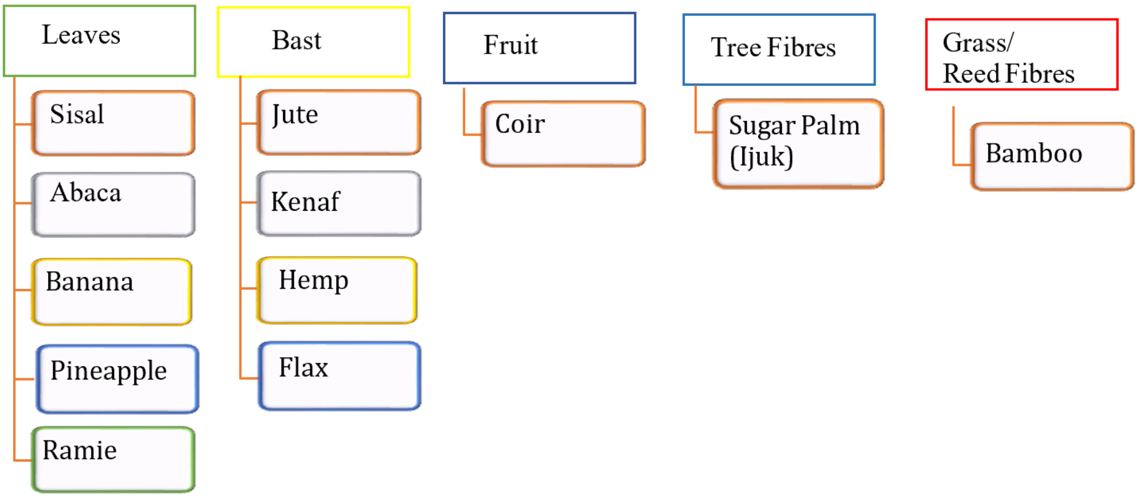

Figure 4. Twelve potential alternatives for natural fibres, sorted by category.

2.3. Identify Structural Hierarchy

The main objective of the Decision Making (DM) process was established in structural hierarchy at Level 1 (goal), that is, the potential natural fibre reinforced composite material for insulation building was ranked according to priority. In Level 2 (criteria), the properties specifications were listed as length (mm), diameter (m), density (g/cm3), tensile strength (MPa), Young's modulus (GPa), elongation at break (%), Moisture Content (%), Hemicellulose (%) and cellulose (%). Lastly, in Level 3 (alternative), the mechanical properties list must meet the target in Level 1. A perspective structural hierarchy is shown in **Figure 5** at phase 1.

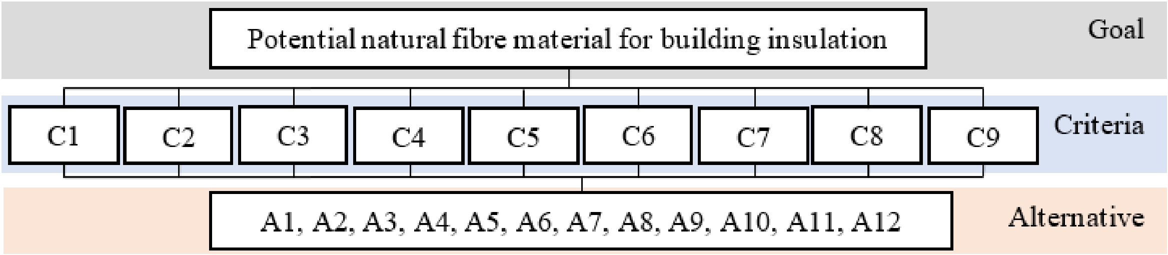

Figure 5. Structural hierarchy of natural fibre reinforced composite for insulation building.

2.4. Phase 2: CRITIC-TOPSIS Analysis

CRITIC-TOPSIS is an element of the MCDM methodology. It is utilised to resolve circumstances requiring a satisfactory compromise among diverse criteria. A bad result in one criterion may be offset by a positive outcome in another criterion [48]. CRITIC-TOPSIS is an evaluative methodology that assesses various materials (alternatives) based on specific criteria. The CRITIC method is an objective approach for assigning weights to criteria. The TOPSIS method is predicated on the premise that the chosen alternatives should be as proximate as feasible to the positive ideal solution and as distant as possible from the negative ideal solution. This is ascertained by computing the Euclidean distance, which quantifies the relative closeness of an alternative to the best solution geometrically. The positive ideal solution denotes the compilation of the maximum attainable values for each attribute, while the negative ideal solution encompasses the minimum achieved values for each attribute. This method is distinguished by its simplicity, clarity, computing efficiency, and ability to assess the relative performance of many alternatives to identify the ideal selection. The CRITIC-TOPSIS method was chosen for this investigation because of its advantages. The ideal material was selected using computations utilising CRITIC-TOPSIS. This study's findings aided DM in enhancing its decision-making process.

2.4.1. Weightage determination using CRITIC method

Steps for weightage determination using CRITIC method are explained as follows:

(i) Step 1: Starting from an initial decision matrix as shown in equation 1.

$$A = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}_{m\,x\,n} \qquad ; i = 1, \ldots, m, j = 1, \ldots, n \tag{1}$$

(ii) Step 2: Normalisation of the decision matrix

The scores of the value criteria cannot be directly compared as they are expressed in different measuring scales or units. To address this, the scores are transformed into a standard scale ranging from 0 to 1 as part of the normalisation process. Initially, the scores in the choice matrix are calculated using the proposed method outlined in equation 2.

$$\overline{X_{ij}} = \frac{x_{ij} - x_j^{worst}}{x_j^{best} - x_j^{worst}} \tag{2}$$

Where, $\overline{X_{ij}}$ represented the normalised score of the alternative i concerning the criterion j, x_{ij} is the actual score of the alternative i concerning the criterion j, x_j^{best} denotes the best score of the criterion j, and x_j^{worst} denotes the worst score of the criterion j.

(iii) Step 3: Distribution of the standard deviation of each criterion

In the third step, the standard deviation of each criterion, s_j, is calculated using equation 3. Note that $\bar{X_j}$ in equation 2 represents the mean score of the criterion j and that m denotes the total number of alternatives as follows.

$$s_j = \sqrt{\left(\frac{\sum_{i=1}^{m} x_{ij} - \overline{x_j}}{m-1}\right)^2} \tag{3}$$

Where, $\bar{X_j}$ represents the mean score of the criterion j and m denotes the total number of alternatives.

(iv) Step 4: Perform the correlation coefficient.

The correlation coefficient between attributes is calculated by equation 4.

$$\rho_{jk} = \frac{\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)(x_{ik} - \bar{x}_k)}{\sqrt{\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)^2 \sum_{i=1}^{m}(x_{ik} - \bar{x}_k)^2}} \tag{4}$$

(v) Step 5: Determine the given criteria weight.

The weights of attributes are calculated by using equation 5.

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \; ; \; j = 1, \ldots, n \tag{5}$$

2.4.2. Material ranking using the TOPSIS method

Ranking is based on several criteria with the following stages:

(i) Step 1: Establishment of criteria for decisions (A) using equation 6.

$$A = \left(x_{ij}\right)_{m\,x\,n} = \begin{bmatrix} x_{12} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{6}$$

(ii) Step 2: Standardise the decision matrix.
The standardise value $\mathrm{r_{ij}}$ is calculated using equation 7.

$$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{j=1}^{j} {f_{ij}}^2}}\,, j=1,2,\ldots,j;\; i=1,2,\ldots,n \tag{7}$$

(iii) Step 3: Perform matrix multiplication on the columns of the normalised decision
The weighted normalised value $\mathrm{v_{ij}}$ is calculated as follows:

$$v_{ij} = w_j \,\mathrm{x}\, r_{ij}\ , j = 1, 2, \ldots, J\ ; i = 1, 2, \ldots, n, \tag{8}$$

where w_j is the weight of the i^{th} criterion, and $\sum_{i=1}^{n} w_j = 1$

(iv) Step 4: Evaluate the closeness to the ideal solution, including the positive ideal (A*) and negative ideal (A^{-}) solutions using equation 9.

$$A^{*} = \left\{\left(\max_i v_{ij} \,\middle|\, j \in C_b\right),\ \left(\min_i v_{ij} \,\middle|\, j \in C_c\right)\right\} = \left\{v^{*}{}_{j} \,\middle|\, j = 1, 2, \ldots, m\right\}$$
$$A^{-} = \left\{\left(\min_i v_{ij} \,\middle|\, j \in C_b\right),\ \left(\max_i v_{ij} \,\middle|\, j \in C_c\right)\right\} = \left\{v^{-}{}_{j} \,\middle|\, j = 1, 2, \ldots, m\right\} \tag{9}$$

(v) Step 5: Evaluate the measures of separation: The measures of separation between each alternative and the positive and negative ideal solutions using equation 10.

$$S_i^{*} = \sqrt{\sum_{j=1}^{m}\left(v_{ij} - v_j^{*}\right)^2}\ ,\quad j = 1, 2, \ldots, m \tag{10}$$

Similarly, the distance from the negative ideal solution is shown in equation 11.

$$S_i^{-} = \sqrt{\sum_{j=1}^{m}\left(v_{ij} - v_j^{-}\right)^2}\ ,\quad j = 1, 2, \ldots, m \tag{11}$$

(vi) Step 6: Evaluate the most effective positive and negative solutions. The proximity of the alternate Pi concerning P* is defined in equation 12.

$$Pi_i^{*} = \frac{S_i^{-}}{S_i^{*} + S_i^{-}}\ , i = 1, 2, \ldots, m \tag{12}$$

(vii) Step 7: Overall ranking of all alternative options.

2.5. Phase 3: Validation of the Method

The proposed approach was validated by referencing its implementation in previous research before applying the CRITIC-TOPSIS method. Validation data were gathered and analysed from prior studies to ensure robustness. The researcher studies an integration of AHP and SAW for the selection of green building materials for insulation. **Table 3** presents the results obtained from the CRITIC-TOPSIS and AHP-SAW methods, which yield comparable rankings. Both methods indicate that the alternative M6 is ranked first.

The most significant observation is that both CRITIC-TOPSIS and AHP-SAW identify M6 as the top-ranked alternative. This provides strong support for the validity of this approach, as it converges with the established AHP-SAW method on the best option. While the exact rank positions of other alternatives might differ slightly, there's a general consistency in the trend. Alternatives that score higher in CRITIC-TOPSIS also tend to score higher in AHP-SAW, and vice versa. Some differences in rank order are expected when comparing different MCDM methods. Each method has its way of aggregating and weighting criteria, leading to variation in the final ranking. For instance, M3 is ranked third by CRITIC-TOPSIS and second by AHP-SAW, and M5 is ranked second by CRITIC-TOPSIS and fourth by AHP-SAW. These variations are not substantial and are common in MCDM comparisons. The actual values obtained using the two methods are different, which is also expected.

To validate the CRITIC-TOPSIS methodology, its result was compared with those obtained by Grecu using the AHP-SAW method for a similar material selection problem in **Table 2**. The results demonstrate a strong agreement between the two methods, with both identifying M6 as the top-ranked alternative. This concordance in the selection of the best option provides substantial support for the validity and reliability of the proposed CRITIC-TOPSIS method. While minor variations in the ranking of other alternatives are observed, this is expected due to inherent differences in the aggregation and weighting mechanisms of the two MCDM methods. The overall consistency in the trend of rankings further reinforces the credibility of the CRITIC-TOPSIS method for material selection.

Table 3. Validation result of CRITIC-TOPSIS and AHP.

Point	**MCDM Method**			
	CRITIC-TOPSIS (current)		**AHP-SAW**	
Alternative	**Value**	**Rank**	**Value**	**Rank**
M1	0.4595	4	0.320479	7
M2	0.3247	8	0.252287	9
M3	0.5132	3	0.462458	2
M4	0.4051	6	0.366561	6
M5	0.5402	2	0.453329	4
M6	**0.9652**	**1**	**0.694619**	**1**
M7	0.0392	9	0.415433	5
M8	0.4058	5	0.461004	3
M9	0.3252	7	0.274518	8

3. RESULTS AND DISCUSSION

Original data properties for insulation building construction natural fibres material are shown in **Table 4**. Regarding the twelve established alternatives, it is composed of nine criteria.

Table 4. Original data for insulation building construction using natural fibre material.

Fibre	**Weight**			**Strength**			**Moisture Resistance**		
	Density (g/cm^3)	**Diam. (µm)**	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**	**Moisture Content (%)**	**Hemi-cellulose (%)**
Kenaf	1.20	24.00	6.20	612.50	41.00	4.80	53.0	9.10	21.00
Ijuk	1.34	221.00	0.00	213.10	4.01	19.40	11.62	48.03	7.09
Hemp	1.47	30.50	30.00	845.00	45.00	3.05	43.00	8.00	20.15
Abaca	1.50	20.00	4.90	621.50	41.00	2.90	59.50	14.00	21.00
Banana	1.35	21.00	0.65	815.75	29.50	5.50	63.00	10.50	12.50
Coir	1.20	18.50	1.65	175.00	6.00	20.00	45.60	10.00	0.30
Flax	1.38	21.50	37.50	850.00	65.00	2.10	75.00	7.00	19.60
Sisal	1.20	27.00	4.40	681.00	15.50	2.45	68.50	11.00	11.00
Jute	1.23	15.00	3.30	547.50	46.25	2.30	63.75	12.00	17.00
Bamboo	0.85	56.50	2.75	566.00	53.00	4.65	34.50	14.00	11.40
Pineapple	1.50	24.50	5.50	1410.00	71.00	2.00	80.50	14.00	17.50
Ramie	1.44	49.00	145.00	915.00	94.70	3.00	71.09	140.50	15.00

3.1. CRITIC Method

The implementation of the CRITIC technique in selecting the performance criterion for the design phase is illustrated below.

(i) Step 1: Starting from an initial decision matrix. The decision matrix is shown in **Table 4**.

(ii) Step 2: Normalisation of the decision matrix. Upon computing x_j^{best} and x_j^{worst}, the normalization of the decision matrix can be ascertained from Equation (2). Where x_j^{best}

denotes the maximum value of the dataset, while x_j^{worst} represents the least value of the dataset. For the case $\bar{x}_{ij}$ = (1.2-0.85)/(1.50-0.85) = 0.5385. The complete results of the decision matrix normalization are presented in **Table 5**.

Table 5. Normalisation of the decision matrix.

Fibre	Weight			Strength			Moisture Resistance		
	Density (g/cm^3)	Diam. (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)	Moisture Content (%)	Hemi-cellulose (%)
Kenaf	0.5385	0.0437	0.0428	0.3543	0.4079	0.1556	0.3920	0.9488	0.0000
Ijuk	0.7462	1.0000	0.0000	0.0309	0.0000	0.9667	1.0000	0.0000	0.6722
Hemp	0.9538	0.0752	0.2069	0.5425	0.4520	0.0583	0.5444	0.9756	0.0411
Abaca	1.0000	0.0243	0.0338	0.3615	0.4079	0.0500	0.3049	0.8294	0.0000
Banana	0.7692	0.0291	0.0045	0.5188	0.2811	0.1944	0.2541	0.9147	0.4106
Coir	0.5385	0.0170	0.0114	0.0000	0.0220	1.0000	0.5067	0.9269	1.0000
Flax	0.8154	0.0316	0.2586	0.5466	0.6725	0.0056	0.0798	1.0000	0.0676
Sisal	0.5385	0.0583	0.0303	0.4097	0.1267	0.0250	0.1742	0.9025	0.4831
Jute	0.5846	0.0000	0.0228	0.3016	0.4658	0.0167	0.2432	0.8781	0.1932
Bamboo	0.0000	0.2015	0.0190	0.3166	0.5402	0.1472	0.6678	0.8294	0.4638
Pineapple	1.0000	0.0461	0.0379	1.0000	0.7387	0.0000	0.0000	0.8294	0.1691
Ramie	0.9077	0.1650	1.0000	0.5992	1.0000	0.0556	0.1366	0.8172	0.2899

Table 5 presents the normalization of the decision matrix for various natural fibres using the CRITIC method, a MCDM approach. The normalization process is essential in CRITIC to bring all the criteria to a common scale, as they originally have different units and ranges. This table enables comparison and evaluation of fibres based on multiple attributes categorized under three main aspects, which are weight, Strength, and Moisture Resistance. The table lists twelve types of natural fibres, including kenaf, Jute, Hemp, Abaca, Banana, Coir, Flax, Sisal, Bamboo, Ijuk, Pineapple, and Ramie. This normalised decision matrix is crucial in the CRITIC method to assess the rank of fibre alternatives without bias from differing scales of measurement. It highlights the relative

strengths and weaknesses of each fibre, aiding in selecting the most suitable based on specific application needs such as mechanical performance, weight, and moisture resistance. Normalised values close to 1 represent fibres that perform best with that specific criterion. Ramie scores highest in terms of Length (1.0000) and Tensile Strength (0.5992), making it strong and long. Flax shows high values for Tensile Strength (0.5466) and Moisture Resistance (1.0000), indicating good mechanical and moisture resistance properties. Jute stands out with the highest Cellulose (1.0000) and Elongation at Break (0.9667), implying high flexibility and a high content of cellulose. Hemp performs consistently well in Strength and Moisture categories, balancing mechanical and water resistance traits. In contrast, Coir shows a Tensile Strength (0.0000), the lowest in the group, indicating poor strength performance.

(iii) Step 3: Determine the standard deviation of each criterion. The standard deviation for each criterion's distribution can be obtained using equation 3. For the illustration $\bar{x}$ = (0.5385+0.7462+0.9538+1.0000+0.7692+0.5385+0.8154+ 0.5385+0.5846+0.0000+1.0000+0.9077)/12 = 0.6994, and $s_j = \sqrt{((0.1163 - 0.6994)^2 + (0.7462 - 0.6994)^2 + (0.9538 - 0.6994)^2 + (1.0000 - 0.6994)^2 + (0.7692 - 0.6994)^2 + (0.5385 - 0.6994)^2 + (0.8154 - 0.6994)^2 + (0.5385 - 0.6994)^2 + (0.5846 - 0.6994)^2 + (0.0000 - 0.6994)^2 + (1.0000 - 0.6994)^2 + (0.9077 - 0.6994)^2)/(12 - 1)}$ = 0.2843. The complete findings of the standard deviation for each criterion are presented in **Table 6**. **Table 6** presents the distribution of each criterion's standard deviation as part of the CRITIC method, which is commonly used in the MCDM process. The goal of this table is to quantify the variability or dispersion of each criterion across different natural fibre alternatives, Standard deviation (STDEV) is a statistical measure that shows how much individual data points deviate from the mean, In the context of the CRITIC method, higher standard deviation indicates greater contrast intensity of the criterion, implying it has more discriminative power in the decision-making process. This table provides critical insights into the weighting of the criteria for the CRITIC method. Criteria with higher standard deviations contribute more to the final decision-making weight, as they provide more differentiation between the alternatives. Therefore, properties such as Elongation at Break, Young Modulus, and Hemicellulose content are expected to have higher importance in evaluating and ranking the natural fibres for applications requiring a balance of mechanical and moisture resistance performance. The highest standard deviation is observed in Elongation at Break (0.3608), indicating that this property varies significantly across different fibres and is therefore a powerful criterion in distinguishing between alternatives. Young's Modulus (0.2953) and Tensile Strength (0.2645) also exhibit substantial variability, highlighting their importance in evaluating fibre strength. Among moisture resistance criteria, Hemicellulose (0.3057) shows notable variability, implying that fibres differ greatly in their hemicellulose content. In contrast, Moisture Content (0.2657) and Cellulose (0.2831) show moderate variability. Density (0.2843) and Length (0.2835) also offer good contrast in the weight category, whereas Diameter (0.27772) has the least variability among weight attributes.

Table 6. Distribution of each criterion's standard deviation.

Fibre	**Weight**			**Strength**			**Moisture Resistance**		
	Density (g/cm^3)	**Diam. (µm)**	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**	**Moisture Content (%)**	**Hemi-cellulose (%)**
Kenaf	0.5385	0.0437	0.0428	0.3543	0.4079	0.1556	0.3920	0.9488	0.0000
Ijuk	0.7462	1.0000	0.0000	0.0309	0.0000	0.9667	1.0000	0.0000	0.6722
Hemp	0.9538	0.0752	0.2069	0.5425	0.4520	0.0583	0.5444	0.9756	0.0411
Abaca	1.0000	0.0243	0.0338	0.3615	0.4079	0.0500	0.3049	0.8294	0.0000
Banana	0.7692	0.0291	0.0045	0.5188	0.2811	0.1944	0.2541	0.9147	0.4106
Coir	0.5385	0.0170	0.0114	0.0000	0.0220	1.0000	0.5067	0.9269	1.0000
Flax	0.8154	0.0316	0.2586	0.5466	0.6725	0.0056	0.0798	1.0000	0.0676
Sisal	0.5385	0.0583	0.0303	0.4097	0.1267	0.0250	0.1742	0.9025	0.4831
Jute	0.5846	0.0000	0.0228	0.3016	0.4658	0.0167	0.2432	0.8781	0.1932
Bamboo	0.0000	0.2015	0.0190	0.3166	0.5402	0.1472	0.6678	0.8294	0.4638
Pineapple	1.0000	0.0461	0.0379	1.0000	0.7387	0.0000	0.0000	0.8294	0.1691
Ramie	0.9077	0.1650	1.0000	0.5992	1.0000	0.0556	0.1366	0.8172	0.2899
STDEV	**0.2843**	**0.2772**	**0.2835**	**0.2645**	**0.2953**	**0.3608**	**0.2831**	**0.2657**	**0.3057**

(iv) Step 4: Determine the correlation coefficient. **Table 7** presents the values of the pairwise criteria correlation coefficients. Equation 4 was employed to ascertain the correlation measure. This table presents pairwise criteria correlation coefficient values, which play a crucial role in the application of the CRITIC method by quantifying the degree of correlation between every pair of the criteria considered in evaluating natural fibres. In the CRITIC method, the importance of each criterion is determined not just by its variability (as shown by standard deviation) but also by how independent it is from other criteria, where the correlation matrix comes in. This table allows us to identify which criteria are redundant due to strong correlations and which provide distinct value in assessing fibre performance. This table is essential for understanding the interdependencies among decision criteria. It enables the CRITIC method to objectively assign weight by penalising criteria that are highly correlated, thereby enhancing the robustness and fairness of the MCDM process in fibre evaluation. Tensile and Young's Modulus (0.7317) is a high correlation in expected since these are both mechanical strength indicators, Elongation at Break and Hemicellulose (0.8137) suggests that fibres with higher hemicellulose tend to stretch more before breaking, Diameter and Cellulose (0.7468) has a larger diameter might associate with higher cellulose content. These three correlations have a strong positive correlation. Meanwhile, Diameter and Moisture Content (-0.9718) indicates that fibres with larger diameters tend to have less moisture content, Tensile strength and Cellulose (-0.7261) suggest an inverse relationship stronger fibre may not necessarily have high cellulose, and Young's Modulus and Elongation at Break (-0.6857) materials that are more rigid tend to elongate less. In contrast, Density and Diameter (-0.0379) or Moisture content and Length (0.1039) indicate little to no linear relationship between these pairs, that in the weak or no correlations group.

Table 7. Pairwise criteria correlation coefficient values.

Fibre	**Weight**			**Strength**			**Moisture Resistance**		
	Density (g/cm^3)	**Diam. (µm)**	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**	**Moisture Content (%)**	**Hemicellulose (%)**
Density (g/cm^3)	1.0000	-0.0379	0.3196	0.4768	0.2652	-0.1718	-0.3785	-0.0369	-0.4136
Diameter (µm)	-0.0379	1.0000	-0.0417	-0.4233	-0.3490	0.6046	0.7468	-0.9718	0.3747
Length (mm)	0.3196	-0.0417	1.0000	0.3071	0.7317	-0.2473	-0.3068	0.1039	-0.1716
Tensile Strength (MPa)	0.4768	-0.4233	0.3071	1.0000	0.7317	-0.7401	-0.7261	0.4046	-0.6014
Young's Modulus (GPa)	0.2652	-0.3490	0.6971	0.7317	1.0000	-0.6857	-0.5820	0.3689	-0.6020
Elongation at Break (%)	-0.1718	0.6046	-0.2473	-0.7401	-0.6857	1.0000	0.6998	-0.6025	0.8137
Cellulose (%)	-0.3785	0.7468	-0.3068	-0.7261	-0.5820	0.6998	1.0000	-0.6761	0.4539
Moisture Content (%)	-0.0369	-0.9718	0.1039	0.4046	0.3689	-0.6025	-0.6761	1.0000	-0.3744
Hemicellulose	-0.4136	0.3747	-0.1716	-0.6014	-0.6020	0.8137	0.4539	-0.3744	1.0000

(v) Step 5: Determine the given criteria weight W_j. After calculating $c_j = \sum_{j=1}^{n} c_j$ The weight of the selected criteria can be determined from equation 5. For the example $c_j = \sum_{j=1}^{n} c_j$ = ((1-1.0000) + (1-(-0.0379)) + (1-0.3196) + (1-0.4768) + (1-0.2652) + (1-(-0.1718) + (1-(-0.3785) + (1-(-0.0369) + (1-(-0.4136)) x 0.2843 = 2.2683, $\sum c_j$ = 2.2683 + 2.0809 + 2.2667 + 2.4084 + 3.0050 + 2.4820 + 2.5995 + 2.6045 = 21.9599, and w_j = 2.2683/21.9599 = 0.1033. The entire results weight of the selected criteria is shown in **Table 8**. **Table 8** presents the determination of the weights of selected criteria using the CRITIC method, a well-established objective weighting technique in MCDM. The CRITIC evaluates the importance of each criterion by considering both the contrast intensity (standard deviation) and the conflict between criteria (correlation). This ensures that the weight assigned to each criterion reflects not only its variability but also its independence from other criteria. In the table, a list of major criteria related to material properties, particularly those relevant to natural fire characterisation, is shown. These include Density, Diameter, Length, Tensile Strength, Young's Modulus, Elongation at Break, Cellulose Content, Moisture Content, and Hemicellulose. The column labelled C_j represents the amount of information or contrast that each criterion contributes, calculated based on the standard deviation and correlation matrix. Meanwhile, W_j is the normalised weight of each criterion, derived by dividing each C_j by the total sum of all C_j values, ensuring the sum of all weights equals one (1). From the results, Elongation at Break (0.1369), Hemicellulose (0.1187), and Moisture Content (0.1184) are the most influential criteria, indicating they have the highest contrast and are less correlated with other criteria. These properties are crucial in determining fibres' flexibility, structural integrity, and water retention capability, respectively. Conversely, Length (0.0944) has the lowest weight, suggesting lower variability or higher correlation with other criteria.
Table 8 illustrates the relative importance of evaluation indicators. The findings show that the ranking order for criteria = Elongation at Break > Cellulose > Diameter > Young's Modulus > Length > Tensile Strength. The most preferred criterion is Elongation at Break, and the least preferred criterion is Tensile Strength. The Elongation at Break (%) and the Cellulose (%) correspond to the two highest weights in the results, indicating that these two performance criteria were given preferences. Whereas Tensile Strength (MPa) has the lowest value corresponding to the least preferred criterion.

Table 8. Determine the weight of the selected criteria.

	Major Criteria	C_j.	W_j.
Density (g/cm^3)	7.9772	2.2683	0.1033
Diameter (µm)	8.0976	2.2445	0.1022
Length (mm)	7.3051	2.0711	0.0944
Tensile Strength (MPa)	8.5708	2.2667	0.1033
Young's Modulus (GPa)	8.1559	2.4084	0.1097
Elongation at Break (%)	**8.3292**	**3.0050**	**0.1369**
Cellulose (%)	8.7688	2.4820	0.1131
Moisture Content (%)	9.7842	2.5995	0.1184
Hemicellulose	8.5206	2.6045	0.1187
TOTAL		**21.9501**	**1.0000**

3.2. TOPSIS Method

The TOPSIS method has been employed to address evaluation and selection issues. This is implementing the TOPSIS method for determining criteria in the design process performance.

(i) Step 1: Set up of criteria for decisions (A). **Table 9** presents the decision matrix. Equation 6 is employed to derive the construction decision matrix. **Table 9** presents the original data matrix integrated with corresponding weights for each criterion, as derived through the CRITIC method. This comprehensive matrix is fundamental in MCDM for evaluating and ranking alternatives. In this case, various natural fibres are based on multiple performance indicators related to physical, mechanical, and moisture resistance properties. The first row of the table lists the weight, which was previously determined and normalised (**Table 8**) using the CRITIC method. Each weight represents the relative importance of a given criterion based on its standard deviation and its correlation with other criteria, ensuring an objective evaluation framework. For instance, "Elongation at Break" holds the highest (0.1368), followed by "Hemicellulose" (0.1186) and "Moisture Content" (0.1184), indicating their significant influence on fibre performance differentiation. The tables list twelve natural fibres, such as kenaf, Ijuk, Hemp, Abaca, and Ramie, alongside their respective values for each criterion. These criteria are grouped under three primary property categories: Weight (Density, Diameter, Length), Strength (Tensile Strength, Young's Modulus, Elongation at Break), and Moisture Resistance (Cellulose, Moisture Content, Hemicellulose). By incorporating weights directly into the data matrix, this format facilitates the application of further MCDM techniques, such as TOPSIS, to perform composite evaluations and ranking. The inclusion of weight ensures that more critical properties, such as fibre extensibility or moisture retention, exert proportionally greater influence in the decision-making process.

Table 9. The original data matrix (including weight).

Fibre	**Weight**			**Strength**			**Moisture Resistance**		
	Density (g/cm^3)	**Diam. (μm)**	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**	**Moisture Content (%)**	**Hemi-cellulose (%)**
Weight	**0.1033**	**0.1022**	**0.0948**	**0.1032**	**0.1097**	**0.1368**	**0.1130**	**0.1184**	**0.1186**
Kenaf	1.20	24.00	6.20	612.50	41.00	4.80	53.0	9.10	21.00
Ijuk	1.34	221.00	0.00	213.10	4.01	19.40	11.62	48.03	7.09
Hemp	1.47	30.50	30.00	845.00	45.00	3.05	43.00	8.00	20.15
Abaca	1.50	20.00	4.90	621.50	41.00	2.90	59.50	14.00	21.00
Banana	1.35	21.00	0.65	815.75	29.50	5.50	63.00	10.50	12.50
Coir	1.20	18.50	1.65	175.00	6.00	20.00	45.60	10.00	0.30
Flax	1.38	21.50	37.50	850.00	65.00	2.10	75.00	7.00	19.60
Sisal	1.20	27.00	4.40	681.00	15.50	2.45	68.50	11.00	11.00
Jute	1.23	15.00	3.30	547.50	46.25	2.30	63.75	12.00	17.00
Bamboo	0.85	56.50	2.75	566.00	53.00	4.65	34.50	14.00	11.40
Pineapple	1.50	24.50	5.50	1410.00	71.00	2.00	80.50	14.00	17.50
Ramie	1.44	49.00	145.00	915.00	94.70	3.00	71.09	140.50	15.00

(ii) Step 2: Standardise the decision matrix. After calculating $\sum {f_{ij}}^2$All standardised decision matrices can be determined from Equation (7). For the example $\sum {f_{ij}}^2$= $(1.20^2) + (1.34^2) + (1.47^2) + (1.50^2) + (1.35^2) + (1.20^2) + (1.23^2) + (0.85^2) + (1.50^2) + (1.44^2)$= 15.6550, $r_{ij} = 1.20/\sqrt{20.7990}$= 0.2631. The entire results of the standardised decision-making matrix are shown in **Table 10**. **Table 10** illustrates the normalised decision-making matrix obtained through the TOPSIS method, a widely recognised MCM technique. The primary objective of TOPSIS is to rank a set of alternatives, various natural fibres, based on their geometric proximity to an ideal solution and a negative ideal solution. The normalised of the decision matrix, as shown in this table, is the foundational step in that process. In this matrix, each fibre is evaluated across multiple criteria such as Density, Diameter, Length, Tensile Strength, Young's Modulus, Elongation at Break, Cellulose, Moisture Content, and Hemicellulose. These attributes span mechanical, physical, and moisture resistance properties, all criteria in evaluating fibres' suitability for composite materials and sustainable applications. Normalisation is necessary in TOPSIS to eliminate unit inconsistencies among the criteria, ensuring comparability. Each value in this table has been derived by dividing the original value by the square root of the sum of squares of the respective criterion across all alternatives. This transformation standardises the data onto a unitless scale, typically between 0 to 1. Additionally, the first row includes the CRITIC-derived weight, which is used to multiply each normalised value, generating a weighted normalised decision matrix. These weights reflect both the variability and the informational independence of each criterion, enhancing the objectivity of the evaluation. For example, Ramie stands out with high normalised values in crucial performance indicators like Tensile Strength (0.3496), Length (0.9466), and Cellulose (0.3488), indicating its strong proximity to the ideal solution. On the other hand, fibres like Ijuk and Coir may show strength in isolated criteria but have lower composite scores, reflecting a greater distance from the ideal. In summary, **Table 10** is critical for applying the TOPSIS method, as it quantifies and normalises the performance of each fibre in a way that enables accurate computation of distance to ideal solutions. This systematic, quantitative approach supports more reliable and transparent decision-making in materials engineering and sustainable product design.

Table 10. Normal decision-making matrix.

Fibre	**Weight**			**Strength**			**Moisture Resistance**		
	Density (g/cm^3)	**Diam. (µm)**	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**	**Moisture Content (%)**	**Hemi-cellulose (%)**
Weight	**0.1033**	**0.1023**	**0.0948**	**0.1033**	**0.1097**	**0.1369**	**0.1131**	**0.1184**	**0.1187**
Kenaf	0.2631	0.0987	0.0405	0.2340	0.2378	0.1602	0.2625	0.1481	0.3866
Ijuk	0.2927	0.9088	0.0000	0.0814	0.0232	0.6475	0.0570	0.7816	0.1304
Hemp	0.3223	0.1254	0.1958	0.3229	0.2610	0.1018	0.2110	0.1302	0.3710

Table 10 (continue). Normal decision-making matrix.

Fibre	Weight			Strength			Moisture Resistance		
	Density (g/cm^3)	**Diam. (μm)**	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**	**Moisture Content (%)**	**Hemi-cellulose (%)**
Abaca	0.3289	0.0822	0.0320	0.2375	0.2378	0.0968	0.2919	0.2278	0.3866
Banana	0.2960	0.0864	0.0042	0.3117	0.1711	0.1836	0.3091	0.1709	0.2301
Coir	0.2631	0.0761	0.0108	0.0669	0.0348	0.6675	0.2237	0.1627	0.0055
Flax	0.3026	0.0884	0.2448	0.3248	0.3770	0.0701	0.3680	0.1139	0.3609
Sisal	0.2631	0.1110	0.0287	0.2602	0.0899	0.0818	0.3361	0.1790	0.2025
Jute	0.2697	0.0617	0.0215	0.2092	0.2682	0.0768	0.3128	0.1953	0.3130
Bamboo	0.1864	0.2323	0.0180	0.2163	0.3074	0.1552	0.1693	0.2278	0.2099
Pineapple	0.3289	0.1007	0.0359	0.5388	0.4118	0.0668	0.3950	0.2278	0.3222
Ramie	0.3157	0.2015	0.9466	0.3496	0.5492	0.1001	0.3488	0.2360	0.2762

(iii) Step 3: Execute matrix multiplication on the columns of the normalised decision matrix using the corresponding weights to produce the weighted normalised decision matrix. The weighted normalised value. The weights normalisation value can be determined from equation 8. For example, we can get: $v_{ij} = 0.2361x0.1033 = 0.0272$. The entire results of the weighted normalize value are shown in **Table 11**. **Table 11** presents a crucial initial step in applying the TOPSIS method for material selection, specifically focusing on natural fibres. It serves as a normalised and weighted decision matrix, a fundamental input for the subsequent ranking of alternatives. Crucially, the table incorporates weights for each criterion, reflecting their relative importance in the DM process. These weights, presented in the second row, are numerical values (ranging from 0.0948 to 0.1369) that sum to unity. For instance, "Elongation at Break" has the highest weight (0.1369), suggesting it is deemed the most critical factor for the application under consideration, while "Length" has the lowest weight (0.0948), indicating its lesser importance, these weights are subjective and determined by the DM based on the specific requirements of the application. The subsequent rows contain the normalised performance values of each fibre against each criterion. The original data for each fibre criterion combination has been transformed through a normalisation process. While the specific normalisation method isn't explicitly stated in the table. The resulting values are dimensionless a fall within a comparable range. This normalisation is essential to eliminate the influence of different measurement units and scales across the criteria, allowing for a fair comparison. Furthermore, each normalised performance value has been multiplied by the corresponding criterion weight. This weighting step integrates the importance of each criterion into the evaluation of each fibre. For example, fibres with high normalised tensile strength value will have an even higher weighted normalised value if Tensile Strength has a substantial weight, Therefore, this table provides a concise and processed representation of the performances of various natural fibres across multiple weighted normalised criteria. It sets the stage for the core TOPSIS calculation, where the weighted normalised performance of each alternative is compared to the ideal positive and negative solutions to determine relative closeness and ultimately ranks the fibres based on their overall sustainability for the intended application. This structured approach ensures a more objective and informed selection process.

Table 11. Decision matrix with weights and normalization.

Fibre	Weight			Strength			Moisture Resistance		
	Density (g/cm^3)	Diam. (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)	Moisture Content (%)	Hemi-cellulose (%)
Weight	**0.1033**	**0.1023**	**0.0948**	**0.1033**	**0.1097**	**0.1369**	**0.1131**	**0.1184**	**0.1187**
Kenaf	0.0272	0.0101	0.0038	0.0242	0.0261	0.0219	0.0297	0.0175	0.0459
Ijuk	0.0303	0.0929	0.0000	0.0084	0.0025	0.0886	0.0064	0.0926	0.0155
Hemp	0.0333	0.0128	0.0185	0.0333	0.0286	0.0139	0.0239	0.0154	0.0440
Abaca	0.0340	0.0084	0.0030	0.0245	0.0261	0.0133	0.0330	0.0270	0.0459
Banana	0.0306	0.0088	0.0004	0.0322	0.0188	0.0251	0.0350	0.0202	0.0273
Coir	0.0272	0.0078	0.0010	0.0069	0.0038	0.0914	0.0253	0.0193	0.0007
Flax	0.0313	0.0090	0.0231	0.0335	0.0414	0.0096	0.0416	0.0135	0.0428
Sisal	0.0272	0.0114	0.0027	0.0269	0.0099	0.0112	0.0380	0.0212	0.0240
Jute	0.0279	0.0063	0.0020	0.0216	0.0294	0.0105	0.0354	0.0231	0.0371
Bamboo	0.0193	0.0238	0.0017	0.00223	0.0337	0.0212	0.0191	0.0270	0.0249
Pineapple	0.0340	0.0103	0.0034	0.0556	0.0452	0.0091	0.0447	0.0270	0.0382
Ramie	0.0326	0.0206	0.0893	0.0361	0.0603	0.0137	0.0394	0.0279	0.0328

(iv) Step 4: Determine the degree of closeness to the optimal solution, positive ideal (A*) and negative ideal (A^-) solutions. The proximity to the ideal solution can be assessed using Equation (9). The positive ideal (A*) represents the dataset's most significant value, 0.0340, while the negative ideal (A-) denotes the least value, 0.0193. **Table 12** presents the comprehensive results about the degree of proximity to the ideal solution. **Table 12** presents a negative ideal solution and a positive ideal solution. The positive ideal solution A* is a hypothetical alternative that maximises the benefit criteria and minimises the cost criteria across all considered attributes. In this table, the row labelled A* contains the best achievable value for each criterion from the set of normalised and weighted values of all the alternatives. For benefit criteria, the highest observed weighted normalised value among all fibres for that specific criterion is selected as the ideal positive value. Conversely, for cost criteria, the lowest observed weighted normalised value is chosen as the positive ideal value. The specific nature of each criterion is crucial for correctly identifying the ideal solutions. Concisely, the negative ideal solutions A- represent a hypothetical alternative that has the worst possible performance across all criteria. The row labelled A contains the least desirable value for each criterion from the normalised and weighted data. For the benefit criteria, the lowest observed weighted normalised value among all fibres is selected as the negative ideal solution value. For cost criteria, the highest observed weighted normalised value is chosen as the negative ideal solution value. The values presented in **Table 12** are directly derived from the weighted and normalised decision matrix. They retain the impact of both the original performance data and assigned weights, ensuring that the ideal solutions reflect the relative importance of each criterion. For instance, if "Elongation at Break" has a high weight, the difference between the positive ideal and negative ideal values for this criterion will have a significant influence on the subsequent distance calculations in TOPSIS.

Table 12. Compared to negative ideal solutions, positive ideal solutions.

Fibre	**Weight**			**Strength**			**Moisture Resistance**		
	Density (g/cm^3)	**Diam. (µm)**	**Length (mm)**	**Tensile Strength (MPa)**	**Young's Modulus (GPa)**	**Elongation at Break (%)**	**Cellulose (%)**	**Moisture Content (%)**	**Hemi-cellulose (%)**
A*	0.0340	0.0929	0.0893	0.0556	0.0603	0.0914	0.0064	0.0135	0.0007
A-	0.0193	0.0063	0.0000	0.0069	0.0025	0.0091	0.0447	0.0926	0.0459

(v) Step 5: Ascertain the separation metrics: The separation metrics of each alternative from the positive ideal solution and the negative ideal solution are as follows:

(vi) All separation measures can be determined from equations 10 and 11. For example,

$$S_i^* = \sqrt{\begin{gathered}(0.0272-0.0340)^2+(0.0101-0.0929)^2+(0.0038-0.0893)^2+(0.0242-0.0556)^2\\+(0.0261-0.0603)^2+(0.0219-0.0914)^2+(0.0297-0.0064)^2+(0.0175-0.0135)^2\\+(0.0459-0.0007)^2\end{gathered}}$$

$$= 0.1543$$

$$S_i^- = \sqrt{\begin{gathered}(0.0272-0.0193)^2+(0.0101-0.0063)^2+(0.0038-0.0000)^2+(0.00242-0.0069)^2\\+(0.0261-0.0025)^2+(0.00219-0.0091)^2+(0.0297-0.0447)^2+(0.0175-0.0926)^2\\+(0.0459-0.0459)^2\end{gathered}}$$

$$= 0.0834$$

The entire results of the separation measure for each performance criterion are shown in **Table 13**. **Table 13** presents a crucial intermediate output in the TOPSIS method. Following the identification of the positive ideal solutions (A*) and negative ideal solutions A-). This table quantifies the separation measure of each alternative from these ideal solutions across the considered performance criteria. These separation measures form the basis for determining the relative closeness of each alternative to the ideal positive solution. By calculating this separation measure for each natural fibre, the TOPSIS method provides a quantitative assessment of how each fibre deviates from both the best and worst possible performance profiles in two single numerical values. Facilitating a more direct comparison. The subsequent step in the TOPSIS method involves using separation to calculate the relative closeness of each alternative to the ideal positive solution. This relative closeness is typically determine by the ratios of S_i^* and S_i^-**.** A higher value of C ranking that the alternative is closed to the ideal positive score A higher value of A*, indicates that the alternative is closer to the deal positive solution and farther from the ideal negative solution, thus representing stone towards the final raking of the alternatives in the TOPSIS methodology, enabling a robust and mathematically the ranking evaluation problems.

Table 13. Separation Measure for each performance criterion.

	Kenaf	**Ijuk**	**Hemp**	**Abaca**	**Banana**	**Coir**	**Flax**	**Sisal**	**Jute**	**Bamboo**	**Pineapple**	**Ramie**
S_i^*	0.1543	0.1415	0.1453	0.1605	0.1524	0.1451	0.1482	0.1600	0.1615	0.1426	0.1557	0.1182
S_i^-	0.0834	0.1278	0.0915	0.0745	0.0834	0.1209	0.0958	0.0785	0.0840	0.0840	0.0938	0.1301

(vii) Step 5: Identify the optimal positive and negative solutions. The relative closeness of the alternative Pi concerning P* is defined as follows: The proximity to the optimal solution can be assessed using equation 12. For the example, *Pi* = 0.0834 / (0.1543+0.0834) = 0.3510. **Table 14** presents the complete results of Relative proximity to the ideal solution.

Table 14 presents the penultimate stage in the TOPSIS method. Building upon the calculated separation measures from the positive ideals and negative ideals. This table displays the relative closeness of each alternative to the ideal positive solution. These metrics provided a normalised score for each alternative, facilitating their final ranking and selection. The resulting *Pi* values range between 0 and 1. Higher values of *Pi* indicate that the i-th alternative is closer performance across the considered criteria, weighted by their importance solution and farther from the ideal solution, signifying a better overall performance across the considered criteria, weighted by their importance. Conversely, a lower *Pi* value suggests that the alternative is closer to the ideal negative solution and farther from the ideal positive solution, indicating a less desirable performance profile. By computing the relative closeness (i.e. *Pi*) for each natural fibre (Kenaf, Ijuk, Hemp, Abaca, Banana, Coir, Flax, Sisal, Jute, Bamboo, Pineapple, and Ramie), the TOPSIS method provides a clear and interpretable basis for ranking the alternatives, in this table, Ramie exhibits the highest relative closeness values (0.5240), suggesting it is the closest to the ideal positive solution and thus the most preferred option among the considered fibres based on the defined criteria and their weights. Following Ramie, Ijuk (0.4745) and Coir (0.4546) show relatively high closeness values, indicating their favourable performance. On the other hand, Abaca (0.3171) and Sisal (0.3292) have lower *Pi* values, suggesting they are relatively further from the ideal positive solution. Equation 12 is used to calculate the relative closeness to the ideal solution.

Table 14 presents twelve natural fibre alternatives, and it was ordered according to their priority Pi scores. Based on the findings, Ramie has the highest Pi score of 0.5240. Ijuk has the second-highest score of 0.4745, followed by Coir, Flax, Hemp, Pineapple, Bamboo, Banana, Kenaf, Sisal, Jute, and Abaca, which gathered Pi values of 0.4546, 0.3925, 0.3864, 0.3758, 0.3538, 0.3510, 0.3292. 0.3243 and 0.3170, respectively. The result showed that Ramie has advantages for insulation in building construction because of its properties.

Ramie is a strong, lustrous, and water-absorbing [49]. On the other hand, Ramie is one of the strongest natural fibres and is even stronger when wet [50]. Ramie is known for its ability to hold shape and reduce wrinkling.

Table 14. Relative closeness to the ideal solution for each performance criterion.

Type	Pi
Kenaf	0.3510
Ijuk	0.4745
Hemp	0.3864
Abaca	0.3170
Banana	0.3538
Coir	0.4546
Flax	0.3925
Sisal	0.3292
Jute	0.3243
Bamboo	0.3706
Pineapple	0.3758
Ramie	0.5240

(viii) Step 6: Establish a ranking of preference. The ranking of each alternative according to the performance score is displayed in **Table 15**. As a result, the ranking results of the CRITIC-TOPSIS method are shown in **Table 15**. The results from synthesising data on the critical criteria were used to generate a list of twelve natural fibres. These fibres were ordered based on their positive ideal solution (Pi) scores, which were calculated using the Microsoft Excel 2016 software and a specific method. According to previous studies [51], Excel has become as common as calculators in the fields of data analysis and decision making. **Table 15** displays the results. Ramie achieved the highest score of 0.5240, positioning it in the highest position in the rating. Ijuk received the grade that is ranked just behind the highest score determined by a score of 0.4745, followed by Coir, Flax, Hemp, Pineapple, Bamboo, Banana, Kenaf, Sisal, Jute, and Abaca with values of 0.4745, 0.4546, 0.3925, 0.3864, 0.3758, 0.3538, 0.3100, 0.3292, 0.3243 and 0.3170, respectively. The selection of natural fibres for composite materials is a complex process that benefits from incorporating multiple evaluation criteria to enhance DM. MCDM tools have been developed to aid in this section by considering various factors such as mechanical properties, cost, and environmental impact. For instance, a previous study [52] introduces a statistical framework for selecting materials for natural fibre reinforced polymer composites, highlighting the necessity of assessing several parameters to choose the most appropriate material for automotive components. From previous reports [53], it emphasises the importance of evaluating various characteristics, including physical, mechanical, chemical, and environmental properties, in selecting natural fibres, noting that a thorough assessment tailored to specific application requirements dramatically impacts the final selection results.

Acknowledging natural fibres' chemical composition and shape is crucial for understanding their distinctive qualities. Integrating supplementary qualities from several evaluation criteria might augment the thoroughness of the selection process for natural fibres. Previous studies [54] underscore the need to examine synthetic and natural fibres' morphological and physico-mechanical properties to guide material selection.

Researchers recognise the TOPSIS method's effectiveness in determining optimal decisions by assessing selection criteria and their interrelationships with competing criteria and alternative options. The principal benefit of utilising the CRITIC-TOPSIS methodology over other MCDM methods is its ability to assess both negative and positive criteria in decision-making processes simultaneously. Furthermore, it is more direct and effective than alternative approaches like AHP. The TOPSIS method identifies the alternative that most closely aligns with the positive ideal solution while diverging from the damaging alternative. This approach offers a more accurate representation of models than non-compensatory alternatives [55, 56].

Table 15. Ranking of each alternative according to the performance score (Pi Score).

Alternatives	Pi	Ranking
Kenaf	0.3510	9
Ijuk	0.4745	2
Hemp	0.3864	5
Abaca	0.3170	12
Banana	0.3538	8
Coir	0.4546	3
Flax	0.3925	4
Sisal	0.3292	10
Jute	0.3243	11
Bamboo	0.3706	7
Pineapple	0.3758	6
Ramie	**0.5240**	**1**

3.3. Sensitivity Analysis

The concluding phase in executing CRITIC-TOPSIS is the sensitivity analysis. Sensitivity analysis is crucial for addressing issues and validating the robustness of results obtained using CRITIC-TOPSIS. Thus, modifying the values by increasing or decreasing the weight of a specific criterion while maintaining others constant will produce varying rankings of options and ultimate decisions [57]. Additionally, sensitivity analysis facilitates examining the stability of ranking outcomes when identifying the most appropriate natural fibre materials for insulation building construction. This research facilitates a comprehensive knowledge of the final ranking's flexibility to alterations in weight assignments. This study employed a Monte Carlo sensitivity analysis.

3.3.1. Monte carlo sensitivity analysis

Monte Carlo sensitivity analysis is a rigorous method utilised to assess the impact of uncertainty in input variables on the results of a model. This method involves several simulations, often numbering in the thousands or millions, in which input values are randomly drawn from specified probability distributions. This approach produces a range of potential outcomes, enabling the formulation of suitable probability distributions derived from historical data, expert judgment, or theoretical assumptions. Subsequently, numerous simulations are executed, each employing a unique set of randomly generated inputs, with matching outputs painstakingly recorded. Examining the resultant output distribution uncovers statistical characteristics such as range, mean, and standard deviation, thereby clarifying the extent to which fluctuations in each input affect total outcome variability [58]. This study is crucial for identifying the inputs most significantly influencing the model's outcomes, improving decision-making under uncertainty. Monte Carlo sensitivity analysis is widely utilised in various domains, including finance [59], engineering [60], project management [61], and environmental science [62]. In epidemiology, this strategy has been employed to control for potential confounding variables, such as the construction sector, in research investigating material selection for insulation building construction.

Combining Monte Carlo sensitivity analysis with the CRITIC-TOPSIS approach can substantially improve decision-making under uncertainty. This integrated methodology employs the CRITIC method to objectively ascertain the weight of criteria by assessing both contrast intensity and conflicts among criteria. In contrast, the TOPSIS method evaluates alternatives according to their closeness to an ideal solution. This combination facilitates a thorough evaluation of options, considering uncertainties in input data and the relative significance of each criterion. For instance, a previous report [63] presented an integrated framework that merges the TOPSIS method with Monte Carlo simulation for risk assessment in project management, illustrating the efficacy of this approach in managing uncertainty and enhancing decision-making processes.

This study thoroughly examines the average rankings of twelve alternatives, including natural fibres such as Kenaf, Jute, and Ramie, based on a Monte Carlo sensitivity analysis depicted in Figure 6. It utilizes a bar chart visualization to effectively demonstrate the performance strength among these options, surpassing basic probability assessments to highlight the consistency of their respective rankings. The "Mean Rank of Alternative (Monte Carlo Sensitivity Analysis)" graphic illustrates the mean rank on the y-axis, spanning from 0 to 9, where lower values signify superior performance. Alternatives are situated along the x-axis. This study reveals that Ijuk exhibits the greatest mean rank, signifying persistent underachievement throughout several scenarios. This suggests a noticeable intrinsic weakness or unique attributes of Ijuk compared to other options. Conversely, alternatives like Banana, Coir, Flax, and Jute demonstrate the lowest mean rank, indicating continual underperformance throughout multiple simulations. These findings highlight the necessity of assessing many parameters throughout the selection process to guarantee that selected natural fibres fulfil particular performance standards. Utilising thorough evaluation approaches, such as Monte Carlo sensitivity analysis, can yield profound insights into the resilience and appropriateness of various natural fibre alternatives [64, 65].

The observed mean ranks, ranging from approximately 5.3 to 9, signify considerable variability in performance consistency. This metric surpasses fundamental probability calculations, offering an advanced understanding of each alternative's performance across the various conditions in the Monte Carlo simulation. This sensitivity analysis provides critical insights into the stability and reliability of each alternative's performance. This is crucial for situations where consistent outcomes are vital.

The divergence between CRITIC-TOPSIS results, which rank Ramie as the premier alternative, and the Monte Carlo sensitivity analysis, indicating a diminished mean rank for Ramie, highlights the necessity of utilizing complementary analytical methods in MCDM. CRITIC-TOPSIS, a methodology aimed at determining the ideal alternative based on a predetermined set of weighted criteria, indicates that Ramie performs exceptionally well under particular, specified situations. In contrast, the Monte Carlo sensitivity analysis, which assesses the stability of rankings under different input parameters, indicates that Ramie's performance is less reliable across several potentials when specific criteria are emphasised. The Monte Carlo analysis indicates its susceptibility to fluctuations, implying that its exceptional performance may not be consistently reproducible. These contradicting conclusions resolve to acknowledge the varied objectives of each method. CRITIC-TOPSIS identifies the optimal choice based on established parameters, whereas Monte Carlo analysis evaluates the reliability of that optimal choice across various scenarios. Consequently, Ramie's elevated position in CRITIC-TOPSIS signifies its potential under particular, weighted criteria. In contrast, its diminished average rank in the Monte Carlo analysis suggests a vulnerability to performance variability when those criteria are altered. This highlights the importance of combining deterministic and stochastic analytical methods to have a thorough knowledge of alternative performance, especially when robustness and reliability are critical.

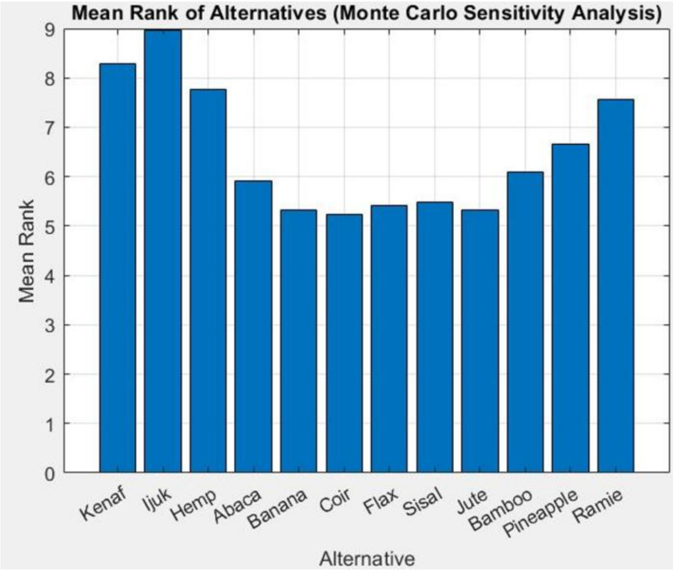

Figure 6. Mean Rank of Alternating using Monte Carlo sensitivity analysis.

3.3.2. Contribution to sustainable development goals (SDGs)

The outcomes of this research align with several United Nations Sustainable Development Goals (SDGs). Specifically, the study supports SDG 9 (Industry, Innovation, and Infrastructure) by introducing innovative material selection methods that advance sustainable construction practices through the integration of CRITIC-TOPSIS and Monte Carlo sensitivity analysis. The promotion of natural fibres for insulation directly addresses SDG 11 (Sustainable Cities and Communities), as these materials enhance energy efficiency, reduce greenhouse gas emissions, and contribute to healthier urban environments. Additionally, the responsible sourcing and utilization of renewable natural fibres reflect the principles of SDG 12 (Responsible Consumption and Production), minimizing environmental degradation and encouraging the efficient use of natural resources. By systematically evaluating the mechanical, thermal, and moisture-resistant properties of various natural fibres, this study offers a data-driven approach that informs sustainable DM in the construction industry.

4. CONCLUSION

This study successfully applied an integrated MCDM framework combining the CRITIC-TOPSIS method and Monte Carlo sensitivity analysis to identify optimal natural fibre materials for sustainable building insulation composites. The CRITIC method objectively determined the weight of nine evaluation criteria, while TOPSIS ranked twelve natural fibres based on their proximity to the ideal solution. Ramie was identified as the most promising material, followed by Ijuk and Coir. The Monte Carlo sensitivity analysis validated the robustness of the ranking results by simulating uncertainty and variability in the criteria weights. The integration of deterministic (CRITIC-TOPSIS) and stochastic (Monte Carlo) approaches ensures more reliable and comprehensive material selection under uncertain conditions. The findings contribute to advancing sustainable material engineering and support decision-makers in selecting eco-friendly insulation materials, ultimately promoting innovation and sustainability in the construction sector while aligning with multiple Sustainable Development Goals (SDGs).

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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