Sensitivity Analysis of the Integrated CRITIC-TOPSIS Method for Selecting Optimal Natural Fibre–Reinforced Composites for Toe Caps in Safety Footwear

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Abstract

The selection of natural fibres for toe caps in safety footwear requires careful evaluation of multiple performance criteria. This process makes the task a multicriteria decision-making problem, as numerous alternatives and requirements must be considered simultaneously. This study applied the CRiteria Importance Through Intercriteria Correlation (CRITIC) method to compute objective criterion weights, which were then integrated into the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to rank and identify the optimum fibre amongst 12 alternatives. A sensitivity analysis was conducted to evaluate the impact of weight variations on the selection results. The combined CRITIC-TOPSIS method effectively determined the optimal natural fibre for safety toe cap applications. Sensitivity analysis confirmed the robustness of the results whilst highlighting the influence of criterion weight variations on final rankings. The proposed integration offers a systematic and reliable approach for material selection in safety footwear. The findings provide useful guidance for the development of natural fibre–reinforced polymer composites and support lightweight and sustainable alternatives for toe caps in safety footwear.

Keywords: Natural fibre composite; Multi-criteria decision Making (MCDM); CRITIC; TOPSIS; Material selection

1. Introduction

Safety footwear, a crucial form of personal protective equipment (PPE), is specifically designed to protect the feet from mechanical impacts and falling objects. Such footwear should remain lightweight to promote comfort and minimise worker fatigue, as reduced mass decreases leg strain during and after prolonged use. The main structural elements of safety footwear include the outsole, the upper and the toe cap. The toe cap serves as the key protective component of the forefoot. Depending on the material used, the toe cap contributes approximately 8% to 15% of the total weight [1]. Commonly adopted materials include steel, aluminium alloys, composites and polymers. In recent years, the structural design and material selection of toe caps have increasingly involved multidisciplinary approaches. Research has largely focused on two main categories: metallic and nonmetallic toe caps. Nonmetallic options are gaining prominence because they are generally lighter than traditional metallic counterparts, thereby providing a highly effective means for weight reduction without compromising safety performance [2].

Most natural fibres are derived from plants or animals. Incorporating natural fibre reinforcements
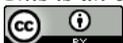
in composites has several benefits, including lightweight properties [3], accessibility, cost-effectiveness, nonabrasiveness, recyclability, low carbon dioxide emissions, biodegradability and renewability [4]. Toe caps are essential components of safety footwear, but they contribute significantly to overall weight. Steel toe caps are being replaced with polymer-based alternatives to reduce added weight [5]. Moreover, natural materials are widely utilised as reinforcements in composite materials because of their environmental sustainability and nontoxicity, thereby ensuring safety for human health [6]. Researchers worldwide have developed biodegradable fibres and polymers to produce innovative biocomposites that can be alternatives to conventional materials [7].

Diakoulaki et al. (1995) proposed the CRiteria Importance Through Intercriteria Correlation (CRITIC) method, which is primarily used to calculate the weight of an attribute. The CRITIC method is one of the most popular and widely applied objective methodologies [8]. It is a correlation-based method that measures the contrast between criteria by calculating the correlation coefficients of all pairs of columns and standard deviations of the standardised criterion values [9,10]. Hwang and Yoon (1981) proposed the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [11], a Multi-Criteria Decision Making (MCDM) method that is widely used in material selection studies [12,13]. Jha et al. (2022) explored material selection for biomedical applications in additive manufacturing using the TOPSIS approach [14]. Hedayati et al. (2022) conducted a multiobjective optimisation study on cakes formulated with fig or date syrup and various hydrocolloids using the TOPSIS method [15]. Considerable research has been conducted on selecting materials for composite product design and fabrication. An innovative study was recently conducted to select biopolymer composites suitable for food packaging reinforced with natural fibres [16].

Previous research has widely utilised MCDM strategies to select materials for various applications. Few studies have explicitly investigated the selection of biocomposite materials for consumer product applications, including toe caps. I. Bianchi et al. (2022) reported that approximately 600 million toe caps are discarded annually without being separable from the shoes. This situation highlights the use of carbon fibre prepreg scraps to prevent their disposal in landfills or by combustion. These scraps can be used to manufacture certified, lightweight toe caps [17]. The use of plastic technology allows for the

replacement of steel toe caps with plastic toe caps [18]. These two are amongst the few recent studies addressing the use of toe caps. To the best of our knowledge, no natural fibre has ever been used as a reinforcing component in toe cap designs.

Therefore, designers and materials engineers would benefit from a systematic and structured strategy for material selection to support the decision-making (DM) process. This study presents a model that utilises the CRITIC-TOPSIS method to select the optimal natural fibre for reinforcing biocomposites in toe cap applications.

2. Materials and Methods

The selection of natural fibres for toe cap applications is conducted using a stepwise approach. The methodology adopted in this study employs a hybrid MCDM approach, in which the CRITIC method and the TOPSIS method are combined. This hybrid framework is designed to evaluate and select the most suitable natural fibre–reinforced material composite for toe cap applications systematically, based on both objective data analysis and proximity to an ideal solution. Figure 1 shows a flowchart that can be used in this research to select the potential toe cap material. The process is structured into four main stages.

The first stage involves defining and structuring the decision problem. In this stage, the problem of selecting a reinforcement material for toe caps is clearly identified. A database of potential natural fibre materials, including alternatives such as jute, kenaf, hemp and flax, is developed. Then, a hierarchical structure is formulated to organise the selection criteria, which may include mechanical strength, moisture resistance and other factors.

In the second stage, the CRITIC method is applied to determine the objective weights of the decision criteria. This stage begins with the formulation of a decision matrix, which quantifies the performance of each material alternative against the set criteria. The data in the matrix are normalised to remove the influence of differing units of measurement. Then, the standard deviation of each criterion is calculated to capture data variability, which reflects the discriminative power of each criterion. The correlation coefficients amongst criteria are computed to identify redundancy or interdependence. The CRITIC method assigns objective weights to each criterion by considering the interplay between variability and correlation, thereby ensuring that the influence of each criterion is determined strictly from the data rather than expert bias.

The third stage employs the TOPSIS method to rank the material alternatives. The weighted decision matrix from the CRITIC stage is used as input. TOPSIS begins by standardising the decision matrix and identifying the positive ideal solution (representing the best values). Then, the method computes the Euclidean distance of each alternative from the ideal solution, which forms the basis for the final ranking. The alternative closest to the positive ideal and farthest from the negative ideal is considered the most suitable for the intended application.

The fourth and final stage involves the interpretation of results and DM. All material alternatives are ranked in order of their suitability based on the relative closeness scores calculated through TOPSIS. This final ranking supports a data-driven and transparent material selection process for toe caps whilst contributing to sustainable and performance-oriented product design.
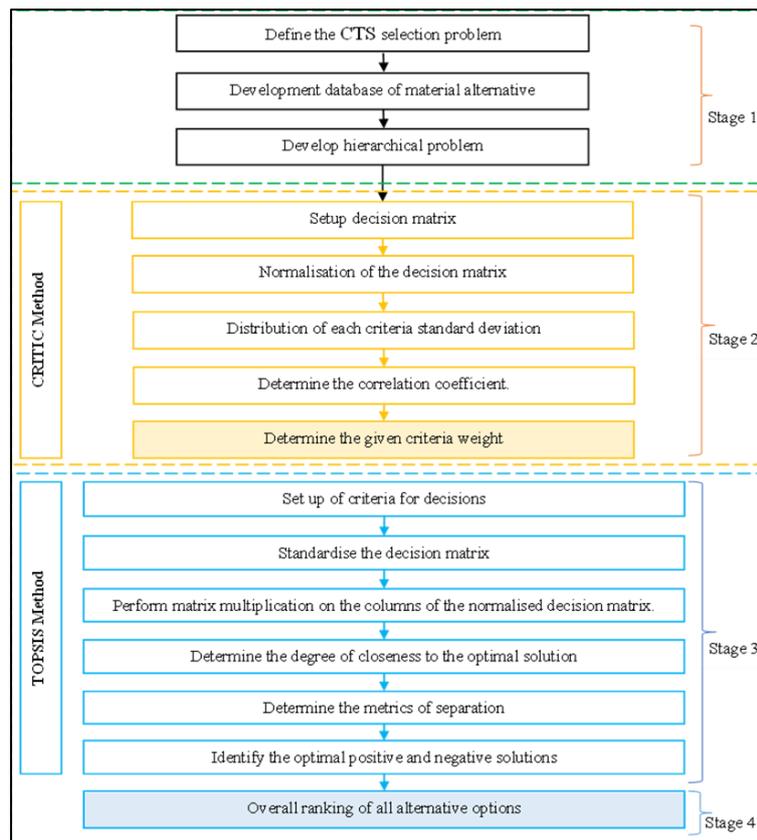

Fig. 1. Flowchart of the toe cap material selection process.

2.1. Stage 1: Setting Up Hierarchical Structure
2.1.1. Defining Problem

The study focuses on developing an MCDM model tailored to the material requirements of toe caps. Safety footwear, an essential component of PPE in many workplaces, helps reduce foot injuries from falling objects [19–21]. This type of footwear is equipped with toe caps designed to protect the front part of the foot. In doing so, it can fulfil its intended protective function. Toe caps should be highly resistant to impact and compression whilst remaining lightweight to satisfy the ergonomic requirements of the footwear [22]. When choosing materials for toe caps, manufacturers should consider two factors: material restrictions and mechanical properties. These factors are important for ensuring safety, comfort and durability.

CRITIC-TOPSIS is a method within the MCDM network. It is employed to identify solutions that achieve a balanced compromise amongst multiple criteria. A negative result in one criterion may be compensated for by a favourable outcome in another criterion [23]. CRITIC-TOPSIS is an evaluation methodology that ranks different materials (alternatives) by considering a certain set of criteria. The CRITIC method is an objective approach for determining the weights of these criteria. The TOPSIS method operates on the principle that the preferred alternative should exhibit the minimum distance from the positive

ideal solution whilst maintaining the maximum distance from the negative ideal solution. The ranking of alternatives is determined by calculating the Euclidean distance, which measures the relative proximity of an alternative to the optimal solution in a geometric sense. The positive ideal solution represents the aggregation of the highest achievable values for each attribute, whereas the negative ideal solution represents the lowest attainable values for each attribute.

This method is characterised by its simplicity, comprehensibility, computational efficiency and capacity to evaluate the relative performance of alternative options to determine the optimal choice. The CRITIC-TOPSIS methodology was selected for this study because of its merits. The optimal material was selected through computations using CRITIC-TOPSIS. The study's findings assisted decision-makers in improving their DM process.

Therefore, 12 characteristics of natural fibres were identified. The criteria were categorised based on the materials requirements for toe cap applications, as well as relevant design and production features. The primary variables for material selection were identified as 'strength' and 'weight'. They were chosen because they allow the evaluation of the mechanical properties and barrier capabilities of natural fibres. Another primary criterion specified was 'moisture resistance'. The critical factor for selecting strength is that safety footwear is primarily designed to protect the user's toes from potential hazards, such as falling items and compression forces [24]. The inadequate water resistance of NRFC has significantly constrained

the broad application of these materials. This limitation was a result of the fibres' natural ability to absorb moisture [25]. Moisture resistance is crucial during toe cap installation inside the footwear, as this process is often performed in a humid environment. Hence, the 'weight' of natural fibre is a key factor because it can affect the overall weight of safety footwear. Consumers also prefer footwear with a lightweight design [26].

2.1.2. Development Alternatives

Twelve natural fibres were chosen based on the availability of comprehensive and comparable data from various sources. Figure 2 presents the natural fibre alternatives grouped according to their classifications. Experimental studies may have been conducted to validate the data and determine the physical properties of the selected natural fibres. Nevertheless, such validation was beyond the scope of this study because of limited resources and time constraints. Hence, data were collected from recent and relevant literature sources. The key distinguishing characteristics of natural composites are their renewability and biodegradability. These materials are environmentally sustainable, and the inclusion of green components in composites provides an alternate approach to managing agricultural residues. Comprehensive and comparable data on 12 natural fibre substitutes, documented in publications from 2018 to 2023, are presented in Table 1.

Table 1,
Proposed database of natural fibre alternatives for toe cap biocomposites from 2018 to 2023 [27–30].

| No.	Fibre	Weight			Strength			Moisture Resistance		
		Density (g/cm3)	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Cellulose (%)	Moisture Content (%)	Hemicellulose (%)
1	Abaca	1.5	20.00	4.90	621.5	41.00	2.90	59.50	14.00	21.00
2	Bamboo	0.85	58.00	2.75	566.00	53.00	4.65	34.50	14.00	11.40
3	Banana	1.35	21.00	0.65	815.75	29.50	5.50	63.00	10.50	17.50
4	Coir	1.2	18.50	1.65	175.00	6.00	20.00	45.60	10.00	0.30
5	Flax	1.38	21.50	37.50	850.00	65.00	2.10	75.00	7.00	19.60
6	Hemp	1.47	30.5	30.00	845.00	45.00	3.05	43.00	8.00	20.15
7	Jute	1.23	15.00	3.40	547.50	46.25	2.30	65.25	12.00	18.50
8	Kenaf	1.2	24.00	6.20	612.52	41.00	4.80	53.50	9.10	17.00
9	Pineapple	1.5	24.50	5.50	1310.00	71.00	2.00	80.50	14.00	17.50
10	Ramie	1.44	49.00	145.00	915.00	94.70	3.00	71.09	14.50	15.00
11	Sisal	1.2	27.00	4.40	681.00	15.50	2.45	68.50	11.00	11.00
12	Ijuk	1.34	221.00	0.00	213.10	4.00	19.40	11.62	48.03	7.09
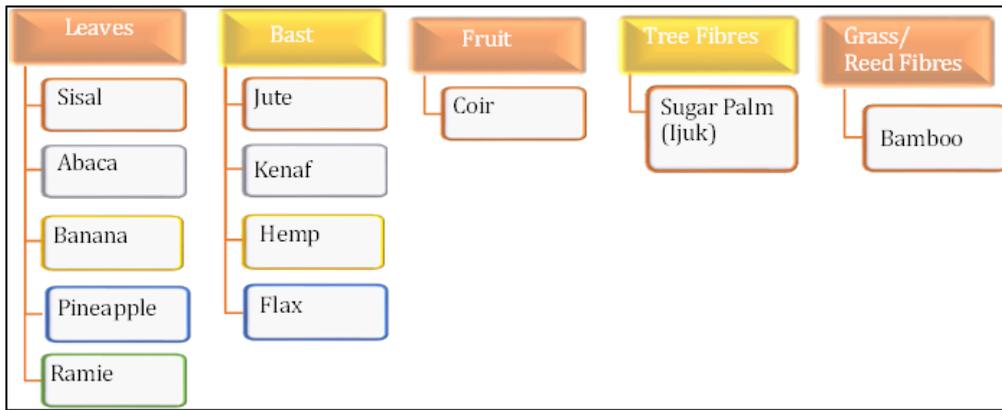
Fig. 2. Twelve potential natural fibre alternatives, grouped by category.

2.1.3. Developed Hierarchical Structure

Initially, the procedure involves developing a hierarchical structure based on the complexity of the selection process, as shown in Figure 3. The hierarchical structure is divided into numerous subproblems. At Level 1, the primary objective is material selection, which is further divided into subobjectives at Level 2 based on density, diameter, length, tensile strength, Young's modulus, elongation at break, cellulose, moisture content and hemicellulose aspects. Alternative options are presented at Level 3. The criteria and decision alternatives are organised within this hierarchical framework.
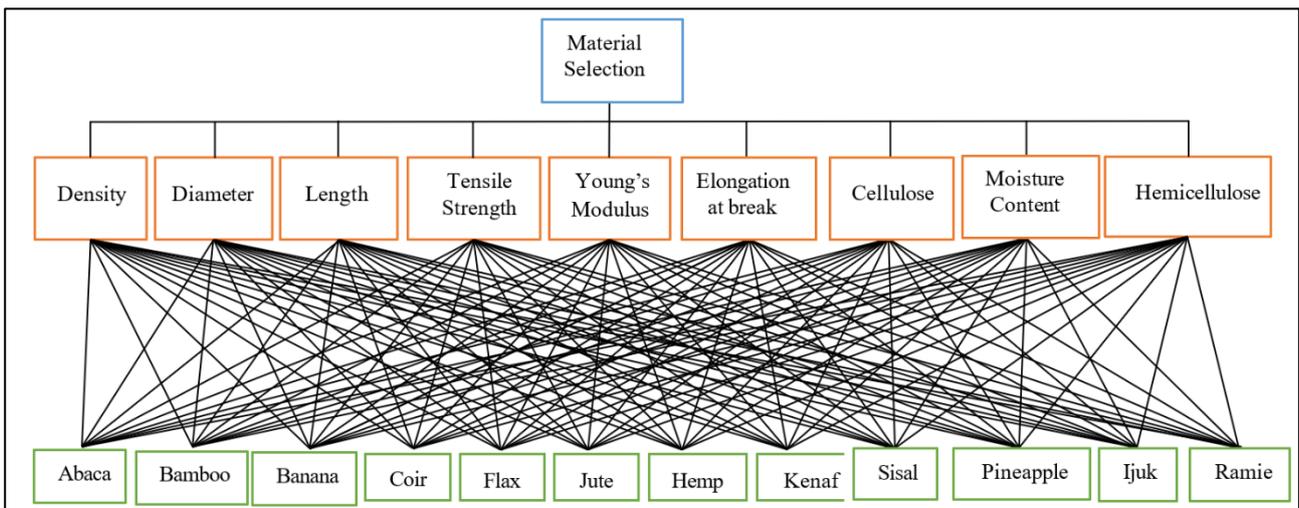

Fig. 3. Hierarchical structure for material selection in toe caps.

2.2. Stage 2: Determining Criterion Weights

The CRITIC method is based on correlation [31]. The standard deviations of the ranked criteria values for each alternative, along with the correlation coefficients between all pairs of criteria, are used to establish the contrasts amongst the criteria. The CRITIC method is one of the most widely known and frequently used objective methods. The CRITIC method belongs to the class of correlation-based methods, which use the standard deviations of the standardised criterion values for alternatives to determine the contrast amongst criteria, along with the correlation coefficients of all pairs of criteria. A CRITIC analysis was conducted to determine the criteria weights before evaluating the performance of various fibres using the TOPSIS method. The criteria weights were calculated using the CRITIC method by completing the following steps:

Step 1. Constructing an initial decision matrix.

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

$$= 1, \ldots, m, j = 1, \ldots, n \qquad \ldots (1)$$

Step 2. Normalising the decision matrix. Eq. (2) and Eq. (3) are used to standardise the positive and negative characteristics of the decision matrix. X_{ij} represents a standardised value of the decision matrix for i_{th} alternative in j_{th} attribute and $X_i^+ = \max(X_1, X_2, \ldots, X_m)$ and $X_i^- = \min(X_1, X_2, \ldots, X_m)$.

$$X_{ij} = \frac{X_{ij} - X_i^-}{X_i^+ - X_i^-} ; i = 1, \ldots, m, j = 1, \ldots, n \quad \ldots (2)$$

$$X_{ij} = \frac{X_{ij} - X_i^+}{X_i^+ - X_i^-} ; i = 1, \ldots, m, j = 1, \ldots, n \quad \ldots (3)$$

Step 3. Computing the standard deviation for each criterion. In this step, the standard deviation of each criterion is calculated. s_j is determined using Eq. (4). X_{ij} in Eq. (2) and Eq. (3) is the mean score of criterion j. m is the total number of alternatives. X_{ij} is the mean score of the criterion j, and m is the total number of alternatives.

$$s_j = \sqrt{\left(\frac{\sum_{i=1}^{m} x_{ij - \bar{x}_j}}{m-1} \right)^2} \qquad \ldots (4)$$

Step 4. Calculating the correlation coefficient. The correlation coefficient between attributes is calculated using Eq. (5).

$$\rho_{jk} = \frac{\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)(x_{ik} - \bar{x}_k)}{\sqrt{\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)^2 \sum_{i=1}^{m}(x_{ik} - \bar{x}_k)^2}} \quad \ldots (5)$$

Step 5. Calculating the weight of attributes. The calculation of attribute weights is based on Eq. (6).

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j} ; \quad j = 1, \ldots, n \qquad \ldots (6)$$

2.3. Stage 3: Evaluating the Performance Score

The TOPSIS method is based on the concept that the optimal alternative has the shortest distance to the positive ideal solution and the greatest distance from the negative ideal solution. The alternatives are ranked by calculating an overall index based on their distances from the ideal solution. The TOPSIS method can be defined as a series of steps, outlined below. The analysis to select the best variant of each fibre is carried out as described in the following steps:

Step 1. Setting up the decision criteria (A). As shown in Eq. (7), the performance ratings of each alternative for each attribute are presented in a decision matrix.

$$A = (x_{ij})_{m \, x \, n} = \begin{bmatrix} x_{12} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \ldots (7)$$

Step 2. Calculating the standardised performance ratings. Vector normalisation is utilised to derive normalised performance evaluations from Eq. (7). In this process, each performance value f_{ij} in f is divided by its magnitude. The standardised ratings r_{ij} ($j = 1,2, \ldots, j; i = 1,2, \ldots, n$) are calculated using Eq. (8).

$$r_{ij} = \frac{f_{ij}}{\sqrt{\sum_{j=1}^{j} f_{ij}^2}}, j = 1,2,\ldots,j; \; i = 1,2,\ldots,n \qquad \ldots (8)$$

Step 3. Constructing the weighted normalised decision matrix. The weighted and normalised performance ratings v_{ij} ($j = 1,2, \ldots, j; i = 1,2, \ldots, n$) are calculated using Eq. (9). Then, the weighted ratings are assembled to form the weighted-normalised decision matrix.

$$v_{ij} = w_i \, x \, r_{ij}, j = 1, 2, \ldots, J ; i = 1, 2, \ldots, n, \ldots (9)$$

Step 4. Determining the positive and negative ideal solutions. The positive and negative ideal solution sets, denoted as A^+ and A^-, are computed using Eqs. (10) and (11).

$$A^+ = [v_1^*, v_2^*, \ldots, v_j^*], \qquad (10)$$

$$A^- = [v_1^-, v_2^-, \ldots, v_j^-], \qquad (11)$$

where
$$A^+ = \left\{ \left(\max_i v_{ij} \mid j \in C_b \right), \left(\min_i v_{ij} \mid j \in C_c \right) \right\} = \{v_j^+ \mid j = 1,2,\ldots,m\}$$

$$A^- = \left\{ \left(\min_i v_{ij} \mid j \in C_b \right), \left(\max_i v_{ij} \mid j \in C_c \right) \right\}$$
.

Step 5. Calculating the separation values. The separation measure is determined by calculating the Euclidean distance between each alternative's rating and positive and negative ideal solutions. Eqs. (12) and (13) show the calculations for the positive and negative separation measures, respectively.

Positive ideal separation, S^+ :

$$S_i^+ = \sqrt{\Sigma_{j=1}^{m}\left(v_{ij} - v_j^+\right)^2} \ , \quad j = 1, 2, \dots, m \ \dots (12)$$

Negative ideal separation, S^- :

$$S_i^- = \sqrt{\sum_{j=1}^{m}\left(v_{ij} - v_j^-\right)^2} \ , \quad j = 1, 2, \dots, m \ \dots (13)$$

Step 6. Determining the positive ideal solution. The overall preference score P_i for each alternative A_i is obtained, as shown in Eq. (14).

$$Pi_i^* = \frac{S_i^-}{S_i^* + S_i^-} \ , i = 1, 2, \dots, m \qquad \dots (14)$$

## 2.4. Stage 4: Selecting the Top-Ranked Alternative

The overall ranking of the alternatives is determined based on their P_i scores, calculated using Eq. (14) and arranged in descending order. The alternative with the highest P_i score is considered the optimal solution.

3. Results and Discussion

The MCDM method refers to the multiple-criteria decision-making process. The CRITIC method and the TOPSIS method were used to analyse case studies involving various types of fibres. The criteria values were initially standardised to evaluate the weights of the criteria using the CRITIC method. The normalised values were derived using Eqs. (2) and (3), and the standard deviation for 'density', 'diameter', 'length', 'tensile strength', 'young's modulus', 'elongation at break', 'cellulose', 'moisture content' and 'hemicellulose' was calculated using Eq. (4). After the criteria values were normalised, the correlations amongst the criteria were determined using Eq. (5). Finally, the criteria weights, presented in Figure 4, were computed using Eq. (6). 'Elongation at break' received the highest weight, whereas 'moisture content' and 'diameter' received the lowest weights according to the CRITIC method.
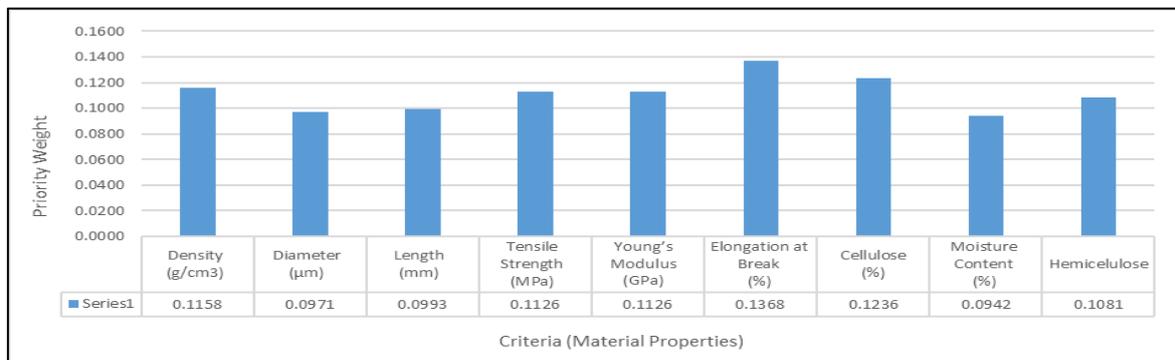
Fig. 4. Criteria weights calculated using the CRITIC method.

The TOPSIS analysis was conducted for each of the 12 natural fibres using the criteria weights obtained from the CRITIC method. The criteria decision values were first established to rank all the alternatives using the TOPSIS method. The standardised performance ratings were determined using Eq. (8). Then, the weighted normalised decision matrix was constructed using Eq. (9). The positive and negative ideal solutions were identified using Eqs. (10) and (11). Subsequently, the separation values were calculated using Eqs. (12) and (13), and the positive ideal solution was determined using Eq. (14). Finally, the overall rankings of all the 12 natural fibre alternatives are presented in Table 2. Coir was selected because of its high score according to the CRITIC-TOPSIS method. Subsequently, the most suitable options amongst the remaining fibres were identified based on their performance scores.

**Table 2,**
Selection of natural fibre alternatives.

No.	Fibre	Separation measure of the group		Positive ideal	Rank
		Si+	Si-	Pi	
1	Abaca	0.0047	0.0003	0.0604	12
2	Bamboo	0.0026	0.0037	0.5839	2
3	Banana	0.0038	0.0010	0.2115	7
4	**Coir**	**0.0023**	**0.0033**	**0.5890**	**1**
5	Flax	0.0042	0.0008	0.1503	9
6	Hemp	0.0045	0.0003	0.0667	11
7	Jute	0.0037	0.0015	0.2938	6
8	Kenaf	0.0033	0.0017	0.3446	4
9	Pineapple	0.0047	0.0004	0.0768	10
10	Ramie	0.0043	0.0009	0.1670	8
11	Sisal	0.0035	0.0017	0.3275	5
12	Ijuk	0.0028	0.0030	0.5203	3

3.1. Calculation Using the CRITIC-TOPSIS Method

The ranking results obtained using the CRITIC-TOPSIS method are presented in column 6 of Table 2. Data from the critical criteria were synthesised to generate a list of 12 natural fibres. Each fibre was ranked according to its P_i score, computed using Microsoft Excel in conjunction with the specified methodology. As noted by Rebman Jr et al. (2023), Comparable with the ubiquity of calculators, Excel has become a widely adopted tool in data analysis and DM [32]. The three primary criteria assessed were weight, strength and moisture resistance. The subcriteria of the 'strength' criterion included tensile strength, Young's modulus and elongation at break. These subcriteria focused specifically on the mechanical properties, as the toe cap design requires strong materials for optimal performance.

Recognising that each natural fibre possesses unique properties that affect its suitability for specific industrial applications in terms of mechanical behaviour and performance is crucial [33]. Furthermore, the scores for each critical criterion were collected and represented graphically for each alternative, as shown in Figure 5. Coir achieved a significantly higher positive ideal score in the 'strength' node than the other fibres. This score was also the highest amongst all parameters, whereas sisal scored the lowest. Banana fibres received similar scores across all nodes. Conversely, bamboo achieved the highest positive ideal score for the 'weight' node.
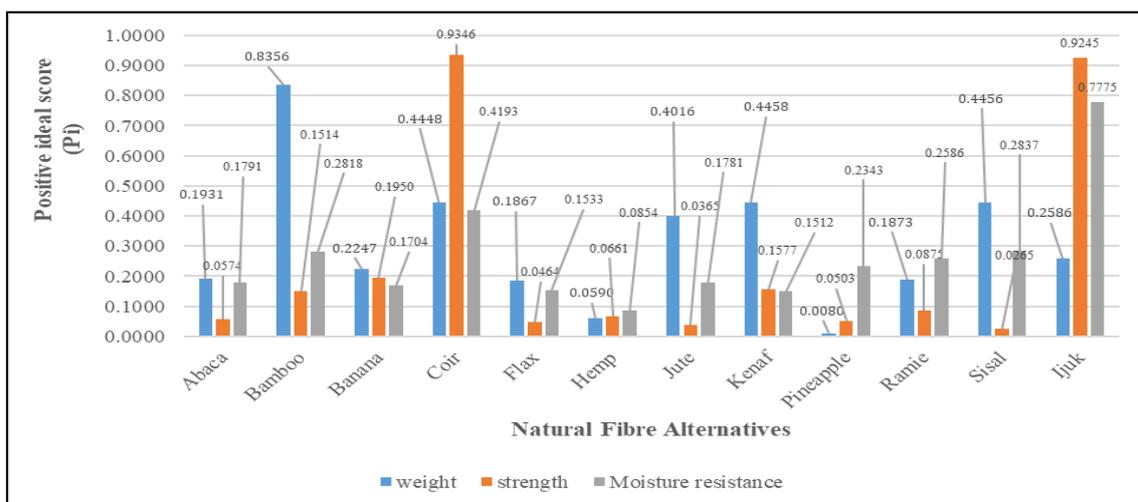
Fig. 5. Natural fibre scores with the corresponding main criteria.

Figure 6 displays the final synthesis results. Coir achieved the highest score of 0.5890, placing it at the top position. Bamboo received the second-highest score of 0.5839, followed by ijuk, kenaf,

sisal, jute, banana and ramie with values of 0.5203, 0.3446, 0.3275, 0.2938, 0.2115 and 0.1670, respectively. Flax, pineapple, hemp and abaca occupied the bottom four positions, with scores of 0.1503, 0.0768, 0.0667 and 0.0604, respectively. These results indicate that coir is the highest-rated material, which is in good agreement with the findings of a previous work [34]. The study confirms that coir is the most suitable natural fibre for various structural and nonstructural applications, as it can serve as a potential reinforcing material.
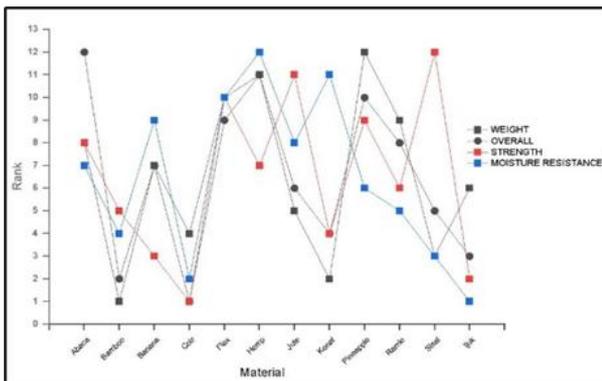

**Fig. 6. Final synthesis results obtained using the CRITIC-TOPSIS method for all criteria.**

The 'weight' criterion recorded the highest score for bamboo, whereas hemp and pineapple received the lowest scores. Ijuk achieved a notable score in the 'moisture resistance' category, whereas hemp performed poorly. Coir attained the highest score in the 'strength' criterion, followed closely by ijuk, with only a small difference between their scores. The 'overall' line in the graph represents the integrated outcome obtained by combining the three criteria: weight, strength and moisture resistance. The overall results closely follow the trend of the weight criterion, highlighting the importance of weight in this study.

Coir was selected as a potential natural fibre for reinforcing biocomposites to be used in toe caps. Bamboo, ijuk, kenaf and sisal consistently ranked amongst the top five, whereas pineapple and hemp consistently ranked amongst the lowest two in all scenarios. Abaca was identified as the least suitable natural fibre for enhancing the strength of biocomposites, based on the specified design criteria. The highest values of 'moisture resistance' were synthesised, and the results of the alternatives are presented in Figure 7(a). Ijuk achieved the highest 'moisture content' score, whereas hemp had the lowest. The 'weight' values for each alternative were also considered, with the findings shown in
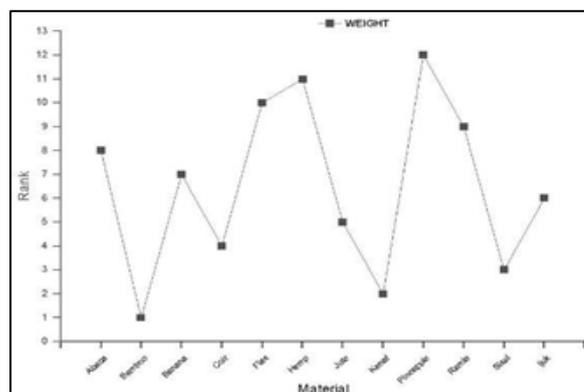
Figure 7(b). Bamboo had the highest 'weight' score, whereas pineapple had the lowest. A similar evaluation was conducted for 'strength'. The results are shown in Figure 7(c). Coir, ijuk, banana, kenaf, bamboo, ramie, hemp, abaca and pineapple all received high scores for 'strength', whereas flax, jute and sisal ranked at the bottom.
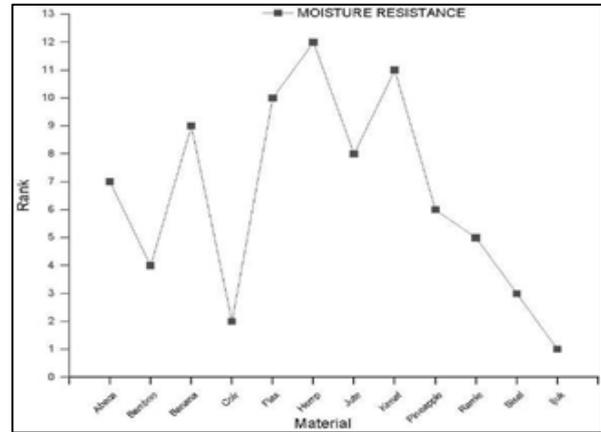
(a)
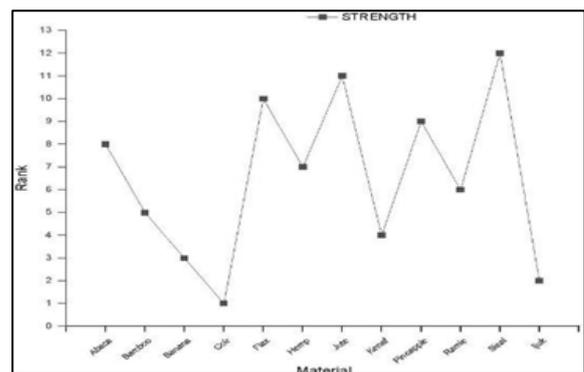
(b)

(c)

Fig. 7. (a) Results for the moisture resistance of the alternatives; (b) results for weight; (c) results for strength.

Although the results were extensively validated, the authors note that the natural fibre selection

approach could be more comprehensive by incorporating additional features from other criteria. Considering multiple aspects in formulating the selection criteria is essential in DM. Consequently, decision makers must establish precise and well-defined criteria based on the specific requirements, as they directly affect the final selection outcomes.

Further measurements should be conducted to determine the timing of fibre harvest, the extraction technique, the aspect ratio and the pretreatment and storage strategies of the fibre [35,36]. Several factors, such as the adhesion between the fibre and the matrix, the fibre volume fraction and the aspect ratio of the fibre, affect the mechanical properties of reinforcement in polymer composites (l/d) and the fibre orientation [37]. Furthermore, the choice of surface treatment and the application of nanotechnology may significantly influence the final selection by enhancing the interfacial bonding with biopolymer matrices [38]. The lack of data on natural fibres' properties and related information in established commercial databases posed a major obstacle in the selection process. Mahajan et al. (2022) highlighted the importance of compiling a dataset for natural fibre substitutes. They also emphasised the importance of dependable and clear data sources on fibre characteristics to enable well-informed selection decisions [39].

In addition to the evaluated mechanical and physical criteria, incorporating economic and manufacturing-related factors can enhance the practical applicability of the study. For instance, cost is a critical consideration in industrial material selection, as high-performance materials may be difficult to implement for large-scale production because of budget constraints [40]. Manufacturing-related criteria, such as fibre aspect ratio and the effects of surface treatments, also play an important role [41]. The fibre aspect ratio influences processability, structural performance and consistency of the final product, whereas surface treatments affect adhesion, durability and moisture resistance [42–44]. Including these factors in the CRITIC-TOPSIS evaluation would provide a comprehensive assessment, which reflects both material performance and manufacturability and can guide realistic DM in industrial applications.

3.2. Sensitivity Analysis

The final step in implementing CRITIC-TOPSIS is sensitivity analysis, which plays a crucial role in ensuring the robustness of the results. Therefore, varying outcomes in the ranking of the alternatives and overall decisions can be observed by modifying the values by increasing or decreasing the weight of certain criteria whilst keeping others constant [45]. Sensitivity analysis also allows for assessing the consistency of rankings when selecting the most suitable natural fibre material for toe caps. It also provides a deep understanding of the adaptability of the final ranking to changes in weight assignments [46]. This study analysed the effect of five scenarios on performance sensitivity using Microsoft Excel. The results were subsequently compared with the initial rankings. In general, the sensitivity analysis confirms that the results of the present study, which identify coir as a potential material for toe caps, are reliable.

The results of the sensitivity analysis are presented in Table 3. Coir consistently ranked highest in four of the five scenarios analysed. When the importance ratings for 'weight' were increased by 20%, coir ranked second, after bamboo. Lightweight components are essential in toe caps to ensure that safety footwear remains comfortable. However, Kropidłowska et al. (2021) emphasised that toe caps must also possess sufficient strength [47]. By contrast, coir ranked first with a 20% increase in 'strength' and 'moisture resistance'. Strength and moisture resistance are critical properties of toe cap materials, which protect the feet from falling objects [48] and wetting due to environmental moisture [49]. Two additional scenarios analysed a condition where 'weight' and 'moisture resistance' were paired with 'strength', and both pairs each increased by 10%. The scenarios linked with 'strength' are important because they influence the toe cap strength in absorbing shock from falling objects. Coir ranked first in both scenarios, confirming that the current CRITIC-TOPSIS method identified the most suitable material for toe caps. In addition, coir's top ranking in nearly all scenarios demonstrates the consistency of the results, which is also supported by the similarity in ranking sequences across three scenarios compared with the original results.

Table 3,
Summary of the sensitivity analysis.

Rank	Original result	20% increment in 'strength'	20% increment in 'weight'	20% increment in 'moisture resistance'	10% increment in 'weight' and 'strength'	10% increment in 'moisture resistance' and 'strength'
#1	**Coir**	**Coir**	Bamboo	**Coir**	**Coir**	**Coir**
#2	Bamboo	Ijuk	Coir	Bamboo	Bamboo	Bamboo
#3	Ijuk	Bamboo	Ijuk	Ijuk	Ijuk	Ijuk
#4	Kenaf	Kenaf	Kenaf	Kenaf	Kenaf	Kenaf
#5	Sisal	Sisal	Sisal	Sisal	Sisal	Sisal
#6	Jute	Jute	Jute	Jute	Jute	Jute
#7	Banana	Banana	Banana	Banana	Banana	Banana
#8	Ramie	Ramie	Ramie	Ramie	Ramie	Ramie
#9	Flax	Flax	Flax	Flax	Flax	Flax
#10	Pineapple	Pineapple	Pineapple	Pineapple	Pineapple	Pineapple
#11	Hemp	Hemp	Hemp	Hemp	Hemp	Hemp
#12	Abaca	Abaca	Abaca	Abaca	Abaca	Abaca

Based on the CRITIC-TOPSIS method, coir was selected as the most suitable natural fibre for toe caps. Bamboo and ijuk consistently ranked within the top three alternatives, whereas pineapple, hemp and abaca consistently ranked amongst the bottom three across all scenarios. The analysis identified that abaca is the least suitable natural fibre for the specified design objective.

Although the results were highly validated, the researchers note that a comprehensive selection could have been achieved by incorporating additional information from other criteria. Considering multiple factors when formulating the selection requirements is important to make well-informed decisions.

4. Conclusion

This study proposed a hybrid MCDM approach that integrates the CRITIC and TOPSIS methods to identify the most suitable natural fibre for reinforcing composites in toe caps. Twelve natural fibres were evaluated against nine mechanical- and manufacturing-related criteria, with coir emerging as the optimal choice, followed closely by bamboo and ijuk. The CRITIC method enabled objective weighting of the criteria, whereas TOPSIS facilitated ranking based on proximity to the ideal solutions. Sensitivity analysis confirmed the robustness of the selection, as coir consistently maintained a top ranking across various scenarios.

The findings highlight the potential of coir as an eco-friendly reinforcement material for sustainable PPE design. However, the study also emphasises the importance of incorporating additional criteria, such as fibre processing techniques, surface treatments and long-term durability, to achieve comprehensive evaluations. Future research should focus on experimental validation, development of reliable databases for natural fibres and integration of advanced material modelling to enhance the accuracy and applicability of selection frameworks in industrial contexts.

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Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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تحليل حساسية طريقة CRITIC-TOPSIS المدعمة المثلى المركبة المواد لاختيار المتكاملة بالألياف الطبيعية لأغطية أصابع القدم في أحذية السلامة

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المستخلص

إن اختيار الألياف الطبيعية لأحذية السلامة ذات المقدمة المغلقة يتطلب تقييمًا دقيقًا لعدة معايير أداء، مما يصعب مسألة اتخاذ القرار بذلك الشأن، حيث يجب مراعاة العديد من البدائل والمتطلبات في آن واحد. تطبق هذه الدراسة طريقة أهمية المعايير من خلال الارتباط بين المعايير لحساب أوزان المعايير الموضوعية، والتي تُدمج بعد ذلك في طريقة ترتيب التفضيلات حسب التشابه مع الحل الأمثل لترتيب وتحديد الألياف المثلى من بين اثني عشر بديلاً. أُجري تحليل حساسية لتقييم تأثير تغيرات الأوزان على نتائج الاختيار. وقد نجحت الطريقة الناتجة كم دمج طريقة أهمية المعايير من خلال الارتباط بين المعايير وطريقة أسلوب ترتيب الأولويات بناءً على التشابه مع الحل الأمثل في تحديد الألياف الطبيعية المثلى لتطبيقات أحذية السلامة ذات المقدمة المغلقة. أكد تحليل الحساسية من متانة النتائج مع تسليط الضوء على تأثير تغيرات أوزان المعايير على الترتيب النهائي. يوفر التكامل المقترح نهجًا منهجيًا وموثوقًا لاختيار المواد في أحذية السلامة. تقدم النتائج إرشادات مفيدة لتطوير مركبات البوليمر المقواة بالألياف الطبيعية، مما يدعم بدائل خفيفة الوزن ومستدامة لأحذية السلامة ذات المقدمة المغلقة.