



Research Article

Selection of optimal coating materials for bamboo reinforcement in concrete using entropy-fuzzy topsis model

Vivek PAHUJA^{1,*} , Pradeep Kumar GHOSH¹ , Anil KUMAR¹ 

¹Department of University Teaching, Chhattisgarh Swami Vivekanand Technical University, Chhattisgarh, 491107, India

ARTICLE INFO

Article history

Received: 11 August 2024

Revised: 03 October 2024

Accepted: 06 March 2025

Keywords:

Bamboo; Concrete; Entropy;

Fuzzy TOPSIS; Material

Selection

ABSTRACT

Bamboo is a viable reinforcement material due to its high strength-to-weight ratio, cost-effectiveness, and eco-friendliness. However, raw bamboo poses challenges such as high water absorption and a weak bond with concrete, which can be mitigated by appropriate coating material. An entropy-driven fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is intended to analyze and determine the optimal coating material. Entropy method is used to compute criteria weights whereas fuzzy-TOPSIS is used to rank alternatives by solving uncertainties and subjective preferences. The data set used was literature-based to make a decision on thirteen coating materials, the properties of which were studied based on four parameters, namely concrete compressive strength, bamboo tensile strength, embedded length and the pullout load. The results show that the epoxy-based resin material Sikadur-752 had the highest relative closeness of 0.6348. To ensure that the model was reliable under different weight scenarios, sensitivity analysis was also carried out. The proposed model advances coating material selection for bamboo reinforcement, offering a framework for future research. This study contributes to the development of bamboo-reinforced concrete construction for improving structural performance and service life.

Cite this article as: Pahuja V, Ghosh PK, Kumar A. Selection of optimal coating materials for bamboo reinforcement in concrete using entropy-fuzzy topsis model. Sigma J Eng Nat Sci 2026;44(2):1004–1015.

INTRODUCTION

The demand for housing continues to rise, driven by population growth and urban migration. In order to construct these houses, huge amounts of steel and concrete are needed, materials that are limited in supply and whose production is extremely polluting, releasing 1.91 tonnes of CO₂ per tonne of steel [1]. This has prompted the exploration of alternative materials that are affordable, sustainable, and

possess adequate structural properties. A few natural and synthetic replacements for steel have been explored in the last few decades, and bamboo has emerged as one of the promising natural alternatives to steel for affordable housing [2–5].

However, raw bamboo presents significant challenges, including high water absorption and poor bonding with concrete. Bamboo absorbs and releases moisture during the

*Corresponding author.

*E-mail address: vivekpahuja97@gmail.com

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkilic



casting and curing process, as shown in Figure 1; During the casting and curing process, bamboo absorbs water from concrete and expands; then releases moisture and contracts.. This process of swelling and shrinkage may affect the integrity of structure. Chemical treatments are provided to address this issue by creating an impermeable coating on the bamboo surface. These treatments also enhance the bond strength between bamboo and concrete by increasing adhesion [6–8]. While many treatments have been explored, the question of which is most effective remains unresolved.

The study of the bond behavior at the bamboo-concrete interface using pull-out tests has been performed on the influence of different chemical treatments, including bitumen asphalt emulsion [9], sulfur [10], varnish [11], sikadur-32 gel [7,12], negrolin [13], SJK-61 epoxy mortar [14], bondtite [15], tack coat [16], water-based epoxy coating [3], sikadur 752 [17], algicoat RC-104 [18], araldite [19], linseed oil [20], spar varnish [21], oil paint [22], Bituminous paint [8], synthetic resin [23], and sikadur-32 LP [24]. The findings highlight the extensive range of existing chemical treatments that could make the bond stronger, which shows the gap between the most efficient ones. Many studies, for instance, test different coating materials under varying conditions, making it challenging to establish a reliable comparison standard. This limitation emphasizes the need for a comprehensive, data-driven approach to material selection.

Multi-criteria decision-making (MCDM) methods have been established and extensively used in different areas to address the problem of choosing the appropriate material among numerous viable choices. For instance, Chanpuyetch et al. [25] utilized AHP and TOPSIS to select bamboo products whereas Özmen-Akyol [26] employed fuzzy TOPSIS in selecting the material used in

marine settings. Likewise, YILDIZ [27] used fuzzy TOPSIS in selecting mobile RFID readers. Rahim et al. [28] utilized fuzzy TOPSIS for material selection in automotive body panels. Prasad et al. [29] proposed a model for selecting appropriate coating materials for magnesium alloys by integrating Fuzzy AHP and TOPSIS techniques. In other studies, Vijayakumar et al. [30] and Çalik [31] used Fuzzy AHP and Fuzzy TOPSIS to evaluate and select projects. Chatterjee [32] introduced VIKOR and ELECTRE for material selection, while Reddy et al. [33] proposed a model for choosing sustainable building materials using entropy-driven fuzzy TOPSIS. A hybrid model for prioritizing key parameters of a sustainable supply chain was proposed by Shirazi et al. [34]. Nevertheless, the techniques have not been widely used in the choice of coating to be used on bamboo when reinforcing concrete. The literature review indicates that Fuzzy TOPSIS model has been a common tool of MCDM that has been able to counter uncertainty and vagueness in the process of decision making [35].

This study is novel as it combines the concepts of entropy and fuzzy TOPSIS to rank and assess coating materials used in the bamboo reinforcement. These contributions are the building of a decision-making model on the selection of materials and the determination of the most suitable coating material to use in the bamboo reinforcement.

The proposed research applies the entropy approach to analyze objective criteria in terms of their overall importance and fuzzy TOPSIS to cope with the uncertainty of the material selection. The sensitivity analysis is used to confirm the strength of the results. The study allows developing a consistent framework of the strengthening of the bond and overall performance of bamboo reinforced concrete structures.

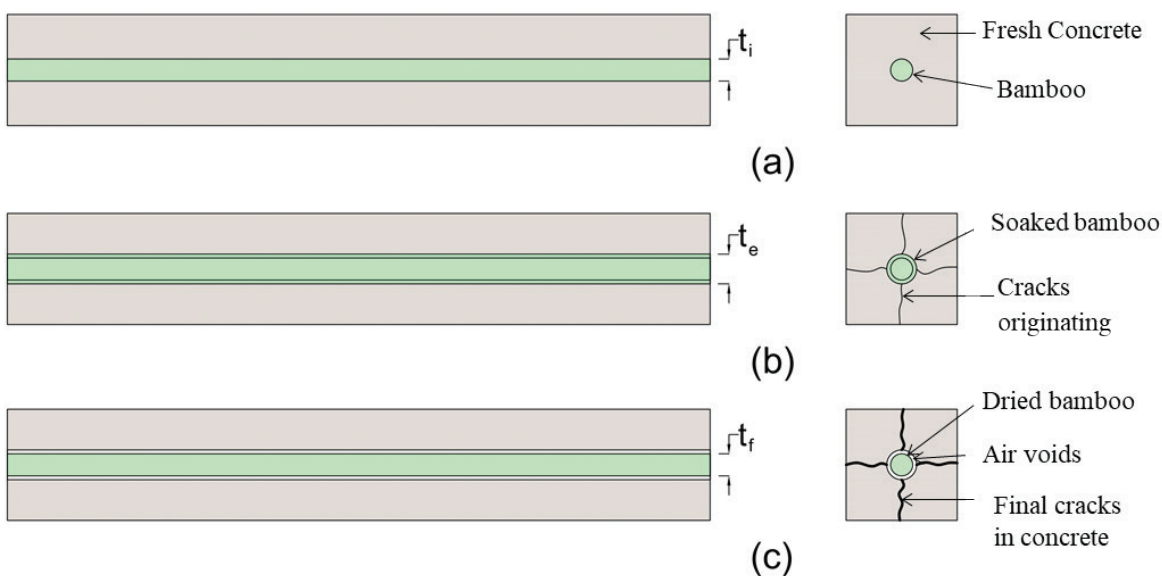


Figure 1. Behavior of untreated bamboo as reinforcement in concrete: (a) in fresh state, (b) in the curing process, and (c) in hardened concrete.

MATERIALS AND METHODS

Following an extensive literature review on the bond properties of bamboo-reinforced concrete, 13 studies were selected based on the availability of data relevant to the decision criteria of the proposed model. The optimal coating material identified in each study is chosen as a decision alternative for this research and is presented in Table 1. Four parameters that influence bond strength, including the compressive strength of concrete (f_c), the tensile strength of bamboo (T), embedded length (l_a), and pullout load (P), were chosen as decision criteria. Each parameter is crucial in determining bond strength, as outlined below. Compressive strength of concrete (f_c) makes the concrete stronger to hold the bamboo, facilitates the transfer of loads and minimizes cracking at the interface, which makes bonding stronger. The tensile strength of bamboo (T) is also significant since the higher the tensile capacity of the bamboo the higher the pullout forces that can be resisted resulting to better bond performance. Additionally, the embedded length (l_a) significantly affects bond strength, with longer lengths providing increased surface area for mechanical interlock, thereby improving resistance against

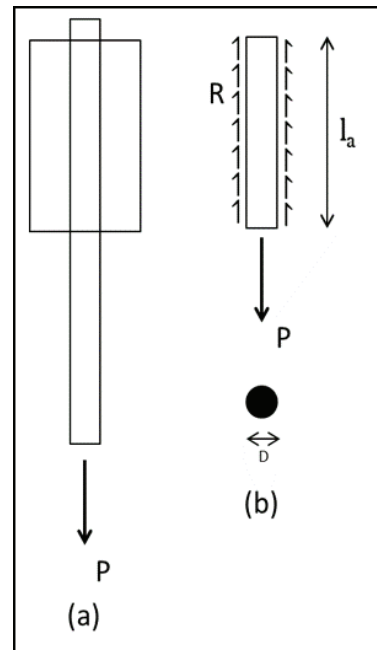


Figure 2. Schematic representation of (a) Pullout samples (b) Forces related to bond.

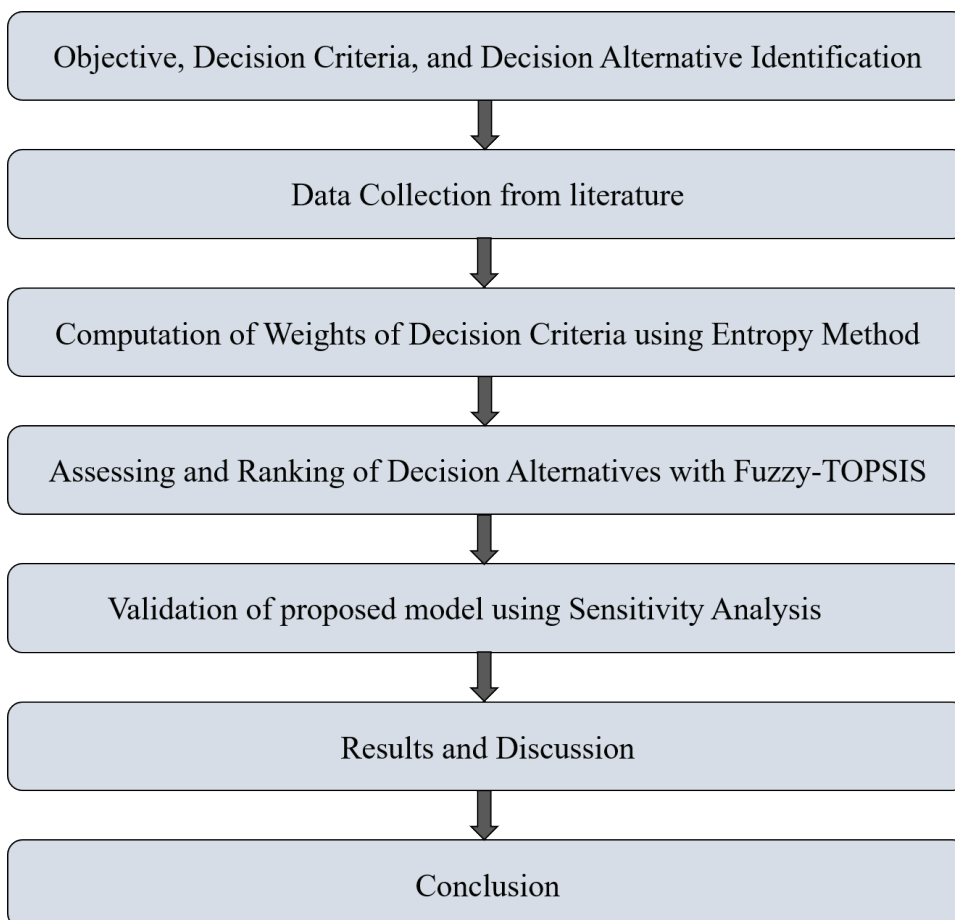


Figure 3. A flow chart for the selection of coating material using Entropy-fuzzy TOPSIS.

pullout. The pullout load (P), on the other hand, is the force applied during bond testing, higher loads require stronger bonds to prevent slippage, making it a key factor in assessing bond performance. The 28-day compressive strength of the concrete and the average ultimate tensile strength of bamboo were obtained from the studies. The embedded length varies depending on the specimen type and is expressed as a percentage to standardize the results across varying specimen sizes. Bond strength depends on the cross-sectional area of bamboo; the smaller the section, the stronger the bond is, and vice-versa. To overcome this, the pullout load is computed through equation 1, which is based on the equilibrium condition as shown in Figure 2.

$$P = \tau \cdot p \cdot l_a \quad (1)$$

Where, P = pullout force applied (kN); τ = bond strength (MPa); l_a = embedded length (mm) of a bamboo; and p = perimeter of bamboo (mm)

This study aims to develop a multi-criteria decision-making (MCDM) model, specifically utilizing the entropy-fuzzy TOPSIS model, to identify the optimal coating materials for bamboo reinforcement in concrete. The proposed model involves two stages: first, the calculation of decision criteria weights using Shannon's entropy method, and second, the evaluation and ranking of decision alternatives (coating material) using fuzzy TOPSIS. Figure 3 illustrates the flowchart of the proposed model.

Shannon Entropy Method

The Shannon Entropy Method is used for objective weight assignment in MCDM. It helps to determine the importance of different factors based on their entropy

Table 1. Data collected from existing literature

Alternative	Author	Concrete strength (MPa)	Tensile strength of Bamboo (MPa)	Embedded length (%)	Coating material	Chemical constituents	Bond strength (MPa)	Pullout load (kN)
A1	Ghavami [7]	20	119.02	33.33	Sikadur 32	Epoxy resin	2.75	24.75
A2	Sakaray et al. [18]	30	125	50	Algicoat RC-104	Polymer admixture	1.64	19.31
A3	Terai and Minami [23]	10	197	85	Synthetic Resin	Synthetic Resin	1.34	22.50
A4	Kute and Wakchaure [8]	22.52	133.6	100	Bituminous Paint	Bitumen	1.19	9.64
A5	Moroz et al. [21]	13.7	84.7	33.33	Spar varnish	Oil and resin	1.49	11.7
A6	Javadian et al. [3]	20	320	66.67	Moisture seal	Water-based epoxy	3.65	29.20
A7	Rahman et al. [35]	20	236.14	50	Bisphenol A	Bisphenol A	1.09	10.69
A8	Khatib and Nounu [20]	40	140	50	Linseed oil	Linseed oil	1.11	7.77
A9	Mali and Datta [15]	28	200	50	Bond tite	Epoxy adhesive	1.4	7.80
A10	Muhtar et al. [17]	31.31	126.68	66.67	Sikadur 752	Epoxy resins	2.25	27.00
A11	Rahim et al. [16]	32.95	169.27	50	Tack coat	Asphalt emulsions	2	9.42
A12	Tazowar et al. [19]	22.4	135	50	Araldite	Methacrylate adhesive	1.24	10.35
A13	Wang et al. [14]	41.1	85.6	50	SJK-61 epoxy mortar	Modified epoxy resin, curing agent, and functional aggregate in a mass ratio of 2:1:10.	4.7	9.23

values. Shannon [36] suggests that in decision analysis, the accuracy and reliability of outcomes are significantly influenced by the quantity and quality of data. Shannon’s entropy measures the valuable information in a dataset and is used to determine criteria weights in MCDM methods like TOPSIS. Since the criteria used in making decisions are ambiguous and vague, the entropy method based on Shannon will be employed in Stage 1 to establish the objective weights. The advantage of Shannon entropy is that it is capable of capturing implicit information across various criteria to do a value dispersion analysis. In addition, studies of TOPSIS have established that there has been an increasing interest in the use of Shannon entropy [37]. The following steps outline Shannon’s entropy methodology in detail:

Step 1: The initial decision matrix (D) is formed for m alternatives and n criteria.

$$D = (x_{ij})_{mn} \tag{2}$$

Where x_{ij} shows the value of j^{th} criterion from the i^{th} alternative.

Step 2: Normalization of initial decision matrix (D)

$$Z_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}}, \quad i = 1,2,3, \dots, m; \quad j = 1,2,3, \dots, n \tag{3}$$

Step 3: The information entropy (e_j) of criterion j is given by

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m z_{ij} \ln z_{ij}, \quad j = 1,2,3, \dots, n \tag{4}$$

Step 4: Compute the entropy weight (w_j) of criterion k

$$w_j = \frac{1-e_j}{\sum_{j=1}^n (1-e_j)}, \quad j = 1,2,3, \dots, n \tag{5}$$

Fuzzy Topsis

Among the widely used multi-criteria decision-making (MCDM) techniques, TOPSIS is an effective and practical method for ranking and selecting alternatives by measuring

their distances from ideal solutions. A TOPSIS model identifies the best solution by choosing the alternative nearest to the fuzzy positive ideal solution (FPIS) and the one furthest to the fuzzy negative ideal solution (FNIS). The FPIS represents the best alternatives by considering the highest performance values, while the FNIS identifies the worst alternatives by considering the lowest performance values. Since fuzzy numbers are commonly used to handle uncertainty and imprecision in decision-making, Fuzzy TOPSIS extends the traditional TOPSIS approach by incorporating fuzzy theory. This enhancement provides a more flexible evaluation of alternatives based on specific criteria, helping decision-makers assess trade-offs more effectively and make informed choices tailored to their priorities. The basic definitions of fuzzy numbers and fuzzy sets are given below [38–41]:

This study uses triangular fuzzy numbers (TFNs) as linguistic variables for the assessment and ranking of alternatives.

Definition 1: A membership function $\mu_{\tilde{A}}(x)$ often known as the grade of membership of x in \tilde{A} , characterizes a fuzzy set \tilde{A} in a universe of discourse X. A triangular fuzzy membership function is shown in Figure 4.

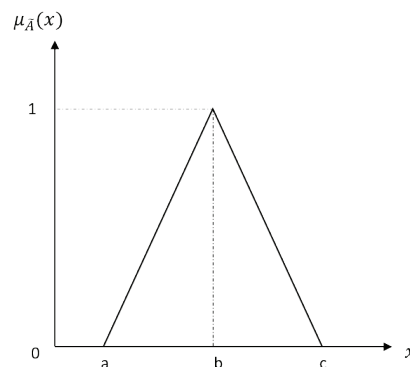


Figure 4. A fuzzy membership function in the form of a triangle.

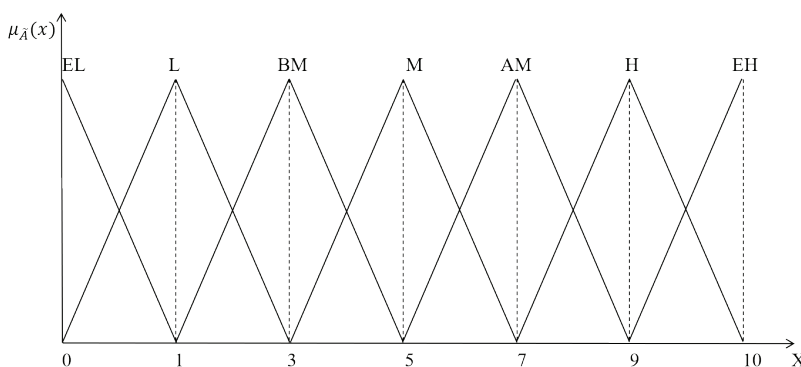


Figure 5. Membership functions of the linguistic variable for evaluating criteria.

Definition 2: A triangular fuzzy number is represented as a triplet $\tilde{A} = (a, b, c)$. The membership function $\mu_{\tilde{A}}(x)$ of triangular fuzzy number (TFN) can be calculated using equation 6.

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & x < a, \\ \frac{x-a}{b-a} & a \leq x \leq b, \\ \frac{c-x}{c-b} & b \leq x \leq c, \\ 0 & x > c \end{cases} \quad (6)$$

Definition 3: Let $\tilde{p} = (p_1, p_2, p_3)$ and $\tilde{q} = (q_1, q_2, q_3)$ be two triangular fuzzy numbers. Then, the arithmetic operation between these two triangular fuzzy numbers is defined as follows:

$$\left\{ \begin{aligned} \tilde{p} + \tilde{q} &= (p_1, p_2, p_3) + (q_1, q_2, q_3) = (p_1 + q_1, p_2 + q_2, p_3 + q_3) \\ \tilde{p} - \tilde{q} &= (p_1, p_2, p_3) - (q_1, q_2, q_3) = (p_1 - q_1, p_2 - q_2, p_3 - q_3) \\ \tilde{p} \times \tilde{q} &= (p_1, p_2, p_3) \times (q_1, q_2, q_3) = (p_1 \cdot q_1, p_2 \cdot q_2, p_3 \cdot q_3) \\ \tilde{p}/\tilde{q} &= (p_1, p_2, p_3)/(q_1, q_2, q_3) = (p_1/q_1, p_2/q_2, p_3/q_3) \\ k\tilde{p} &= k(p_1, p_2, p_3) = (kp_1, kp_2, kp_3) \end{aligned} \right\} \quad (7)$$

This study employs triangular fuzzy numbers (TFNs) as linguistic variables to assess and rank alternatives. As shown in Figure 5, the criteria ratings from the fuzzy decision matrix are converted into TFNs. Following are the steps used in this study to implement the fuzzy-TOPSIS model [38,42,43]:

Step 1: Construct a fuzzy decision matrix based on the ratings of m alternatives and n criteria using equation 8. Ratings for each alternative are assigned using linguistic variables represented by triangular fuzzy numbers (TFNs), as shown in Table 2.

$$\tilde{D} = \begin{pmatrix} \tilde{k}_{11} & \tilde{k}_{12} & \dots & \tilde{k}_{1n} \\ \tilde{k}_{21} & \tilde{k}_{22} & \dots & \tilde{k}_{2n} \\ \dots & \dots & \tilde{k}_{ij} & \dots \\ \tilde{k}_{m1} & \tilde{k}_{m2} & \dots & \tilde{k}_{mn} \end{pmatrix} \quad (8)$$

Where, rows represent alternatives ($i = 1, 2, \dots, m$) and the columns represent criteria ($j = 1, 2, \dots, n$)

Step 2: Calculate the normalized fuzzy decision matrix (\tilde{T}) which can be represented by equation 9.

$$\tilde{T} = [\tilde{t}_{ij}]_{m \times n} \quad (i = 1, 2, \dots, m; \quad j = 1, 2, \dots, n) \quad (9)$$

The value of the beneficial criteria (\tilde{t}_{ij}), is calculated using the following formula:

$$\tilde{t}_{ij} = \left(\frac{p_{ij}}{r_j^+}, \frac{q_{ij}}{r_j^+}, \frac{r_{ij}}{r_j^+} \right) \quad (10)$$

$$\tilde{t}_{ij} = \left(\frac{p_j^-}{r_{ij}^-}, \frac{p_j^-}{q_{ij}^-}, \frac{p_j^-}{p_{ij}^-} \right) \quad (11)$$

Where r_j^+ = maximum r_{ij} and p_j^- = minimum p_{ij}

Step 3: Determine the weighted normalized fuzzy decision matrix (\tilde{V}) The normalized fuzzy decision matrix and weight vector of evaluation criteria are used to compute the weighted triangular fuzzy decision matrix.

$$\tilde{V} = [\tilde{v}_{ij}]_{m \times n} \quad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (12)$$

$$\tilde{v}_{ij} = \tilde{t}_{ij} \times \tilde{w}_j \quad (13)$$

Step 4: Calculation of fuzzy positive ideal solutions (FPIS) and fuzzy negative ideal solutions (FNIS) can be accomplished using equations 14 and 15.

$$A^G = \{(\max \tilde{r}_{ij} \mid j \in J); (\min \tilde{r}_{ij} \mid j \in J')\} \text{ or} \quad (14)$$

$$A^G = \{\tilde{v}_1^+, \tilde{v}_2^+, \dots, \tilde{v}_n^+\}$$

$$A^B = \{(\min \tilde{r}_{ij} \mid j \in J); (\max \tilde{r}_{ij} \mid j \in J')\} \text{ or} \quad (15)$$

$$A^B = \{\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-\}$$

Where $J = \{j = 1, 2, \dots, n \mid j \text{ associated with positive attribute}\}$ and $J' = \{j = 1, 2, \dots, n \mid j \text{ associated with negative attribute}\}$

Step 5: The separation measure of each alternative can be calculated using equations 16 and 17.

$$L_i^G = \sum_{j=1}^n d(\tilde{v}_{ij}; \tilde{v}_j^+) \quad i = 1, 2, \dots, m; \quad j = 1, 2, \dots, n \quad (16)$$

$$L_i^B = \sum_{j=1}^n d(\tilde{v}_{ij}; \tilde{v}_j^-) \quad i = 1, 2, \dots, m; \quad j = 1, 2, \dots, n \quad (17)$$

Where L_i^G and L_i^B are the distances of each alternative, forming the best and worst fuzzy solution, respectively. And d represents the distance between two fuzzy numbers and calculated by

$$d(\tilde{p}, \tilde{q}) = \sqrt{\frac{1}{3} [(p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_3 - q_3)^2]} \quad (18)$$

Step 6: Obtain the relative closeness to the ideal solution using equation 19.

$$C_i^+ = \frac{L_i^B}{L_i^G + L_i^B} \quad i = 1, 2, \dots, m; \quad 0 \leq C_i^+ \leq 1 \quad (19)$$

Table 2. Linguistic variables represented by triangular fuzzy numbers (TFNs)

Linguistic variable	Triangular fuzzy numbers (TFNs)
Extremely low importance (EL)	(0, 0, 1)
Low importance (L)	(0, 1, 3)
Below moderate importance (BM)	(1, 3, 5)
Moderate importance (M)	(3, 5, 7)
Above moderate importance (AM)	(5, 7, 9)
High importance (H)	(7, 9, 10)
Extremely high importance (EH)	(9, 10, 10)

Table 3. Variation in criteria weights in percentage

Criteria	Change in weights (%)					
	C1	C2	C3	C4	C5	C6
Concrete strength	-6.4	+6.4	-13	+13	-19	+19
Tensile strength of bamboo	-6.4	+6.4	-13	+13	-19	+19
Embedded length	-6.4	+6.4	-13	+13	-19	+19
Pullout load	+10	-10	+20	-20	+30	-30

Step 7: Create a set of alternatives in descending order of preference based on relative closeness. The most preferred alternative is the one with the maximum (C_i^+), while the least preferred alternative is the one with the minimum (C_i^-).

Validation of the Proposed Model Using Sensitivity Analysis

A sensitivity analysis is conducted to confirm the stability of the proposed Entropy-Fuzzy TOPSIS model by systematically changing the weight of the criteria. The analysis is required to ensure that the outcomes are not too dependent on specific weight distributions and that results are consistent under different conditions. The objective is to assess how material rankings changed under various weighting scenarios, thereby verifying the model's reliability and robustness. This analysis enables an evaluation of the stability and consistency of the rankings produced by the Entropy-Fuzzy TOPSIS model under varying conditions [44,45]. In this study, the criteria weights were adjusted by $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$, with the remaining weights proportionally modified to maintain a total of 100%. Six conditions resulting from these adjustments are labeled C1, C2,

C3, C4, C5, and C6, as shown in Table 3. These results are then compared to the proposed model, labeled C0.

RESULTS AND DISCUSSION

The findings of this study are categorized into three segments. In Section 2.1, the entropy weight method is employed to calculate the decision criteria weights. The performance and ranking of the coating materials are then determined using the fuzzy TOPSIS model, as outlined in Section 2.2. Validation of the entropy-fuzzy TOPSIS model is detailed in Section 2.3.

Weight Calculation Using Entropy Weight Method

The weights of the decision criteria are determined using the entropy weight method. The initial decision matrix for the coating material with all the chosen criteria is shown in Table 4.

A normalized decision matrix is created by normalizing the initial decision matrix, as shown in Table 5.

The information entropy for each decision criterion (e_j) and entropy weight for each criterion (w_j) are calculated and given in Table 6,

Table 4. The initial decision matrix for the coating material concerning decision criteria

Alternative	Concrete strength (MPa)	Tensile strength of Bamboo (MPa)	Embedded length (%)	Pullout load (kN)
A1	20	119.02	33.33	24.75
A2	30	125	50	19.31
A3	10	197	85	22.50
A4	22.52	133.6	100	9.64
A5	13.70	84.7	33.33	11.7
A6	20	320	66.67	29.20
A7	20	236.14	50	10.69
A8	40	140	50	7.77
A9	28	200	50	7.80
A10	31.31	126.68	66.67	27.00
A11	32.95	169.27	50	9.42
A12	22.4	135	50	10.35
A13	41.1	85.6	50	9.23

Table 5. Normalized decision matrix

Alternative	Concrete strength (MPa)	Tensile strength of Bamboo (MPa)	Embedded length (%)	Pullout load (kN)
A1	0.0602	0.0574	0.0453	0.1241
A2	0.0904	0.0603	0.0680	0.0969
A3	0.0301	0.0951	0.1156	0.1129
A4	0.0678	0.0645	0.1361	0.0484
A5	0.0413	0.0409	0.0453	0.0587
A6	0.0602	0.1544	0.0907	0.1465
A7	0.0602	0.1140	0.0680	0.0536
A8	0.1205	0.0676	0.0680	0.0390
A9	0.0843	0.0965	0.0680	0.0391
A10	0.0943	0.0611	0.0907	0.1354
A11	0.0993	0.0817	0.0680	0.0473
A12	0.0675	0.0652	0.0680	0.0519
A13	0.1238	0.0413	0.0680	0.0463

Table 6. Information entropy (e_j) and entropy weight (w_j) of the decision criteria.

Criteria	Concrete strength	Tensile strength of Bamboo	Embedded length	Pullout load
e_j	0.9749	0.9721	0.9812	0.9538
w_j	0.2128	0.2363	0.1594	0.3915

The entropy weights (w_j) for the selected decision criteria are shown in Figure 6. According to the outcomes, the most significant decision criterion in the evaluation of the performance of coating materials is the pullout load with the maximum weight of 0.3915. Bamboo tensile strength is second with a weight of 0.2363. Concrete strength is followed by weight of 0.2128 and embedded length has least weight of 0.1594.

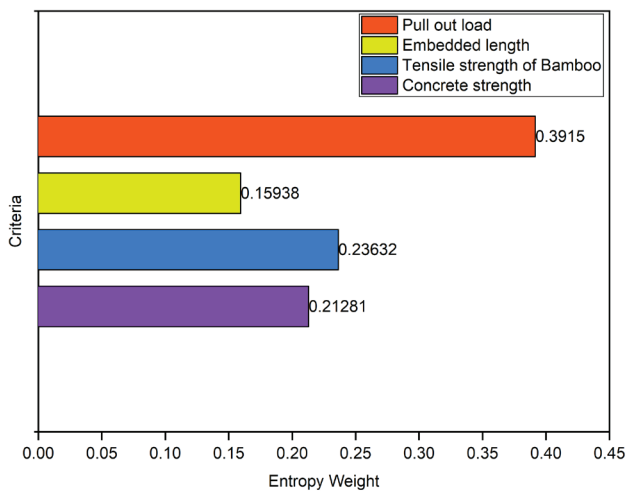


Figure 6. Entropy weight of decision criteria.

Assessment and Ranking of Coating Materials Using Fuzzy Topsis

The fuzzy decision matrix is obtained by converting the decision criteria of each coating material into TFNs to reflect the uncertainty and ambiguity in the data. The mapping of each criterion is determined by the location of the rating within the range of minimum and maximum values. The resulting fuzzy decision matrix, encompassing all decision criteria for the coating material, is shown in Table 7.

After normalizing the fuzzy decision matrix, the normalized fuzzy decision matrix is obtained. By multiplying normalized values by weights for each decision criterion in the weighted normalized fuzzy decision matrix, the weighted normalized fuzzy decision matrix is formed. Table 8 presents the weighted normalized fuzzy decision matrix for the coating material with the decision criteria.

In the next step, the distance of each alternative from the FPIS and FNIS is calculated. The closeness coefficients of each alternative are determined, and these coefficients are then used to rank them. Table 9 presents the entropy-fuzzy TOPSIS closeness coefficients along with the resulting ranking of alternatives.

The findings indicate that the coefficient values lie between 0.0533 and 0.6348 with the highest coefficient value of 0.6348 belonging to alternative A10. This alternative is an epoxy resin based material known as Sikadur-752, it is therefore considered the most suitable. Figure 7 shows

Table 7. The fuzzy decision matrix for the alternatives concerning decision criteria

Alternative	Concrete strength	Tensile strength of bamboo	Embedded length	Pullout load
A1	(1,3,5)	(0,1,3)	(0,0,1)	(7,9,10)
A2	(5,7,9)	(0,1,3)	(0,1,3)	(3,5,7)
A3	(0,0,1)	(3,5,7)	(7,9,10)	(5,7,9)
A4	(1,3,5)	(0,1,3)	(9,10,10)	(0,0,1)
A5	(0,0,1)	(0,0,1)	(0,0,1)	(0,1,3)
A6	(1,3,5)	(9,10,10)	(3,5,7)	(9,10,10)
A7	(1,3,5)	(5,7,9)	(0,1,3)	(0,0,1)
A8	(9,10,10)	(0,1,3)	(0,1,3)	(0,0,1)
A9	(5,7,9)	(3,5,7)	(0,1,3)	(0,0,1)
A10	(5,7,9)	(0,1,3)	(3,5,7)	(9,10,10)
A11	(7,9,10)	(1,3,5)	(0,1,3)	(0,0,1)
A12	(1,3,5)	(0,1,3)	(0,1,3)	(0,0,1)
A13	(9,10,10)	(0,0,1)	(0,1,3)	(0,0,1)

Table 8. The weighted normalized fuzzy decision matrix for alternatives based on decision criteria

Alternative	Concrete strength	Tensile strength of Bamboo	Embedded length	Pullout load
A1	(0.0213,0.0638,0.1062)	(0.0000,0.0236,0.0709)	(0.0000,0.0000,0.0159)	(0.2740,0.3523,0.3915)
A2	(0.1064,0.1490,0.1915)	(0.0000,0.0236,0.0709)	(0.0000,0.0159,0.0478)	(0.1174,0.1957,0.2740)
A3	(0.0000,0.0000,0.0213)	(0.0709,0.1182,0.1654)	(0.1116,0.1434,0.1594)	(0.1957,0.2740,0.3523)
A4	(0.0213,0.0638,0.1064)	(0.0000,0.0236,0.0709)	(0.0478,0.0797,0.1116)	(0.3523,0.3915,0.3915)
A5	(0.0000,0.0000,0.0213)	(0.0000,0.0000,0.0236)	(0.0000,0.0000,0.0159)	(0.0000,0.0391,0.1174)
A6	(0.0213,0.0638,0.1064)	(0.2127,0.2363,0.2363)	(0.0000,0.0159,0.0478)	(0.0000,0.0000,0.0391)
A7	(0.0213,0.0638,0.1064)	(0.1182,0.1654,0.2127)	(0.1434,0.1594,0.1594)	(0.0000,0.0000,0.0391)
A8	(0.1915,0.2128,0.2128)	(0.0000,0.0236,0.0709)	(0.0000,0.0159,0.0478)	(0.0000,0.0000,0.0391)
A9	(0.1064,0.1490,0.1915)	(0.0709,0.1182,0.1654)	(0.0000,0.0159,0.0478)	(0.0000,0.0000,0.0391)
A10	(0.1064,0.1490,0.1915)	(0.0000,0.0236,0.0709)	(0.0478,0.0797,0.1116)	(0.3523,0.3915,0.3915)
A11	(0.1490,0.1915,0.2128)	(0.0236,0.0709,0.1182)	(0.0000,0.0159,0.0478)	(0.0000,0.0000,0.0391)
A12	(0.0213,0.0638,0.1064)	(0.0000,0.0236,0.0709)	(0.0000,0.0159,0.0478)	(0.0000,0.0000,0.0391)
A13	(0.1915,0.2128,0.2128)	(0.0000,0.0000,0.0236)	(0.0000,0.0159,0.0478)	(0.0000,0.0000,0.0391)

the rankings of all the alternatives, according to their relative closeness coefficients.

Validation of the Proposed Entropy-Fuzzy Topsis Model

The proposed entropy-fuzzy TOPSIS model is validated through a sensitivity analysis. In this analysis, the weight of the most influential criterion, pullout load, which had the highest weight of 0.3915, is adjusted by $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$. The weights of the remaining criteria were proportionally adjusted to keep the total weight constant. Figure 8 presents the performance of the alternatives under different conditions in terms of relative closeness.

The analysis results are compared to the proposed model, revealing that material rankings remained consistent across all weight variation scenarios. It is interesting to note that alternative A9, Sikadur-752, always ranked first, regardless of the variations in weight distributions. These results indicate that epoxy resin-based material,

Table 9. Distance from FPIS & FNIS, relative closeness and ranking of coating material

Alternative	L_i^G	L_i^B	Closeness coefficient	Ranking
A1	0.5420	0.4215	0.4375	4
A2	0.5836	0.3540	0.3776	5
A3	0.4488	0.3992	0.4707	3
A4	0.4195	0.5055	0.5465	2
A5	0.8970	0.0505	0.0533	13
A6	0.6439	0.0832	0.1145	11
A7	0.5798	0.2116	0.2674	6
A8	0.6977	0.2194	0.2393	7
A9	0.6763	0.1649	0.1960	10
A10	0.3378	0.5872	0.6348	1
A11	0.6873	0.1990	0.2246	9
A12	0.8420	0.0832	0.0899	12
A13	0.7204	0.2194	0.2335	8

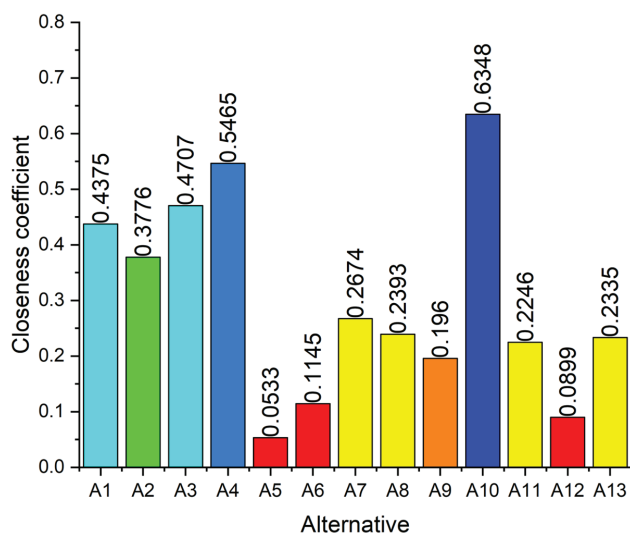


Figure 7. Ranking of coating materials based on their closeness coefficient.

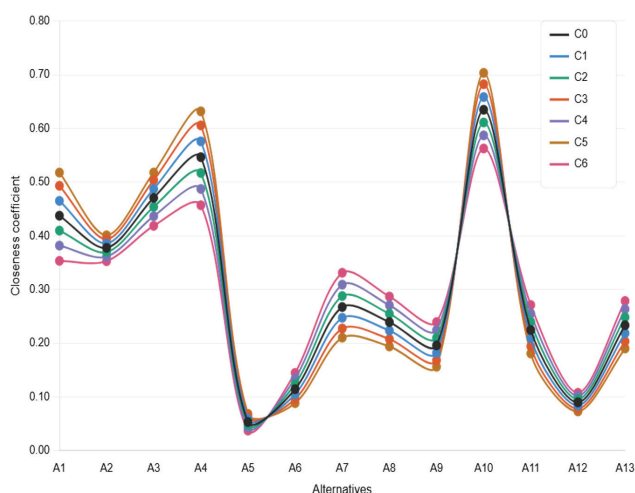


Figure 8. Performance of the alternatives under different conditions.

Sikadur-752 is the most suitable option. The sensitivity of rankings to different weights shows the strength of the Entropy-Fuzzy TOPSIS model that prioritizes materials using the criteria chosen. This consistency confirms the accuracy of the model in the decision making process since it is able to determine the best performing materials even when weighting changes are made subjectively.

CONCLUSION

The proposed study introduces a combined entropy-fuzzy TOPSIS model that is used to select an optimal coating material to be used in reinforcing bamboo in concrete. The model offers an effective, data-driven approach

to the selection of a coating material by applying a comprehensive assessment of those materials in four crucial parameters, such as compressive strength of concrete, tensile strength of bamboo, embedded length, and pullout load.

The results determine an epoxy resin-based material, Sikadur-752 (alternative A10), as the best coating material, out of the 13 alternatives, with a relative closeness value of 0.6348. The strength of the selection model is tested using the sensitivity analysis, where the weight of the most influential criterion can be varied as high as 30 per cent, with corresponding changes of the other criteria. These findings confirm that this model is a trustworthy and effective approach to choosing the optimal coating materials that can be used to avoid delay and minimize costs. Epoxy resin Sikadur-752, with its superior bonding properties can be used as a bonding agent to bamboo reinforcement in concrete structures to significantly improve their performance.

The limitations of the proposed model are that lack of quantitative data on certain selection criteria and uncertainties about the economic feasibility, environmental impact, and long-term stability of coating materials. Future studies may fill in these gaps by adding more criteria, e.g., the water absorption properties of bamboo, the cost of bamboo, and the thickness and durability of the coating materials, thus allowing a more in-depth and reliable study.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

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

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

CONFLICT OF INTEREST

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

REFERENCES

- [1] World Steel Association. Sustainability Indicators 2023 Report. Available at: <https://worldsteel.org/wp-content/uploads/Sustainability-indicators-report-2023.pdf>. Accessed on Apr 3, 2026.
- [2] Mondal B, Maity D, Patra PK. Load and resistance factor design for bamboo reinforced concrete beam in ultimate flexural limit state. *Struct Saf* 2023;102:102323. [\[CrossRef\]](#)
- [3] Javadian A, Wielopolski M, Smith IFC, Hebel DE. Bond-behavior study of newly developed bamboo-composite reinforcement in concrete. *Constr Build Mater* 2016;122:110–117. [\[CrossRef\]](#)
- [4] Karthik S, Rao PRM, Awoyera PO. Strength properties of bamboo and steel reinforced concrete containing manufactured sand and mineral admixtures. *J King Saud Univ Eng Sci* 2017;29:400–406. [\[CrossRef\]](#)
- [5] Puri V, Chakraborty P, Anand S, Majumdar S. Bamboo reinforced prefabricated wall panels for low cost housing. *J Build Eng* 2017;9:52–59. [\[CrossRef\]](#)
- [6] Kankam JA, Perry SH. Variability of bond strength between bamboo and concrete. *ACI Mater J* 1989;86:615–618. [\[CrossRef\]](#)
- [7] Ghavami K. Bamboo as reinforcement in structural concrete elements. *Cem Concr Compos* 2005;27:637–649. [\[CrossRef\]](#)
- [8] Kute SY, Wakchaure MR. Performance Evaluation for Enhancement of Some of the Engineering Properties of Bamboo as Reinforcement in Concrete. *J Inst Eng Ser A* 2014;94:235–242. [\[CrossRef\]](#)
- [9] Glenn HE. Bamboo reinforcement in portland cement concrete. Texas, United States: Engineering Experiment Station; 1950.
- [10] Fang HY, Fay SM. Mechanism of bamboo-water-concrete interaction. Proceedings of the International Conference on Materials of Construction for Developing Countries. Bangkok, Thailand; 1978. p. 37–48.
- [11] Mulyati M, Arman A. The Evaluation of Bond Strength of Bamboo Reinforcement in Concrete. *Mater Sci* 2016;690–695. [\[CrossRef\]](#)
- [12] Agarwal A, Nanda B, Maity D. Experimental investigation on chemically treated bamboo reinforced concrete beams and columns. *Constr Build Mater* 2014;71:610–617. [\[CrossRef\]](#)
- [13] Ghavami K. Ultimate load behaviour of bamboo-reinforced lightweight concrete beams. *Cem Concr Compos* 1995;17:281–288. [\[CrossRef\]](#)
- [14] Wang G, Wei Y, Chen S, Zhao K, Zhou Z. Bond performance between surface-modified bamboo bars and concrete under pull-out loading. *J Build Eng* 2023;79:107920. [\[CrossRef\]](#)
- [15] Mali PR, Datta D. Experimental study on improving bamboo concrete bond strength. *Adv Concr Constr* 2019;7:191–201.
- [16] Rahim NL, Ibrahim NM, Salehuddin S, Mohammed SA, Othman MZ. Investigation of bamboo as concrete reinforcement in the construction for low-cost housing industry. *IOP Conf Ser Earth Environ Sci* 2020;476. [\[CrossRef\]](#)
- [17] Muhtar, Dewi SM, Wisnumurti, Munawir A. Enhancing bamboo reinforcement using a hose-clamp to increase bond-stress and slip resistance. *J Build Eng* 2019;26:100896. [\[CrossRef\]](#)
- [18] Sakaray H, Togati NVVK, Reddy IVR. Investigation on properties of bamboo as reinforcing material in concrete. *Int J Eng Res Appl* 2012;2:77–83.
- [19] Tazowar M, Farhan A, Siddique A, Ahmed I. A novel approach for enhancing the bond performance of bamboo reinforced concrete by surface treatment and corrugation. *Constr Build Mater* 2023;409133728. [\[CrossRef\]](#)
- [20] Khatib A, Nounu G. Corrugated bamboo as reinforcement in concrete. *Proc Inst Civ Eng Struct Build* 2017;170:311–318. [\[CrossRef\]](#)
- [21] Moroz JG, Lissel SL, Hagel MD. Performance of bamboo reinforced concrete masonry shear walls. *Constr Build Mater* 2014;61:125–137. [\[CrossRef\]](#)
- [22] Wairagade VR, Sonar IP. Bamboo concrete bond strength. *Int J Eng Adv Technol* 2019;9:747–752. [\[CrossRef\]](#)
- [23] Terai M, Minami K. Research and Development on Bamboo Reinforced Concrete Structure. *World Conf Earthq Eng* 2012;15:1–10.
- [24] Mondal B, Maity D, Patra PK. Bond Behavior between Bamboo and Normal-Strength Concrete: Experimental and Numerical Investigation. *Pract Period Struct Des Constr* 2022;27:1–11. [\[CrossRef\]](#)
- [25] Chanpuyetch W, Niemsakul J, Atthirawong W, Supeekit T. An integrated AHP-TOPSIS approach for bamboo product evaluation and selection in rural communities. *Decis Anal J* 2024;12:100503. [\[CrossRef\]](#)
- [26] Akyol SO, Baba A, Salman S. Selection of Material for Marine Environments Using Fuzzy TOPSIS Approach. *J Inf Technol* 2021;14:11–22. [\[CrossRef\]](#)
- [27] Yildiz A, Karakoyun F, Parlak IE. The Most Suitable Mobile Rfid Reader Selection By Using Interval Type-2 Fuzzy Topsis Method. *Sigma J Eng Nat Sci* 2018;36:717–729.
- [28] Rahim AAA, Musa SN, Ramesh S, Lim MK. Development of a fuzzy-TOPSIS multi-criteria decision-making model for material selection with the integration of safety, health and environment risk assessment. *Proc Inst Mech Eng Part L J Mater Des Appl* 2021;235:1532–1550. [\[CrossRef\]](#)

- [29] Prasad RV, Rajesh R, Thirumalaikumarasamy D. Selection of coating material for magnesium alloy using Fuzzy AHP-TOPSIS. *Sadhana Acad Proc Eng Sci* 2020;45. [\[CrossRef\]](#)
- [30] Vijayakumar SR, Suresh P, Sasikumar K, Pasupathi K, Yuvaraj T, Velmurugan D. Evaluation and selection of projects using hybrid MCDM technique under fuzzy environment based on financial factors. *Mater Today Proc* 2022;60:1347–1352. [\[CrossRef\]](#)
- [31] Calik A. A Comparative Perspective in Sustainable Supplier Selection By Integrated Mcdm Techniques. *Sigma J Eng Nat Sci* 2020;38:835–852.
- [32] Chatterjee AK. Sustainable construction and green buildings on the foundation of building ecology. *Indian Concr J* 2009;83:27–30.
- [33] Reddy AS, Kumar PR, Raj PA. Entropy-based fuzzy TOPSIS framework for selection of a sustainable building material. *Int J Constr Manag* 2022;22:1194–1205. [\[CrossRef\]](#)
- [34] Shirazi A. Prioritizing Key Parameters for Sustainable Supply Chain Development in the Construction Industry Using a Copeland Hybrid Method. *Environ Energy Econ Res* 2024;8.
- [35] Rahman N, Shing LW, Simon L, Philipp M, Alireza J, Hebel Dirk E, et al. Enhanced bamboo composite with protective coating for structural concrete application. *Energy Procedia* 2017;143:167–172. [\[CrossRef\]](#)
- [36] Shannon CE. A mathematical theory of communication. *Bell Syst Tech J* 1948;27:379–423. [\[CrossRef\]](#)
- [37] Sahu SK, Shekhar S, Khan A, Soni DL, Gangwar PK, Gupta M. A hybrid approach for the machinability analysis of Incoloy 825 using the entropy-MOORA method. *High Temp Mater Process* 2024;43. [\[CrossRef\]](#)
- [38] Sodhi B, Tadinada P. A Simplified Description of Fuzzy TOPSIS. *arXiv* 2012;6–8.
- [39] Tzeng GH, Huang JJ. *Multiple Attribute Decision Making*. 1st ed. New York: CRC Press; 2011.
- [40] Mayyas A, Omar MA, Hayajneh MT. Eco-material selection using fuzzy TOPSIS method. *Int J Sustain Eng* 2016;9:292–304. [\[CrossRef\]](#)
- [41] Khan A, Maity K. Application potential of combined fuzzy-TOPSIS approach in minimization of surface roughness, cutting force and tool wear during machining of CP-Ti grade II. *Soft Comput* 2019;23:6667–6678. [\[CrossRef\]](#)
- [42] Rasi M, Abadi HMD. Proposing a framework for identifying the competitive advantage of small and medium-sized manufacturing organizations under uncertainty conditions. *J Decis Oper Res* 2022;7:515–529.
- [43] Abadi HMD, Sadra A. Customer Clustering via Combined TOPSIS-Fuzzy -K-MEANS Method to Design an Efficient Customer Relationship System : A Real-life Case Study in the Copper Industry. *Fuzzy Optim Model J* 2024;5:13–26.
- [44] Triantaphyllou E, Sánchez A. A sensitivity analysis approach for some deterministic multi-criteria decision-making methods. *Decis Sci* 1997;28:151–194. [\[CrossRef\]](#)
- [45] Kaymak U, van Nauta Lemke HR. A sensitivity analysis approach to introducing weight factors into decision functions in fuzzy multicriteria decision making. *Fuzzy sets Syst.* 1998;97:169–82. [\[CrossRef\]](#)