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Optimal Fiber Selection for Automobile Roof Top Application Using a Multi Criteria Decision-Making Framework

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ABSTRACT

In this paper, a comprehensive study was conducted on the selection of various fibers for automotive applications using two Multi-criteria decision-making (MCDM) procedures. These techniques are the Analytical Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The selection of fiber materials is essential for maximizing the performance, low running cost, and less environmental effect in automotive applications. In many cases, the selection of fiber is done based on experience or random approaches that involve trial and error. However, the multi-criteria decision making (MCDM) methods offer a methodical approach to the management of complex problems by considering numerous criteria at the same time. AHP is used to determine the relative significance of each criterion, whereas TOPSIS is used to rank the fibers based on how close they are to an ideal solution. The findings highlight the need to make crucial decisions, which can offer an appropriate insight into selecting materials for automobiles from among a good variety of alternatives. Different Weightage structures used in the paper are helpful is assessing the robustness of the solution. Therefore, the researchers can directly employ these strategies which rely on simple mathematics, which can guarantee an appropriate solution for a difficult decision-making problem.

1. INTRODUCTION

Lightweight materials are becoming increasingly popular in the automobile sector, and this trend is expected to continue as time goes on [1]. The requirements for lightweighting and the selection of appropriate materials are becoming increasingly difficult for designers working on automobiles because of the numerous developments that have occurred over the course of time in the last decade. The automobile industry is forced to explore lightweight materials without compromising their functionality because of the rising demand for fuel-efficient cars, electric vehicles, and autonomous vehicles. It is imperative that emphasis be placed on materials that are lighter, stronger, more durable, and sustainable to lower the carbon footprint and the additional miles that can be driven on a single charge in the case of electric vehicles.

Materials science is crucial for determining how cars will develop in the future, from improved electronics and interior design to structural elements and powertrain systems. The choice of materials significantly affects a vehicle's performance, economy, and environmental sustainability [2]. The need for high-performance materials suited to certain applications has grown as automobiles have become more complex, adding cutting-edge technologies and functionalities. To ensure that the chosen materials meet the strict requirements of the automotive industry, which include not only performance targets but also considerations of cost, manufacturability, recyclability, and regulatory compliance, a rigorous and methodical approach to material evaluation and selection is required. Material selection has become a complex and multidimensional task owing to the growing complexity of vehicle design and growing emphasis on sustainability. Creative solutions and advanced tools are required to successfully navigate the confusing landscape of material properties and performance characteristics.

Both natural and synthetic fibers are essential to enhance the mechanical properties of composite materials, providing exceptional strength-to-weight ratios, and making it possible to create components that are both strong and lightweight. These materials play a key role in achieving weight reduction goals, which are necessary to increase the fuel economy and reduce emissions. Fiber-reinforced composites also provide design flexibility, enabling the development of intricate forms and integrated features that enhance the vehicle performance and appearance. Choosing natural or synthetic fibers is difficult [3]. Natural fibers are made from renewable resources, making them eco-friendly and sometimes cheaper. They may not always satisfy the existing performance standards of demanding automotive applications; nevertheless, their characteristics can change based on the source, processing, and environmental factors [4]. Although synthetic fibers, which are designed to have certain qualities, provide better mechanical performance and consistency, their manufacture and disposal can result in increased cost and environmental issues. To achieve the intended mix of performance, affordability, and sustainability, the right fiber type must be chosen, and fiber-matrix combinations must be optimized.

Selection of the best material for a particular automotive application is a difficult task that requires a careful evaluation of numerous variables [5]. These standards frequently clash, necessitating careful prioritization and trade-offs. For instance, high-performance materials may have better mechanical qualities but are unaffordable or challenging to produce. Conversely, inexpensive materials may be readily available but may not meet the performance requirements of the application. Conventional material selection techniques, often based on subjective assessment or constrained comparisons, cannot handle this intricacy. They fall short of offering a methodical and clear framework for decision-making, and have difficulty capturing the complex interactions between different criteria. Methodologies known as Multi-Criteria Decision-Making (MCDM) provide a potent solution for this problem [6]. MCDM techniques offer a methodical and structured strategy for assessing options when there are several frequently incompatible criteria. Using these techniques, decision makers can rank the options according to their overall performance and assess the relative importance of various factors. MCDM techniques increase the possibility of selecting the best material for a particular application and enable informed decision making by offering an open and impartial framework.

Numerous material selection challenges in a range of industries have demonstrated the successful application of MCDM approaches [7, 8]. To assess and rank various material possibilities, researchers have used techniques such as AHP and TOPSIS, considering variables including cost, environmental effect, mechanical qualities, and manufacturability [5, 9]. Materials for vehicle body panels have been selected using AHP, considering factors such as weight, strength, and stiffness [10, 11]. TOPSIS has been used to assess several alloys for aerospace applications, accounting for cost, corrosion resistance, and fatigue resistance. However, given the intricate interactions between multiple variables, more research is required to fully understand the specific use of AHP and TOPSIS in the context of fiber selection for automotive applications. This study fills this gap by assessing several fiber choices for automotive applications using a combined AHP-TOPSIS approach.

The Analytic Hierarchy Process (AHP) is extensively utilized to organize decision-making issues and extract priority weights from expert assessments, particularly when subjective evaluation is essential. Onat et al. [12] employed AHP to identify appropriate composite materials for lightweight vehicle components, concluding that AHP offers a clear hierarchical perspective on the significance of criteria. Conversely, TOPSIS is proficient in ranking alternatives according to their closeness to an optimal solution, rendering it appropriate for performance-oriented decisions. Jahan and Edwards [13] utilized TOPSIS for the selection of materials for biomedical devices, demonstrating its consistency and computational efficiency. Similarly, Chatterjee et al. [14, 15] employed TOPSIS to evaluate polymer matrix composites, showcasing its efficacy in managing competing criteria. These investigations confirm that both AHP and TOPSIS, when utilized independently, provide effective, clear, and pragmatic methodologies for material selection problems.

A crucial topic in the field of automotive materials research, the evaluation and selection of fibers for automotive applications, is the specific emphasis of this effort. Although earlier research examined the application of MCDM techniques for material selection, this study explores the unique potential and constraints related to fiber selection. This work is unusual because it takes a targeted approach to address the factors pertaining to fiber characteristics, processing, and use in the automobile industry. To guarantee a thorough assessment, this study attempts to offer a clear and systematic framework for fiber selection that incorporates both quantitative and qualitative factors. Additionally, this study investigates the synergies between TOPSIS and AHP, utilizing the advantages of each approach to produce a solid and trustworthy decision-making tool. The problem statement is defined in Section 2, which also describes the difficulties in selecting the best fibers based on several frequently incompatible criteria. The method used, which combines the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) for ranking options and the Analytical Hierarchy Process (AHP) for weighing criteria, is explained in detail in Section 3. The results from the AHP-TOPSIS study, such as the importance of each criterion, rankings of the fibers, and sensitivity analysis, are presented and discussed in Sections 4 and 5. Section 6 concludes the paper by highlighting its contributions and summarizing its main conclusions.

2. PROBLEM STATEMENT

Material selection is challenging when attempting to achieve balance between conflicting objectives. This problem includes 10 different fiber materials, each showing varying degrees of quality in five key characteristics: density, tensile strength, Young's modulus, elongation at break, and availability, as shown in Table 1.

However, the complexities associated with these traits pose challenges. For example, compared to alternatives such as E-glass, carbon fiber is less remarkable in terms of elongation and density, but excels in terms of tensile strength and Young's modulus. Similarly, hemp exhibits high availability, but poor mechanical qualities. This discrepancy emphasizes how challenging it is to choose just one "best" material. Finding a compromise solution that strikes a balance between these opposing qualities to attain the best possible performance within the intended application is the goal.

Conventional approaches to material selection, which usually rely on crude weighting schemes or comparisons based on a single criterion, are inadequate for handling this complexity. These methods struggle to provide a comprehensive evaluation that considers the intended balance and overlooks the complex interactions between many qualities. Consequently, a strong approach is needed to manage the multifaceted nature of the problem while making it easier to find a compromise solution that meets various engineering needs. This approach calls for the use of multi-attribute decision-making (MADM) techniques, which are created to address complicated decision issues with numerous criteria and options [16]. These techniques provide a simple way to evaluate the different options, considering the importance of each factor and ultimately ranking the materials based on how well they work and how acceptable they are as a compromise solution. The different fiber types and their characteristics are listed in Table 1.

Table 1. Selected fibres and their properties [17-19]

Material No.	Fiber Type	Density (gm/cm^3)	Tensile Strength (MPa)	Young's Modulus (Gpa)	Elongation at Break(%)	Availability 1-Abondently Available 10 -Least Available
1	E Glass	2.6	2500	76	4	1
2	Carbon Fiber	1.8	4000	228	2	1
3	Kevlar	1.44	3400	41.4	3	2
4	Bessalt	2.65	3000	86	4	3
5	Kanef	1	750	45	3	6
6	Jute	1.4	620	40	4.5	5
7	Flex	1.05	1000	52	5	5
8	Bamboo	1.4	620	42	2	3
9	Banana	1.35	720	30	2	5
10	Hemp	1.5	900	60	1.6	8

3. METHODOLOGY

3.1 Analytical Hierarchy Process (AHP)

Thomas Saaty created the Analytical Hierarchy Process (AHP), a structured decision-making method for handling complex decisions with multiple criteria. It offers a hierarchical framework to deconstruct complex problems into smaller, easier-to-manage components, allowing for systematic evaluation of alternatives. AHP is especially helpful when dealing with subjective judgments and intangible criteria, which makes it appropriate for material selection problems in which availability or environmental impact must be considered in addition to quantifiable properties [20]. Figure 1 outlines the steps involved in the AHP process.

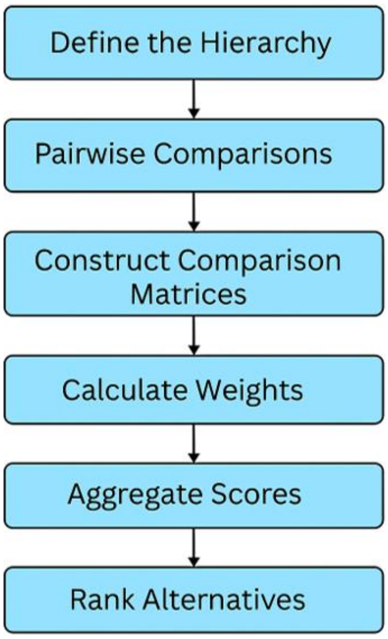

Figure 1. AHP flow diagram

When choosing materials, AHP offers an organized method for combining quantitative and qualitative factors. Decision-makers can compare the performance of various materials and carefully assess the significance of each criterion by decomposing the decision into a hierarchy. The pairwise comparison technique makes it easier to quantify subjective assessments, such as the relative weights assigned to cost and performance. The robustness of the decision is further improved by AHP's capacity to manage judgmental discrepancies [21].

3.2 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS, developed by Hwang and Yoon, is a multi-criteria decision-making method that assesses alternatives based on their proximity to an ideal answer and their distance from a non-ideal solution. The optimal solution signifies the most favorable values across all criteria, whereas the negative ideal solution denotes the least favorable values. TOPSIS finds the option closest to the ideal solution and farthest from the negative ideal solution. This method is straightforward and efficient in terms of computation, which contributes to its widespread use in material selection [22]. Figure 2 illustrates the TOPSIS methodology.

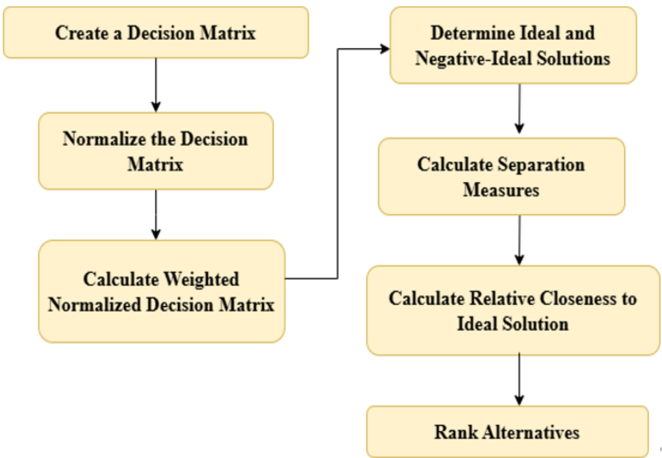

Figure 2. TOPSIS methodology diagram

TOPSIS formulas are widely available on the web, and TOPSIS methods have proven to be clear and efficient for ranking materials according to their overall performance across various criteria [23, 24]. TOPSIS offers a comprehensive evaluation of the suitability of each material by analyzing both the closeness to the ideal solution and the distance from the negative-ideal solution. The method works well for both benefits and costs, where higher values show better or worse results, making it useful for different material selection situations. Computational efficiency is a significant advantage when managing a substantial quantity of materials and criteria.

3.3 Entropy based weighting method

Traditional MADM methods apply weights and ratings based on decision-makers' subjective inputs, which are inefficient and inconsistent. The entropy approach objectively determines weights based on data fluctuations, thus making it more dependable. It prioritizes informational criteria and downplays those criteria with little variation. We discuss the step-by-step approach of the entropy method below.

Step 1: Normalize the decision matrix for each criterion and obtain the value P_{ij} for each criterion P_{ij}.

$$P_{ij} = \frac{x_{ij}}{\sum_{i=j}^{m} x_{ij}} \tag{1}$$

where, x_{ij} are the values in decision table.

Step 2: After obtaining normalized decision matrix, calculate the entropy values e_j.

$$e_j = -k\sum_{j=1}^{n} p_{ij} \ln p_{ij} \tag{2}$$

k is a constant, let $k = (\ln(m))^{-1}$.

Step 3: Calculate the degree of divergence d_j for each criterion C_j(j= 1, 2, ..., n).

$$d_j = 1 - e_j \tag{3}$$

Step 4: Obtain the objective weight W_j of each criterion using Eq. (4).

$$W_j = \frac{d_j}{\sum_{k=1}^{n} d_k} \tag{4}$$

4. RESULTS

A structured decision-making process was utilized to assess and rank the performance of the alternative composite materials. AHP and TOPSIS methods, along with two different weighting methods, were used to evaluate the robustness of the proposed methods. Table 2 presents the normalized decision-making matrix for Table 1, prioritized according to specified characteristics.

Table 2. Normalized decision-making matrix

Material. No.	Fiber Type	Density (gm/cm^3)	Tensile Strength (MPa)	Young's Modulus (Gpa)	Elongation at Break(%)	Availability
1	E Glass	0.3846	0.9412	0.4350	0.8000	1.0000
2	Carbon Fiber	0.5556	1.0000	1.0000	0.5000	1.0000
3	Kevlar	0.6944	1.0000	0.6650	0.6000	0.3333
4	Bessalt	0.3774	0.9412	0.4300	0.8000	0.3333
5	Kanef	1.0000	0.2206	0.2250	0.6000	0.1667
6	Jute	0.7143	0.1824	0.2000	0.9000	0.2000
7	Flex	0.9524	0.2941	0.2600	1.0000	0.2000
8	Bamboo	0.7143	0.1824	0.2100	0.4000	0.3333
9	Banana	0.7407	0.2118	0.1500	0.4000	0.2000
10	Hemp	0.6667	0.2647	0.3650	0.3200	0.1667

Calculating the weights for each criterion is a crucial step after establishing a normalized matrix. These weights, which can be calculated using data analysis methods or expert opinions, show the importance of each criterion in decision making. Because these weights have a direct impact on how the options are prioritized in the review process that follows, their computation must be performed accurately. Ranking the options according to their total performance scores is based on the weighted matrix produced.

4.1 Equal weightage method

The equal-weighting method assigns equal weights to all assessing elements, presuming that none are more significant than the others. Multi-criteria decision-making frequently employs this straightforward objective method as a foundational model [5, 10, 11]. As there are five factors, Table 3 lists the weighting factors with equal weights.

4.1.1 AHP method

The priority scores for each criterion were calculated by solving n × n comparison matrices using the pairwise comparison method described in Section 3.1. Based on expert judgment, these scores are normalized weights that show the importance of each component in relation to the others. Table 4 lists the ranks of each material, as well as the performance scores of the suggested materials using AHP with an equal weighting approach.

4.1.2 TOPSIS method

Section 3.1 indicated the use of the TOPSIS-based evaluation approach to assess the performance of the suggested materials. The weighted normalized decision matrix was constructed using both the calculated and equal weights after the decision matrix was built, and the performance data were adjusted. We computed the separation measures for each alternative by identifying the ideal and negative-ideal solutions. S+ and S- are used to measure closeness to the best choice, making it easier to select the top-ranked option. The relative closeness values obtained from these calculations were used to rank materials. V+ (ideal) and V- (negative ideal) help compare each material with the best and worst performance. Tables 5 and 6 show the results of the calculation of the V+, V −, S+, and S − scores. Table 7 summarizes the relevant performance scores, and final rankings obtained using the TOPSIS method with uniform weights.

Table 3. weightage factors using equal weightage method

Density (gm/cm^3)	Tensile Strength (MPa)	Young's Modulus (Gpa)	Elongation at Break(%)	Availability
0.2	0.2	0.2	0.2	0.2

Table 4. Performance scores and Rank scenario using AHP Method with equal weighing method

Material. No.	Fiber Type	Performance Scores	Rank
1	E Glass	0.1455	2
2	Carbon Fiber	0.1720	1
3	Kevlar	0.1283	3
4	Bessalt	0.1111	4
5	Kanef	0.0767	7
6	Jute	0.0768	6
7	Flex	0.0943	5
8	Bamboo	0.0682	8
9	Banana	0.0603	10
10	Hemp	0.0668	9

Table 5. Ideal best and ideal least values of proposed parameters

Parameters	Density (gm/cm^3)	Tensile Strength (MPa)	Young's Modulus (Gpa)	Elongation at Break(%)	Availability
V+	0.0370	0.0989	0.1356	0.0945	0.0151
V-	0.0981	0.0180	0.0203	0.0302	0.0905

Table 6. Measure of closeness to ideal values (S+, S-) in TOPSIS for all materials

Material. No.	Fiber Type	S+	S-
1	E Glass	0.0988	0.1219
2	Carbon Fiber	0.0557	0.1637
3	Kevlar	0.0683	0.1272
4	Bessalt	0.1049	0.1057
5	Kanef	0.1552	0.0674
6	Jute	0.1492	0.0736
7	Flex	0.1363	0.1363
8	Bamboo	0.1495	0.0656
9	Banana	0.1624	0.0511
10	Hemp	0.1512	0.0522

Table 7. Performance scores and rank scenario using TOPSIS method with equal weighing method

Material. No.	Fiber Type	Performance Scores	Rank
1	E Glass	0.5523	3
2	Carbon Fiber	0.7459	1
3	Kevlar	0.6505	2
4	Bessalt	0.5019	4
5	Kanef	0.3028	8
6	Jute	0.3303	6
7	Flex	0.3992	5
8	Bamboo	0.3051	7
9	Banana	0.2392	10
10	Hemp	0.2568	9

4.2 Entropy method

The entropy technique assesses the relative significance of each criterion in a decision-making context. It examines the degree of variation in the data for each criterion; the more variation, the more valuable the information provided by the criterion [5, 25]. The objective assignment of weights based on data features is advantageous.

The entropy method of weights has already been tested by researchers using both AHP and TOPSIS, and they have found successful outcomes that aid in precise decision-making [25, 26]. Table 8 lists the weighting factors as per the entropy calculated using the formulae [5, 25-27].

4.2.1 AHP method

The AHP technique uses entropy-based weights to account for real variation in the data for each criterion. Their use improved the evaluation's dependability and helped eliminate personal bias. Table 9 displays the scores and rankings obtained using these data-driven weights.

4.2.2 TOPSIS method

The TOPSIS method also employs entropy-based weights to assign equal weights to each criterion, considering the available data. These weights are used to calculate the closeness of each material to the best possible option. V+ and V- represent the best and worst values for each criterion, respectively, which help define the ideal and least ideal options, whereas S+ and S- show how far each alternative is from the best and worst options. The Tables 10-12 clearly rank them, displaying the final results obtained using this approach.

Table 8. Weightage factors using entropy method

Density (gm/cm^3)	Tensile Strength (MPa)	Young's Modulus (Gpa)	Elongation at Break(%)	Availability
0.0802	0.3703	0.2640	0.0939	0.1917

Table 9. Performance scores and rank scenario using AHP method with entropy weighing method

Material No.	Fiber Type	Performance Scores	Rank
1	E Glass	0.1608	2
2	Carbon Fiber	0.2004	1
3	Kevlar	0.1486	3
4	Bessalt	0.1279	4
5	Kanef	0.0595	7
6	Jute	0.0578	8
7	Flex	0.074	5
8	Bamboo	0.0576	9
9	Banana	0.0494	10
10	Hemp	0.0639	6

Table 10. The determined ideal best and ideal worst values for each of the considered parameters

Fiber Type	Density (gm/cm^3)	Tensile Strength (MPa)	Young's Modulus (Gpa)	Elongation at Break(%)	Availability
V+	0.0149	0.1831	0.179	0.0443	0.0144
V-	0.0394	0.0334	0.0269	0.0142	0.0867

Table 11. The calculated separation measures in the TOPSIS method

Material. No.	Fiber Type	S+	S-
1	E Glass	0.1048	0.1661
2	Carbon Fiber	0.0251	0.2259
3	Kevlar	0.0692	0.1824
4	Bessalt	0.1097	0.1554
5	Kanef	0.2125	0.0314
6	Jute	0.2152	0.036
7	Flex	0.1939	0.0499
8	Bamboo	0.2098	0.0485
9	Banana	0.2192	0.025
10	Hemp	0.193	0.0447

Table 12. Performance scores calculated using the TOPSIS method with Entropy weights and ranking of materials

Material. No.	Fiber Type	Performance Scores	Rank
1	E Glass	0.6131	3
2	Carbon Fiber	0.8998	1
3	Kevlar	0.725	2
4	Bessalt	0.5861	4
5	Kanef	0.1286	9
6	Jute	0.1432	8
7	Flex	0.2046	5
8	Bamboo	0.1878	7
9	Banana	0.1022	10
10	Hemp	0.1882	6

5. DISCUSSION

Ten different fiber-reinforced composites were ranked using two different decision-making methods: one that gives equal importance to all factors and another that uses weight based on entropy. The combined rankings are shown in Table 13.

Carbon fiber continuously achieved the highest ranking in both AHP and TOPSIS, demonstrating its outstanding mechanical performance attributes, including high tensile strength and stiffness. The table also demonstrates the impact of the weighting method on material ranking. Carbon fiber continued to be the best, even after objective weights were applied using the entropy technique, which solely depends on facts and not professional judgment. The graph demonstrates that its performance is robust across all important parameters and is not restricted to any one area, which is consistent with earlier findings in composite research [28].

Carbon fiber is ranked first (rank 1), as shown by the radar chart, which consistently places it in the innermost position across all four methods, AHP and TOPSIS, using both equal and entropy-based weights. This central position, shown in

Figure 3, shows that it performs exceptionally well for all evaluation criteria because it is closest to the center of the radar chart.

The results of this study align with previous research, indicating that carbon fiber is among the most reliable and effective materials for applications necessitating strong mechanical performance, especially in rooftop vehicle contexts [29-31].

Table 13. Ranks summary of materials using different approaches

Material. No.	Fiber Type	Rank of Materials using Equal Weightage AHP Method	Rank of Materials using Equal Weightage TOPSIS Method	Rank of Materials using Entropy Weights AHP Method	Rank of Materials using Entropy Weights TOPSIS Method
1	E Glass	2	3	2	3
2	Carbon Fiber	1	1	1	1
3	Kevlar	3	2	3	2
4	Bessalt	4	4	4	4
5	Kanef	7	8	7	9
6	Jute	6	6	8	8
7	Flex	5	5	5	5
8	Bamboo	8	7	9	7
9	Banana	10	10	10	10
10	Hemp	9	9	6	6

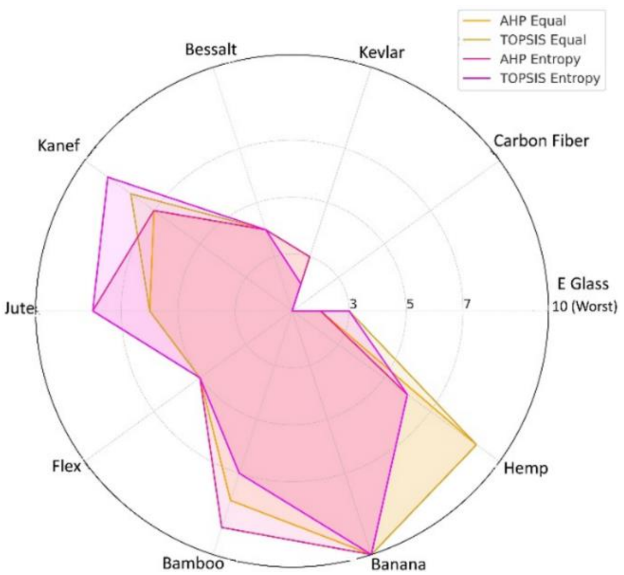

Figure 3. Radar diagram to show multivariate comparison of proposed methods

6. CONCLUSIONS

This study uses AHP and TOPSIS MCDM methodologies to analyze fiber selection for automotive applications. Employing multi-criteria decision-making (MCDM) techniques offers a methodical and mathematically grounded alternative to subjective fiber selection. Using both TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and AHP (Analytic Hierarchy Process) shows different methods of evaluating options, with TOPSIS looking at how close options are to the best solution, and AHP focusing on the importance of different criteria. Notably, despite these methodological differences, carbon fiber consistently emerged as a superior material across all analyses. The robustness of this finding is further substantiated through a sensitivity analysis, where variations in criteria weights consistently identify carbon fiber as the ideal choice. This consistent performance underscores the inherent strength and durability of the material, highlighting its strong suitability for demanding automotive applications. The current work focuses on only static performance attributes, and future studies will expand to include fuzzy based hybrid model with dynamic loading conditions, cost, recyclability, and real-world automotive case studies.

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