Comprehensive Evaluation of Materials for Small Wind Turbine Blades Using Various MCDM Techniques

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Abstract- Best material selection among various possible materials for small wind turbine blades is a vital task as it needs to meet the different selection criteria. This research paper is a comprehensive work that includes identification of ten possible better materials, finding ten all-encompassing material selection criteria and the use of four suitable mathematical techniques to get the appropriate results. The identified materials are the appropriate combinations of metal, plastics, natural materials and hybrid natural-synthetic materials. The quantitative and qualitative data used are collected from experts, manufacturers, testing laboratories and academic researchers. The three different criteria weights are calculated from the analytic hierarchy process, entropy weight method and the average of these two methods. These weights are used in simple additive weighting method, weighted product method, technique for order preference by similarity to ideal solution method and R-method to get the rankings of the materials. A good, acceptable similarity is observed for first three materials rankings. Epoxy based hybrid cotton-glass fiber reinforced plastic is observed as an evolving best compromised material for small wind turbine blades.

Keywords - Composite materials, MCDM, natural fibers, R-method, small wind turbine blade.

1. Introduction

The small wind turbine market is expected to grow considerably in the coming years as per World Wind Energy Association's report [1]. Blade is one of the major parts of Small Wind Turbine (SWT) and focused by the many researchers to have better aerodynamics and few worked on strength design. Most of the research works available on SWT blades are related to the design of airfoil for low Reynolds number and performance evaluation of the rotor using computational and experimental techniques [2-4]. In the SWT blade design process, after the aerodynamic design, next important step is the strength design including material selection. The rotating wind turbine blades are continuously subjected to fatigue loads due to the random nature of wind speed and direction. Hence, the blade should have sufficient strength to withstand such conditions for a long term designed life which is possible through proper strength design. Only a few researchers have reported the research on strength design and materials for SWT blades [6-8].

The authors of available research articles have focused only on high strength to weight ratio as a major criteria for SWT blades and many other substantial criteria are ignored. Glass Fiber Reinforced Plastic (GFRP) and Carbon Fiber Reinforced Plastic (CFRP) are the commonly used materials for SWT blades because of high strength to weight ratio. The GFRP and CFRP are adopted in SWT blades by referring to their use in the large wind turbine blades. There is possibility to use other materials for SWT blades which may not suitable for large wind turbine blades. Hence, a few researchers have thought of such alternatives and proposed few alternative materials specifically suitable for SWT blades. Additionally, in the last two decades, with the increasing concerns about the environment and sustainable development, researchers have recognized the need for green materials in renewable energy devices [6, 9]. Few researchers have also suggested and carried out research on wood and aluminium blades [8-10]. Some researchers have projected the use of natural fibers and a combination of natural & glass fibers for SWT blades [6, 9]. Though, researchers have suggested new materials for SWT blades, it is very important to compare these proposed materials using systematic mathematical tools in order to get the best one. The selection of appropriate material for SWT blade is a challenging task as multiple criteria are to be fulfilled by the selected material. The identification of appropriate material among various alternatives and criteria needs a comprehensive evaluation and use of suitable Multi-criteria decision making techniques [11, 12].

This paper has presented a comprehensive evaluation of various alternative materials for SWT blades considering multiple criteria, using different Multi-criteria decision making (MCDM) techniques. The alternative materials are ranked considering the identified criteria through the implementation of numbers of MCDM techniques. Overall, this paper is a noteworthy combination of ten alternatives, ten criteria, two weight calculating methods and four MCDM techniques to select the best material for SWT blades.

2. Methodology

This research paper is focused to find the best material for SWT blade by evaluating the various alternative materials using various mathematical approaches. The selection of the best material was accomplished through various steps as per the flowchart of methodology shown in Fig. 1.

The first four steps, i) identification of criteria for SWT blades, ii) Selection of alternative materials for SWT blade, iii) Choosing weight calculation techniques & MCDM techniques, and iv) data collection are discussed in this section. A brief information about weight calculation and MCDM techniques along with required calculations to get the rankings of the materials by individual MCDM technique is presented in sections three and four respectively. The section five compared the ranking results of MCDM techniques followed by a comparative evaluation.

2.1. Identification of Desired Properties (Attributes) for SWT Blades

Based on the working conditions, expected long life of 20 to 25 years and requirement of better performance, the ten significant expected properties are identified from the available research articles and their significance [6-8, 11-17] is summarized in Fig. 2. The desirable properties of the SWT blades include tensile strength, flexural strength, corrosion resistance, durability, availability, environment friendly and production rates which should have higher values. The properties such as material density, blade cost and manufacturing setup cost should be lesser.

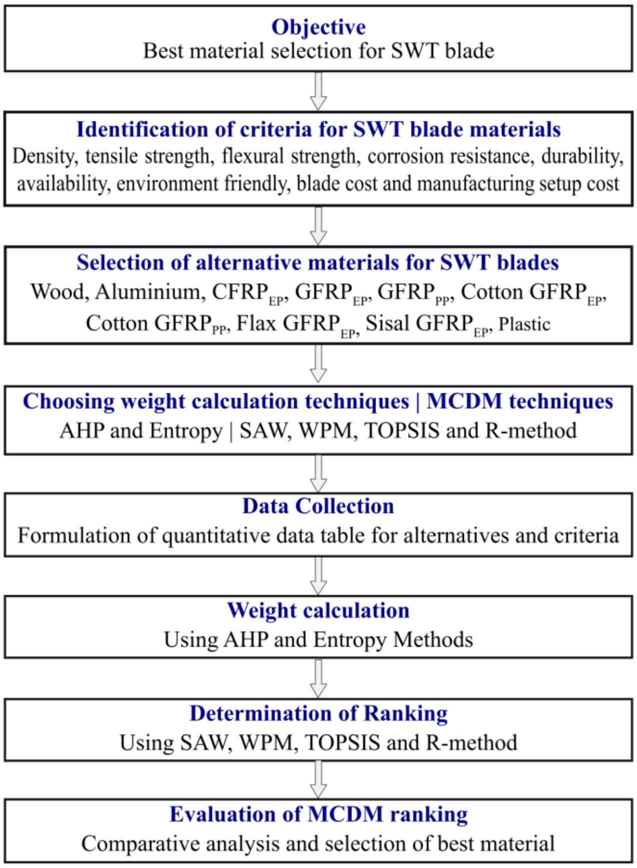

Fig. 1. The methodology used to select the best material for SWT blades

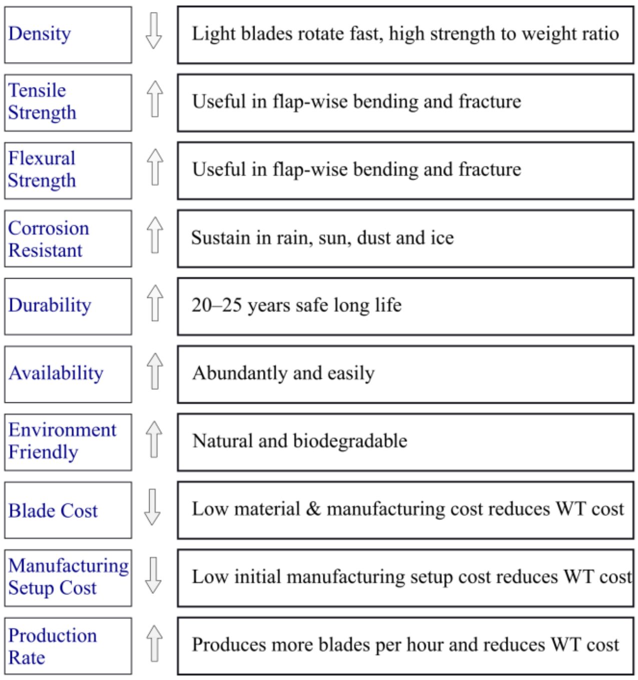

Fig. 2. Summary of Expected Properties for SWT Blade

2.2. Alternative Materials for SWT Blade

Toady research in material science is at its peak and everyday new materials are available for various applications in the form of composite materials to meet specific requirement. In the literature, only a few researchers have carried out experimental work on SWT blades and some have suggested alternatives to GFRP and CFRP. For this research, some alternative materials are selected from the literature and some are considered by the authors as a perceptive alternative to meet the criteria shown in Fig. 2. The materials selected for evaluation include alloy metal, non-metals, natural materials, synthetic materials and combinations of natural and synthetic materials. Wood, epoxy based Carbon FRP ($CFRP_{EP}$), epoxy based Glass FRP ($GFRP_{EP}$), polypropylene based Glass FRP with ($GFRP_{PP}$), epoxy based Cotton-Glass FRP ($CGFRP_{EP}$), polypropylene based Cotton-Glass FRP ($CGFRP_{PP}$), epoxy based Flax-Glass FRP ($FGFRP_{EP}$), epoxy based Sisal-Glass FRP with ($SGFRP_{EP}$), plastic are some better materials considered for analysis. The material properties are taken from various research articles [11,13, 18-21].

Among the selected materials none of the materials are meeting all criteria to be required by SWT blade. Each individual material has some strengths and some weaknesses. For each criterion top three materials are ranked among the considered materials and this ranking is represented by Fig. 3. For example, the material with low density is the most desirable. The density of wood is lowest and is considered the first ranked material as shown by green color. Plastic and cotton-glass (pp) are followed by the wood and ranked as the second (blue color) and third (yellow color) respectively. Similarly, the material ranking for other criteria is given.

2.3. Choosing Weight Calculation Techniques and MCDM Techniques

From Fig. 3., it is clear that no material can be declared as the best, simply by observation. Also, every criterion has different importance. It is a very complex task to decide the importance of every criterion and assign the correct weight to these criteria. The decision of any MCDM technique is significantly dependent on the weight of the criteria. Hence, it is very important to assign the appropriate weight to the criteria and suitable weighing methods should be applied. The weighing methods are mainly classified as subjective weighting methods (for data obtained through an expert's opinion) and objective weighting methods (for confirming calculated or experimental data). The MCDM problem comprising both types of data can be solved by using integrated weighting methods. Analytic Hierarchy Process (AHP) is one of the widely used important and effective subjective weighing methods. Entropy method is preferred by many researchers as an objective weighing method. Hence, for such complex problem of the present research, it is decided to adopt AHP and Entropy as weight calculating techniques accurately and effectively [22-24].

The next important step is to choose the appropriate MCDM techniques in order to get more accurate results. There are more than fifty MCDM techniques available to solve different engineering problems. They have their own merits and demerits and all are not giving the same results. Hence, it is worthwhile to use more than one method and take a decision based on their results. Simple Additive Weighting (SAW) and the Weighted Product Model (WPM) are the primary MCDM methods characterized by simplicity and quick solution. From the published research, it is observed that AHP is termed an effective MCDM technique. In fact, in AHP after comparing pairwise matrices and solving them, the weightage is calculated and same weightage is used in the WPM [13].

For the current research, AHP is already chosen as a weighing method. Furthermore, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one of the most preferred methods for material selection because of its accuracy and better results compared to others. Additionally, R-method is a comparatively new MCDM technique and various research problems are solved by this technique in the last three years [23-26]. Hence, it is decided to use SAW, WPM, TOPSIS and R-method to evaluate the materials in this research paper.

Fig. 3. The major three ranking criteria for considering alternative materials for SWT blades

2.4. Formulation of Quantitative Data Matrix Table

Among the ten selected criteria, densities, tensile strengths and flexural strengths are the quantitative criteria which are collected from various research papers and experts. The corrosion resistance, durability, availability and environment friendly are the qualitative criteria and their values are decided based on research articles and opinions from experts. Blade costs and setup costs are obtained from the different manufacturers.

These experts and manufacturers include persons from various backgrounds such as composite fiber manufacturers (Mr. Kaustubh Barve, K. S. Industries, Pune, India and Mr. Santosh Gaikwad, Fiber Glass Industries, Pune, India), Material testing expert (Mr. Ashok Bhagat, Praj Metallurgical Laboratory, Pune, India), academic researchers (Dr. Swanand Kulkarni and Dr. Balasaheb S. Gandhare, SKN College of Engineering, Pandharpur, India.).

The quantitative and qualitative data collected from research articles [27-35], experts and manufacturers are presented in the Table 1. For the conversion of qualitative data to quantitative data, eleven point scale [36] in which; Exceptionally Low (ECL) = 0, Extremely Low (EXL) = 0.1, Very Low (VL) = 0.2, Low (L) = 0.3, Below Average (BA) = 0.4, Average (A) = 0.5, Above Average (AA) = 0.6, High (H) = 0.7, Very High (VH) = 0.8, Extremely High (EXH) = 0.9, Exceptionally High (ECH) = 1 are the assigned values for the present study. The qualitative data is converted using the scale is shown in Table 2.

3. Weight Calculations for Considered Criteria

As discussed earlier, AHP and Entropy are the selected methods for weightage calculations. This section describes the overview of these methods and the application of these methods to the research problem under consideration.

3.1. Weight Calculation by Analytic Hierarchy Process

Following stepwise procedure is followed to get weightage by AHP [11,13, 37].

Table 1. Quantitative and qualitative data for alternative materials and criteria for SWT Blade

Attributes Alternatives	Density (kg/m^3)	Tensile Strength (MPa)	Flexural Strength (MPa)	Corrosion resistance	Durability	Availability	Environment Friendly	Blade Cost (USD)	Setup Cost (USD)	Production Rate
Desirable	Less	More	More	More	More	More	More	Less	Less	More
Wood	625	70	147	VL	VL	L	VH	90	7000	L
Aluminium	2700	229	299	H	L	H	A	150	24000	VH
$CFRP_{EP}$	1400	440	286	EXH	EXH	EXL	EXL	160	3000	H
$GFRP_{EP}$	1700	190	252	EXH	H	VH	EXL	30	3000	H
$GFRP_{PP}$	1350	150	199	H	L	VH	EXL	26	3000	A
$CGFRP_{EP}$	1300	165	218	VH	H	EXH	H	22	3000	H
$CGFRP_{PP}$	1200	135	179	H	VL	EXH	H	20	3000	BA
$FGFRP_{EP}$	1320	88	122	A	VL	A	H	30	3000	L
$SGFRP_{EP}$	1340	80	113	A	VL	A	H	24	3000	L
Plastic	1250	40	75	VH	L	VH	EXL	10	18000	ECH

Table 2. Quantitative data for alternative materials and criteria for SWT Blade

Attributes Alternatives	Density (kg/m^3)	Tensile Strength (MPa)	Flexural strength (MPa)	Corrosion resistance	Durability	Availability	Environment Friendly	Blade Cost (USD)	Setup Cost (USD)	Production Rate
Desirable	Less	More	More	More	More	More	More	Less	Less	More
Wood	625	70	147	0.3	0.2	0.3	0.8	90	7000	0.3
Aluminium	2700	229	299	0.7	0.3	0.7	0.5	150	24000	0.8
$CFRP_{EP}$	1400	440	286	0.9	0.9	0.1	0.1	160	3000	0.7
$GFRP_{EP}$	1700	190	252	0.9	0.7	0.8	0.1	30	3000	0.7
$GFRP_{PP}$	1350	150	199	0.7	0.3	0.8	0.1	26	3000	0.5
$CGFRP_{EP}$	1300	165	218	0.8	0.7	0.9	0.7	22	3000	0.7
$CGFRP_{PP}$	1200	135	179	0.7	0.2	0.9	0.7	20	3000	0.4
$FGFRP_{EP}$	1320	88	122	0.5	0.2	0.5	0.7	30	3000	0.3
$SGFRP_{EP}$	1340	80	113	0.5	0.2	0.5	0.7	24	3000	0.3
Plastic	1250	40	75	0.8	0.3	0.8	0.1	10	18000	1.0

Step 1: Preparation of pairwise comparison matrix and relative criteria rating from the equal to extreme importance [33].

$$B_{M*M} = \begin{bmatrix} 1 & b_{12} & b_{13} & b_{14} & - & b_{13} \\ b_{21} & 1 & b_{23} & b_{24} & - & b_{2m} \\ b_{31} & b_{32} & 1 & b_{34} & - & b_{3m} \\ b_{41} & b_{42} & b_{43} & 1 & - & b_{4m} \\ - & - & - & - & - & - \\ b_{m1} & b_{m2} & b_{m3} & b_{m4} & - & 1 \end{bmatrix} \quad (1)$$

Step 2: To find the relative normalized weight (W_j) of each attribute (Table 3)

i) Calculate the geometric mean (*GM*) by Eq. (2) of i^th^ row.

$$GM_j = \left[\prod_{j=1}^{M} b_{ij} \right]^{\left(\frac{1}{M}\right)} \quad (2)$$

ii) The relative normalized weight (W_j) of all attributes Eq. (3)

$$W_j = \frac{GM_j}{\sum_{j=1}^{M} GM_j} \quad (3)$$

Step 3: To find the Matrix value and Eigenvalue (λ_{max}). A_2 as a weight (W_j) and Eigenvalue (λ_{max}) = Average of matrix A_4.

$$[A_3] = [A_1] \times [A_2] \text{ and } [A_4] = [A_3] \div [A_2] \quad (4)$$

Step 4: To determine the consistency (*CR*) of judgement and Consistency index (*CI*), where, M = Number of criteria. The random index (*RI*) is taken as 1.49 for 10 alternatives [37].

$$CI = (\lambda_{\max} - M)/(M-1) \quad (5)$$

$$CR = (CI)/(RI) \quad (6)$$

From Eq. 5, CI = 0.00778 and from Eq. 6, CR = 0.0052 < 0.1 and hence well acceptable, which shows that the developed pairwise comparison matrix is consistent for the all ten attributes. The pairwise comparison matrix, calculated values of *GM*, criteria weights and λ_{max} are shown in Table 3.

3.2. Weight Calculation by Entropy Method

Shannon and Weaver (1947), proposed this method to measure the disorder or randomness in the problem on the basis of probability theory. Also able to evaluate uncertain information which gives the reflection on weights of attributes. To establish the weights of attributes applied the following steps [38-39].

Step 1. Normalization of decision matrix by using Eq. (7)

$$r_{ij} = (x_{ij}) \Big/ \left(\sum_{i=1}^{n} x_{ij} \right) \text{ where, } j \in [1....m] \quad (7)$$

Step 2. Entropy measure (e_j), computes the available data in the normalized matrix and makes the sequence of each criteria / attributes by using Eq. (8).

$$e_j = -\frac{1}{\log n} \sum_{i=1}^{n} r_{ij} \log(r_{ij}) \quad \text{where, } i \in [1....n],\ j \in [1....m] \quad (8)$$

Step 3. Calculate the degree of diversion (*DJ*) by Eq. (9).

$$d_j = 1 - e_j,\ j \in [1....m] \quad (9)$$

Step 4. Calculate the criteria/ objective weight by using Eq. (10).

$$W_j = (d_j) \Big/ \left(\sum_{j=1}^{m} d_j \right) \text{ where, } j \in [1....m] \quad (10)$$

The normalized decision matrix and weightage obtained by Entropy Method are presented in Table 4 and Table 5 respectively.

The percentage weights calculated for different criteria using AHP and Entropy methods are shown in Fig. 4 and Fig. 5 respectively.

Table 3. Pairwise comparison matrix and Weight calculation for Criteria for the AHP

Matrix	**[A1]**											**[A2]**	**[A3]**	**[A4]**
Attributes	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**GM**	Weight		
A1	1	2	2	3	3	2	2	3	3	4	2.352	0.2086	2.117	10.150
A2	0.5	1	1	2	2	1	1	2	2	3	1.374	0.1219	1.222	10.026
A3	0.5	1	1	2	2	1	1	2	2	3	1.374	0.1219	1.222	10.026
A4	0.33	0.5	0.5	1	1	0.5	0.5	1	1	2	0.727	0.0645	0.646	10.019
A5	0.33	0.5	0.5	1	1	0.5	0.5	1	1	2	0.727	0.0645	0.646	10.019
A6	0.5	1	1	2	2	1	1	2	2	3	1.374	0.1219	1.222	10.026
A7	0.5	1	1	2	2	1	1	3	3	4	1.533	0.1360	1.382	10.164
A8	0.33	0.5	0.5	1	1	0.5	0.33	1	1	2	0.698	0.0620	0.624	10.067
A9	0.33	0.5	0.5	1	1	0.5	0.33	1	1	2	0.698	0.0620	0.624	10.067
A10	0.25	0.33	0.33	0.5	0.5	0.33	0.25	0.5	0.5	1	0.413	0.0366	0.371	10.131

Table 4. Normalized decision matrix for Entropy Method

Attributes / Alternatives	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Wood	0.0441	0.0441	0.0778	0.0441	0.0500	0.0476	0.1778	0.1601	0.1000	0.0526
Aluminium	0.1903	0.1443	0.1582	0.1029	0.0750	0.1111	0.1111	0.2669	0.3429	0.1404
$CFRP_{EP}$	0.0987	0.2773	0.1513	0.1324	0.2250	0.0159	0.0222	0.2847	0.0429	0.1228
$GFRP_{EP}$	0.1198	0.1197	0.1333	0.1324	0.1750	0.1270	0.0222	0.0534	0.0429	0.1228
$GFRP_{PP}$	0.0952	0.0945	0.1053	0.1029	0.0750	0.1270	0.0222	0.0463	0.0429	0.0877
$CGFRP_{EP}$	0.0916	0.1040	0.1153	0.1176	0.1750	0.1429	0.1556	0.0391	0.0429	0.1228
$CGFRP_{PP}$	0.0846	0.0851	0.0947	0.1029	0.0500	0.1429	0.1556	0.0356	0.0429	0.0702
$FGFRP_{EP}$	0.0931	0.0555	0.0646	0.0735	0.0500	0.0794	0.1556	0.0534	0.0429	0.0526
$SGFRP_{EP}$	0.0945	0.0504	0.0598	0.0735	0.0500	0.0794	0.1556	0.0427	0.0429	0.0526
Plastic	0.0881	0.0252	0.0397	0.1176	0.0750	0.1270	0.0222	0.0178	0.2571	0.1754

Table 5. Wight calculated by Entropy Method

Attributes / Alternatives	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Wood	-0.1376	-0.1377	-0.1986	-0.1377	-0.1498	-0.1450	-0.3071	-0.2933	-0.2303	-0.1550
Aluminium	-0.3158	-0.2793	-0.2917	-0.2340	-0.1943	-0.2441	-0.2441	-0.3525	-0.3670	-0.2756
$CFRP_{EP}$	-0.2286	-0.3557	-0.2857	-0.2677	-0.3356	-0.0658	-0.0846	-0.3577	-0.1350	-0.2575
$GFRP_{EP}$	-0.2543	-0.2541	-0.2687	-0.2677	-0.3050	-0.2621	-0.0846	-0.1564	-0.1350	-0.2575
$GFRP_{PP}$	-0.2238	-0.2230	-0.2370	-0.2340	-0.1943	-0.2621	-0.0846	-0.1422	-0.1350	-0.2135
$CGFRP_{EP}$	-0.2190	-0.2354	-0.2491	-0.2518	-0.3050	-0.2780	-0.2895	-0.1269	-0.1350	-0.2575
$CGFRP_{PP}$	-0.2089	-0.2096	-0.2232	-0.2340	-0.1498	-0.2780	-0.2895	-0.1187	-0.1350	-0.1864
$FGFRP_{EP}$	-0.2210	-0.1604	-0.1769	-0.1919	-0.1498	-0.2011	-0.2895	-0.1564	-0.1350	-0.1550
$SGFRP_{EP}$	-0.2229	-0.1506	-0.1684	-0.1919	-0.1498	-0.2011	-0.2895	-0.1347	-0.1350	-0.1550
Plastic	-0.2141	-0.0928	-0.1280	-0.2518	-0.1943	-0.2621	-0.0846	-0.0717	-0.3492	-0.3053
$\sum r_{ij} \times LN(r_{ij})$	-2.2459	-2.0985	-2.2275	-2.2625	-2.1276	-2.1992	-2.0474	-1.9105	-1.8915	-2.2184
e_j	0.9754	0.9114	0.9674	0.9826	0.9240	0.9551	0.8892	0.8297	0.8215	0.9634
$1-e_j$	0.0246	0.0886	0.0326	0.0174	0.0760	0.0449	0.1108	0.1703	0.1785	0.0366
Sum $(1-e_j)$	0.7804									
W_j	0.0316	0.1136	0.0418	0.0223	0.0974	0.0575	0.1420	0.2182	0.2288	0.0469

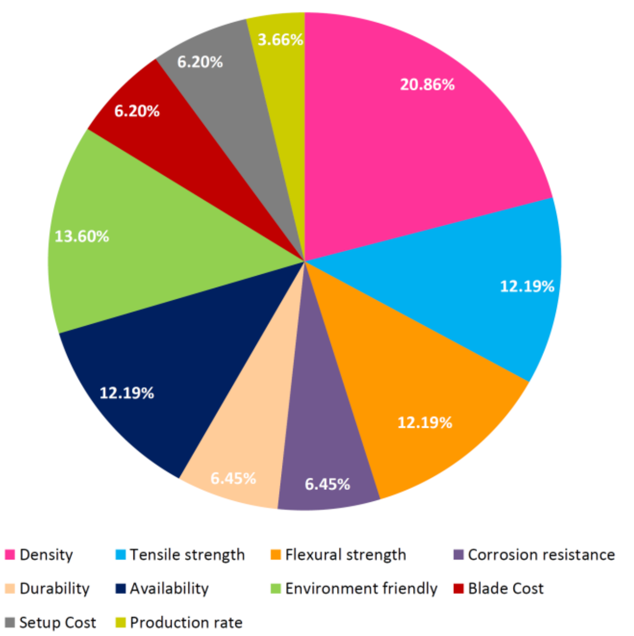

Fig. 4. Criteria weightage calculated using the AHP method.

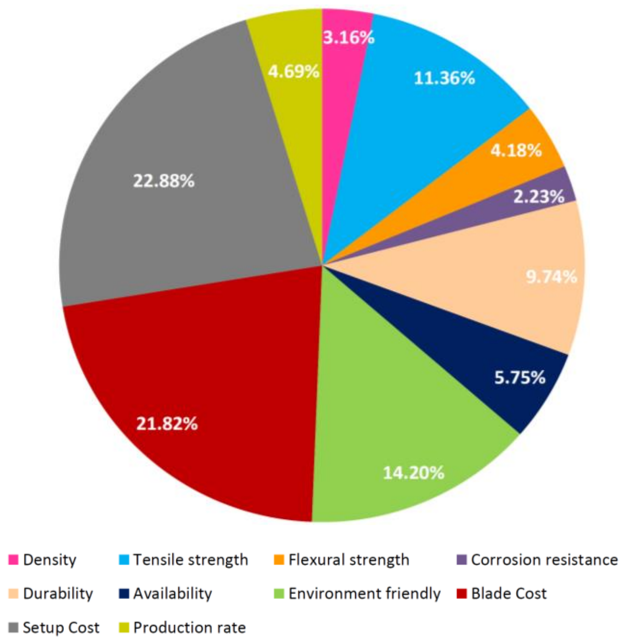

Fig. 5. Criteria weightage calculated using Entropy method

4. Determining the Materials Rankings by Different MCDM Techniques

This section presents the brief procedure of SAW, WPM, TOPSIS and R-Method and the ranking is calculated by these methods. The results presented in this section for the calculation of the ranking are based on the weight calculated by AHP method.

4.1. SAW (Simple Additive Weighting) Method

SAW is the simplest MCDM technique suggested by Fishburn 1967, in which each alternative is assessed with respect to every attribute and gives the result in a few simple steps as below.

Step 1. Comparison of the best maximum and best minimum value on the basis of beneficial and non-beneficial attributes by Eq. 11 and Eq. 12 respectively, for all alternatives to normalize the matrix [40].

$$m_{ij(Norm)} = m_{ij} \Big/ M_i^{+} \tag{11}$$

$$m_{ij(Norm)} = M_i^{-} \Big/ m_{ij} \tag{12}$$

Step 2. Calculation of Performance index (P_i) of the alternative (A_i) by multiplication of each normalized major value (m_{ij}) and weight matrix value (W_j) and its addition as per the Eq. (13).

$$P_i = \sum_{j=1}^{M} m_{ij(Norm)} \times W_{ij} \tag{13}$$

Step 3. In the descending order of arranged values, the highest value is considered as best solution.

The normalized weightage matrix with performance index and ranking using SAW method is shown in Table 6.

4.2. Weighted Product Method (WPM)

In the WPM method only the second step is different from SAW method. In step 2, the performance index is measured for each alternative as per the Eq. 14 and multiplied with subsequent attributes [37, 41].

$$P_i = \prod_{j=1}^{M} \left[\left(m_{ij} \right)_{Norm} \right]^{W_{ij}} \tag{14}$$

The performance index is arranged in descending order and the highest value is considered the best solution. The normalized weightage matrix with performance index and ranking using WPM method are shown in Table 7.

Table 6. Normalized weighted matrix with Performance Index and Ranking uses SAW method

Attributes / Alternative	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	P_i	Rank
Wood	1.00	0.16	0.49	0.33	0.22	0.33	1.00	0.11	0.43	0.30	0.54	5
Aluminium	0.23	0.52	1.00	0.78	0.33	0.78	0.63	0.07	0.13	0.80	0.53	6
$CFRP_{EP}$	0.45	1.00	0.96	1.00	1.00	0.11	0.13	0.06	1.00	0.70	0.58	3
$GFRP_{EP}$	0.37	0.43	0.84	1.00	0.78	0.89	0.13	0.33	1.00	0.70	0.58	4
$GFRP_{PP}$	0.46	0.34	0.67	0.78	0.33	0.89	0.13	0.38	1.00	0.50	0.52	7
$CGFRP_{EP}$	0.48	0.38	0.73	0.89	0.78	1.00	0.88	0.45	1.00	0.70	0.70	1
$CGFRP_{PP}$	0.52	0.31	0.60	0.78	0.22	1.00	0.88	0.50	1.00	0.40	0.63	2
$FGFRP_{EP}$	0.47	0.20	0.41	0.56	0.22	0.56	0.88	0.33	1.00	0.30	0.50	8
$SGFRP_{EP}$	0.47	0.18	0.38	0.56	0.22	0.56	0.88	0.42	1.00	0.30	0.50	9
Plastic	0.50	0.09	0.25	0.89	0.33	0.89	0.13	1.00	0.17	1.00	0.46	10
Weightage	0.21	0.12	0.12	0.06	0.06	0.12	0.14	0.06	0.06	0.04		

Table 7. Normalized weighted matrix with Performance Index and Ranking uses WPM method

Attributes / Alternative	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	*Pi*	Rank
Wood	1	0.16	0.49	0.33	0.22	0.33	1	0.11	0.43	0.3	0.43	7
Aluminium	0.23	0.52	1	0.78	0.33	0.78	0.63	0.07	0.13	0.8	0.42	8
$CFRP_{EP}$	0.45	1.00	0.96	1	1	0.11	0.13	0.06	1	0.7	0.40	9
$GFRP_{EP}$	0.37	0.43	0.84	1	0.78	0.89	0.13	0.33	1	0.7	0.48	3
$GFRP_{PP}$	0.46	0.34	0.67	0.78	0.33	0.89	0.13	0.38	1	0.5	0.44	6
$CGFRP_{EP}$	0.48	0.38	0.73	0.89	0.78	1	0.88	0.45	1	0.7	0.66	1
$CGFRP_{PP}$	0.52	0.31	0.60	0.78	0.22	1	0.88	0.50	1	0.4	0.58	2
$FGFRP_{EP}$	0.47	0.20	0.41	0.56	0.22	0.56	0.88	0.33	1	0.3	0.45	4
$SGFRP_{EP}$	0.47	0.18	0.38	0.56	0.22	0.56	0.88	0.42	1	0.3	0.45	5
Plastic	0.50	0.09	0.25	0.89	0.33	0.89	0.13	1	0.2	1.0	0.34	10
Weightage	0.21	0.12	0.12	0.06	0.06	0.12	0.14	0.06	0.06	0.04		

4.3. TOPSIS Method

This easy method with better stability was developed by Hwang and Yoon which is preferred by many researchers [37, 42]. This method aims to select the option which is nearest to the best possible option and farthest to worst possible option. This method works as below.

Step 1: Make the decision objective and select the evaluation attributes.

Step 2: Make the matrix with the available information like the first eleven decision columns shown in Table 8. The element m_{ij} indicates j^{th} value for attribute and i^{th} value for an alternative. Take an appropriate scale for subjective attribute values and assigned alternatives with normalized values of attributes.

Step 3: Solving the normalized decision matrix (R_{ij}) by using an Eq. (15)

$$R_{ij} = m_{ij} \Big/ \left[\sum_{j=1}^{M} m_{ij}^2 \right]^{1/2} \tag{15}$$

Step 4: Assigning the appropriate weightage to the attributes with respect to the objective. And the sum of all weights should be 1 ($\sum w_j = 1$).

Step 5: To find the weighted, normalized matrix V_{ij} used the Eq (16).

$$V_{ij} = W_i \times R_{ij} \tag{16}$$

Step 6: To find ideal best (positive) and ideal worst (negative) solutions using Eq. (17) to (20). In these equations i = 1, 2, 3... N, J = beneficial attributes and J^o = non-beneficial attributes. V_j^+ provides the best ideal value and V_j^- provides the worst ideal value after solving. [33].

$$V^+ = \left\{ \left(\frac{\sum_i^{\max} v_{ij}}{i} \in J \right), \left(\frac{\sum_i^{\min} v_{ij}}{i} \in J^o \right) \right\} \tag{17}$$

$$= \left\{ V_1^+, V_2^+, V_3^+ ......, V_m^+ \right\} \tag{18}$$

$$V^- = \left\{ \left(\frac{\sum_i^{\min} v_{ij}}{j} \in J \right), \left(\frac{\sum_i^{\max} v_{ij}}{j} \in J^o \right) \right\} \tag{19}$$

$$= \left\{ V_1^-, V_2^-, V_3^- ......, V_m^- \right\} \tag{20}$$

Step 7: To find best separation measure based on the Euclidean distance of each alternative used Eq (21) and (22).

$$S_i^+ = \left\{ \sum_{j=1}^{M} \left(V_{ij} - V_j^+ \right)^2 \right\}^{0.5} \tag{21}$$

$$S_i^- = \left\{ \sum_{j=1}^{M} \left(V_{ij} - V_j^- \right)^2 \right\}^{0.5} \tag{22}$$

Step 8: Find the relative closeness of the alternative to the ideal solution (P_i), used the Eq. (23)

$$P_i = S_i^- \Big/ \left(S_i^+ + S_i^- \right) \tag{23}$$

Step 9: Arranging the values of P_i in descending order and considering maximum value as the best solution as shown in Table 8.

4.4. R-Method

The R - method is used to rank Pareto-optimal solutions and chose the best one for MCDM problems. The method has the potential to solve any type of MCDM problem. This method is the solution to time-consuming method, qualitative data and partial data. There is a scope to give same rank by taking an average of common values [25].

Step 1: Developing a decision table (like Table 9. for the present study) with the performance data of the various possibilities that meet the objectives and assigning the weightage to each attribute as per the importance of property in actual application.

Step 2: Assigning the ranks to the alternatives as per beneficial or non-beneficial attributes in terms of 1, 2, 3...n. Then assigning the value to rank by using respective columns attributes prepared as per Eq. (24), where, W_j = weight of objective / alternative j, r_k= rank of objective / alternative k, n = number of objectives/alternatives, j = 1, 2, 3, …, n and k = 1, 2, 3, …, n.

Table 8. Normalized weighted matrix with Performance Index and Ranking uses WPM method

Attributes / Alternatives	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	***Pi***	**Rank**
Wood	1	0.16	0.49	0.33	0.22	0.33	1	0.11	0.43	0.3	0.43	7
Aluminium	0.23	0.52	1	0.78	0.33	0.78	0.63	0.07	0.13	0.8	0.42	8
$CFRP_{EP}$	0.45	1.00	0.96	1	1	0.11	0.13	0.06	1	0.7	0.40	9
$GFRP_{EP}$	0.37	0.43	0.84	1	0.78	0.89	0.13	0.33	1	0.7	0.48	3
$GFRP_{PP}$	0.46	0.34	0.67	0.78	0.33	0.89	0.13	0.38	1	0.5	0.44	6
$CGFRP_{EP}$	0.48	0.38	0.73	0.89	0.78	1	0.88	0.45	1	0.7	0.66	1
$CGFRP_{PP}$	0.52	0.31	0.60	0.78	0.22	1	0.88	0.50	1	0.4	0.58	2
$FGFRP_{EP}$	0.47	0.20	0.41	0.56	0.22	0.56	0.88	0.33	1	0.3	0.45	4
$SGFRP_{EP}$	0.47	0.18	0.38	0.56	0.22	0.56	0.88	0.42	1	0.3	0.45	5
Plastic	0.50	0.09	0.25	0.89	0.33	0.89	0.13	1	0.2	1.0	0.34	10
Weightage	0.21	0.12	0.12	0.06	0.06	0.12	0.14	0.06	0.06	0.04		

$$W_i = \frac{\left[1 \Big/ \sum_{k=1}^{j} \left(1/r_k \right) \right]}{\sum_{j=1}^{n} \left[1 \Big/ \sum_{k=1}^{j} \left(1/r_k \right) \right]} \tag{24}$$

Step 3: Calculating the Performance Index (P_i) of all the alternatives by the addition of the product of weight and major value (m_{ij}) as presented in Table 10 for the present study. This table also shows ranking obtained by R-method.

5. Discussion on Comparative Evaluation of MCDM Results

The materials ranking on the basis of AHP weightage are evaluated by SAW, WPM, TOPSIS and R-method are shown in Table 6, 7, 8 and 10 respectively. Additionally, the rankings of materials are also calculated using these four methods, on the basis of weights obtained through Entropy method and the average weight of AHP & Entropy method. All these ranking results for different weights are tabulated in Table 11 and also presented in Fig. 6. The average is calculated by considering all twelve ranks of the individual material. The graphs in Fig. 6 are plotted as per the ranking presented in Table 11. From the comparison of ranks obtained through different methods and weights, it is observed that $CGFRP_{EP}$ is an emerging best compromised option for SWT blades followed by $CGFRP_{PP}$ at second rank. $GFRP_{EP}$ and $CFRP_{EP}$ are in the third and fourth ranks respectively. In some previous research work either $GFRP_{EP}$ or $CFRP_{EP}$ was found as the best materials for SWT blades. However, $GFRP_{EP}$ is preferred because of its low cost. In this research work $CGFRP_{EP}$, $CGFRP_{PP}$, $SGFRP_{EP}$ and $FGFRP_{EP}$ are added in competition first time and $CGFRP_{EP}$ and $CGFRP_{PP}$ are found first two better materials.

From the comparison, it is seen that, $CGFRP_{EP}$ has first rank for all weights, when using SAW, WPM and TOPSIS methods. In the case of R-method, the ranks of $CGFRP_{EP}$ are observed as 3, 2 and 2 based on AHP, Entropy and average weights respectively. It is well accepted as $CGFRP_{EP}$ is in the first rank, in other methods. Hence, it is decided to accept $CGFRP_{EP}$ as a best compromised material for SWT blade. These results are comprehensive as they are based on most of the criteria to be considered along with two weight calculation methods and four ranking techniques. The values of the criteria like availability, blade cost and manufacturing setup cost are based on the Indian scenario and can be changed slightly as per geographical regions and the final results may change accordingly.

Table 9. Ranking for beneficial and non-beneficial attributes for R-method

Attributes / Alternatives	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Desirable	B	B	B	B	B	B	B	NB	NB	B
Wood	1	9	7	10	8.5	9	1	8	8	9
Aluminium	10	2	1	6	5	6	6	9	10	2
$CFRP_{EP}$	8	1	2	1.5	1	10	8.5	10	4	4
$GFRP_{EP}$	9	3	3	1.5	2.5	4	8.5	6.5	4	4
$GFRP_{PP}$	7	5	5	6	5	4	8.5	5	4	6
$CGFRP_{EP}$	4	4	4	3.5	2.5	1.5	3.5	3	4	4
$CGFRP_{PP}$	2	6	6	6	8.5	1.5	3.5	2	4	7
$FGFRP_{EP}$	5	7	8	8.5	8.5	7.5	3.5	6.5	4	9
$SGFRP_{EP}$	6	8	9	8.5	8.5	7.5	3.5	4	4	9
Plastic	3	10	10	3.5	5	4	8.5	1	9	1
Wt. Rank	1	4	4	6.5	6.5	4	2	8.5	8.5	10

Table 10. Weighted Normalized Matrix, Performance Index and Ranking uses R-method

Attributes / Alternative	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	C. Sco.	Rank
Wood	0.20	0.07	0.08	0.07	0.07	0.07	0.20	0.07	0.07	0.07	0.12	1
Aluminium	0.07	0.13	0.20	0.08	0.09	0.08	0.08	0.07	0.07	0.13	0.10	6
$CFRP_{EP}$	0.07	0.20	0.13	0.17	0.20	0.07	0.07	0.07	0.10	0.10	0.11	2
$GFRP_{EP}$	0.07	0.11	0.11	0.17	0.12	0.10	0.07	0.08	0.10	0.10	0.10	7
$GFRP_{PP}$	0.08	0.09	0.09	0.08	0.09	0.10	0.07	0.09	0.10	0.08	0.08	8
$CGFRP_{EP}$	0.10	0.10	0.10	0.10	0.12	0.17	0.10	0.11	0.10	0.10	0.11	3
$CGFRP_{PP}$	0.13	0.08	0.08	0.08	0.07	0.17	0.10	0.13	0.10	0.08	0.11	4
$FGFRP_{EP}$	0.09	0.08	0.07	0.07	0.07	0.08	0.10	0.08	0.10	0.07	0.08	9
$SGFRP_{EP}$	0.08	0.07	0.07	0.07	0.07	0.08	0.10	0.10	0.10	0.07	0.08	10
Plastic	0.11	0.07	0.07	0.10	0.09	0.10	0.07	0.20	0.07	0.20	0.10	5
Wt.	0.20	0.10	0.10	0.08	0.08	0.10	0.13	0.07	0.07	0.07		

Table 11. Materials Ranking of various methods using weights of AHP, Entropy and Average

	Weightage by AHP	Weightage by Entropy	Average (AHP & Entropy)		

Alternatives / Methods	SAW	WPM	TOPSIS	R-Method	SAW	WPM	TOPSIS	R-Method	SAW	WPM	TOPSIS	R-Method	Average	Rank
$CGFRP_{EP}$	1	1	1	3	1	1	1	2	1	1	1	2	1.3	1
$CGFRP_{PP}$	2	2	2	4	2	2	2	4	2	2	2	4	2.5	2
$GFRP_{EP}$	4	3	5	7	3	3	3	5	3	3	3	6	4.0	3
$CFRP_{EP}$	3	9	3	2	4	7	8	1	4	7	7	1	4.7	4
$GFRP_{PP}$	5	7	4	1	9	9	7	6	8	8	8	5	6.4	5
$SGFRP_{EP}$	9	5	8	10	5	4	4	9	5	4	5	9	6.4	6
$FGFRP_{EP}$	8	4	7	9	6	5	5	10	6	5	4	10	6.6	7
Wood	7	6	6	8	7	6	6	8	7	6	6	8	6.8	8
Plastic	10	10	9	5	8	8	9	3	9	10	9	3	7.8	9
Aluminium	6	8	10	6	10	10	10	7	10	9	10	7	8.6	10

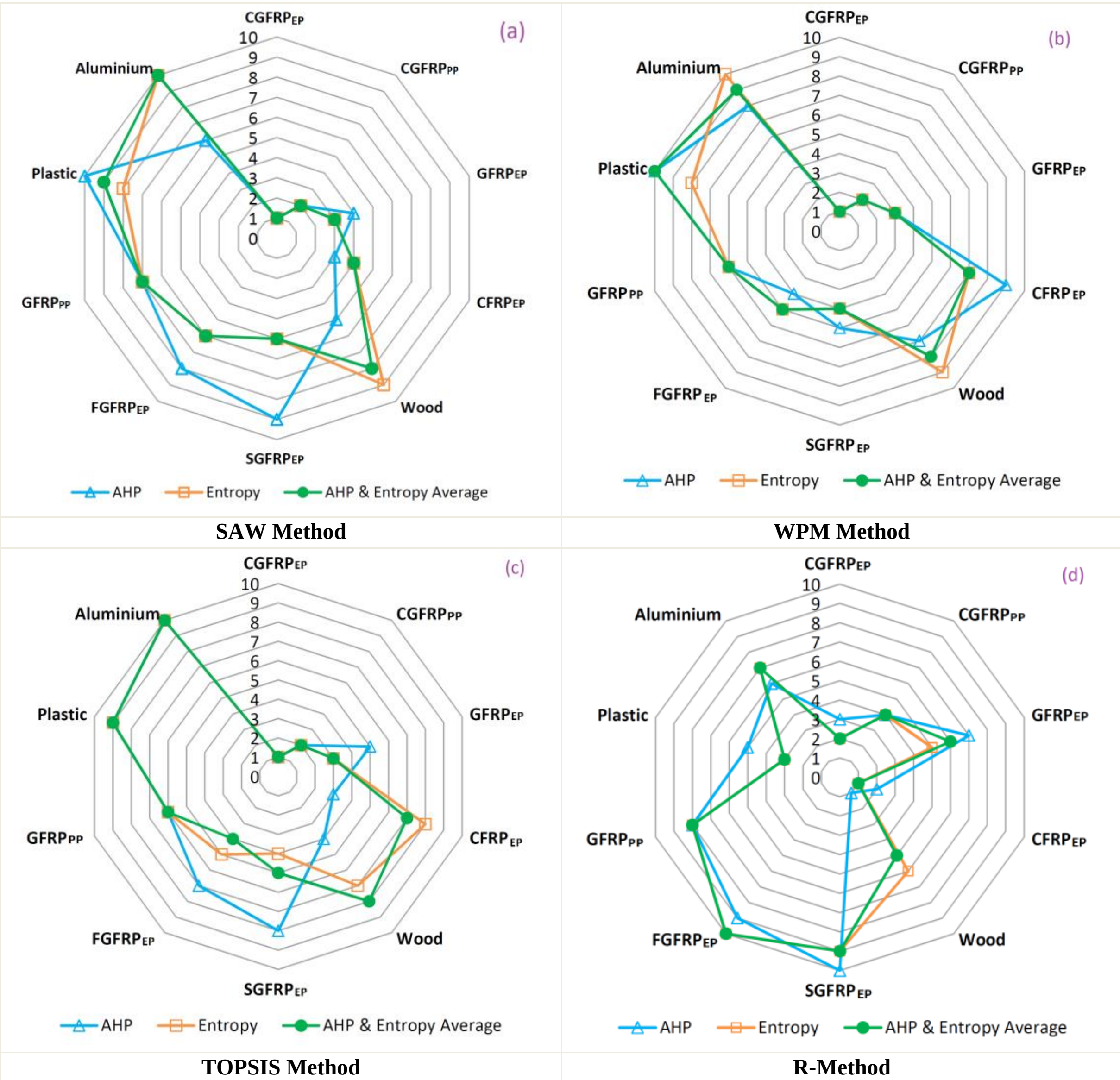

Fig. 6. Ranking Comparison of various methods using weights of AHP, Entropy and Average

6. Conclusion

This research has identified the need to replace part of the synthetic glass fiber with natural fibers like cotton, flax and sisal in the form of hybrid composites for SWT blades. These materials are compared with some existing materials to select the best material, through four MCDM techniques like SAW, WPM, TOPSIS and R-method in which the weights calculated by AHP and Entropy methods are used. The use of average weightage of AHP and Entropy method in this research paper is found as a suitable method and can be a better approach to solve other problems using MCDM.

SAW, WPM and TOPSIS methods show good agreement of ranking for the first three materials. The variation in the ranking is observed through R-method for cotton-glass FRP but is still acceptable as it is closed to and immediately following the first rank. The results obtained through this work imply to use of epoxy based cotton-glass FRP as a best compromised alternative for SWT blades. PP based cotton-glass FRP is shown as a second alternative. The combinations of flax-glass and sisal-glass are not observed as suitable for SWT blades.

Future research indicates to determine the appropriate percentage of natural cotton fiber and synthetic glass fiber to get optimum desired properties for SWT blades.

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