Performance Evaluation of Self-Healing Flame-Retardant Polymer Composites using TOPSIS Methodology for Next-Generation Applications

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Abstract: Self-healing flame-retardant polymer composites represent an innovative advancement in materials science, offering a unique blend of fire resistance and autonomous repair capabilities. These materials tackle critical issues of material degradation and fire safety across diverse industries by incorporating self-healing mechanisms alongside flame retardant properties. Techniques such as microcapsules, vascular networks, and dynamic covalent bonds enable autonomous healing of microscopic defects while preserving flame retardancy and extending service life. This study assesses the performance of four self-healing flame-retardant polymer composites using the TOPSIS methodology, considering criteria such as mechanical strength, flame retardancy, self-healing, residual strength, processing time, and cost. The Epoxy-Carbon Fiber and Epoxy-Kevlar Fiber Composites emerge as top performers, showing promise for applications requiring fire resistance and durability, like aerospace and automotive sectors. Addressing challenges such as scalable manufacturing, optimizing healing kinetics, and enhancing characterization techniques is essential to fully realize the potential of these materials for future applications, enhancing safety and sustainability across industries.

Keywords: *Self-Healing Polymers, Flame Retardant Composites, MCDM, Autonomous Repair, Fire Resistance, and Advanced Materials.*

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I. INTRODUCTION

The development of advanced materials with enhanced safety features and prolonged service life has become a paramount pursuit in various industries. One such innovative solution that has garnered significant attention is the integration of self-healing capabilities into flame-retardant polymer composites. These cutting-edge materials offer a unique combination of fire resistance and autonomous repair mechanisms, making them highly attractive for applications where both fire safety and durability are critical. By incorporating self-healing functionalities, these composites can autonomously heal microscopic defects and cracks, thereby extending their service life while maintaining their flame-retardant properties. This groundbreaking approach has the potential to revolutionize various sectors, including aerospace, automotive, construction, and electronics, where fire hazards and material degradation pose significant challenges [1, 2, 3]. Traditional flame-retardant materials often suffer from degradation and loss of effectiveness over time due to a multitude of factors, including environmental exposure, thermal cycling, and mechanical stresses. This degradation compromises not only the structural integrity of the material but also its fire resistance, potentially leading to catastrophic consequences. Self-healing flame-retardant polymer composites address this challenge by introducing dynamic covalent bonds or supramolecular interactions that endow the material with the ability to autonomously repair microscopic defects and cracks. This self-healing process not only extends the service life of the material but also maintains its flame-retardant properties, ensuring long-lasting fire protection and enhanced safety [4, 5]. Several innovative strategies have been explored to achieve self-healing functionality in flame-retardant polymer composites. One approach involves the incorporation of microcapsules or vascular networks containing healing agents, such as monomers or reactive components. When a crack or damage occurs within the composite matrix, these microcapsules rupture, releasing the healing agents, which then polymerize and seal the defect. Simultaneously, flame-retardant additives or inherently flame-resistant polymers are integrated into the composite matrix, imparting fire resistance. This synergistic combination of self-healing and flame retardancy offers a robust solution for applications where both properties are essential [6, 7, 8].

Another promising strategy utilizes reversible covalent bonds or dynamic non-covalent interactions, such as hydrogen bonding, ionic interactions, or metal-ligand coordination. These dynamic bonds possess the remarkable ability to dissociate and re-associate upon exposure to specific stimuli, such as heat or light, enabling the material to self-heal and recover its mechanical and flame-retardant properties. This approach often involves the incorporation of functional groups or molecular architectures that promote self-healing behavior while maintaining flame retardancy. By harnessing these dynamic interactions, researchers have developed self-healing flame-retardant polymer composites that can autonomously repair damage while maintaining their fire resistance, offering a promising solution for applications where both properties are crucial [9, 10, 11]. Self-healing flame-retardant polymer composites have demonstrated remarkable potential in various cutting-edge applications. For instance, in the aerospace industry, where fire safety and structural integrity are of paramount importance, these materials can be utilized in aircraft components, offering enhanced durability and fire resistance. Similarly, in the construction sector, these composites can be employed in building materials, providing improved fire safety and extended service life for structures. Additionally, these innovative materials have applications in the electronics industry, where self-healing capabilities can mitigate the risk of electrical failures and ensure the reliability of electronic devices, while also offering fire protection [12, 13, 14]. In the automotive sector, self-healing flame-retardant polymer composites can be utilized in various components, such as interior panels, structural elements, and electrical systems, providing both fire resistance and the ability to autonomously repair minor damages, thereby enhancing passenger safety and extending the lifespan of vehicles. Furthermore, these materials have potential applications in protective gear and firefighting equipment, where both self-healing and flame retardancy are crucial for ensuring the safety and durability of the equipment under extreme conditions [15, 16, 17].

Despite the significant progress in this field, several challenges remain to be addressed. One key challenge is the development of scalable and cost-effective manufacturing processes for self-healing flame-retardant polymer composites, ensuring their commercial viability and widespread adoption. Additionally, researchers are continuously exploring new self-healing mechanisms and flame-retardant strategies to further enhance the performance and versatility of these materials. Another area of focus is the optimization of self-healing kinetics and efficiency, ensuring rapid and reliable repair of damages under various environmental conditions [18, 19, 20]. Furthermore, the development of advanced characterization techniques and predictive modeling tools is crucial for understanding the complex interplay between self-healing mechanisms and flame-retardant properties, enabling the rational design of these materials. Interdisciplinary collaboration among material scientists, chemists, engineers, and computational experts is essential to address these challenges and unlock the full potential of self-healing flame-retardant polymer composites for next-generation applications [21, 22, 23].

II. METHODOLOGY

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a widely adopted multi-criteria decision-making (MCDM) method that has gained significant recognition and application across various domains. Developed by Hwang and Yoon in 1981, TOPSIS is based on the concept of selecting the alternative that is closest to the positive ideal solution and farthest from the negative ideal solution. This approach allows decision-makers to evaluate and rank a set of alternatives based on multiple conflicting criteria, making it a valuable tool for addressing complex decision-making problems [24]. The fundamental principle of TOPSIS revolves around the notion that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. The positive ideal solution is a hypothetical solution that maximizes the benefit criteria and minimizes the cost criteria, while the negative ideal solution is the opposite, minimizing the benefit criteria and maximizing the cost criteria. By calculating the distances from each alternative to these ideal solutions, TOPSIS provides a ranking based on relative closeness to the positive ideal solution [25]. The TOPSIS methodology consists of several steps, which are typically followed in a systematic manner. First, the decision matrix is constructed, representing the performance of each alternative against the defined criteria. This matrix is then normalized to eliminate the influence of different units or scales among the criteria. Next, the weighted normalized decision matrix is calculated by multiplying the normalized values by the corresponding criteria weights, reflecting the relative importance of each criterion [26].

Subsequently, the positive and negative ideal solutions are determined by identifying the maximum and minimum values, respectively, from the weighted normalized decision matrix. These ideal solutions serve as reference points for evaluating the alternatives. The distances of each alternative from the positive and negative ideal solutions are then calculated using appropriate distance measures, such as the Euclidean or Manhattan distance. Finally, the relative closeness of each alternative to the positive ideal solution is computed, and the alternatives are ranked based on these closeness values, with the highest value representing the most preferred alternative [27]. One of the key advantages of TOPSIS is its ability to handle both quantitative and qualitative criteria, making it applicable to a wide range of decision-making problems. Additionally, the method is relatively simple to implement and understand, making it accessible to decision-makers from various backgrounds. Furthermore, TOPSIS provides a clear ranking of alternatives, facilitating the decision-making process and enabling effective communication of the results [28]. TOPSIS has found numerous applications across various fields, including engineering, manufacturing, supply chain management, project selection, and resource allocation. In the manufacturing sector, TOPSIS has been utilized for selecting the most suitable manufacturing process, evaluating the performance of suppliers, and optimizing production plans. In supply chain management, it has been employed for supplier selection, logistics optimization, and risk

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assessment. Additionally, TOPSIS has been applied in project selection, where multiple criteria such as cost, duration, and risk need to be considered [29].

Despite its widespread adoption and advantages, TOPSIS is not without limitations. One of the main challenges is the determination of appropriate criteria weights, which can significantly influence the final ranking of alternatives. Various methods, such as the Analytic Hierarchy Process (AHP) or entropy-based approaches, have been employed to derive criteria weights, but subjectivity and inconsistencies may still arise. Additionally, TOPSIS assumes linear relationships among the criteria, which may not always be accurate in real-world scenarios [30]. To address these limitations and enhance the applicability of TOPSIS, researchers have proposed various extensions and modifications to the original method. These include approaches such as fuzzy TOPSIS, which incorporates fuzzy set theory to handle uncertainty and imprecision in decision-making, and interval TOPSIS, which accounts for interval data. Furthermore, integrating TOPSIS with other MCDM methods, such as AHP or DEMATEL (Decision Making Trial and Evaluation Laboratory), has been explored to improve the robustness and accuracy of the decision-making process [31]. As decision-making problems continue to increase in complexity, the need for effective MCDM methods like TOPSIS becomes increasingly vital. Ongoing research efforts are focused on further enhancing the methodology, incorporating advanced techniques from fields such as artificial intelligence and machine learning, and developing user-friendly software tools to facilitate the application of TOPSIS in various domains. Additionally, the integration of TOPSIS with other decision-making approaches and its application in emerging areas, such as sustainable development and risk management, presents exciting opportunities for future research [32].

This research evaluates the effectiveness of four polymer composites with self-healing properties and flame retardancy using the TOPSIS approach. It examines various factors including mechanical strength, flame resistance, ability to self-heal, residual strength after healing, processing duration, and material cost. Mechanical Strength (MPa): Elevated mechanical strength is often beneficial across various applications, signifying the material's capacity to endure applied forces without failure. This characteristic is typically viewed favorably due to its association with durability and overall performance. LOI (%): The Limiting Oxygen Index serves as an indicator of a material's resistance to combustion, with higher values indicating improved flame retardancy. A heightened LOI is generally desirable, reflecting enhanced fire safety attributes and making it a positive factor in material evaluation. Flame Rating: Flame rating assesses a material's ability to resist ignition and sustain combustion, with superior ratings indicating heightened flame resistance. Preferably, materials with higher flame ratings, such as V-0, are favored over those with lower ratings like HB, positioning it as a positive criterion for material assessment. Healing Cycles: While an increased number of healing cycles can be advantageous for self-repairing materials, it's essential to consider other performance metrics. In specific situations, materials with fewer healing cycles but superior performance in alternative areas may be preferred, justifying its inclusion in the evaluation criteria. Residual Strength (%): Residual strength gauges a material's ability to maintain mechanical strength post-healing procedures. A higher percentage denotes enhanced post-healing performance, typically considered advantageous and thus viewed positively. Healing Time (min): Reduced healing times are preferable as they indicate swift repair and recovery processes, particularly crucial in applications where prompt restoration of material integrity is paramount. Processing Time (h): Decreased processing times are advantageous as they result in expedited production and reduced manufacturing expenses. Therefore, the minimization of processing time is usually desirable, establishing it as a negative parameter in material selection. Cost ($/kg): Lower material costs are generally preferred for their contribution to cost-effectiveness and broader accessibility. Thus, the reduction of cost per kilogram is deemed advantageous in both material selection and production processes.

III. ANALYSIS AND DISCUSSION

Table 1 illustrates four distinct composite materials, each characterized by unique combinations of matrix polymers, reinforcement materials, self-healing additives, flame-retardant additives, processing techniques, and healing triggers. In SC-1, carbon fibers reinforce an epoxy matrix, which includes microcapsules of epoxy resin for self-repair and melamine polyphosphate for flame retardancy. Compression molding is the chosen processing method, with healing initiated by heat at 80°C. SC-2 utilizes glass fibers to reinforce a vinyl ester matrix. It incorporates a vascular network containing a healing agent and ammonium polyphosphate as a

flame-retardant additive. The processing technique is hand lay-up, with healing triggered by applying pressure at 10 MPa. SC-3 employs nanoclay reinforcement in a polyurethane matrix. Self-healing is facilitated by microcapsules containing a catalyst, while phosphorylated clay serves as a flame-retardantadditive. 3D printing (FDM) is the processing technique, with healing activated by exposure to UV light. In SC-4, Kevlar fibers reinforce an epoxy matrix. It incorporates hollow fibers with a healing agent and magnesium hydroxide for flame retardancy. Compression molding is employed for processing, with healing initiated by heat at 100°C.

Table 2 provides information regarding the mechanical properties, Limiting Oxygen Index (LOI), healing capabilities, residual strength, healing and processing times, and cost per kilogram for four distinct composite materials. For SC-1, the composite presents a mechanical strength of 75 MPa, an LOI of 28%, and the capacity for three healing cycles. Following healing, it maintains 90% of its original strength, with a healing duration of 5 minutes and a processing time of 2 hours. The cost per kilogram stands at $35. SC-2 showcases a mechanical strength of 50 MPa, an LOI of 25%, and the ability to undergo two healing cycles. Post-healing, it retains 80% of its initial strength, with a healing period of 10 minutes and a processing time of 1 hour. The cost per kilogram is $28.

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In SC-3, the composite displays a mechanical strength of 40 MPa, an LOI of 32%, and is limited to one healing cycle. It retains 75% of its strength post-healing, with a healing time of 3 minutes and a processing time of 4 hours. The cost per kilogram amounts to $42. Lastly, SC-4 features a mechanical strength of 80 MPa, an LOI of 29%, and the capability for four healing cycles. Following healing, it retains 95% of its original strength, with a healing duration of 7 minutes and a processing time of 2.5 hours. The cost per kilogram is $40.

Table 3 presents normalized data using the TOPSIS method for four composite materials across various parameters. SC-1 scores highest in mechanical strength (0.5906), while SC-4 leads in healing cycles (0.7303) and residual strength (0.5564). SC-3 demonstrates the highest LOI (0.5593). SC-2 has the lowest scores overall, particularly in mechanical strength (0.3937) and healing time (0.1916). Normalization allows for comparison across diverse metrics, aiding in the assessment of composite performance.

Table 4 presents normalized data for four composite materials using identical values across all parameters. Each composite, represented by SC-1, SC-2, SC-3, and SC-4, receives equal scores of 0.1429 for mechanical strength, LOI, healing cycles, residual strength, healing time, processing time, and cost per kilogram. This uniformity suggests a lack of variability or distinction among the composites in terms of their performance across the specified metrics. Further analysis or contextual information would be necessary to differentiate the materials based on other criteria or real-world applications.

Table 5 provides weighted normalized data for four composite materials across various parameters. SC-1 scores lowest in mechanical strength (0.0844) and LOI (0.0699), while SC-4 achieves the highest score in healing cycles (0.1043). SC-3 leads in LOI (0.0799). SC-2 has the lowest scores overall, particularly in mechanical strength (0.0562) and processing time (0.0274). Weighted normalization allows for prioritization of parameters based on their relative importance, providing a more nuanced evaluation of composite performance tailored to specific criteria or objectives.

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Table 6 illustrates the optimal (A+) and suboptimal (A-) values obtained through the TOPSIS method across seven criteria for four composite materials. The A+ values denote the most desirable performance level for each criterion, while the A- values indicate the least desirable performance. For example, A+ values range from 0.0317 to 0.1056, reflecting superior performance in parameters like healing time and LOI. Conversely, A- values range from 0.0261 to 0.1095, representing inferior performance across these criteria. These benchmarks enable a comparative assessment of the composites' relative performance.

Table 1. Different Polymer Composites Materials

Sample ID	Matrix Polymer	Reinforcement	Self-Healing Additive	Flame-retardant Additive	Processing Technique	Healing Trigger
SC-1	Epoxy	Carbon Fiber	Microcapsules with epoxy resin	Melamine polyphosphate	Compression Molding	Heat (80°C)
SC-2	Vinyl Ester	Glass Fiber	Vascular network with healing agent	Ammonium polyphosphate	Hand Lay-up	Pressure (10 MPa)
SC-3	Polyurethane	Nanoclay	Microcapsules with catalyst	Phosphorylated clay	3D Printing (FDM)	Light (UV)
SC-4	Epoxy	Kevlar fibers	Hollow fibers with healing agent	Magnesium hydroxide	Compression Molding	Heat (100°C)

Here, SC-1 - Epoxy-Carbon Fiber Composite with Self-Healing Epoxy Resin, SC-2 - Vinyl Ester-Glass Fiber Composite with Vascular Network Healing, SC-3 - Polyurethane-Nanoclay Composite with UV Light Triggered Healing, SC4- - Epoxy-Kevlar Fiber Composite with Hollow Fiber Healing

Table 2. Mechanical Properties of Composite materials

Composites	Mechanical Strength (MPa)	LOI (%)	Healing Cycles	Residual Strength (%)	Healing Time (min)	Processing Time (h)	Cost ($/kg)
SC-1	75	28	3	90	5	2	35
SC-2	50	25	2	80	10	1	28
SC-3	40	32	1	75	3	4	42
SC-4	80	29	4	95	7	2.5	40

Table 3. Normalized Data

0.5906244	0.489349	0.5477226	0.5271367	0.3696106	0.3831305	0.4774849
0.3937496	0.4369187	0.3651484	0.4685659	0.7392213	0.1915653	0.3819879
0.3149997	0.559256	0.1825742	0.4392806	0.2217664	0.766261	0.5729819
0.6299994	0.5068257	0.7302967	0.556422	0.5174549	0.4789131	0.545697

Table 4. Weight

0.1428571	0.1428571	0.1428571	0.1428571	0.1428571	0.1428571	0.1428571
0.1428571	0.1428571	0.1428571	0.1428571	0.1428571	0.1428571	0.1428571
0.1428571	0.1428571	0.1428571	0.1428571	0.1428571	0.1428571	0.1428571
0.1428571	0.1428571	0.1428571	0.1428571	0.1428571	0.1428571	0.1428571

Table 5. Weighted Normalized Data

0.0844	0.0699	0.0782	0.0753	0.0528	0.0547	0.0682
0.0562	0.0624	0.0522	0.0669	0.1056	0.0274	0.0546
0.0450	0.0799	0.0261	0.0628	0.0317	0.1095	0.0819
0.0900	0.0724	0.1043	0.0795	0.0739	0.0684	0.0780

Table 6. The Ideal Best (A+) and Ideal Worst Values (A-)

A+	0.0899999	0.0798937	0.1043281	0.0794889	0.0316809	0.0273665	0.0545697
A-	0.045	0.062417	0.026082	0.0627544	0.105603	0.1094659	0.0818546

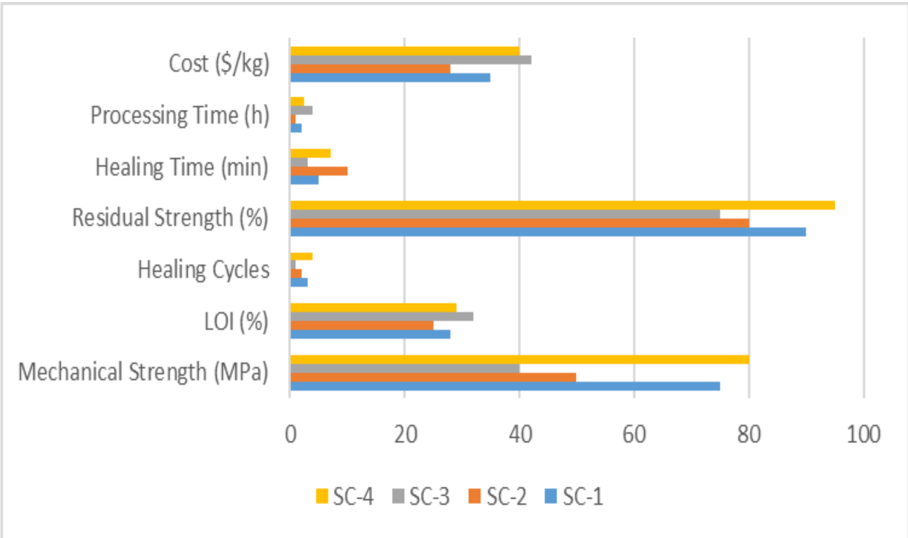

Fig 1. Mechanical Characteristics

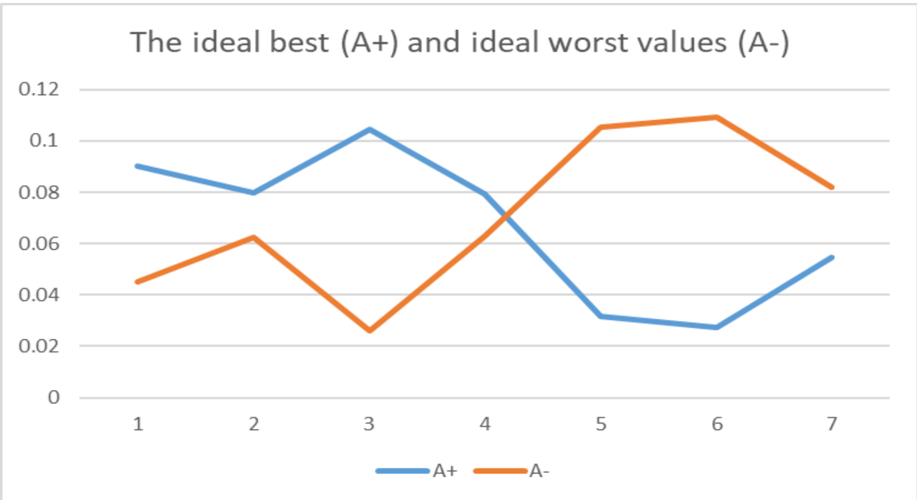

Fig 2. The Ideal Best A+ and Ideal Worst Vales A-

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Fig 3. Comparison between Composite Materials Positive Ideal and Negative-Ideal Solutions

Figure 1 outlines data on the Mechanical characteristics, Limiting Oxygen Index (LOI), self-healing capabilities, residual strength, healing and processing durations, and cost per kilogram for four distinct composite materials. In the case of SC-1, the composite demonstrates a mechanical strength of 75 MPa, an LOI of 28%, and the ability to undergo three healing cycles. After the healing process, it retains 90% of its initial strength, with a healing duration of 5 minutes and a processing time of 2 hours. The cost per kilogram is $35. SC-2 exhibits a mechanical strength of 50 MPa, an LOI of 25%, and the capacity for two healing cycles. Post-healing, it preserves 80% of its original strength, with a healing period lasting 10 minutes and a processing time of 1 hour. The cost per kilogram is $28. In the instance of SC-3, the composite shows a mechanical strength of 40 MPa, an LOI of 32%, and is limited to one healing cycle. It retains 75% of its strength following healing, with a healing duration of 3 minutes and a processing time of 4 hours. The cost per kilogram is $42. Lastly, SC-4 features a mechanical strength of 80 MPa, an LOI of 29%, and the capability for four healing cycles. After healing, it maintains 95% of its initial strength, with a healing duration of 7 minutes and a processing time of 2.5 hours. The cost per kilogram is $40.

Figure 2 depicts the optimal (A+) and suboptimal (A-) values derived using the TOPSIS method for seven criteria applied to four composite materials. A+ values signify the most desirable performance for each criterion, while A- values indicate the least desirable. For instance, A+ values span from 0.0317 to 0.1056, showcasing superior performance in factors such as healing time and LOI. Conversely, A- values range from 0.0261 to 0.1095, indicating poorer performance across these metrics. These benchmarks facilitate a comparative evaluation of the composites' relative performance.

Figure 3 illustrates the difference between each composite material and the Positive ideal and negative-ideal solutions, as determined by the TOPSIS method. SC-1 exhibits a Si+ value of 0.0470, indicating its proximity to the ideal solution, and a Si- value of 0.1022, suggesting its distance from the negative-ideal solution. SC-2 possesses a Si+ value of 0.0989 and a Si- value of 0.0912, implying a slightly greater separation from the ideal solution compared to SC-1. SC-3 shows a higher Si+ value of 0.1261 and a lower Si- value of 0.0760, indicating a larger deviation from both the ideal and negative-ideal solutions, respectively. SC-4 demonstrates a Si+ value of 0.0638 and a Si- value of 0.1060, positioning it closer to the ideal solution but farther from the negative-ideal solution than SC-1.

Table 8. Cci and Rank

Composites	Cci	Rank
SC-1	0.6850286	1
SC-2	0.4795411	3
SC-3	0.3758464	4
SC-4	0.6241555	2

Table 8 displays the Closeness Coefficient values and respective rankings of composite materials as determined by the TOPSIS method. The Epoxy-Carbon Fiber Composite containing Self-Healing Epoxy Resin achieves the highest Cci value of 0.685, securing the top position. Following closely is the Epoxy-Kevlar Fiber Composite with Hollow Fiber Healing, obtaining a Cci value of 0.624 and ranking second. The Vinyl Ester-Glass Fiber Composite featuring Vascular Network Healing ranks third, with a Cci value of 0.480, while the Polyurethane-Nanoclay Composite with UV Light Triggered Healing comes fourth, registering a Cci value of 0.376. These rankings offer insights into the comparative performance of the composites, with the Epoxy-Carbon Fiber Composite leading followed closely by the Epoxy-Kevlar Fiber Composite, whereas the remaining two composites trail behind in terms of assessed effectiveness using the TOPSIS method.

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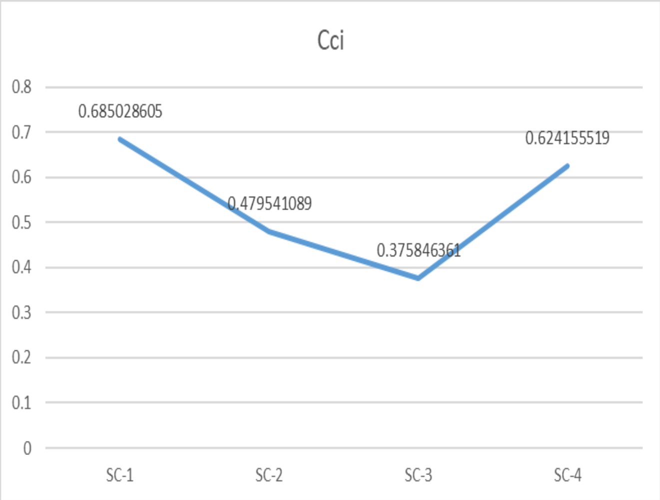

Fig 4. Closeness Coefficient Values

Figure 4 displays the Closeness Coefficient values acquired through the TOPSIS method for four composite materials. SC-1 showcases a Cci value of 0.6850, indicating a relatively higher level of proximity to the ideal solution compared to the other composites. SC-4 closely follows with a Cci value of 0.6242, suggesting significant closeness to the ideal solution. Conversely, SC-3 presents the lowest Cci value of 0.3758, indicating a greater deviation from the ideal solution. SC-2 falls in between, with a Cci value of 0.4795, representing a moderate degree of closeness to the ideal solution among the examined composites.

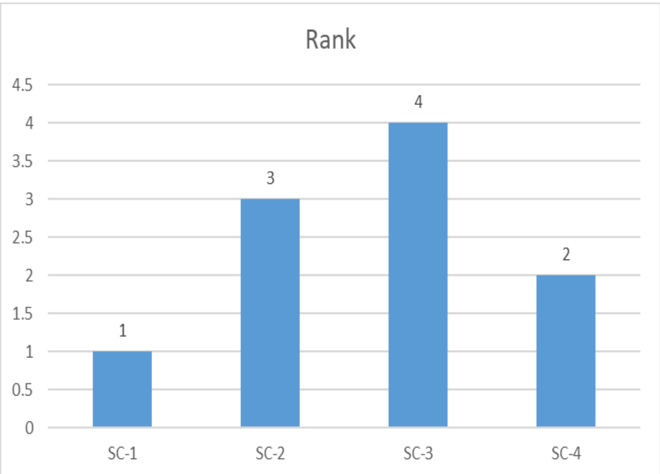

Fig 5. Ranking of Composite Materials

Figure 5 illustrates the ranking of composite materials utilizing the TOPSIS method. SC-1 claims the top spot, denoting its superior overall performance relative to the other composites. SC-4 secures the second position, indicating its relatively strong performance, trailed by SC-2 in third place and SC-3 in fourth. This ranking establishes a distinct hierarchy among the composites, with SC-1 emerging as the highest performer, closely pursued by SC-4, while SC-2 and SC-3 hold lower positions based on their evaluated performance employing the TOPSIS method.

IV. CONCLUSION

The development of self-healing flame-retardant polymer composites represents a significant advancement in the field of advanced materials. By integrating self-healing capabilities with flame retardancy, these composites offer a unique combination of properties that address the critical challenges of material degradation and fire safety. Through the incorporation of innovative strategies such as microcapsules, vascular networks, and dynamic covalent bonds, these materials can autonomously repair microscopic defects and cracks while maintaining their flame-retardant properties, extending their service life and enhancing overall safety. The TOPSIS methodology employed in this study provides a systematic approach to evaluate and rank the performance of different composite materials based on multiple criteria. By considering factors such as mechanical strength, flame retardancy, self-healing capabilities, residual strength, processing time, and cost, the analysis offers insights into the relative strengths and weaknesses of each composite. The Epoxy-Carbon Fiber Composite and the Epoxy-Kevlar Fiber Composite emerged as the top performers, demonstrating their potential for applications where both fire resistance and durability are critical, such as aerospace, automotive, and construction. While the present study highlights the promising prospects of self-healing flame-retardant polymer composites, ongoing research efforts are crucial to address remaining challenges. These include developing scalable and cost-effective manufacturing processes, optimizing self-healing kinetics and efficiency, and advancing characterization techniques and predictive modeling tools. Interdisciplinary collaboration among various experts will be instrumental in unlocking the full potential of these innovative materials for next-generation applications, further contributing to enhanced safety and sustainability across various industries.

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