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Enhancing Mechanical Properties of High-Performance Fibre-Reinforced Composites Through Strategic Hybridization and COPRAS-based Optimization

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ABSTRACT

Advanced Fibre-reinforced composites, renowned for their remarkable mechanical properties including high strength, stiffness, and fatigue resistance, have garnered considerable attention. To elevate these materials' performance and meet the escalating demands of modern applications, researchers have delved into hybridization strategies. Hybridization entails amalgamating diverse Fibres, encompassing carbon, glass, aramid, and natural Fibres, within a single composite matrix to engender synergistic effects and attain superior mechanical performance. This study employs the COPRAS (Complex Proportional Assessment) multi-criteria decision-making method to comprehensively assess the mechanical properties and manufacturing intricacies of various carbon Fibre hybrid composites. Parameters such as tensile strength, flexural strength, impact strength, compressive strength, density, cost, and manufacturing complexity are meticulously scrutinized. Findings reveal that integrating alternative Fibres, particularly natural variants like kenaf and bamboo, markedly enhances the mechanical attributes of carbon Fibre-based composites. Nonetheless, this enhancement is accompanied by escalated manufacturing intricacies and costs. The COPRAS method furnishes a systematic framework for prioritizing hybrid composites based on their significance, utility, and the delicate balance between benefits and costs. Insights gleaned from this study can aid decision-makers in aligning material selection with specific application requisites and financial constraints, ultimately fostering the development of advanced, cost-effective, and sustainable composite solutions. Integrating the COPRAS approach with emerging technologies such as artificial intelligence and automated manufacturing holds promise for further augmenting the optimization and adoption of high-performance Fibre-reinforced composites.

1. INTRODUCTION

Advanced Fibre-reinforced composites, known for their remarkable mechanical attributes like strength, stiffness, and endurance, have attracted significant interest across various industries such as aerospace, automotive, marine, and sports equipment production. Despite their already impressive capabilities, researchers are actively seeking ways to elevate their performance even further to keep up with the escalating demands of modern applications. One promising avenue gaining momentum is hybridization, where different Fibre types are integrated within a single composite matrix to synergistically enhance mechanical properties. Hybrid composites present a promising solution to overcome the limitations of single-Fibre-reinforced materials by harnessing the unique qualities of diverse Fibres. Through meticulous selection and blending of Fibres like carbon, glass, aramid, and natural Fibres, researchers can customize composite properties to meet

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specific application needs. This hybrid approach facilitates the fine-tuning of critical performance parameters such as tensile strength, elasticity modulus, impact resistance, and fatigue durability, thus broadening the scope of applications for Fibre-reinforced composites. Hybridization in composites involves merging different Fibre types to leverage their complementary attributes, thereby enhancing mechanical performance synergistically. For instance, carbon Fibres boast high tensile strength and stiffness but may suffer from brittleness and limited impact resistance, whereas glass Fibres excel in impact resistance but lag behind in tensile strength compared to carbon Fibres. Through hybridization, a composite material can harness the strength of carbon Fibres while bolstering impact resistance with glass Fibres [1]. Moreover, hybridization enables optimizing cost-performance balances in composite materials. Despite their superior mechanical properties, carbon Fibres often come with higher production costs compared to glass or natural Fibres. By integrating less costly Fibres into the composite matrix and strategically placing high-performance Fibres in crucial load-bearing areas, researchers can achieve a cost-efficient solution without compromising mechanical performance [2]. This approach proves particularly advantageous in applications where cost considerations significantly influence decision-making, such as automotive components and consumer goods. Several research studies have showcased the effectiveness of hybridization in bolstering the mechanical attributes of Fibre-reinforced composites. In their extensive analysis, Liu and Zhang (2018) delved into the synergistic effects observed in hybrid composites, underscoring the pivotal role of factors like Fibre selection, orientation, and volume fraction in optimizing mechanical performance [3]. Similarly, Gupta et al. (2019) shed light on the mechanical characteristics and fracture patterns of hybrid Fibre-reinforced composites, stressing the significance of interfacial bonding and interactions between Fibres and the matrix in dictating composite behavior [4]. Beyond conventional synthetic Fibres, scholars have delved into incorporating natural Fibres, such as jute, hemp, and flax, into hybrid composite frameworks. Ferreira and Rezende (2020) scrutinized the progression of hybrid composites employing natural Fibres, showcasing their potential for sustainable applications across construction, packaging, and automotive sectors [5]. Hybrid natural Fibre-reinforced composites offer benefits such as diminished environmental impact, heightened energy absorption, and improved damping qualities compared to their synthetic counterparts. Moreover, advancements in manufacturing methods and processing technologies have facilitated the creation of intricate hybrid composite structures with tailored characteristics. For instance, additive manufacturing allows for the precise positioning of various Fibre types within the composite matrix, enabling the creation of customized designs optimized for specific loading conditions [6]. Additionally, the introduction of automated Fibre placement (AFP) and automated tape laying (ATL) technologies has simplified the production process of hybrid composites, reduced production times and enhancing manufacturing efficiency [7]. High-performance Fibre-reinforced composites have attracted considerable attention owing to their exceptional mechanical properties, including elevated strength, stiffness, and fatigue resistance. These materials are extensively utilized across industries such as aerospace, automotive, marine, and sports equipment manufacturing [8]. However, to continually push the boundaries of performance and meet the escalating demands of advanced applications, researchers have been exploring innovative strategies to enhance the mechanical attributes of these composites. One promising avenue that has gained significant traction is hybridization, which entails blending different Fibre types within a single composite matrix to generate synergistic effects and attain superior mechanical performance [9]. Hybrid composites present an enticing solution to overcome the constraints of single-Fibre-reinforced materials by harnessing the distinct attributes of various Fibres. Through meticulous selection and blending of different Fibre types like carbon, glass, aramid, and natural Fibres, researchers can customize composite properties to fulfill specific application needs [10]. This hybridization strategy facilitates the optimization of crucial performance parameters such as tensile strength, elasticity modulus, impact resistance, and fatigue life, thereby broadening the potential applications of Fibre-reinforced composites [11]. The essence of hybridization in composites lies in amalgamating the complementary traits of diverse Fibre types to achieve a synergistic improvement in mechanical performance [12]. For instance, while carbon Fibres boast high tensile strength and stiffness, they may demonstrate brittle characteristics and limited impact resistance. Conversely, glass Fibres exhibit excellent impact resistance but comparatively lower tensile strength than carbon Fibres. Through the fusion of carbon and glass Fibres, it becomes feasible to fabricate a composite material that leverages the superior strength of carbon Fibres while enhancing impact resistance via the inclusion of glass Fibres [13]. Moreover, hybridization enables the fine-tuning of cost-performance balances in composite materials [14]. Despite their superior mechanical attributes, carbon Fibres frequently entail higher production expenses in contrast to glass or natural Fibres. Through the integration of more economical Fibres into the composite matrix and judiciously situating high-performance Fibres in vital load-bearing areas, researchers can attain a cost-efficient solution devoid of sacrificing mechanical prowess [15]. This methodology holds particular relevance for applications where cost considerations wield substantial influence, such as automotive components and consumer goods.

2. METHODOLOGY

The COPRAS method is rooted in the principles of Multi-Criteria Decision Making (MCDM), aimed at aiding decision-makers in selecting the optimal choice from a pool of options based on multiple conflicting criteria. Essentially, COPRAS employs a systematic process to rank alternatives by evaluating their performance across a predefined set of criteria. This method utilizes a matrix-based structure to organize the decision problem, where rows represent alternatives and columns depict evaluation criteria [16]. COPRAS finds widespread application across diverse domains such as engineering, management, finance, and environmental sciences. In engineering, for instance, it facilitates tasks like project selection, supplier assessment, and product design by incorporating factors such as cost, quality, and reliability to systematically evaluate competing alternatives. Similarly, in financial management, COPRAS assists in portfolio selection, investment prioritization, and risk analysis, aiding stakeholders in optimizing resource allocation and managing financial uncertainties [17]. A significant advantage of the COPRAS method lies in its capability to tackle intricate decision problems involving numerous criteria and alternatives. Unlike simplistic scoring approaches, COPRAS considers the relative significance of criteria and their interrelations, providing a more nuanced assessment of alternatives. Moreover, COPRAS offers flexibility in integrating qualitative criteria and expert opinions, enabling decision-makers to incorporate subjective preferences and uncertainties into the decision-making process [18]. Additionally, COPRAS boasts computational efficiency and ease of implementation, making it accessible to decision-makers with diverse levels of expertise. It does not necessitate sophisticated mathematical algorithms or extensive computational resources, rendering it suitable for real-world decision-making scenarios characterized by constraints on time and resources. Moreover, COPRAS yields transparent outcomes that are easily interpretable and communicable to stakeholders, facilitating consensus-building and enhancing decision transparency [19]. However, despite its merits, the COPRAS method encounters certain limitations. One of the primary challenges lies in determining criteria weights, often relying on subjective judgments or expert opinions. The absence of standardized procedures for weight elicitation can introduce bias and uncertainty into the decision-making process, potentially undermining the credibility of results. Furthermore, COPRAS assumes linear relationships between criteria and alternatives, overlooking nonlinearities and synergistic effects that may exist in complex decision contexts [20]. Moreover, COPRAS may encounter difficulties in handling uncertainties and imprecise information inherent in real-world decision problems. The method does not explicitly address uncertainty in criteria values or preferences, potentially leading to suboptimal decision outcomes. Additionally, COPRAS may exhibit sensitivity to changes in criteria weights or ranking methods, raising concerns about the robustness and reliability of outcomes [21]. Despite its limitations, the COPRAS method is undergoing continuous refinement and evolution propelled by advancements in decision science and computational techniques. Researchers are actively exploring extensions and enhancements of COPRAS to overcome its inherent weaknesses and broaden its applicability across various domains. Future research endeavors aim to develop robust methodologies for criteria weighting, integrate uncertainty analysis techniques, and employ advanced mathematical models to capture nonlinear relationships and intricate decision dynamics [22]. In recent years, there has been a growing trend of applying the COPRAS method in the realm of sustainable development and environmental management. With increasing recognition of environmental challenges and the imperative for sustainable practices, decision-makers are confronted with intricate trade-offs among economic, social, and environmental objectives. COPRAS offers a structured framework for incorporating sustainability criteria into decision-making processes, enabling stakeholders to assess the environmental repercussions of alternative courses of action [23]. Furthermore, the COPRAS method serves as a valuable tool for addressing social and ethical considerations in decision-making. Across sectors such as healthcare, public policy, and social services, decision-makers encounter the challenge of balancing the needs and preferences of diverse stakeholders, including patients, citizens, and policymakers. COPRAS facilitates the explicit incorporation of social criteria such as equity, accessibility, and cultural sensitivity, ensuring that decisions align with societal values and norms [24]. Moreover, the COPRAS method can serve as a catalyst for stakeholder engagement and participatory decision-making processes.

Involving relevant stakeholders in defining criteria, weighting factors, and evaluating alternatives fosters transparency, accountability, and consensus-building. This engagement not only bolsters the legitimacy and acceptability of decision outcomes but also instills a sense of ownership and empowerment among stakeholders, leading to more sustainable and equitable solutions [25]. Looking ahead, the continued evolution of the COPRAS method hinges on interdisciplinary collaboration and integration with other decision support tools and techniques. Researchers are exploring synergies between COPRAS and other Multi-Criteria Decision Making (MCDM) methods like Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and ELECTRE. This collaborative approach aims to address the limitations of individual methods while leveraging their respective strengths [26]. Furthermore, the fusion of COPRAS with artificial intelligence (AI) and machine learning (ML) algorithms holds promise for augmenting decision-making capabilities and automating decision processes. AI-driven COPRAS models can analyze vast datasets, discern patterns and trends, and provide insights to inform more data-driven decisions. By harnessing AI, COPRAS can surmount computational challenges and navigate the complexities inherent in real-world decision problems [27]. The COPRAS method presents a systematic and adaptable approach to multi-criteria decision-making, with applications spanning various domains such as engineering, finance, environmental management, and healthcare. Its capacity to integrate quantitative and qualitative criteria, tackle intricate decision challenges, and promote stakeholder engagement renders it invaluable for decision-makers confronting uncertain and dynamic environments. While COPRAS has its limitations, ongoing research and innovation hold the potential to further enhance its efficacy and relevance in addressing real-world issues and advancing sustainable development. Hybrid composites, especially those combining carbon Fibre with various other Fibres, have garnered significant attention in the pursuit of high-performance materials with enhanced mechanical properties. Among these hybrids, the combinations of carbon Fibre with glass Fibre and aramid Fibre have been extensively studied and utilized in various industries due to their favorable balance of strength, stiffness, and cost-effectiveness. However, recent research has delved deeper into exploring alternative Fibre combinations to further enhance the mechanical properties of composites while addressing specific application requirements and sustainability concerns. In the realm of composite materials, the mechanical properties play a pivotal role in determining their applicability across various industries. Tensile strength, flexural strength, impact strength, compressive strength, density, cost, and manufacturing complexity are critical parameters influencing material selection and performance evaluation. Tensile strength refers to the maximum stress a material can withstand before undergoing permanent deformation or failure when subjected to tensile loading. Flexural strength measures a material's ability to resist deformation under bending forces, often crucial in structural applications. Impact strength represents a material's ability to absorb energy during sudden loading, indicating its toughness and resistance to fracture. Compressive strength, on the other hand, assesses a material's ability to withstand compressive forces without collapsing. Density is a fundamental property influencing weight and volume considerations, especially in weight-sensitive applications such as aerospace. Cost and manufacturing complexity are equally significant. Cost per kilogram directly impacts the economic viability of material choices, balancing performance with affordability. Manufacturing complexity encompasses various factors, including processing steps, tooling requirements, and expertise needed for fabrication. A higher manufacturing complexity may entail increased production costs and lead times, affecting overall feasibility and scalability. For each of these parameters, composite materials are evaluated against performance requirements and application-specific demands. The ideal composite achieves a balance, exhibiting high mechanical strength, impact resistance, and stiffness while maintaining a competitive cost and manageable manufacturing complexity. Furthermore, advancements in composite manufacturing technologies continuously push the boundaries, enabling the development of novel materials with enhanced properties and reduced production complexities.

3. ANALYSIS AND DISCUSSION

Table 1 provides an overview of the mechanical characteristics of carbon Fibre hybrid composites, illustrating variations in strength, stiffness, and other pertinent factors. Commencing with the Carbon Fibre/Glass Fibre blend, it showcases moderate Tensile Strength at 850 MPa and Flexural Strength at 1200 MPa, alongside a low Impact Strength of 90 kJ/m$\hat{2}$ and Compressive Strength of 750 MPa. As we examine Carbon Fibre hybrids incorporating Aramid, Basalt, Flax, Hemp, Bamboo, and Kenaf Fibres, a discernible pattern of increasing strength and stiffness emerges. Particularly noteworthy is

TABLE 1. High-Performance Fibre-Reinforced Composites

Alternative	E1	E2	E3	E4	E5	E6	E7
A1	850	1200	90	750	1.55	25	Low
A2	900	1300	100	800	1.60	28	Medium
A3	920	1350	110	820	1.62	30	Medium
A4	950	1400	115	850	1.65	32	High
A5	980	1450	120	880	1.68	35	High
A6	1000	1500	125	900	1.70	38	Very High
A7	1020	1550	130	920	1.72	40	Very High

the Carbon Fibre/Kenaf Fibre Hybrid Composite, which exhibits the highest values across most parameters, including Tensile Strength (1020 MPa), Flexural Strength (1550 MPa), and Impact Strength (130 kJ/m$\hat{2}$). Nevertheless, this enhanced performance is accompanied by elevated costs and manufacturing complexities, underscoring the importance of carefully assessing trade-offs to align with specific application requisites and financial considerations.

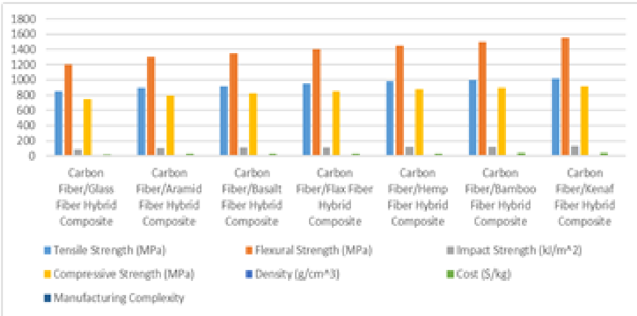

FIGURE 1. High-Performance Fibre-Reinforced Composites

Figure 1 illustrates a comparative examination of various hybrid composites combining carbon Fibre with alternative Fibres, outlining their mechanical attributes and manufacturing intricacies. The data demonstrates a significant enhancement in the tensile strength, flexural strength, impact strength, and compressive strength of the composites as compared to pure carbon Fibre when alternative Fibres are integrated. Among the hybrid variations, the carbon Fibre/glass Fibre composite showcases the least tensile and flexural strengths yet presents the lowest complexity and cost in manufacturing. Conversely, the carbon Fibre/kenaf Fibre composite showcases the highest tensile and flexural strengths, albeit with heightened manufacturing complexity and cost. Significantly, the inclusion of natural Fibres such as flax, hemp, bamboo, and kenaf amplifies the mechanical properties of the composites, particularly in terms of tensile and flexural strengths. However, this enhancement is accompanied by escalated manufacturing intricacies and costs due to the detailed processing involved in reinforcing with natural Fibres.

TABLE 2. Normalized Data

	E1	E2	E3	E4	E5	E6	E7
A1	0.12840	0.12308	0.11392	0.12669	0.13455	0.10965	0.06667
A2	0.13595	0.13333	0.12658	0.13514	0.13889	0.12281	0.11111
A3	0.13897	0.13846	0.13924	0.13851	0.14063	0.13158	0.11111
A4	0.14350	0.14359	0.14557	0.14358	0.14323	0.14035	0.15556
A5	0.14804	0.14872	0.15190	0.14865	0.14583	0.15351	0.15556
A6	0.15106	0.15385	0.15823	0.15203	0.14757	0.16667	0.20000
A7	0.15408	0.15897	0.16456	0.15541	0.14931	0.17544	0.20000

Table 2 displays normalized data utilizing the COPRAS technique to assess carbon Fibre hybrid composites. Mechanical properties and manufacturing complexity of each composite are depicted as dimensionless figures, facilitating comparison. Elevated normalized values signify superior performance in respective aspects. Results indicate that carbon Fibre/kenaf Fibre and carbon Fibre/bamboo Fibre hybrids demonstrate the highest normalized values across most parameters, suggesting enhanced mechanical characteristics. However, they also entail higher manufacturing complexities. Conversely, the carbon

Fibre/glass Fibre hybrid composite exhibits relatively lower normalized values, indicating moderate performance with reduced manufacturing complexity. These normalized values assist in prioritizing composite materials based on desired mechanical attributes and manufacturing complexities.

TABLE 3. Weight Distributed

	E1	E2	E3	E4	E5	E6	E7
A1	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286
A2	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286
A3	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286
A4	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286
A5	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286
A6	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286
A7	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286	0.14286

Table 3 demonstrates the equal allocation of weight across mechanical properties and manufacturing complexity for various carbon Fibre hybrid composites. Each composite receives a uniform share of 14.286% for all parameters, indicating a fair distribution of importance during evaluation. This balanced approach implies that no single property or aspect is favored over others in the assessment of these composites. As a result, decisions regarding material selection or optimization may require additional criteria beyond those listed in the table to ensure a thorough evaluation and informed decision-making process.

TABLE 4. Weighted Normalized Data

Alternative	E1	E2	E3	E4	E5	E6	E7
A1	0.0183427	0.0175824	0.0162749	0.0180985	0.0192212	0.0156642	0.0095238
A2	0.0194217	0.0190476	0.0180832	0.0193050	0.0198413	0.0175439	0.0158730
A3	0.0198533	0.0197802	0.0198915	0.0197876	0.0200893	0.0187970	0.0158730
A4	0.0205006	0.0205128	0.0207957	0.0205116	0.0204613	0.0200501	0.0222222
A5	0.0211480	0.0212454	0.0216998	0.0212355	0.0208333	0.0219298	0.0222222
A6	0.0215796	0.0219780	0.0226040	0.0217181	0.0210813	0.0238095	0.0285714
A7	0.0220112	0.0227106	0.0235081	0.0222008	0.0213294	0.0250627	0.0285714

Table 4 displays weighted normalized data derived using the COPRAS method to evaluate carbon Fibre hybrid composites. Each composite's mechanical properties and manufacturing complexity are depicted as weighted normalized values, with higher values indicating superior performance in respective parameters. The findings indicate that carbon Fibre/kenaf Fibre and carbon Fibre/bamboo Fibre hybrids showcase the highest weighted normalized values across most characteristics, suggesting improved mechanical properties. However, they also involve greater manufacturing complexities. In contrast, the carbon Fibre/glass Fibre hybrid composite exhibits relatively lower weighted normalized values, signifying moderate performance with less manufacturing complexity. These weighted normalized values facilitate the prioritization of composite materials based on desired mechanical attributes and manufacturing intricacies.

TABLE 5. Bi and Ci

Composite	Bi	Ci
Carbon Fibre/Glass Fibre Hybrid Composite	0.070298	0.044409
Carbon Fibre/Aramid Fibre Hybrid Composite	0.075857	0.053258
Carbon Fibre/Basalt Fibre Hybrid Composite	0.079313	0.054759
Carbon Fibre/Flax Fibre Hybrid Composite	0.082321	0.062734
Carbon Fibre/Hemp Fibre Hybrid Composite	0.085329	0.064985
Carbon Fibre/Bamboo Fibre Hybrid Composite	0.087880	0.073462
Carbon Fibre/Kenaf Fibre Hybrid Composite	0.090431	0.074963

Table 5 illustrates the cumulative benefit criteria (Bi) and cost criterion (Ci) for diverse carbon Fibre hybrid composites computed via the COPRAS technique. Bi reflects the amalgamated evaluation of the composites' advantageous attributes, whereas Ci signifies the assessment of their related costs. Elevated Bi values imply heightened overall benefits across various criteria, while lower Ci values indicate reduced associated costs. This examination assists in pinpointing composite materials that provide favorable mechanical properties and manufacturing advantages in proportion to their costs, thereby facilitating decision-making in material selection and optimization endeavors.

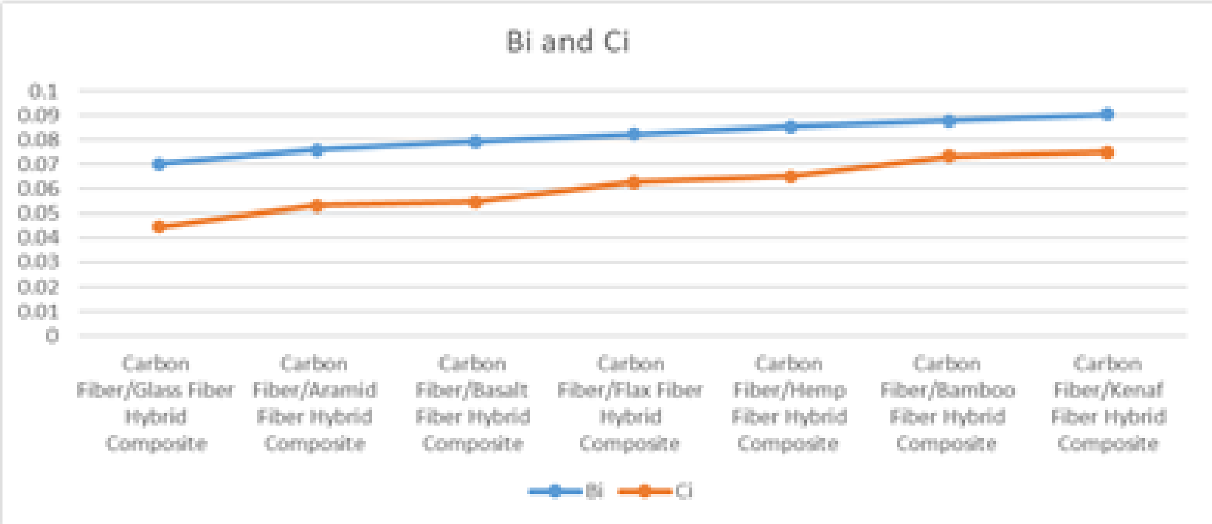

FIGURE 2. Bi and Ci

Figure 2 depicts the combined benefit criteria (Bi) and cost criterion (Ci) for diverse carbon Fibre hybrid composites, as determined through the COPRAS method. Bi represents the comprehensive evaluation of the composites' advantageous features, while Ci signifies the assessment of their respective expenses. Elevated Bi values indicate heightened overall benefits across multiple criteria, while lower Ci values indicate reduced associated costs. This analysis is pivotal in identifying composite materials that offer favorable mechanical properties and manufacturing efficiencies relative to their cost implications. By offering a holistic view of the trade-offs between benefits and costs, it assists decision-makers in selecting optimal composite solutions tailored to specific applications, thereby facilitating informed decision-making and optimization strategies across various industries.

TABLE 6. Rank

Composite	Qi	Ui	Rank
Carbon Fibre/Glass Fibre Hybrid Composite	0.152196	100.00000	1
Carbon Fibre/Aramid Fibre Hybrid Composite	0.144147	94.71186	3
Carbon Fibre/Basalt Fibre Hybrid Composite	0.145730	95.75201	2
Carbon Fibre/Flax Fibre Hybrid Composite	0.140296	92.18122	5
Carbon Fibre/Hemp Fibre Hybrid Composite	0.141295	92.83779	4
Carbon Fibre/Bamboo Fibre Hybrid Composite	0.137388	90.27067	7
Carbon Fibre/Kenaf Fibre Hybrid Composite	0.138948	91.29538	6

Table 6 presents the significance of alternatives (Qi) and the utility function (Ui) derived using the COPRAS method for various carbon Fibre hybrid composites. Qi assesses the relative importance or relevance of each composite during evaluation, with higher values indicating greater significance. Meanwhile, Ui reflects the utility or effectiveness of each composite, calculated from its Qi value and other relevant factors. The ranking column provides a clear depiction of the composites' order based on their utility function scores, offering insights into their comparative performance. The carbon Fibre/glass Fibre hybrid composite emerges as the most notable alternative, with the highest Qi value and utility function score, securing the top rank. This composite is evidently regarded as highly significant in terms of its utility and effectiveness. Conversely, the carbon Fibre/bamboo Fibre hybrid composite holds the lowest rank due to its comparatively lower Qi and Ui values. Despite its potential benefits, it appears to be less favored overall. These rankings are pivotal for decision-makers in material selection and optimization processes. By emphasizing the significance and effectiveness of each composite, stakeholders can make informed decisions about their utilization in specific applications. Composites with higher ranks may be prioritized for applications where superior performance is crucial, while those with lower ranks may still have utility in less demanding scenarios. Ultimately, the insights from Table 6 enable decision-makers to align their choices with the desired outcomes and requirements of the given context.

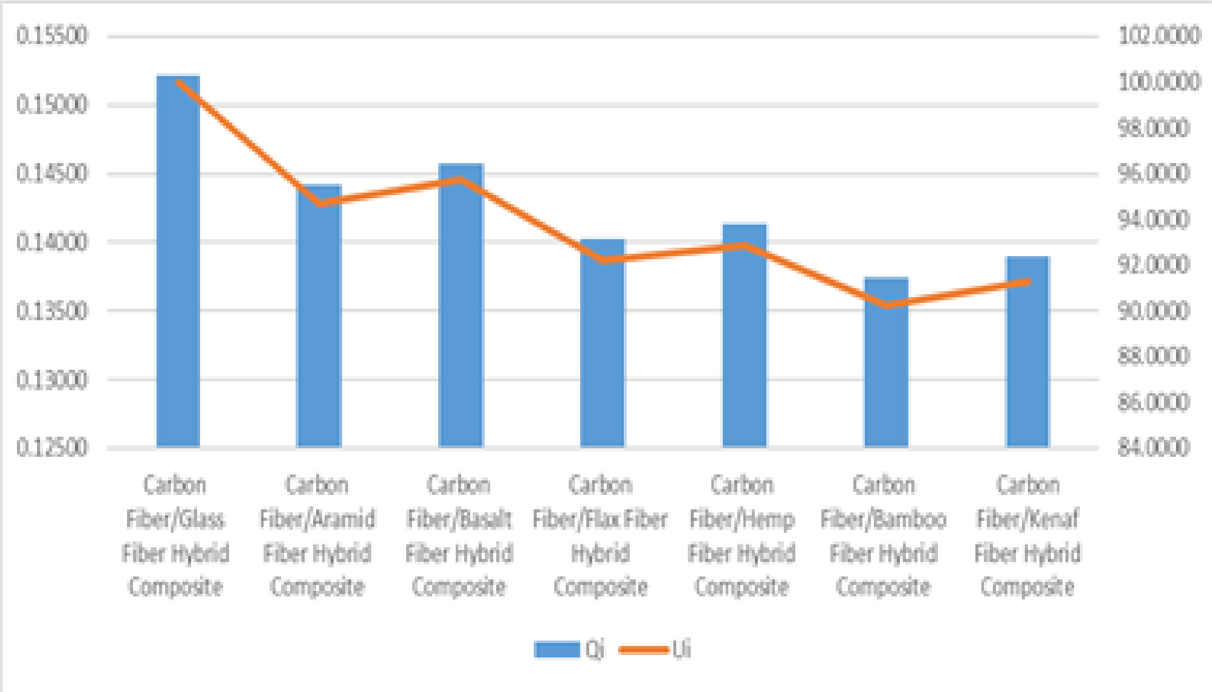

FIGURE 3. . Rank

Figure 3 presents the Qi (significance of alternatives) and Ui (utility function) values for various carbon Fibre hybrid composites. The Qi values quantify the relative importance of each composite, with higher values indicating greater significance in the evaluation process. Meanwhile, the Ui values represent the utility or effectiveness of each composite, derived from its Qi value and other relevant factors. These values offer insights into the comparative performance of the composites, aiding decision-makers in material selection and optimization processes. In this figure, the carbon Fibre/glass Fibre hybrid composite exhibits the highest Qi value and utility function score, indicating its considerable significance and effectiveness compared to other alternatives.

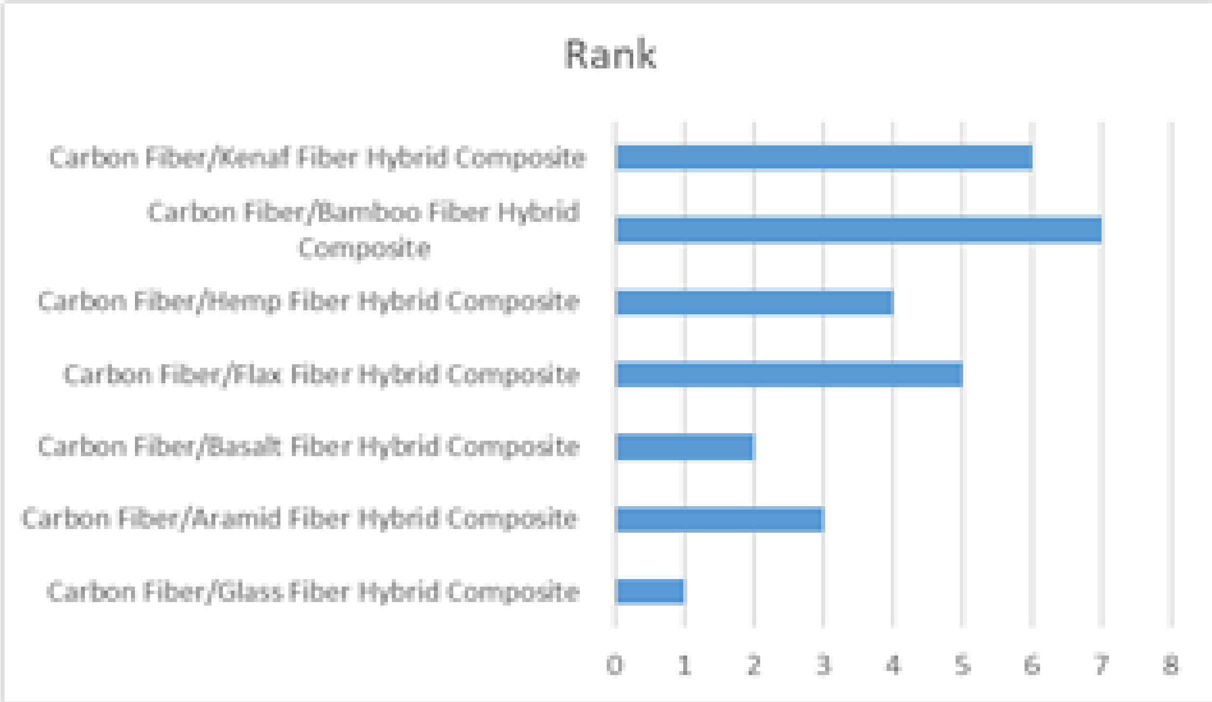

FIGURE 4. Rank

Figure 4 presents the ranking of various carbon Fibre hybrid composites based on their performance. The ranking column indicates the order in which the composites are positioned, with lower numbers representing higher ranks. Accordingly, the carbon Fibre/glass Fibre hybrid composite secures the top rank, denoting its superior performance compared to others. Conversely, the carbon Fibre/bamboo Fibre hybrid composite occupies the lowest rank, indicating comparatively weaker performance in the evaluation. These rankings offer valuable insights into the relative effectiveness of each composite, assisting decision-makers in prioritizing materials for specific applications. By considering the rankings provided in Figure 4, stakeholders can make informed decisions regarding material selection, optimizing their choices to align with the desired outcomes and requirements of the given context. The thorough examination conducted through the COPRAS technique offers valuable insights into the mechanical characteristics, manufacturing intricacies, and financial implications of diverse carbon Fibre hybrid composites. The incorporation of alternative Fibres alongside carbon Fibre leads to significant enhancements in both strength and rigidity, with the Carbon Fibre/Kenaf Fibre Hybrid Composite showcasing superior performance across most metrics. Nonetheless, this advancement comes with heightened complexities in production and associated costs, highlighting a discernible trade-off between performance and feasibility. The findings emphasize the necessity of carefully weighing these trade-offs during material selection to align with specific application needs and financial constraints. Through the provision of standardized data, weighted assessments, and rankings of significance and utility, this analysis facilitates decision-makers in prioritizing composite materials according to their desired attributes, thus streamlining the decision-making process. In essence, the COPRAS method emerges as a valuable instrument for scrutinizing and refining composite solutions, empowering stakeholders to make informed decisions that harmonize performance, manufacturability, and cost-effectiveness.

4. CONCLUSION

The extensive analysis conducted in this study provides valuable insights into the complexities of blending carbon Fibre with various alternative Fibres to augment the mechanical properties of high-performance composites. The findings indicate that integrating alternative Fibres like glass, aramid, basalt, flax, hemp, bamboo, and kenaf can substantially enhance the tensile strength, flexural strength, impact resistance, and compressive strength of carbon Fibre-based composites. Among the hybrid variants investigated, the carbon Fibre/kenaf Fibre composite emerges as the most promising, displaying superior mechanical characteristics with the highest tensile strength, flexural strength, and impact resistance. However, this heightened performance is offset by increased manufacturing complexity and cost. Conversely, the carbon Fibre/glass Fibre hybrid presents a more balanced profile, offering relatively lower mechanical properties alongside reduced complexity and production costs. The application of the COPRAS multi-criteria decision-making method furnishes a structured framework for assessing and prioritizing the diverse carbon Fibre hybrid composites. The utilization of normalized data, weighted evaluations, and rankings of significance and utility empowers decision-makers to align material selection with specific application needs and financial limitations. The insights gleaned from this study underscore the importance of striking a balance between material performance, manufacturability, and cost-effectiveness in the advancement of composite solutions. While pursuing exceptional mechanical properties is essential, it must be tempered by considerations of production feasibility and economic viability. The COPRAS analysis facilitates this delicate equilibrium, guiding stakeholders in optimizing the trade-offs between composite performance and practical implementation. Looking ahead, further exploration of hybrid composites, particularly those incorporating natural Fibres, holds promise for addressing sustainability concerns and broadening the scope of high-performance materials' applications. Advances in manufacturing technologies, such as automated Fibre placement and additive manufacturing, stand to streamline the production of these tailored composite solutions. Additionally, integrating the COPRAS method with emerging techniques like artificial intelligence and machine learning may enhance decision-making capabilities and accelerate the adoption of innovative composite materials across diverse industries. The strategic amalgamation of carbon Fibre with alternative Fibres, coupled with the application of the COPRAS decision-making framework, presents a potent approach to enhancing the mechanical properties of high-performance composites while addressing practical considerations of cost and manufacturability. This multifaceted analysis furnishes a valuable roadmap for material scientists, engineers, and industry stakeholders to navigate the intricate terrain of composite material selection and optimization, ultimately propelling the development of advanced, cost-effective, and sustainable solutions that meet the evolving demands of modern applications.

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