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Business Strategies for Carbon Fiber-reinforced Polymer Recycling in the Aviation Industry: A Literature Review

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Abstract: This study investigates business management strategies to enhance the effectiveness and longevity of CFRP-Cs applications in the aviation industry. In the current scenario, the transport industry has increasingly turned to lightweight materials for external structures. The automobile, aviation, and train sectors are particularly keen on utilizing Carbon Fiber-Reinforced Polymers (CFRPs) due to their lightweight nature, erosion resistance, and various functional elements beneficial for the transport industry (Bonfanti et al., 2023). However, CFRP composites (CFRP-Cs) pose challenges in the recycling process due to their compounds. The recycling process can only be conducted under extreme conditions, and direct reuse of these CFRP-Cs is difficult to process. A systematic literature review is conducted to examine the use and state of the art of CFRP fibers, the recycling processes adopted, and their associated challenges, benefits, and guidelines. The existing state of the art suggests that the use of CFRP cannot be avoided. However, for environmental sustainability, business strategies should focus on creating a market for CFRP recycling (Deng et al., 2020) and fostering consensus for the progressive use of recycled materials across industries. This involves developing guidelines within a sliding directive to ensure the necessary mechanical performance of CFRP-Cs while promoting environmental responsibility.

Keywords: aviation industry, business management strategies, carbon fiber-reinforced polymers, composites, recycling.

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INTRODUCTION

Global warming has become a critical issue and all the countries are focusing on the resolution to achieve sustainable development in their business operations (Navarrete et al., 2020; Strielkowski et al., 2021; Ni et al., 2023). Transport industry is one of industries which have caused serious environmental damage and to some extent it is continuing (Gopalraj & Kärki, 2020; Nundy et al., 2021; Yang et al., 2023). Currently many business management strategies are developed to focus on development of designs and productions with the reusable materials (Huang et al., 2020; Diaz et al., 2021; Hegab et al., 2023). Aviation industry is also keen to use recyclable materials which can increase their profit without affecting the environment (Firmansyah & Estutik, 2020; Korba et al., 2023). Aviation industry has seen poor management in designing and producing the environmentally friendly materials because of political issues and to achieve steep economic growth as a consequence the Aviation industry has become major cause of increasing pollution levels and increasing the hazardous wastes (Butenegro et al., 2021). It is the responsibility of corporate societies in Aviation to focus on reducing the energy and use reusable materials and develop strategies to manage their waste and make them recyclable at various stages at inter-industrial levels (Naim et al., 2022).

Carbon fiber reinforced polymer (CFRPs) is a kind of one of the composite materials (CMts) which is procedure to repair and strengthen reinforced concrete assemblies and used in Aviation for its benefits. The composites of CFRP are important materials in the Aviation industry. The CFRP-Cs develop materials are good for groundbreaking and can be applied for several functionalities in different industries (Naim et al., 2022). These composites consist of carbon fibers combined with resin (Magd et al., 2022). However, CFRP faces certain challenges in its application, such as the susceptibility of the resin matrix to oxidation and degradation when exposed to high temperatures. Additionally, the carbon fibers pose difficulties in cutting as they tend to rupture instead of being easily cropped. To overcome this challenge CFRP technologies work to manage the CFRP wastes.

Carbon fiber is highly favored in the aviation industry due to two key characteristics. Firstly, its crashworthiness, which refers to the ability of a composite material to absorb energy during an automotive crash, is crucial for enhancing passenger safety (Zhang et al., 2022). In passenger vehicles, crashworthiness determines the capacity of the structure to absorb impact energy and protect the occupants. To assess the crashworthiness in terms of specific energy absorption (SEA), a comparison was made between a composite material system incorporating chopped carbon fiber (CCF) and other fiber resin systems (Naim, 2021). The amount of these material systems required to ensure passenger safety in a midsize car traveling at different speeds was calculated and compared (Berbou & Sadqi, 2020). The chopped carbon fiber composite material exhibited the highest SEA compared to all other composites studied. This finding demonstrates the potential for successful analysis of various carbon fiber grades and resin combinations for use in automotive applications (Butenegro et al., 2021).

The second notable property of carbon fiber is its ability to reduce weight without compromising strength and speed characteristics. This aspect holds great significance for the present and future of the automotive manufacturing industry (Gopalraj & Kärki, 2020). For instance, the body of the BMW i3, an electric car, predominantly consists of carbon fiber. This product as referred by BMW is CFRPs, which is a durable and lightweight but costly composite material reinforced with fiberglass reinforced polymers. The car body made from CFRPs is calculated to be 50% lighter than steel. Further this material was found to be 30% lighter than aluminum, showcasing the potential for weight reduction while maintaining structural integrity and performance properties (Naim, 2021).

The pursuit of improved performance and enhanced usability has led to a growing demand for materials that meet these objectives (Kamal et al., 2022). Composites have emerged as promising options for fulfilling these requirements as they bring together materials with a high modulus of elasticity and the ability for convenient molding (Ateeq et al., 2023). These attributes make composites highly attractive for a range of industries such as civil construction, automotive, aerospace, wind energy, and sporting goods (Huang et al., 2020). The use of composites, particularly those reinforced with fibers, offers significant advantages including durability, lightweight characteristics, and the capability to be molded into intricate shapes (Zhang et al., 2022). Composites can be broadly categorized into two main types based on the polymers utilized: thermoplastics and thermosets (Gopalraj & Kärki, 2020). Thermoplastics have the ability to undergo melting and reprocessing upon heating. In contrast, thermoset polymers lack this property, and their structures remain unchanged even under high pressures and temperatures, ensuring sustained performance (Zhang et al., 2022). These unique characteristics make composites with thermoset polymers highly desirable in the aerospace sector (Abdel-Azim & Soliman, 2020). However, the growing utilization of such materials raises concerns about potential adverse environmental effects.

Thermoset composites derive their strength from the cross-linking of polymer chains. However, this cross-linking process renders the composites extremely challenging to recycle. Recycling thermoset composites necessitates extreme conditions and the removal of fibers, which adds complexity to the recycling process (Butenegro et al., 2021).

The difficulty in recycling the fibers within thermoset polymers leads to high processing costs. The fundamental contrast between thermoplastics and thermosets lies in their behavior during the curing process. Thermosets undergo strengthening upon curing, but they form chemical bonds that prevent them from being remolded. On the other hand, thermoplastics do not form any chemical bonds during curing, allowing them to be reshaped and recycled (Gopalraj & Kärki, 2020).

The aviation industry has shown significant interest in CFRPs due to their lightweight nature, exceptional mechanical properties, and resistance to corrosion (Butenegro et al., 2021). Furthermore, aircraft manufacturing companies have launched extensive marketing campaigns to promote these materials. Consequently, CFRPs have gained immense importance in the aviation sector, emerging as a crucial material for the development of new commercial airplanes (Joof et al., 2023). Recognizing the significance of CFRPs, two major players in the aerospace industry, Boeing and Airbus, have incorporated a higher proportion of this composite material into their latest aircraft models. Considering the global production requirements of CFRPs by the four main aircraft companies, namely Airbus, Boeing, Embraer, and Bombardier, the increased utilization of CFRPs indicates a substantial generation of waste material that will need to be recycled in the next three decades (Zhang et al., 2022).

The projected rise in CFRP waste generation has raised concerns regarding its environmental impact and economic implications, thereby emphasizing the need for effective waste recycling (Naini & Reddy, 2023). While this situation can be viewed as a problem, it also presents an opportunity and challenge for producers, consumers, and suppliers to address. Developing a recycling market for CFRP waste becomes a potential avenue to overcome these environmental and economic concerns (Ringvold et al., 2023).

The current research is based on finding solutions from state of art that have provided various solutions for the applications of CFRPs for longer usage and explores recycling and reuse at various levels in aviation industry (Gopalraj & Kärki, 2020).

METHODS

Systematic literature reviews (SLRs) are commonly used in research to synthesize and analyze existing evidence on a particular topic. While traditional SLRs follow a well-defined and structured process, there are alternative research methods and approaches that can be employed to complement or enhance the systematic review process. Here are some alternative research methods for conducting literature reviews:

Scoping Reviews

Scoping reviews aim to map the existing literature on a broad topic, identifying key concepts, theories, and knowledge gaps. They are less restrictive in terms of study design and quality, allowing for a broader inclusion of diverse literature. Useful for exploring emerging areas of research or interdisciplinary topics.

Rapid Reviews
Rapid reviews streamline the systematic review process by omitting some steps, such as extensive searching and detailed quality assessments. They are particularly useful when time constraints are a concern, providing a quicker overview of the existing evidence. May involve trade-offs in terms of comprehensiveness and rigor.

Realist Reviews
Realist reviews focus on understanding how and why interventions work in particular contexts. Emphasizes the importance of context, mechanisms, and outcomes (CMO) configurations. Suitable for complex interventions and situations where the effectiveness of an intervention may vary across different contexts.

Meta-narrative Reviews
Meta-narrative reviews explore the different perspectives and theories that have evolved over time within a particular field. Useful for understanding the historical development and evolution of ideas within a research domain.

Umbrella Reviews
Umbrella reviews synthesize evidence from multiple systematic reviews and meta-analyses on a related set of topics. Provide a higher-level overview and synthesis of existing evidence. Useful for capturing the breadth of knowledge and identifying consistent findings or discrepancies across multiple reviews.

Critical Interpretive Synthesis (CIS)
CIS involves combining elements of systematic review and interpretive research. Focuses on developing a deep understanding of the literature, emphasizing interpretation and critical analysis. Particularly suitable for topics where the context and social factors play a significant role.

Mixed-Methods Reviews
Integrates both qualitative and quantitative research evidence. Useful when the research question requires a comprehensive understanding that cannot be addressed by one type of data alone. Requires expertise in both qualitative and quantitative research methods.

Network Meta-Analysis (NMA)
NMA extends traditional meta-analysis by comparing multiple interventions simultaneously, allowing for a more comprehensive evaluation of treatment effects. Particularly useful when there are multiple treatment options for a given condition. When choosing an alternative research method, it's important to consider the specific goals of the review, the nature of the research question, available resources, and the expertise of the research team. It's also advisable to clearly justify the chosen approach in the review protocol or methodology section to enhance transparency and reproducibility.

The research findings are based on the study and analysis of existing researches to provide best solutions. This review paper aims to discover possible explanations to the problem of CFRP recycling in the aviation industry. Systematic literature review method is applied for the results analysis from the years (2015 to 2023) but for general concepts and applications other recent researches are referred too. All the research papers referred were from the Scopus, Web of Science and Google scholar's data base. Figure 1 represents the research methodology of this paper.

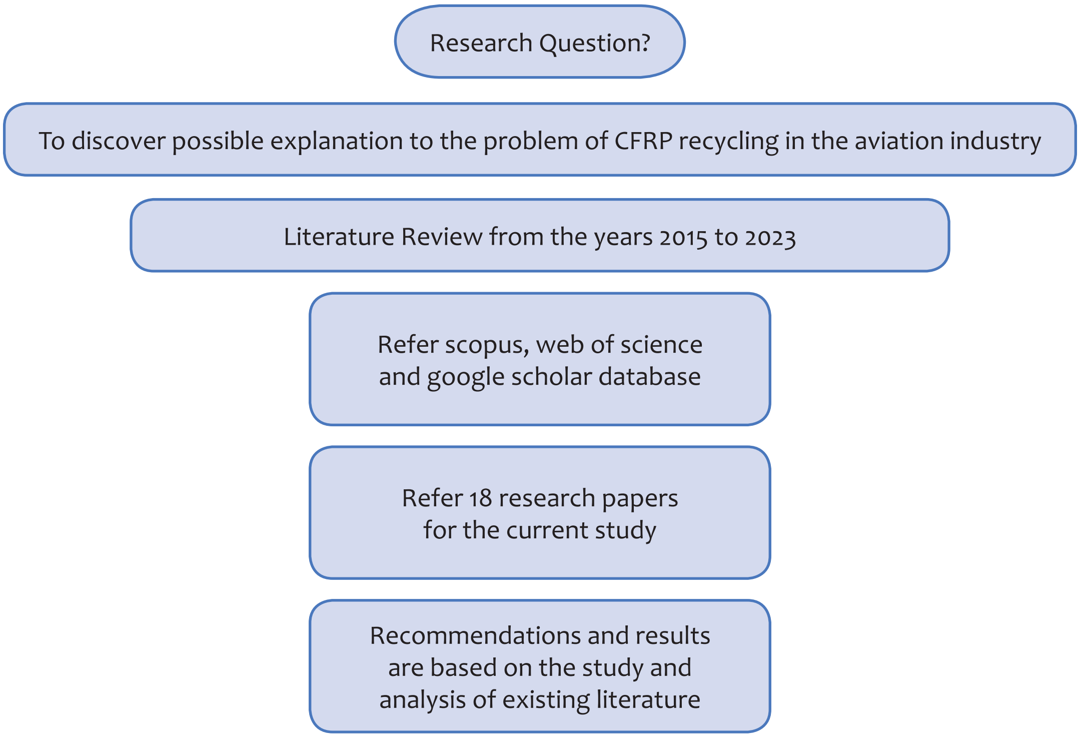

Figure 1 Process of Systematic Literature Review for CFRP recycling in Aviation Industry

Systematic study is done for 18 existing state of art literature and five parameters were identified for the results and analysis for the research questions. The criteria covered in this research are Sustainable alternatives, increased use of thermoplastics, fiber orientation in the composites, actions necessary to create a market for recycled CFRP in aviation industry and legislative Material certification for CFRP.

RESULTS AND DISCUSSION

The results are based on the study of state of art for CFRP in Aviation and proposed solutions are discussed in this section.

Sustainable Alternatives

The state of art recommended three methodologies to define more sustainable substitutions in the use of CMt as shown in Table 1.

Table 1 Proposed solution to derive solutions for CFRP in Aviation

Proposed Alternatives	Offered Solutions
Develop new material with CMt	Recyclable CMt
Apply new tools to separate materials	New technologies in recycling
New production technologies	Use recycling process for existing fibers rather using new materials

As an example Figure 2 shows the CMt for two aircrafts 777 and 787, this distribution helps the researchers to understand the material distribution for aircrafts and the materials which could be recyclable and the level of waste that would be released from these productions (Ringvold et al., 2023).

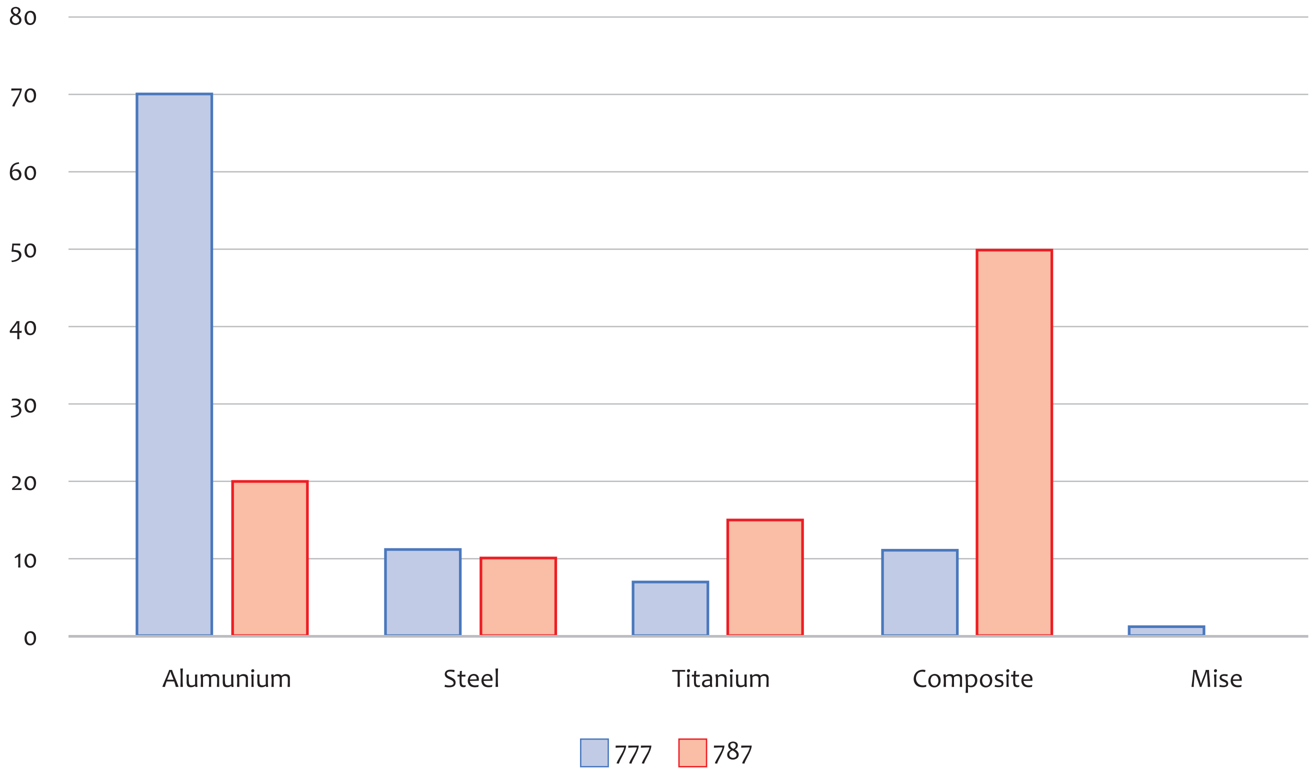

Figure 2 Material distributions for a selection of Boeing products
(Bledzki et al., 2020)

The options for CMt suggested that if more green compounds are used like the material of thermoset would preserve environment and reduce wastes. The benefit of using these CMts is to increase the possibilities of returning to the nature for future use because these materials are mostly extracted from non-fossil (Gunjal & Belokar, 2023).

The critical issue is that the type of medium used depends on the kind of fiber and its utilization in Aviation. The studies suggested that in the Aviation industry, natural fibers can be used in place of artificial fibers. There many common natural fibers like flax, bamboo, jute, sisal, hemp, coir, ramie, and sugar cane bagasse but not all could CFRP and used in the manufacturing of amenities in Aviation (Ringvold et al., 2023). Figure 3 shows the results of using carbon fiber and glass fiber from 1989 to 2019 in the amenities of Aviation industry.

The natural fibers cannot be compared to the CMt derived from the carbon fiber but there are many designs in aviation industry that can take advantage of these renewable resources (Liu et al., 2021). Therefore, the research suggests a recommendation of using the CMts from the polymers that are extracted from non-renewable resources and reinforced with natural fibers. This will facilitate in redeployment of processes at high temperatures, lower the use of fibers and this medium can be crushed and added as filler in other CMts (Gunjal & Belokar, 2023).

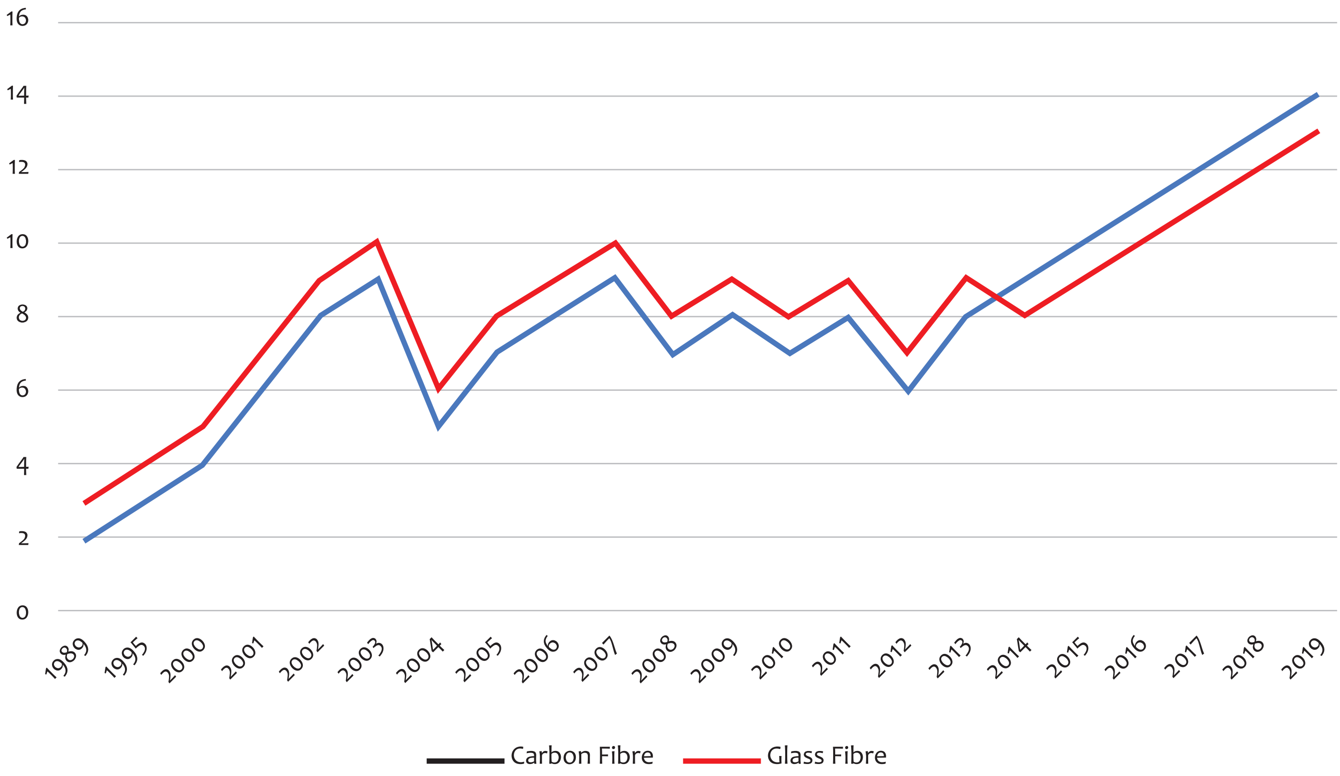

Figure 3 Use of Carbon and Glass Fibers in Aviation for the period 2019 (Bledzki et al., 2020)

Increased use of thermoplastics

The materials having the prospects of reusing and recycling are the best options but not all such materials are strong, safe and light weighted to be used in the Aviation industry (Iveson et al., 2022). CFRP has all such benefits and therefore are highly recommended to be utilized in the Aviation. But the issue comes in the disposing CFRP therefore solutions should be based on having the same characteristics of CFRP and should be easily disposed and recyclable (Iveson et al., 2022).

Three studies were referred to recommend the solutions where the first study suggested the use of high voltage technique to enhance the recycling of CMt (Bledzki et al., 2020). Second study suggested that thermoplastics CMt can improve the structures and designs in Aviation industry in place of use of use of steel and third study proposed that compound of CFRP and thermoplastics polymers to increase the possibilities of recycling (Iveson et al., 2022).

Fiber orientation in the composites

The studies suggested that the fiber is a composite of two types of classifications (Gunjal & Belokar, 2023); Long CMt and Short CMt and studies suggested the application of Long CMt because it has higher rate of recovery in the design level in Aviation (Iveson et al., 2022). Short CMt is a nonaligned fiber and therefore has difficulty in recovering (Bledzki et al., 2020).

Actions necessary to create a market for recycled CFRP

The sustainable material is considered for the level and functionality of recycling and the process of disposing in a way that it reduces the damage level of environment (Bonfanti et al., 2023). The marketing approach for CFRP focuses on applying a strategy of win-win situation. CFRP cannot be replaced for few instances in the aviation industry and disposing of these CMt is based on depositing the composites in landfills which eventually causes many environmental issues (Iveson et al., 2022). To overcome this issue, the study suggested that the process of recycling of CFRP should not restrict only to the Aviation industry rather it should include all the sectors in transport industry and other related industry for the recycling and disposing the CFRP (Bonfanti et al., 2023). This approach would have prolonged the use of CFRP in an Aviation sector and create an optimum procedure of recycling and disposing the CMt of CFRP (Akbar & Liew, 2020). The major actions necessary to create the market for recycled CFRP depends on the involvement of stakeholders and environmental activists and legal representatives. With the contribution of all entities the market for recycled CFRP aims to identify the amount of CMt to be recycled, requirements to recover the fibers and use the CMt in other markets or other industries (Gunjal & Belokar, 2023). To promote this notion, business management develops several policies which are certified and regulated by legislation at the national as well as international levels (Gopalraj & Kärki, 2020).

Legislative Material certification for CFRP

In the applications of CFRP in aviation, there are no specific legal rules suggested however there are few validations done for the recycling of CFRP (Akbar & Liew, 2020). These validations require certifications at two steps. The primary step focus on the material used in the Aviation and later steps certifies the industry's role in recycling and disposing the CFRP. The most important consideration here is to certify CFRP-Cs is for its reuse from the original materials (Gopalraj & Kärki, 2020). These CFRP-Cs are mostly specified for physical, mechanical and chemical attributes. The study suggested that these material certificates should validate recycling procedures, potentiality to recover, margin to recycle, use in other industries apart from Aviation and number of times it may recycled before its end of life. The certification is a process from the production to the disposing of CFRP-Cs of CFRP used in the Aviation (Gunjal & Belokar, 2023).

The study also suggests that these rules for CFRP-Cs may not develop a good recycling process or methodologies of disposing CFRP but may streamline the process and motivate the entities to participate in preserving the environment. Also the studies explained how Aviation industry took the initiative to establish the parameter in using, recycling and disposing the CFRP in Aviation (Gopalraj & Kärki, 2020).

CONCLUSION

The study suggests that business management strategies can play a crucial role in enhancing the market for CFRP, as well as in developing effective processes for recycling and disposing of CFRP components in various industries. Parameters for CFRP Effectiveness: The research analyzes five parameters that contribute to the effectiveness and prolonged use of CFRP in aviation. These parameters could include factors such as material composition, manufacturing processes, structural design, maintenance practices, and environmental considerations. Business Management Strategies: The recommendation for implementing business management strategies suggests that the success and widespread adoption of CFRP in aviation are not solely dependent on technical aspects. Effective management strategies can influence the market dynamics, production processes, and the overall success of CFRP applications in the aviation industry. Recycling and Disposal Processes: The study emphasizes the importance of developing efficient and environmentally friendly methods for recycling and disposing of CFRP components. This aligns with the growing concern for sustainability in industries, including aviation, and highlights the need for responsible end-of-life management of CFRP materials. Matrix of CFRP in Aviation: The research recommends exploring the matrix of CFRP for designing, structuring, and manufacturing in the aviation industry. This implies that the composition and arrangement of CFRP components are critical factors in optimizing their performance and longevity in aviation applications. Sustainable Alternatives: The study suggests exploring alternative polymers that can be combined with CFRP to create strong, light, and safe structures in aviation. This indicates a consideration for sustainable materials and an openness to incorporating diverse materials for improved performance while maintaining environmental responsibility. Limitations in CFRP Replacement: Acknowledging that many aviation designs are heavily reliant on CFRP, the research points out the challenges in completely replacing CFRP. This might be due to the specific material properties, lightweight characteristics, or other unique features that CFRP provides, making it difficult to substitute in certain applications. New Recycling Processes: The research suggests that while complete replacement of CFRP may be challenging, implementing business strategies for creating new recycling processes can be a viable solution. This approach aims to reduce waste, prevent environmental impact, and contribute to the overall sustainability of CFRP applications in aviation.

This research contributes in analyzing the five parameters that can make CFRP effective and prolonged in Aviation. The study of existing state of art recommends the business management strategies can enhance the market, process of recycling and disposing of CFRP-Cs in different industries. Many studies recommended the matrix of CFRP-Cs for the designing, structuring and manufacturing in Aviation industry. For sustainable alternatives the studies suggested other polymers with the compound of CFRP-Cs for building strong, light and safe structures in Aviation. There are limitations in the real replacement of CFRP-Cs because many designs are completely based on the utilization of CFRP but business strategies for creating new recycling process may prevent and reduce the wastes caused by CFRP and contribute in preserving the environment. In conclusion, the research highlights the multifaceted nature of CFRP utilization in aviation, considering technical parameters, business strategies, environmental sustainability, and the potential for incorporating alternative materials. It underscores the importance of a holistic approach that combines technical excellence with strategic and sustainable management practices.

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