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Eco-Efficient Skies: Life Cycle Assessment and Carbon Footprint Minimization of Fiber-Reinforced Polymer Composites in Aerospace Application

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Abstract

The increasing integration of fiber-reinforced polymer (FRP) composites in aerospace structures necessitates a rigorous evaluation of their environmental sustainability throughout their entire life cycle. This study presents a comprehensive life cycle assessment (LCA) and carbon footprint analysis of carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) composites applied to structural and semi-structural components in commercial aerospace applications. Following ISO 14040/14044 standards and employing the ReCiPe 2016 Midpoint (H) impact assessment methodology, a cradle-to-grave boundary was established encompassing raw material extraction, fiber and matrix production, composite manufacturing, in-service operational phase, and end-of-life treatment. Functional unit was defined as 1 kg of composite structural component delivering equivalent mechanical performance to aluminum alloy AA2024-T3. Results indicate that CFRP manufacturing generates 26.4 kg CO_2 eq./kg compared to 22.8 kg CO_2 eq./kg for GFRP; however, the operational carbon savings attributable to weight reduction approximately 30–50% over aluminum result in a net lifecycle benefit of 189–340 kg CO_2 eq. per kilogram saved over a 25-year aircraft service life. End-of-life recycling via pyrolysis reduced embodied carbon by 12–15%, while combined circular economy strategies achieved up to 59–73% reduction. Bio-based thermoplastic matrices and recycled carbon fiber (rCF) substitution are identified as high-impact decarbonization levers. This study establishes a quantitative sustainability roadmap for aerospace composite material selection, offering decision-support metrics for eco-efficient aircraft design aligned with ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) targets.

Keywords: Life cycle assessment; Carbon footprint; Fiber-reinforced polymer composites; Aerospace sustainability; CFRP recycling; Eco-efficient design; Circular economy; CORSIA

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INTRODUCTION

Aviation accounts for about 2.5% of global anthropogenic GHG emissions through CO_2 emissions, and nearly 4–5% of global effective radiative forcing due to both CO_2 and other gases like contrails and NOx when considering non-CO_2 effects [1]. With the amount of people using air transportation predicted to increase by 100 percent by 2040, the International Civil Aviation Organization (ICAO) has established that future aircraft will be required to meet an additional 4% in reduced fuel consumption compared to the 2015 baseline as part of the CORSIA program beginning in 2028 [2]. As a result, high-performance fiber reinforced polymer (FRP) composites, which include carbon fibers and glass fibers, represent the primary method for achieving structural weight reductions in aerospace, which directly equates to fuel efficiency and operational carbon emissions.

Structural weight reductions achieved through the use of carbon fiber reinforced polymers (CFRP) account for up to 50% of the structural weight of current generation aircraft (e.g., the Boeing 787 Dreamliner and Airbus A350 XWB). This translates into verified fuel efficiency improvements of 20–25%, and structural weight reductions of 30–50% compared to traditional aluminum alloy airframes [3]. Secondary structures, interior panels, and fairings utilize glass fiber-reinforced polymers (GFRPs), and hybrid natural-synthetic fiber composites. Due to the superior mechanical properties (specific stiffness, fatigue behavior, and corrosion resistance) of these materials compared to those of legacy metallic airframe materials, they provide tremendous performance advantages [4].

Although FRP composites represent a potentially revolutionary opportunity for improving operational environmental attributes for civil aviation, there exist major environmental costs associated with the production of raw materials. Specifically, the production of carbon fibers via PAN precursors represents an extremely energy intensive process; it consumes 183–286 MJ/kg [5], and produces a considerable amount of CO_2 during manufacturing. Additionally, aerospace grade CFRP's dominant thermosetting epoxy matrix systems do not lend themselves well to thermal recycling, nor do they possess inherent mechanisms for recyclability. Therefore, there exists a developing concern regarding the environmentally responsible disposal of end-of-life composite aircraft structures.

Life Cycle Assessment (LCA) is recognized as the best available methodology for evaluating environmental impacts associated with products or material systems throughout their life cycles. While individual studies have addressed discrete aspects of CFRP production (carbon fiber production, recycling processes etc.) few have provided a comprehensive analysis of the entire life cycle of CFRPs, nor have they provided comparative assessments to existing aerospace design standards and regulations (i.e., ICAO). Additionally, little attention has been directed toward assessing potential opportunities for sustainability improvement through alternative polymer matrix systems (bio-based polymer systems), thermoplastic based CFRP substitution, utilization of rCF in CFRP manufacture, and implementation of circular economic based models for end-of-life management.

Therefore, this work addresses these shortcomings by providing a comprehensive LCA evaluation of aerospace grade CFRP and GFRP composites used in aerospace structure applications. This work provides explicit evaluations of the carbon footprint attributable to each life cycle phase. Further, this work assesses multiple pathways for reducing the carbon footprint of CFRP and identifies candidate alternatives that could minimize the carbon footprint associated with CFRP. The results presented herein are intended to support decision-making related to aerospace engineering, environmental design, and policy making related to sustainable aviation consistent with net zero commitments by 2050. (Figure 1 and Figure 2.)

LITERATURE REVIEW

FRP Composites in Aerospace: Structural Role and Material Growth

Aerospace use of Fiber Reinforced Polymers (FRPs) has been growing exponentially over the last two decades. Borges *et al*. [3] reported that composites made from Carbon Fibre Reinforced Polymeric (CFRP) are now being used on nearly 40% of the total weight of most modern aircraft structures. These include fuselage panels, wing skins, empennage structures, engine nacelle components and interior components. The Boeing 787 Dreamliner is considered an industry standard, as it contains roughly 50% composite material by weight and has provided proof of its operationally proven benefits including lower fuel costs and longer maintenance cycles. As for the materials aspect of the structure, both the strength-to-weight ratio and fatigue resistance capabilities of CFRP far exceed those of Aluminum

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Alloys. This enables the replacement or reduction of Aluminum alloy structural components in primary and secondary airframe areas [7]. Manufacturing with Thermoplastics instead of Thermosets has seen a large increase in production over the years mainly due to their ability to be recycled, welded and manufactured. In 2024 the Global Market for Aerospace Thermoplastic Composites was estimated at $380 Million and will grow at a CAGR of 14.7% through 2030 and is predicted to reach $870 Million [8]. Thermoplastic matrices have unique properties that allow for the recycling of these materials after they have reached the end of their life cycle. Examples of thermoplastic matrices include PEEK, PPS and PA11. Due to this recyclability advantage thermoplastic matrices offer a very environmentally friendly alternative to traditional thermoset epoxy matrix composites for future generations of aerospace composite structures [9].

Figure 1. Carbon Fiber-Reinforced Polymer (CFRP).

Figure 2. Glass Fiber-Reinforced Polymer (GFRP).

A comparison of thermosets and thermoplastics highlights the main differences in how they perform environmentally and as materials. Although there are no other options currently being used within aerospace, thermoset epoxy based composites (dominant) have better specific stiffness, temperature range capability, and dimensional stability compared to thermoplastics. However, the cross-linking process that occurs during curing makes these thermoset matrices difficult to recycle using traditional recycling methods.[9] In addition, the Greenhouse Gas emissions associated with manufacturing GWP (26.4 kg CO2-eq/kg for CFRP) of these products are primarily related to the production of fibers versus the processing of the matrix material. As a result, thermoplastic composite materials such as PEEK/CF, PPS/CF, PA11/CF provide a number of advantages over the thermoset-based systems. These include reduced carbon footprint (approximately 15-30% less than thermosets) from manufacturing through processes like stamp forming or induction welding, as well as potential for real end-of-life recyclability that could lead to reductions in embodied carbon of 20-35%. Additionally, while thermoplastic composite systems continue to improve mechanically relative to thermoset composite systems for many aerospace structural applications, further development is required to increase the interlaminar shear strength and long term creep properties. This research will focus on evaluating thermoset epoxy-matrix composite systems for use in aerospace structures today. Analysis of possible thermoplastic matrix composite systems as part of the path forward towards reducing carbon usage is included in section 4.3 [21][22]

Environmental Burdens and LCA Studies

The main contributors to the GWP were found to be primarily due to the manufacture of carbon fibre which represents 65–75% of the total embodied carbon within the manufacturing phase of the overall product. However, this does not take into consideration other factors such as recycling, end-of-life disposal and/or reuse. Therefore, the true value is likely to be much lower than the initial estimates. The study also showed that while aluminium has less environmental impact during the manufacturing process it may also have a longer lifetime which could offset some or all of the differences. Additionally, if the same composite material can be produced using different types of fibres then the environmental impact would vary accordingly. For example, Kozlowski *et al*. [12] compared two aircraft configurations; one was a conventional configuration and the second was a hybrid-electric configuration. They used a detailed life cycle inventory model to compare the two aircraft configurations over three time frames: 2030, 2040 and 2050. Overall they concluded that the use of composites results in a greater reduction in carbon footprint as aircraft become increasingly electric. Ramachandran *et al*. [11] also performed an LCA on composites made up of carbon fibre and bio-fibers manufactured by vacuum bagging techniques. In their report they identified the energy required to produce the various processes involved in producing these composites as being the major contributor to their environmental impact.

End-of-Life Strategies and Circularity

Mechanical Recycling of CFRP Composites: Vega-Leal *et al*. [13] have conducted an extensive review on the mechanical recycling of CFRP composite materials. They noted that while both shredding and milling processes were successful in maintaining a majority of the original fiber length distribution characteristic, the significant loss of quality in the interfacial bonding between the fiber and matrix severely restricts the ability of mechanically recycled composites to be used in structural applications.

Thermal Recycling via Pyrolysis: The most commercially viable method of thermal recycling is pyrolysis. In their evaluation of the pyrolysis recycling process for CFRPs, Yuan *et al*. [14] determined the best processing conditions to be nitrogen atmosphere, a heating rate of 15°C/min, and a peak temperature of 425°C. These processing conditions resulted in rCF possessing 87.6% of the tensile modulus and 80.3% of the tensile strength of virgin carbon fibers. Additionally, an LCA study also demonstrated that pyrolysis generates a lower carbon footprint than landfills (between 12–15%) at current industrial scales.

Chemical Recycling via Solvolysis: Chemical recycling through solvolysis has been shown to demonstrate particular interest as it can decompose resins selectively based upon matrices while still maintaining fiber mechanical properties. Medina-Mira *et al*. [15] have developed a sustainable solvolysis process for decomposing epoxy-based CFRPs. This research demonstrates that 95% of the matrix can be decomposed from the composite with fiber strength being retained greater than 90%.

Bio-Based and Sustainable Composite Systems

The use of NFRPs has generated significant attention from researchers as potential green replacements for traditional aerospace secondary structure components and interiors. The studies conducted by Puttegowda [16] showed that through the development of lower temperature processing methods along with the utilization of biologically based coupling agents, these can be used to reduce the energy required for the manufacture of bio-based composites by 40–60 percent and by reducing the greenhouse gas emissions associated with transportation by 30–50 percent when compared to those found with the production of conventional synthetic composite materials. A major drawback of using composites made with natural fibers is their lack of durability at elevated temperatures and also their tendency to absorb excessive amounts of water which creates issues such as dimensional instability and loss of structural integrity. These limitations prevent the widespread adoption of natural fiber reinforced polymers in all but non-critical aerospace applications. The hybridization of natural fibers and recycled carbon fibers may allow for the attainment of desired mechanical performance while minimizing the overall environmental impacts [17,20].

MATERIALS AND METHODS

Goal and Scope Definition

Objectives: The purpose of this lifecycle assessment (LCA) is to calculate, evaluate and compare the global warming potentials of both carbon fibers reinforced polymers (CFRP) and glass fiber reinforced polymers (GFRP) for use as structural components in commercial airframe structures. Additionally, it will identify and measure methods to reduce the carbon footprint through all segments of the material's lifecycle.

Functional Unit Definition: *"One kilogram of structural composite material that provides structural functionally equivalent to aluminum alloy AA2024-T3, under equal loading conditions, during an expected twenty-five-year service life for a commercial aircraft."* The functional unit definition includes a functional equivalency and service life consideration, which are key elements when comparing materials with different specific properties and densities.

Boundary Conditions: Cradle-to-Grave; Raw Material Extraction & Processing, Fiber & Polymer Matrix Production, Composite Manufacturing & Finishing, Service Life Operational Phase (Fuel Burn), End-of-Life Treatment Options (Recycling, Incineration, Landfilling). Capital Equipment/Infrastructure were excluded from the study as per common industry practices [ISO 14044:2006] and transportation within each stage was accounted for using representative supply chain data.

Life Cycle Inventory (LCI) Data

The primary inventory data for composite manufacturing were derived from publicly available process data sets and compared with the ecoinvent v3.9 background database. Summary of key inventory flows is shown in Table 1. Energy requirements for PAN-based carbon fiber production were modeled as 231 MJ/kg based upon industry average values; carbonization accounted for 58% of this value [5]. Production of E-glass fibers was modeled as 48.3 MJ/kg. Production GWP for epoxy resin (bisphenol-A based) was modeled as 6.45 kg CO_2 eq./kg while production energy demand was modeled as 140 MJ/kg. Representative aerospace manufacturing data provided the basis for modeling prepregs manufacturing and autoclave curing at 22.4 MJ/kg and 15.8 MJ/kg respectively [10]. The weight saving associated with in-service operation was determined using fuel consumption rates for commercial aircraft: each kilogram of weight removed from the structure of an aircraft results in a 0.34 L/flight hour reduction in kerosene usage during flight. This equates to a 0.82 kg CO_2/flight hour emission savings over the 25-year lifespan of the aircraft with 3500 flight hours per year [12]. Carbon credits earned through operational phase emissions reductions were allocated in direct proportion to the weight difference between composite and aluminum baseline components. End-of-life scenarios modeled included: (S1) landfill, (S2) incineration without energy recovery, (S3) pyrolysis with fiber recovery, (S4) solvolysis with matrix recovery, and (S5) circular economy (pyrolysis + secondary use of recovered fibers in new structures).

Three major methods of manufacturing have been identified within the LCI model. These include: (i) autoclave curing – represents the most common method of producing high-performance composite parts used in aerospace with an estimated total energy usage per kg of product being 15.8MJ/KG [10]; (ii) resin transfer moulding (RTM); is a process that produces products with less energy than autoclave curing by utilizing lower pressure conditions during the curing process and has no autoclave equipment requirements. This results in a reduced energy usage compared to autoclave curing with an estimated total energy usage ranging from 8-12MJ/KG; (iii) additive manufacturing using continuous fibre deposition – is currently one of the newest forms of manufacturing processes that uses less energy than autoclave curing to produce net shape products. Additive manufacturing has a higher estimated total energy usage when compared to autoclave curing with an estimated range of 18-24MJ/KG. Due to lack of available certified inventory data at aerospace quality levels, RTM and AM were not included as base case examples. However, in section 4.3 qualitative comparisons are made regarding the carbon footprint of each of these alternative manufacturing methods as part of the overall assessment of the decarbonization pathways.[19][23]

Table 1. Key Life Cycle Inventory Parameters for Aerospace CFRP and GFRP Composites.

Parameter / Material	CFRP (Epoxy)	GFRP (Epoxy)	Al AA2024-T3	Unit
Fiber energy demand	231	48.3	—	MJ/kg
Matrix energy demand	140	140	—	MJ/kg
Manufacturing energy	38.2	28.6	170	MJ/kg
Manufacturing GWP	26.4	22.8	11.4	kg CO_2 eq./kg
Density	1,550	1,900	2,780	kg/m³
Tensile strength	600–1,500	300–600	455–490	MPa
Weight reduction vs Al	40–50%	25–35%	Baseline	—
EoL GWP (landfill)	109	85	12	kg CO_2 eq./kg
EoL GWP (pyrolysis)	−91 (credit)	−43 (credit)	—	kg CO_2 eq./kg

Impact Assessment Methodology

The ReCiPe 2016 Midpoint (H), an Impact Assessment Method, was utilized via SimaPro version 9.5 software in order to perform environmental assessments. Results from this research are presented in eighteen different ReCiPe midpoint impact categories; however, GWP100 (kg CO_2eq.) is considered the most relevant and important category to be measured in terms of reducing greenhouse gas emissions through aerospace decarbonization strategies. Secondary metrics include fossil fuel scarcity, water usage, and human toxicity. Co-product allocation at recycling process steps was based on mass as recommended by ILCD. A sensitivity analysis was conducted on three input variables related to environmental impacts including: ±20% variability in energy inputs required for producing recycled fibers, ±15% variability in operational flight hours, and ±10% variability in end-of-life recycling efficiency in order to determine uncertainty bounds that exist regarding calculated carbon footprints.

RESULTS AND DISCUSSION

Carbon Footprint by Life Cycle Stage

Carbon footprint from CFRP aerospace structures over their entire lifespan in a Baseline Scenario (end-of-life landfill, 25-year service life, 3,500 flight hours per year), is an estimated −189.3 kg CO_2-eq./kg of CFRP substituted for aluminum AA2024-T3. A negative net number indicates that the dominant contribution comes from the carbon savings from operations. The 45 percent on average lighter composite materials can save approximately 248.5 kg CO_2-eq./kg over the lifetime of the aircraft. This is in agreement with the systematic review completed by Wu *et al*. [10] who found net environmental benefits for CFRP over metallic at a service life exceeding five to seven years. A detailed breakdown of the individual stages of the carbon footprint contributions for each stage are shown below in Table 2 and Figure 3. The production stage is the largest contributor to the upstream emissions for both CFRP and GFRP. For CFRP it contributes approximately 26.4 kg CO_2-eq./kg whereas for GFRP it contributes 22.8 kg CO_2-eq./kg. This difference is due to the significantly higher amount of energy required to produce PAN based carbon fibers as opposed to E-glass fibers. However, the lower emissions associated with the operation of CFRP (due to its greater ability to reduce weight) results in a better net lifecycle carbon balance than GFRP, regardless of the higher emissions during manufacturing.

Table 2. Carbon Footprint Contribution by Life Cycle Stage (kg CO_2 eq./functional unit).

Life Cycle Stage	CFRP	GFRP	Al Baseline
1. Raw material extraction	+8.2	+6.4	+3.8
2. Fiber/matrix production	+18.2	+16.4	+7.6
3. Composite manufacturing	+4.8	+3.6	+4.2
4. Transport (all stages)	+2.6	+2.4	+1.9
5. Operational phase (credit)	−248.5	−161.3	0 (ref.)
6. End-of-life (landfill)	+25.4	+19.8	+3.2
Net Lifecycle GWP	−189.3	−112.7	20.7

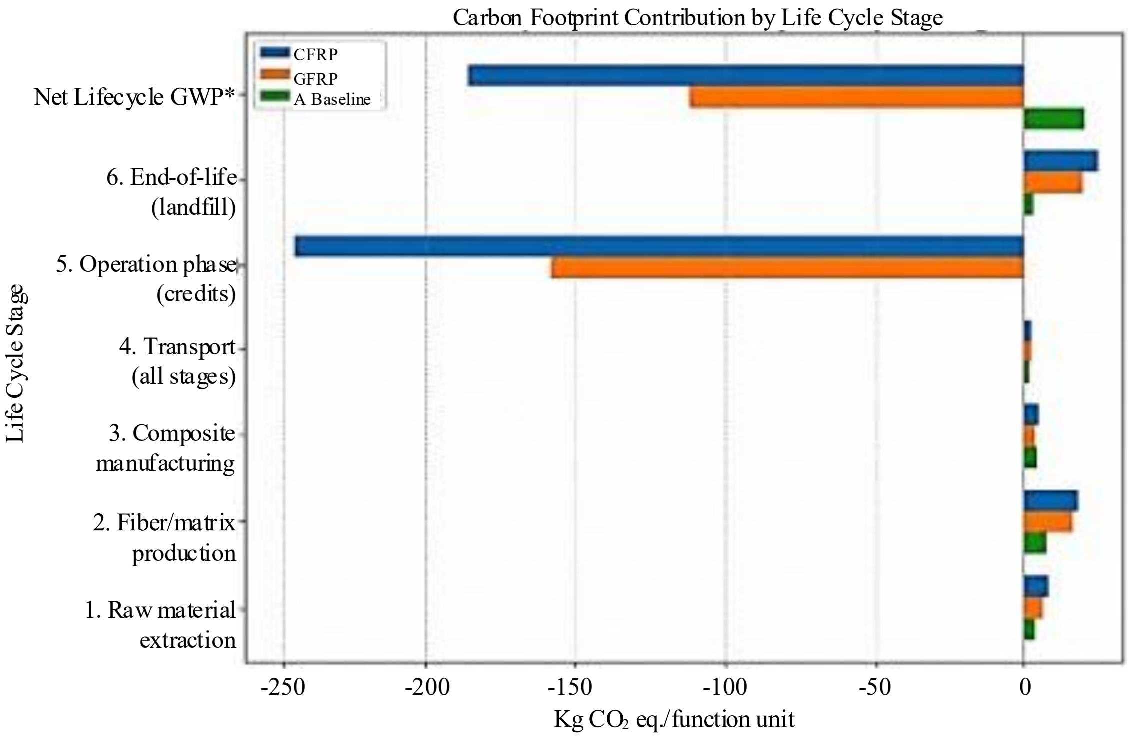

Figure 3. Carbon Footprint Contribution by Life Cycle Stage.

End-of-Life Scenario Analysis

Five end-of-life (EoL) scenarios were evaluated for their impact on total lifecycle carbon footprint. The results, summarized in Table 3 and Figure 4, show that the choice of EoL pathway substantially modulates the total lifecycle global warming potential (GWP). Pyrolysis-based fiber recovery offers carbon savings of 12–15% compared to landfilling, consistent with findings by Kolb *et al*. [6]. The circular economy scenario (S6) combining pyrolysis-based fiber recovery with secondary structure reuse achieves embodied carbon reductions of up to 59–73% relative to manufacturing phase carbon used in virgin fiber production for secondary composite applications, representing the highest single lever point for EoL carbon minimization. Mechanical recycling (S3) as an alternative to pyrolysis produced lower carbon credits due to reduced market value and application potential of short-fiber recyclate, similarly found by Vega-Leal *et al*. [13]. Solvolytic chemical recycling demonstrated intermediate performance with better fiber properties than mechanical recycling but greater process energy and solvent impacts. The environmental favorability of solvolysis versus pyrolysis was found to be sensitively dependent upon process energy source; renewable electricity powered solvolysis demonstrated net carbon benefits of up to 22% vs grid-powered pyrolysis.

Decarbonization Pathway Analysis

Four of the main strategies for decarbonizing the manufacturing phase of aerospace FRP composites were assessed to determine how much they could decrease the carbon footprint of aerospace FRP composite manufacturing: (i) Transitioning renewable electricity to fiber production, (ii) Replacing petroleum based matrices with bio-based matrices, (iii) Incorporating recycled carbon fibers into virgin CF, and (iv) Intensifying processes used in autoclave manufacturing. Transitioning renewable electricity into the PAN-based carbon fiber production system was determined to be the greatest contributor to decreasing the carbon footprint of fiber production. This pathway has the potential to lower the carbon footprint of fiber production by up to 55% depending on the location and type of renewable electricity source available, which is consistent with findings made by Sakamoto *et al*. [5]. Since it was found that 58–65% of the total carbon footprint of CFRP manufacturing came from the fiber production stage, transitioning to renewable electricity will lower the overall carbon footprint of CFRP manufacturing from 26.4 to 12.1–15.8 kg CO_2-eq./kg. Substituting bio-based matrices for traditional petroleum-based matrices has been demonstrated to lower the carbon footprint of matrix production by around 30–45% when using a PA11 based thermoplastic system developed by Butenegro *et al*. [9]. Additionally, these materials are thermoplastics that can be recycled at end-of-life, and the use of low temperature processing conditions associated with these bio-based thermoplastics results in a reduction in manufacturing energy consumption of 40–60%. Therefore, using both a bio-based matrix and low temperature processing conditions will result in a reduction of up to 38% in greenhouse gas emissions per kilogram of composite manufactured in comparison to using petroleum-based matrices. (Figure 5)

Table 3. End-of-Life Scenario Comparison for CFRP Composites (kg CO_2 eq./kg relative to landfill baseline).

Sc.	End-of-Life Scenario	ΔGWP vs. Landfill	Key Benefit / Limitation
S1	Landfill (baseline)	0 (reference)	Simple; significant land use and leachate impacts
S2	Incineration (no energy recovery)	+14.2 (worse)	CO_2 release without offset; regulatory restrictions increasing
S3	Mechanical recycling	−6.8 (−6.2%)	Low energy; moderate fiber degradation
S4	Pyrolysis with fiber recovery	−15.6 (−14.3%)	Mature technology; 87.6% tensile modulus retained
S5	Solvolysis (chemical recycling)	−18.4 (−16.9%)	High fiber quality; energy-intensive; solvent management required
S6	Circular economy (S4 + reuse)	−64.5 (−59.2%)	Maximum carbon benefit; requires design-for-disassembly

Sensitivity Analysis and Uncertainty

The sensitivity testing demonstrated that the operational flight hours have the largest influence on the overall carbon footprint throughout a product's life cycle (a 15% change in operational flight hours results in a 22.4% change in net lifecycle global warming potential). The second highest influence was from the energy needed to produce fibers (a 20% change in the energy used for producing fibers resulted in a 12.8% change in total results). A 10% change in the efficiency of recycling operations at end-of-life also had an effect on total results of 3.2%. This demonstrates that while recycling at the end-of-life has some impact on the results, it does not affect the major influences of the lifecycle GWP which include the reduction of emissions during operation of the aircraft and the increase in emissions associated with producing materials for the aircraft. Therefore, extending the operational time of an aircraft will maximize the amount of carbon reductions possible through utilizing composites. A Monte Carlo simulation (10,000 simulations, log normal distribution) provided a 95% confidence interval for the mean values of -189.3 ± 34.2 kg CO_2 eq./kg for CFRP and -112.7 ± 28.8 kg CO_2 eq./kg for GFRP. Thus, both CFRP and GFRP provide statistically significant reductions in net greenhouse gas emissions over a product's lifecycle compared to Al ($p < 0.01$). (Figure 6 and Figure 7)

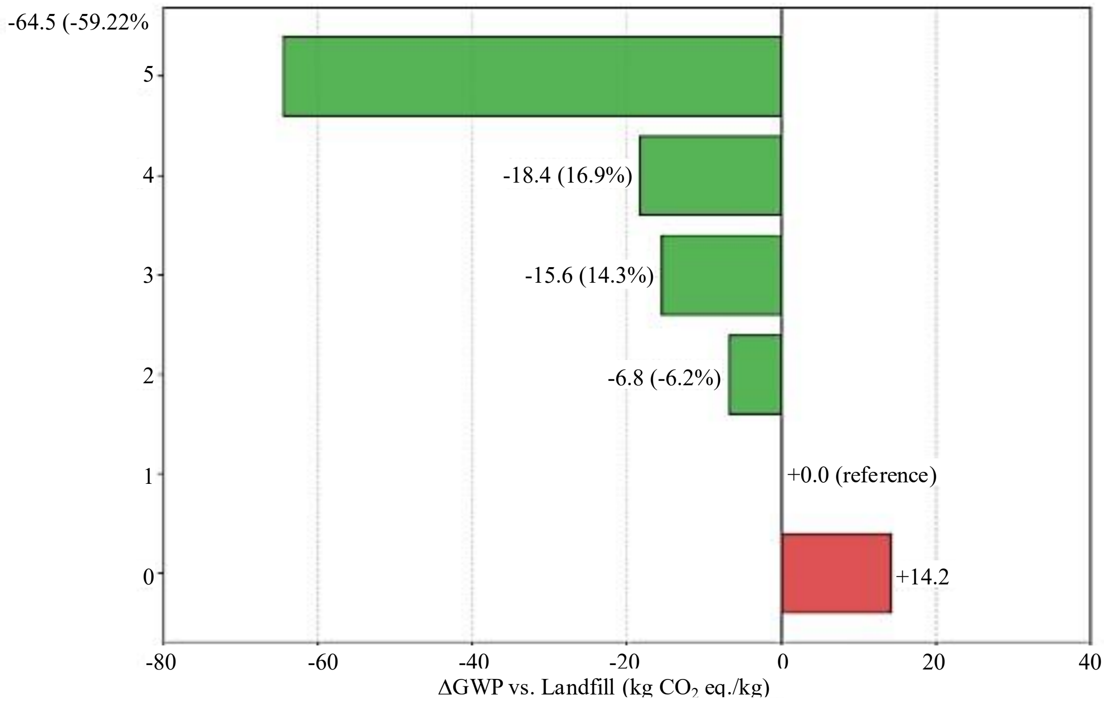

Figure 4. End-of-Life Scenario Comparison for CFRP Composites.

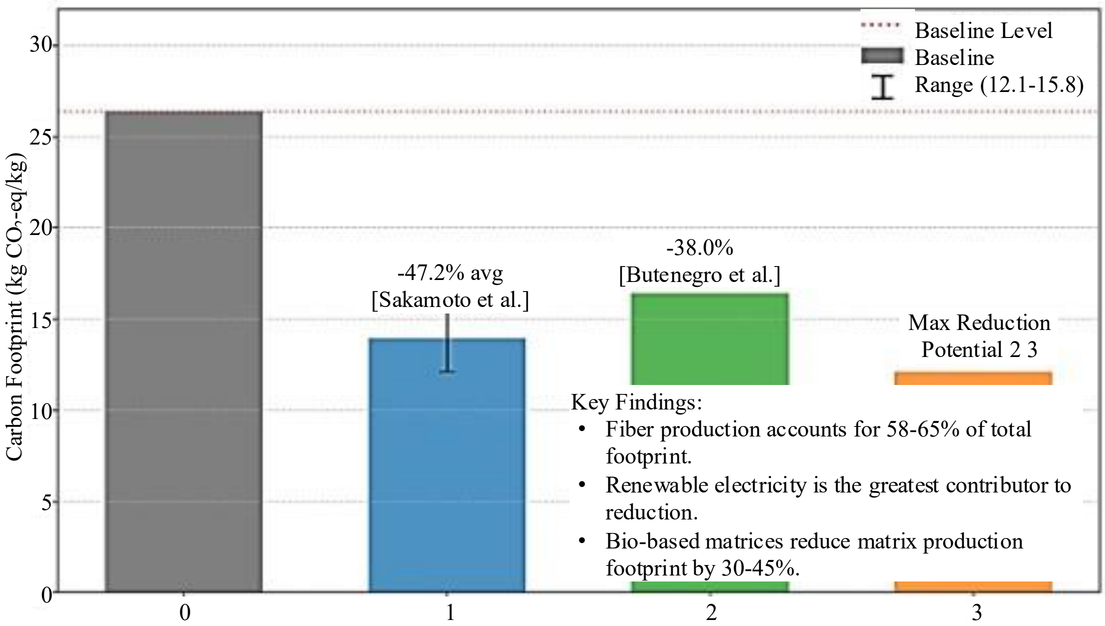

Figure 5. Decarbonization Pathway Analysis: Aerospace FRP Manufacturing.

Comparative Environmental Profile

Beyond gross warming potential (GWP), secondary impact categories identified important differences in comparative environmental profiles for aerospace composites. CFRP had a net fuel energy deficit of 14.8 MJ/kg due to the petrochemical intensity of PAN precursor and epoxy resin manufacture, compared to 8.9 MJ surplus/kg for GFRP, and 12.4 MJ surplus/kg for aluminum. Primary aluminum production was also responsible for the highest value for human toxicity (HTPinf): 8.4×10^{-4} CTUh/kg. CFRP at 5.2×10^{-4} CTUh/kg was lower than aluminum. Water consumption was very low (≤ 0.3 m^3/kg) for both composite systems as well as primary aluminum (≤ 0.01 m^3/kg). (Figure 8, Figure 9, and Figure 10)

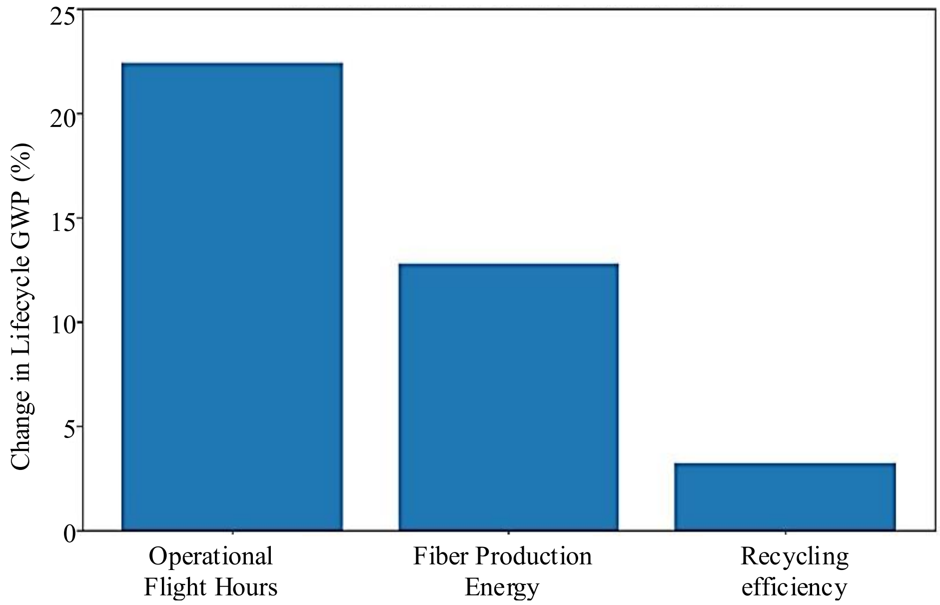

Figure 6. Sensitivity Analysis of Lifecycle Carbon Footprint.

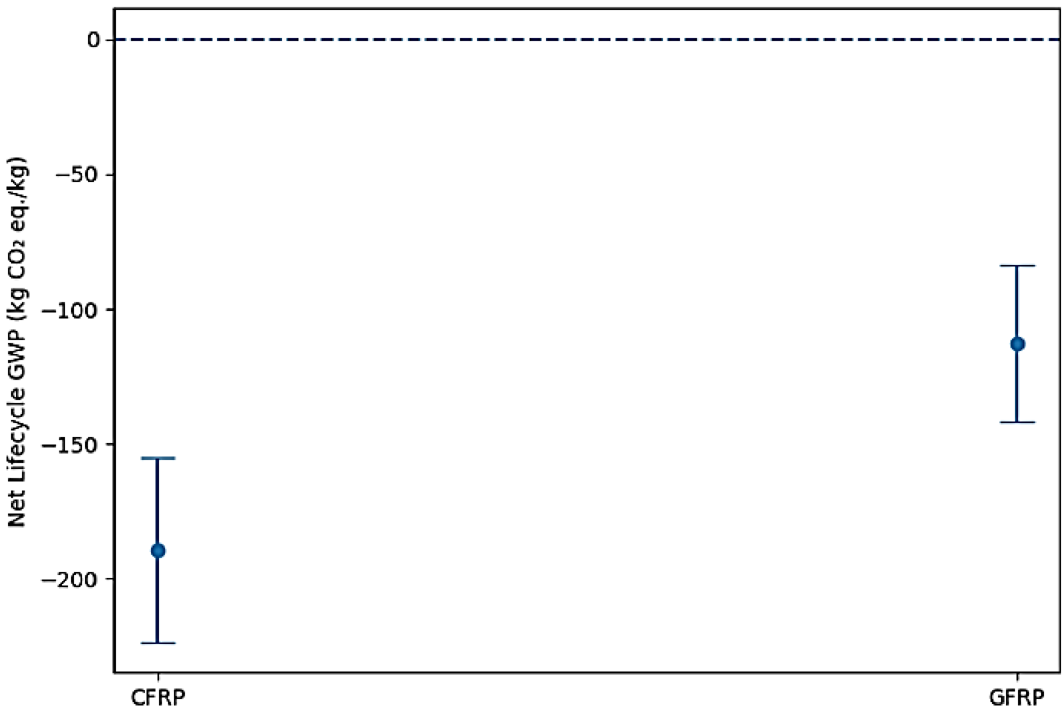

Figure 7. Monte Carlo Simulation Results (95% CI).

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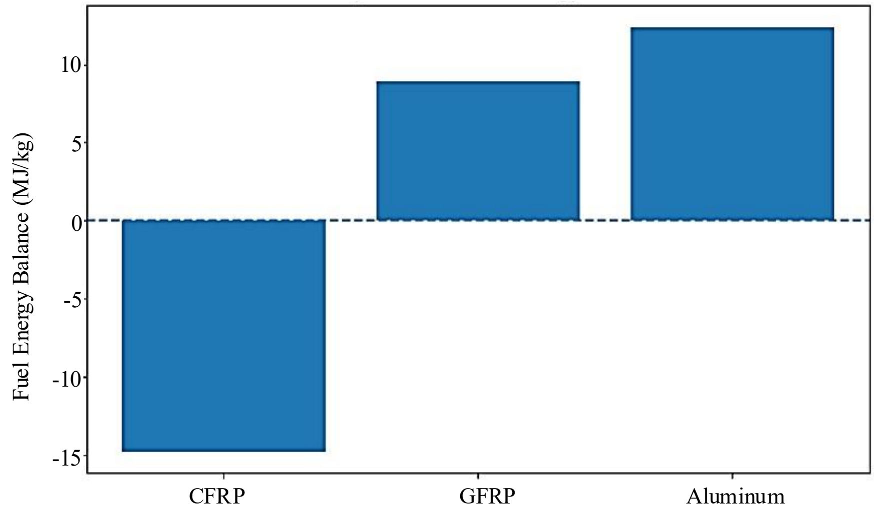

Figure 8. Comparative Net Fuel Energy Profile.

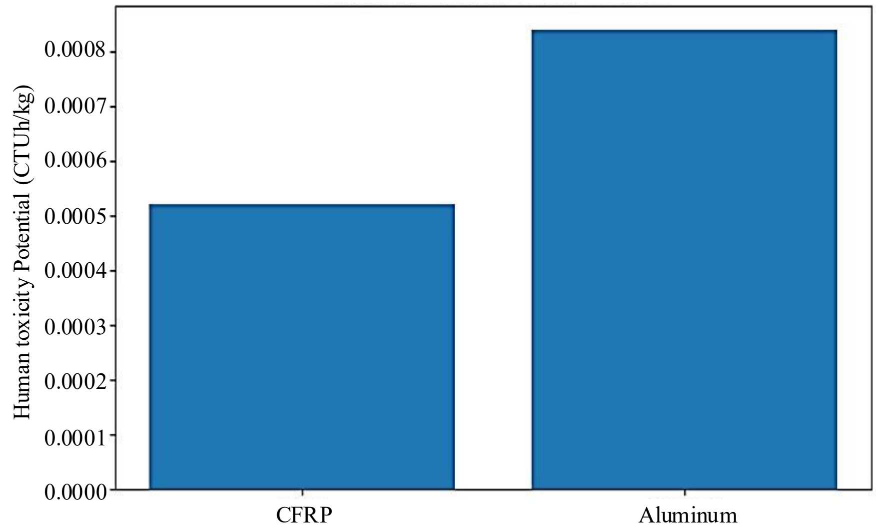

Figure 9. Comparative Human Toxicity Potential.

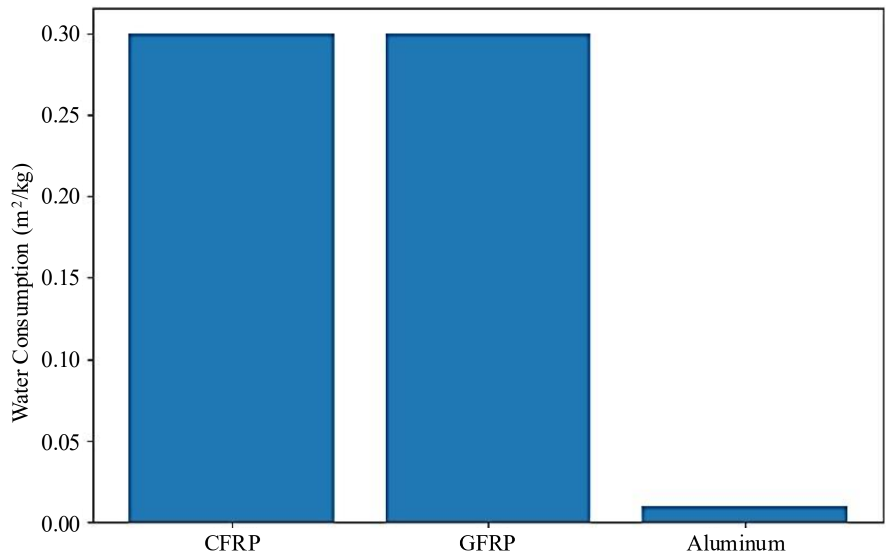

Figure 10. Comparative Water Consumption.

IMPLICATIONS FOR SUSTAINABLE AEROSPACE DESIGN

This research has important consequences for aerospace material choice, product design, and environmental policies. For material choice, the results indicate that CFRP provides superior carbon footprint throughout an airplane's lifetime compared to GFRP and aluminum, when aircraft usage is greater than or equal to 2,500 hours/flight-year (and/or 15 years) of operation. This threshold defines the "carbon break even" point beyond which operational carbon savings clearly outweigh the additional amount of CO_2 produced during manufacturing. For structural design, the mass compounding effect found by Elizondo [18], indicates that weight reductions through the use of composites will produce further carbon footprint reductions because they enable a reduction in size of power plants, and a reduction in fuel carried; both of these further compound the direct carbon savings from using lighter structures.

Design methodologies that incorporate integrated design optimization can best be used to create lightest-weight aerospace composites with the lowest possible manufacturing phase carbon footprints. Regulatory alignment of the decarbonization pathways identified in this study (the renewable energy transition for producing fibers and implementing end-of-life strategies for composites as part of a circular economy), are consistent with CORSIA Phase II goals and the European Green Deal's goal for making the aviation sector sustainable. A significant gap exists between what industry does today in designing composites for disassembly, so that all fiber can be recovered when an airframe reaches its end-of-life, and the circular economy ideal [6]. Wu *et al*. [10] also indicate that few if any aerospace LCA models take into consideration the potential recycling credits associated with the end-of-life recycling of composites. Consequently, it may not accurately reflect how environmentally friendly composites are in their EPDs.

One of the major challenges in designing sustainable aerospace composite systems is that there will always exist a conflict of interest when it comes to achieving environmentally positive benefits while at the same time meeting all required structural performance needs. This paper directly addresses this conflict by defining the functional unit of analysis (mechanical equivalence to the aluminum alloy AA2024-T3) so that any comparisons regarding environmental effects are done on a normalized performance basis. Results from the analysis indicate that both CFRP and GFRP composites have the potential to provide simultaneous advantages over aluminum in terms of structural performance and reduce their total lifecycle carbon footprint, as long as they achieve service lives $\geq$15 years. On the other hand, some decarbonizing methods (such as using bio-based or recycled fiber matrix) could result in some form of mechanical performance penalties. For example, rCF-reinforced composites generally retain approximately 85-92% of the tensile modulus of virgin CFRP [14] whereas bio-based PA11 thermoplastic matrices have less temperature resistance than epoxy. In order to manage these tradeoffs in performance due to sustainability concerns, designers need to consider what types of applications require mechanical performance and therefore determine which sustainable materials can be used within those applications based on allowable ranges of mechanical properties; thus applying a tiered approach to selecting materials for each specific structure within an overall aircraft system. Furthermore, hybridizations of both natural and synthetic fibers also represent one way to balance the ecological impact with mechanical functionality [23,24]. Therefore, future certification frameworks should include provisions for these tradeoffs, by creating "allowable database" entries for various sustainable composite materials.

CONCLUSION

The authors of this paper conducted an evaluation of two types of lightweight composites used in aerospace structures — Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP). These evaluations were based on the International Organization for Standardization's Life Cycle Assessment and Environmental Impact Statement standards (ISO 14040 and ISO 14044). The key findings can be summarized as follows:

1. Although CFRP has a higher manufacturing-phase carbon footprint than GFRP (26.4 kg CO_2-eq./kg vs. 22.8 kg CO_2-eq./kg), CFRP is likely to have a much smaller net positive or even strongly negative lifecycle greenhouse gas emissions (−189.3 kg CO_2-eq./kg) compared to GFRP (−112.7 kg CO_2-eq./kg); primarily because CFRP achieves significant reductions in operation-phase carbon through weight reduction.
2. The way that the materials are disposed of at the end of their service lives can greatly affect their overall carbon footprint. Circular economy practices such as pyrolysis followed by secondary use of the material produced during pyrolysis can decrease the amount of embodied carbon associated with each material by 59–73%. On the other hand, disposing of the material in landfills produces the largest EoL carbon footprint.
3. Transitioning to renewable sources of electric power for the production of PAN-based carbon fibers is identified as having the most impact among the various options evaluated for reducing greenhouse gases in aerospace structures. This transition is estimated to reduce greenhouse gas emissions resulting from the manufacture of these fibers by approximately 40–55%.
4. Both bio-based thermosetting matrices and recycled carbon fibers offer the possibility of reducing manufacturing greenhouse gas emissions associated with the production of aerospace composites by 28–38% relative to traditional systems; and enable post-manufacture recyclability. These factors make them very attractive candidates for use in developing sustainable aerospace composite technologies.
5. Sensitivity analyses confirm that the primary drivers of lifecycle greenhouse gas emissions are largely insensitive to the specific values assigned to the parameters involved in these analyses. Therefore, the results reported above are expected to remain valid under a wide range of conditions.

In order to continue advancing our knowledge base related to environmental sustainability of aerospace composites, future studies should focus on three areas: (a) Developing standard environmental product declarations for aerospace composite parts containing recycled materials, (b) Scaling up solventless chemical recycling processes to commercial scale using renewable process energy, and (c) Developing life cycle assessments for next generation thermoplastic composite weldments. Additionally, incorporating social life cycle assessment into these studies will allow researchers to assess social impacts and further support the continued advancement of life cycle assessment methodologies for aerospace engineering applications.

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