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Advancing carbon fiber and its composites technology: Korea's strategic growth and innovation

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Abstract

This research provides a comprehensive analysis of Korea's carbon fiber and composites manufacturing industry, highlighting its pivotal role in advancing global sustainability and technological innovation. By examining the industry's structure, major advancements, and sustainability efforts, the study emphasizes Korea's strategic positioning as a global leader in composite materials. Major producers such as Hyosung, Toray Korea's, and Kolon dominate the market, supported by innovative smaller companies like Korea Carbon and Hyundai Fiber, which specialize in applied products. The domestic prepreg market features key players, including SK Chemicals and Joyang Chemical, showcasing robust production capabilities. Korean industries, particularly in automotive and aerospace, have spearheaded significant R&D efforts aimed at reducing CO_2 emissions. For example, Hyundai Motor Group leverages carbon fiber reinforced polymers (CFRP) to revolutionize vehicle design, enhancing fuel efficiency and reducing weight. Similarly, Hanwha Advanced Materials and Kolon Industries contribute to cutting-edge lightweight, high-strength composites for critical applications. Industries, research institutes and universities in Korea drive advancements through innovative techniques like automated fiber placement (AFP). Import and export trends underline Korea's growing role as a leading exporter of carbon fiber products, further solidifying its global impact. Applications of carbon fiber composites extend to automotive manufacturing, marine and shipbuilding, aerospace, and hydrogen storage, with a clear focus on fostering sustainable practices and regulatory compliance. This study underscores Korea's transformative contributions to the global carbon fiber and its composite industry and commitment to innovation, sustainability, and environmental stewardship.

Keywords

Carbon fiber; Carbon fiber composites; Technology development; Carbon emission reduction; Sustainable development

1. Introduction

Carbon fiber and carbon fiber composites are materials known for their exceptional strength, lightweight nature, and versatility [[1], [2], [3], [4]]. It is renowned for its extraordinary strength-to-weight ratio, making it stronger than steel yet significantly lighter. Carbon fiber's versatility is evident across industries [[5], [6], [7], [8]]: in aerospace, it contributes to the lightweight design of aircraft components like fuselages and wings, enhancing fuel efficiency and performance; the automotive sector benefits from its use in reducing vehicle weight, improving fuel efficiency, and bolstering safety with carbon fiber reinforced polymers (CFRP) in chassis and body panels [9,10]; in sports and recreation, its strength and lightness enhance equipment performance, from tennis rackets to bicycles, allowing athletes to exert more power with less effort [11]; marine vessels, including boats and yachts, utilize carbon fiber composites for improved speed, fuel efficiency, and structural integrity [[12], [13], [14]]; wind energy harnesses its strength and stiffness in turbine blades, optimizing energy capture efficiency while reducing maintenance costs [[15], [16], [17]]; infrastructure and construction rely on carbon fiber composites for strengthening and retrofitting structures, offering increased durability and seismic resistance [18,19]; and in the medical field, carbon fiber's biocompatibility and radiolucency make it invaluable for orthopedic implants, prosthetics, surgical instruments, and diagnostic equipment, showcasing its wide-ranging impact on innovation and efficiency across diverse sectors [20,21]. However, the increasing demand for carbon fiber and its composites raises concerns about sustainability and recycling. Recent research has focused on high-performance recycling methods for carbon fiber composites, enabling the recovery of both resin and fiber for reuse [22]. Advanced topological structures in recyclable bio-based epoxy composites have shown promising improvements in mechanical properties, enhancing the viability of sustainable solutions [23]. Additionally, innovative interface-strengthening techniques are being developed to facilitate high-value recycling of carbon fiber composites, ensuring their extended lifecycle and reducing environmental impact [24]. Based on the above-mentioned diverse application of the carbon fiber and its composites, the requirement of the cabon fiber increased rapidly, according to the report of the polaris market research, global carbon fiber market was valued at USD 7.48 billion in 2023 and is expected to grow at 12.9 % CAGR for next 10 years as shown in Fig. 1 [[25], [26], [27], [28]]. Key factors driving the growth of the carbon fiber market include the rising demand for electric vehicles, increased investment in renewable energy sources, and the ongoing trend towards lightweight, high-performance materials [[29], [30], [31], [32]]. In order to meet the demands of the carbon and its composites market the Korea government started to build the carbon valley USD 144.4 million investment from 2011 to 2016. The Korea's Ministry of Knowledge Economy (MKE) designated Jeonju, the capital of Jeollabuk-do, and the bordering city of Wanju as Carbon Valley [33] Zones in August 2010. It was invested for the construction projects about 14 % of total investment, 86 % for the carbon source materials and carbon application technology. Hyosung Advanced Materials one of the major producers of the carbon fiber, according to the report in March 2, 2023, Hyosung Advanced Materials, unveiled plans to invest $38.5 million in expanding carbon fiber production at its JeonJu facility in Korea. Set the operations in April 2023, this expansion project marks the establishment of Hyosung's fourth polyacrylonitrile (PAN) carbon fiber line, adding 2500 metric tonnes of capacity and elevating the company's total capacity to 9000 metric tonnes annually [34]. Notably, this initiative represents the third announced carbon fiber expansion by Hyosung, following previous announcements in 2020 and 2021. The primary objective of this expansion is to address the surging demand for storage solutions for environmentally friendly vehicle fuels, such as hydrogen and natural gas. With the anticipated resurgence of the hydrogen economy, Hyosung foresees a rise in demand for pressure vessels to store the gas, with applications spanning hydrogen-fueled vehicles, fuelling stations, and gas transport. Hyosung's proprietary carbon fiber brand, TANSOME, introduced in 2011, stands as Korea's pioneering high-strength/high-strain fiber. Production of TANSOME has been ongoing at the JeonJu site since 2013. Aligning with its ambitious vision, Hyosung announced in 2019 a comprehensive investment plan exceeding $820 million, aimed at achieving a total carbon fiber output of 24,000 tons annually by 2028. The ultimate aspiration is to secure a prominent position among the top three global carbon fiber manufacturers, capturing over 10 % of the global market share.

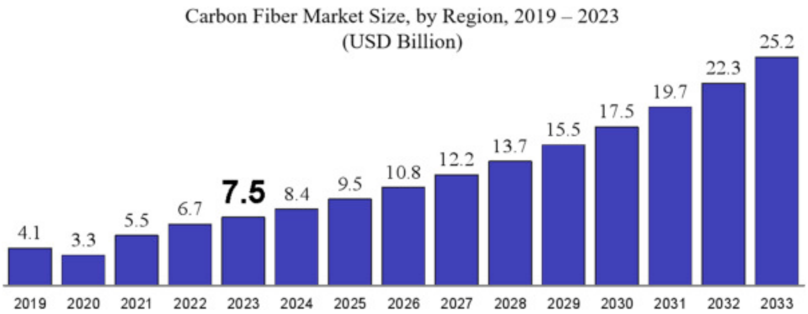

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Fig. 1. Carbon Fiber Market Size, by region 2019–2023.

The aim of this study is to investigate specific strategies for enhancing the domestic carbon fiber and its composites industry while bolstering research and industrial competitiveness. This entails analysing the research, industry, market, and trade aspects of carbon fiber and its composites both domestically and internationally, with the goal of devising measures to ensure global competitiveness. To advance the domestic carbon fiber and its composites research and industry while ensuring competitiveness, Korea is proposing a response plan founded on thorough research and industry analysis, coupled with a comprehensive diagnosis of competitiveness. The industry is poised for significant growth, with a projected Compound Annual Growth Rate (CAGR) exceeding 11 % by 2023. Recognizing the competitive landscape, with countries like Japan, the United States, Germany, and China leading in carbon valley initiatives, Korea is actively pursuing policies to bolster domestic production of carbon fiber and its composites. The research of this study mainly contains the four major part: technological trends in the industry and research of the carbon fiber and its composites, import/exports trends environment, and industrial competitiveness, future direction on the carbon fiber and its composites industry and research.

2. Carbon fiber and its composites manufacturing in Korea

The domestic carbon fiber materials company can be divided broadly in the two parts, example materials field and applied product fields. Materials field is manly comprised the large companies with annual sales exceeding the millions of the USD. There are three major companies, Hyosung, Toray Korea's, and Kolon, producing the carbon fiber in the Korea as mentioned in Table 1. Toray is a Japanese company; however, it has production facilities in South Korea, known as Toray Korea. The companies those manufacturing the fabric using the carbon fiber as the raw materials are Korea Carbon, Korea Advanced Materials, Hyundai Fiber, Gangnam Fiber, Saenal Tech, JMC, KGF, etc., mainly small and medium size companies as mentioned in Table 2. The domestic prepreg market is mainly produced and supplied by about the 10 companies ranging from the large companies to small and medium-sized companies, including the Korea Carbon, SK Chemicals, TB Carbon, and Joyang Chemical. The manufacturing of the applied products in the domestic carbon fiber field are conducting business and research and development with the companies in each product group, and the field in which actual sales are generated are mainly industrial materials, such as sports leisure and electronics, machinery, etc. There are many companies in the aerospace and automobile field those are only parts supplier or they are still in the research and development stages. In the aerospace field, Korean Air, Korea Aerospace, and Hanwha Advanced Materials mainly produce carbon fiber composites parts for airlines and defense industries, followed by Hankuk Fiber, Tech Aviation, and Kolon. Most of them are in the defense industries, and the civil aviation sector is not that big compared to the overseas. In the automobiles field, various parts and materials companies are participating along with automakes such as, Hyundai Motor Company, Renault Korea, SungWoo HiTech, Kolon Glotech, Hanwha Advanced Materials, Iljin Hisolus/Aetherct, and Elim D&P/Tera/BOBS.

Table 1. Status of domestic carbon fiber and processed materials companies.

Carbon fiber	Carbon fiber pre-preg
Toray Advanced Materials korea	Hankuk Carbon
Hyosung Advanced Materials	TB Carbon
Korea Carbon	HD Fiber
Korea Advanced Materials	Hanwha Advanced Materials
Saenal Tech	Other small and medium size companies
KGF	

Table 2. Current status of composites materials parts manufacturing companies using domestic carbon fiber.

Field		Participating Companies
Aerospace		**Korean Air, Korea Aerospace Industry, Hankuk Fiber, Songwol Technologies, Kolon DACC Composite, HIZE Composites Industries**
Transpotation	Automobile	Hyundai Motor Company, Renault Korea, Shina T&C, SungWoo HiTech, Tera Engineering, Korea Mold, Carbon Art, Hyundai Steel, Kolon Glotech, Hanwha Advanced Materials, Iljin Hisolus/Aetherct, Elim D&P/Tera/BOBS, etc.
	Ship hull	Kostech, and Ventus
Energy	Pressure Vessels	Iljin Hysolus, ENERGYN
	Electric wire	Dain
	Fuel cell	VINATech
	Wind power generation	Human Composites, Geum Poong Energy, Korea Mold etc.
Architecture/Civil Engineering	Earthquake-resistant reinforcement etc.	Hankuk Carbon, JMC, Hanil Carbon, etc.
Electronic/Mechanical	Robot	Carbon Craft, KM, Lacomtech, etc.
	Drone	Sungjin Energy
	Roll	JWIN Hyundai
Sports/Leisure	Golf shaft	Ahwagolf, PHOENIX
	Fishing rod	N.S Black Hole, KWF, KUMYANG, KIGANISM, NDF, DIF
	Archery	FIVICS, WIAWIS
	Bicycle	Samchuly Bicycle, JS Composites, TPOL, Comet Bicycle, Alton Sports, Amotion etc.
Medical Equipment	Medical Devices	J-One, Carbon Craft, Biolux, Nano Focus Ray, Dongyang Carbon etc.

3. Research and innovation in carbon fiber composites in Korea

Carbon fiber composites have gained significant attention in various industries due to their lightweight, high strength, and durability properties. In Korea, there has been notable research and innovation in the development and application of carbon fiber composites across different sectors, driven by both governmental initiatives and private sector investments.

3.1. Research and development in Korea Industries

Research and development (R&D) in Korean industries are crucial drivers of innovation and competitiveness in the global market, as outlined in various research activities in Table 3.

Table 3. Overview of research and development activities in Korean industries, institutes, and Universities.

```
Research and Development in Korean Industries
|
|-- Hyundai Motor Company
|     |
|     |-- Structural Parts
|     |     |-- 2014-2015: Innovating CFRP roof panels and the HED-9 Intrado
|     |     |-- 2015: Investment in multi-material joining and forming technology
|     |     |-- 2018-2019: Testing and producing rear partition panel using fiber spray and WCM processes
|     |     |-- 2022-2023: Applying automatic fiber placement techniques
|     |     |-- 2022-2023: Investment in electrification and aims for EV sales
|     |
|     |-- Exterior and Interior Parts
|     |     |-- 2016-2017: Producing lightweight, high-quality carbon fiber parts
|     |     |-- 2018-2019: Mass production of components using advanced processes
|     |     |-- 2020-2021: Introduction of "N Performance" with improved carbon fiber parts
|     |     |-- 2022-2023: Exploration of bio-based materials for sustainability
|     |
|     |-- Chassis
|     |     |-- 2015-2016: Focus on small vehicle leaf springs
|     |     |-- 2017-2019: Adapting springs for heavy vehicles
|     |     |-- 2020-2021: Development of 3D braiding strut bars
|     |     |-- 2022-2023: Development of CFRP wheels using RTM
|     |
|     |-- Hydrogen Tank and Future Mobility
|           |-- 2015-2016: New material assessment
|           |-- 2017-2019: Hydrogen tank qualification tests
|           |-- 2020-2023: Accelerating lightweight solutions
|
|-- Hanwha Advanced Materials
|     |
|     |-- Research and Development
|           |-- Production of composite material using SMC technology
|           |-- Development of UV-SMC material with superior UV performance
|
|-- SungWoo HiTech
|     |
|     |-- Research and Development
|           |-- Development of advanced composite-material forming techniques
|           |-- Integration of body, engine, and drive systems using advanced composites
|
|-- KOLON Industry
|     |
|     |-- Research and Development
|           |-- Specializes in advanced composite materials for aviation and defense systems
|           |-- Offers solutions from material selection to production and testing
|
|-- Hyosung R&D Labs
|     |
|     |-- Research and Development
|           |-- Focus on securing capabilities for the company's expansion into new business domains
|           |-- Development of innovative products and processes
|
|-- Korea Aerospace Industry
|     |
|     |-- Research and Development
|           |-- Known for aircraft, helicopters, and aerospace components
|           |-- Develops parts like fuselage panels or wing components using advanced manufacturing techniques
|
|-- Hankuk Fiber Composites
|     |
|     |-- Research and Development
|           |-- Offers a wide range of advanced prepregs tailored for various industries
|           |-- Developing materials for zero-emission transportation and advancements in fire-retardant battery enclosures and pressure vessels
|
|-- Korea Composites Inc
|     |
|     |-- Research and Development
|           |-- Leader in composite parts manufacturing and MRO services
|           |-- Focus on delivering top-quality composite parts
|
|-- ANH Structure
|     |
|     |-- Research and Development
|           |-- Specializes in aerospace, contributing to the defense aerospace sector
|           |-- Developing platforms for electric, hydrogen, and air mobility vehicles
|
|-- Songwol Technologies
|     |
|     |-- Research and Development
|           |-- Excels in R&D, holding certifications like NADCAP and AS9100
|           |-- Contributing significantly to the industry with a meticulous composite manufacturing process
|
|-- Other Companies' Research and Development
|     |-- Companies like SK innovation, LOTTE CHEMICAL, ILJIN Hysolus, Shinsung, AJIN, T4L, Dong Sung TCS, and AETHERCT are driving advancements in their respective domains
|-- TB Carbon
|     |
|     |-- Research and Development
|           |-- Specializes in Carbon Prepreg technology
|           |-- Focus on R&D with advanced equipment

|-- Research and Development in Korean Research Institutes and Universities
|
|-- Key Institutes and Universities
|     |
|     |-- KIMS: Liquid composite molding, Pultrusion, Hot press molding
|     |-- KIMCD: Hot press molding
|     |-- KOTMI: Hot press molding, Automated Fiber Placement (AFP)
|     |-- K-carbon: Pultrusion, HP-RTM
|     |-- KIST Jeonbuk: HP-RTM
|     |-- KITECH: Hot Press Molding
|     |-- UNIST: Autoclave, Simulation
|     |-- Pusan National University: Compression Forming
|     |-- Hanyang University: RTM
|     |-- Seoul National University: Press Molding
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3.1.1. Hyundai Motor Group, revolutionizing automotive composite materials

The Hyundai Automotive Group has been actively involved in research activities concerning composites across various facets of vehicle design and manufacturing [35]. Their efforts encompass structural parts, interior and exterior components, chassis, hydrogen tank development, and future mobility solutions. Between 2014 and 2015, Hyundai began innovating CFRP roof panels and the HED-9 Intrado, using new manufacturing techniques [36] to revolutionize car construction. In 2015, the Hyundai Motor Company invested 12.38 billion KRW in multi-material joining and forming technology, focusing on carbon fiber composites for a multi-material body-in-white (BIW) structure [37]. From 2018-19, Hyundai tested the CFRP roof panel and produced a rear partition panel using fiber spray and WCM processes. From 2022-23, automatic fiber placement (AFP) techniques were applied for optimization. Hyundai Motor Group is at the forefront of research integrating AFP techniques into automotive manufacturing. The AFP can be applied for the production of flat panels, curved beams, and metal hybrid bonding. While specific public disclosures from Hyundai are limited. A notable example is the development of a prototype carbon fiber hood for an electric vehicle, where the company utilized AFP to reduce production costs as shown Fig. 2 [38]. Initially, the carbon fiber composite hood was 5.8 times more expensive than its steel counterpart, but through the implementation of AFP, Hyundai was able to lower this to 4.9 times the cost of steel. This initiative reflects Hyundai's commitment to exploring advanced manufacturing techniques to enhance efficiency and reduce costs. While AFP is more commonly associated with the aerospace industry, its application in automotive manufacturing is gaining traction as companies like Hyundai seek to leverage its benefits for producing lightweight and high-strength components. These advancements are expected to enhance the performance and efficiency of future electric and autonomous vehicles, reduce environmental impact through lightweight and sustainable material usage. Set new benchmarks for precision manufacturing in the automotive industry.

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Fig. 2. Carbon fiber hood for electric vehicle developed by Hyundai Motor using AFP machines.

Hyundai Motor Group plans to invest 68 trillion won ($50 billion) in electrification and aims to sell 1.5 million EVs annually by 2030 [39]. In 2023, Hyundai sold 695,000 eco-friendly vehicles, a 37.1 % increase from the previous year. Earlier this year, Hyundai Motor Co. and KIA Corp. reorganized their R&D unit and created a new division for software-defined vehicles (SDVs) and mobility solutions. From 2018-19, Hyundai's EV underbody R&D using pultrusion saved 65 % weight. By 2022–23, they developed a multi-rib pultrusion process for low-cost materials. Hyundai's research and innovation progressed through phases. From 2016 to 2017, they focused on producing lightweight, high-quality carbon fiber parts. By 2018–2019, they achieved mass production of components like bumpers and mirrors using advanced processes. In 2020–2021, Hyundai introduced performance lines such as "N Performance" with improved carbon fiber parts. By 2022–2023, they explored bio-based materials to enhance sustainability while maintaining performance. Hyundai Motor Group's innovation in composite materials for chassis is outlined through their focus on small vehicle leaf springs in 2015–16, achieving rapid curing and high durability. From 2017-19, the focus shifted to adapting these springs for heavy vehicles, optimizing curing for thicker applications. In 2020–21, innovation advanced to 3D braiding strut bars for complex geometries. By 2022–23, they developed CFRP wheels using RTM, ensuring they met or exceeded traditional wheels in strength and performance. Hyundai Motor Group's research and innovation from 2015 to 2023 in hydrogen tank and future mobility include assessing new materials, especially carbon fiber and epoxy matrices, for strength, stiffness, and durability in 2015–2016. From 2017 to 2019, efforts shifted to qualifying hydrogen tanks per standards like KGS, EC79, and ECE R134, ensuring safety and reliability.

Hyundai Automotive Group's research on composites focuses on developing lightweight, high-performance materials for vehicle structures, interiors, and mobility solutions. Advancements include CFRP and GFRP panels, multi-material body-in-white structures, and automated fiber placement for enhanced strength and efficiency. Key innovations in interior and exterior trims involve PCM-based preforming, high-athletic GFRP, and crash-resistant pultrusion techniques. Chassis and hydrogen tank research emphasize composite leaf springs, 3D braiding strut bars, CFRP wheels, and hydrogen tank qualification to improve durability and sustainability. The introduction of composite battery cases and drive shafts enhances safety and performance in next-generation mobility. Hyundai's commitment to sustainability is evident in bio-based materials and low-cost, high-strength pultrusion methods. Their work accelerates lightweight solutions through documentation and technical engineering support, driving the future of automotive manufacturing with advanced composite technologies that optimize weight, safety, and production efficiency for electric, hydrogen, and high-performance vehicles. Future research in automotive composites focuses on sustainable materials, multi-material structures, and lightweight solutions for enhanced performance and efficiency. Battery housing advancements emphasize composite-based structures to reduce weight while maintaining strength. Electric motors integrate CFRP rotors and aluminum stators for improved efficiency. Multi-material BIW structures enhance durability and noise control. Composite exterior panels and natural fiber trims promote sustainability. Chassis innovations include magnesium sub-frames and lightweight materials for better handling. Interiors incorporate bio-based, recyclable materials with self-cleaning surfaces for enhanced comfort. These advancements align with Hyundai's commitment to eco-friendly, high-performance solutions for future mobility.

3.1.2. Hanwha Advanced Materials, pioneering lightweight and eco-friendly solutions

Established in 1965, Hanwha Advanced Materials has pioneered innovative, eco-conscious products meeting global demand [40]. With local production and R&D centers in Korea, spun off from Hanwha Solutions in December 2022, they are recognized globally as an advanced materials specialist, offering lightweight composites and solar materials. Entering automotive materials in 1986, they've crafted high-strength, super-lightweight products using original technologies. Their diverse portfolio includes StrongLite, SuperLite, Expanded Polypropylene (EPP), Sheet Molding Compound (SMC), Long Fiber Thermoplastic (LFT), and Continuous Fiber-Reinforced Thermoplastic Composite (CFRTPC). As the sole producer of multiple materials, they offer comprehensive solutions. With factories in key regions and major automotive clients like Hyundai, Kia, BMW, and Toyota, they dominate markets with StrongLite and SuperLite [41] materials. They are committed to R&D, focusing on lightweight trends, smart cars, and EVs. Hanwha Advanced Materials utilizes Sheet Molding Compound (SMC) technology to produce a composite material with excellent moldability and low stickiness. SMC is made by impregnating chopped fiber strands into a compound of unsaturated polyester resin, filler, and other agents, enhancing its viscosity and strength. This material is used in the construction and automotive industries [42,43], notably for battery cases in electric and hybrid vehicles. Hanwha, in collaboration with IDI Composites, developed UV-SMC material with superior UV performance and impressive mechanical properties, including a tensile modulus of 14 GPa and tensile strength of 200 MPa. For the company in the pursuit of next-generation advancements, a diverse array of materials are being incorporated to enhance the light-weighting concept. Efforts to reduce the weight of floor beds are underway, achieved through the utilization of fabric-reinforced SMC and the exploration of material diversification. Furthermore, the implementation of UV GMT technology aims to enhance surface quality. Notably, there is significant interest surrounding textile SMC local reinforcement products and UV SMC technology. Hanwha's research in composite materials focuses for automotive, aerospace, defense, and renewable energy applications. In the automotive sector, they develop CFRP and GFRP components to enhance fuel efficiency and crash resistance. Aerospace research emphasizes high-performance thermoplastic composites for lighter, more durable aircraft structures. In defense, Hanwha advances ballistic composite materials for superior impact resistance in protective armor. Their renewable energy efforts include composite wind turbine blades for improved efficiency and longevity. Prioritizing sustainability and innovation, Hanwha integrates advanced manufacturing techniques to enhance performance, durability, and environmental benefits across multiple industries.

3.1.3. SungWoo HiTech: advancing lightweight platforms for mobility

SungWoo HiTech's entry into the composite materials sector is driven by its R&D centers and research labs, fostering innovation and technological advancements. The Yangsan R&D Center, expanded and relocated in 2014, focuses on prototyping and testing composites. The Suwon Research Lab, established in 2015, develops specialized CAD/CAE technologies for designing and simulating composites. The Wuxi Research Lab, opened in 2012, also engages in prototyping and materials testing. SungWoo HiTech expanded into North America with the Detroit Office in 2016. They are currently developing advanced composite-material forming techniques: Composite-Material PCM Forming, RTM Forming, and Hybrid Simultaneous Forming. Since 2022, they have been developing the CTB platform, integrating body, engine, and drive systems using advanced composites, reducing vehicle weight by 21 % and enhancing efficiency. Future plans include platforms for electric, hydrogen, and air mobility vehicles, leveraging lightweight materials for sustainable, advanced transportation solutions.

Sungwoo Hitech is actively engaged in research and development of composite materials to enhance automotive manufacturing. Their focus includes advanced forming techniques such as Composite-Material PCM Forming, which involves molding and curing carbon fiber prepreg materials under heat and pressure, and Composite-Material RTM Forming, where resin is injected into fiber preforms within a mold and cured under controlled conditions. Additionally, they are developing Composite-Material Hybrid Simultaneous Forming, combining metallic or non-metallic materials with preformed reinforcements to create complex structures. These innovations aim to produce lightweight, high-strength automotive components, contributing to vehicle weight reduction and improved performance.

3.1.4. Kolon Industries: innovating aerospace and defense composites

Established in 2001, KOLON Industry specializes in advanced composite materials for aviation and defense systems, developing ultra-lightweight, ultra-strong, and ultra-high-temperature products. They offer solutions from material selection to production and testing, aiming to lead the advanced composite materials sector, a future core business of the KOLON Group. They are expanding into emerging markets like space satellites, projectiles, and Urban Air Mobility (UAM). Key products include aircraft fuel tanks, airframe structures, engine vanes, submarine hulls, sonar domes, guided weapon launchers, bulletproof materials, satellite structures, and combustion tubes. R&D efforts supported national projects such as the Smart UAV 1 with Korea Aerospace Industries (2005–2009), high-pressure vessels for natural gas/hydrogen storage (2005–2007), and the Composite Window Frame for aircraft with the Korea Institute of Industrial Technology Evaluation and Planning (2005–2007) [44]. Other initiatives include the Technology Development of Core Components for High Voltage Power Equipment with KERI (2007–2010), the Aviation Safety Technology Development Program with Korea Aerospace Industries (2008–2009), and the Global Shared Growth R&BD program (2012–2015). KOLON DACC's innovations include external fuel tanks for T/TA/FA-50 and KT(O)-1 aircraft [45], and the Wing Assembly for Korea GPS Guided Bomb deployment, enhancing battlefield readiness. Their innovative portfolio reinforces their leadership in aerospace technology development, advancing military capabilities and national security. KOLON DACC has advanced military and marine technology through R&D. Key contributions include the K21 Armored Vehicle with a composite hull for enhanced protection [46], the VLS Gas Management System using high-temperature resistant materials [47], and submarine projects like Jangbogo-III and Indonesia Type 209 [48]. KOLON DACC's R&D focuses on diverse composite materials. Innovations include the Composites LCD Rubbing Roller [49], high-pressure vessels like Type III CNG and hydrogen CNG composites [50], and specialized medical and firefighting vessels. They also produce composite TV back covers [51], automotive leaf springs, and Composite Deck Gates, emphasizing innovation and sustainability.

In 2020, Kolon Clotech entered automotive parts manufacturing, solidified with the AP Pohang Plant in 2022 for small production [52]. The AP Cheonan Factory became the LFI Automated Mass Production Main Factory in 2024 [53]. Using advanced processes, they produce automotive components [54] like roofs, hoods, and doors.

Kolon Industries advancements include the development of aramid fibers, known for their exceptional strength and heat resistance, utilized in automotive and aerospace industries. The company is also pioneering in eco-friendly materials, such as biodegradable plastics and recycled polymers, contributing to environmental sustainability. Through participation in global exhibitions like JEC World 2022, Kolon showcases its innovative composite material solutions, emphasizing lightweight and durable components for ground, air, and space mobility. These efforts underscore Kolon's commitment to leading in advanced materials for a sustainable future.

3.1.5. Hyosung R&D labs: leading innovation in synthetic fibers and composites

Established in 1971 as Korea's inaugural private research center, Hyosung R&D Labs has been at the forefront of innovation within the synthetic fibers industry, playing a pivotal role in driving Korea's industrial advancement throughout the 1970s. In a landmark development in September 2006, the integration of the Central R&D Center and Manufacturing Technologies Lab culminated in the formation of Hyosung R&D Labs. This strategic consolidation was further refined in 2011, with the labs categorized into five Major Research Groups, each tailored to leverage the company's foundational technology for the creation of novel growth opportunities. Committed to technological advancement, Hyosung R&D Labs dedicates itself to securing the necessary capabilities for the company's expansion into new business domains while concurrently fostering the development of innovative products and processes within existing sectors, with the aim of accelerating their commercialization. Established in December 1999, TB Carbon Co., Ltd leads the Korean carbon composite industry, specializing in Carbon Prepreg technology [[55], [56], [57]]. Their composites are used in automotive, aerospace, and sports leisure. The TB CARBON Advanced Composite Material R&D Center [58], established in 2009, focuses on R&D with advanced equipment. Hyosung Advanced Materials has made significant strides in composite materials research, particularly in the aerospace and automotive sectors. The company developed ultra-high-strength carbon fibers and achieved domestic certification for aerospace-grade prepreg materials. Their advancements also include the development of pressure vessel towpregs, which improve the safety and efficiency of critical components. Additionally, Hyosung has prioritized sustainability by creating recycled PET yarns for various applications, including automotive and textiles. They also introduced antimicrobial safety belts for vehicles, further enhancing safety and hygiene standards, demonstrating their leadership in innovative composite solutions.

3.2. Research and development in Korea research institutes and universities

In Korea, a robust landscape of research and development initiatives in composite materials thrives, led by renowned research institutes and university laboratories as mentioned in Table 3. These efforts span diverse research fields and techniques, contributing to the evolution of composite materials technology across industries. The Korea Institute of Materials Science (KIMS) pioneers research in carbon fiber composite sheet construction methods and high-content thermoplastic composites, utilizing techniques like liquid composite molding and hot press molding to yield structures with tailored properties. The Korea Institute of Materials Convergence Technology (KIMCO) focuses on high-performance core convergence materials, enhancing mechanical properties through hot press molding. The Korea Textile Machinery Convergence Research Institute (KOTMI) develops processes for recycled carbon fiber (rCF) composites, promoting sustainability through advanced techniques like hot press molding and automated fiber placement (AFP). The Korea Carbon Industry Promotion Agency (K-Carbon) advances functional carbon fiber and carbon black composites through pultrusion and high-pressure resin transfer molding (HP-RTM), serving the automotive, aerospace, and electronics industries. Additionally, K-Carbon conducts research and development in carbon composite materials technology, including Automated Fiber Placement (AFP) and Automated Tape Placement (ATP), facilitating product manufacturing through advanced equipment under the leadership of the Carbon Commercialization Technology Center [59,60]. Academic institutions such as the KIST Jeonbuk Institute of Advanced Composite Materials and the Research Institute of Medium & Small Shipbuilding (RIMS) drive innovation in composite applications through techniques like HP-RTM and resin infusion. The Korea Institute of Industrial Technology (KITECH) specializes in carbon fiber-reinforced thermoplastic composite manufacturing for automotive and aerospace applications. Universities such as the Ulsan National Institute of Science and Technology (UNIST) conduct experimentation for composites using advanced techniques like autoclave processing and simulation. Specialized labs across universities contribute expertise in multifunctional composites, structural battery composites, and convergence materials and applications. These collaborative efforts reflect Korea's dedication to advancing composite materials technology across industries. Leveraging cutting-edge research and manufacturing techniques, Korea aims to lead in the global composite materials market and drive innovation in next-generation composite structures. Key research entities include KIMS, KIMCO, KOTMI, K-carbon, KIST Jeonbuk, RIMS, KITECH, UNIST, and others, employing various techniques such as liquid composite molding, pultrusion, hot press molding, AFP, HP-RTM, and autoclave processing to innovate and enhance composite material applications across multiple sectors.

3.3. Past technological R&D roadmap for composite materials in Korea based on the major companies

Fig. 3 details the past development achievements, gaps, and opportunities from 2014 to 2023 for various companies in the composite materials industry. Hyundai Motor Company focused on CFRP roof panels and advanced joining technology, addressing gaps in manufacturing and structural optimization with opportunities in new carbon fiber composites and full vehicle structure implementation. SungWoo HiTech developed 3D braiding strut bars, aiming to overcome challenges in complex geometries and structural integrity with topology optimization and vehicle weight reduction opportunities. KOLON Industry advanced composite materials for aviation and defense, targeting gaps in ultra-lightweight and high-temperature materials with opportunities in space technology and national security enhancements. Hyosung R&D Labs innovated synthetic fibers, seeking to expand into new domains with R&D capabilities for diverse applications. TB Carbon developed Carbon Prepreg technology, addressing cost-effective production gaps with opportunities in automotive, aerospace, and sports sectors. Korea

Aerospace Industry developed aerospace composite materials, aiming to fill gaps in high-performance, lightweight components with opportunities to enhance aircraft performance. Each company demonstrates a commitment to advancing composite materials, addressing industry gaps, and leveraging new opportunities for technological and market expansion.

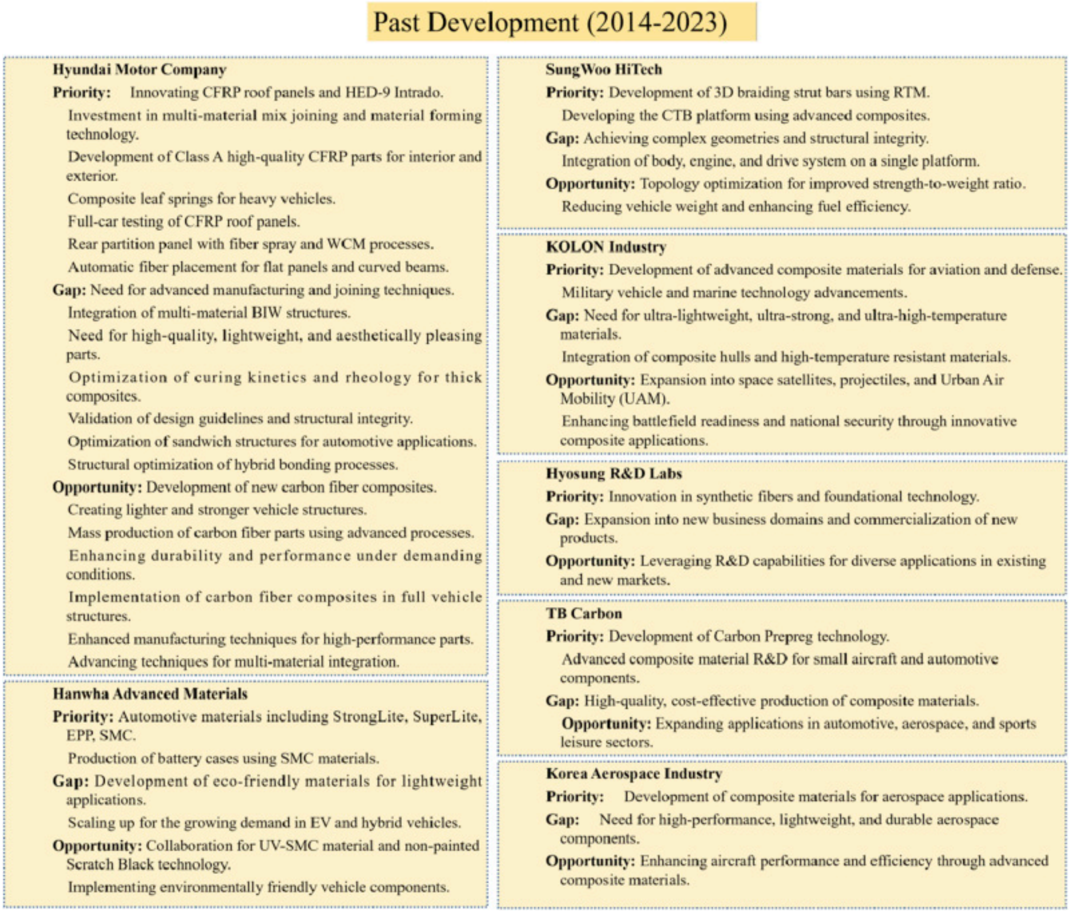

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Fig. 3. Technological R&D roadmap for composite materials in Korea.

3.4. Future technological R&D roadmap for composite materials in Korea based on the major companies

Fig. 4 outlines future directions for various companies in the composite materials industry post-2023. Hyundai Motor Company focuses on electrification, autonomous driving, and advanced air mobility, with a gap in transitioning to all-electric models, aiming to lead in sustainable composites. Hanwha Advanced Materials prioritizes lightweight composites and material diversity, addressing UV performance and mechanical properties, seeking leadership in EV and smart car trends. SungWoo HiTech develops platforms for electric, hydrogen vehicles, and air mobility, with a gap in lightweight materials, aiming to shape future transportation with sustainable solutions. KOLON Industry advances automotive parts manufacturing, addressing mass production scaling, leveraging long fiber injection for innovation. Hyosung R&D Labs focuses on advanced composites, targeting high performance and cost-effective production, aiming to expand applications in multiple industries. TB Carbon emphasizes composite material R&D for small aircraft and automotive components, addressing thermal-shock resistance and mechanical properties, seeking innovative applications. Korea Aerospace Industry aims for innovations in light utility aircraft and advanced composites, addressing fuel efficiency and operational flexibility, expanding applications in civil and military aviation. Each company targets advancements in composites, addressing current gaps, and leveraging future opportunities.

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Fig. 4. Future technological R&D roadmap for composite materials in Korea.

3.5. Roadmap for sustainable development of composite materials in Korea

The roadmap (as shown in Fig. 5) for sustainable development of composite materials in Korea emphasizes key initiatives including recycling carbon fiber, developing sustainable epoxy resin, and aligning local goals with global sustainability objectives. Comprehensive Life Cycle Assessments (LCA) are crucial to achieving carbon neutrality, while CFRP rehabilitation and regulatory trends are monitored to stay compliant and innovative. The development of CFRP hydrogen storage containers and sustainable automotive applications are prioritized to enhance safety and efficiency. Ongoing research and collaboration among institutions are fostered to address emerging sustainability topics. Regular stakeholder engagement ensures transparency and progress tracking. Investing in research and development drives innovation, with an emphasis on bio-based and recyclable materials. Quarterly reviews and adaptive strategies maintain momentum, while advocacy for supportive policies promotes regulatory alignment. This cohesive approach aims to position Korea as a leader in sustainable composite materials development, leveraging innovation and collaboration for significant advancements.

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Fig. 5. Roadmap for sustainable development of composite materials in Korea.

4. Applications of carbon fiber and its composites technology in Korea

4.1. Automotive industry

The Korea automotive industry is focusing on lightweight vehicle design to meet stringent environmental regulations and fuel efficiency standards, aligning with global trends to reduce greenhouse gas emissions as mandated by the 2015 Paris Agreement. To achieve carbon neutrality by 2050, the Korean government aims to enhance fuel efficiency regulations by over 30 % by 2030 compared to 2020 levels [61]. This has driven significant research into advanced materials, including carbon fiber and its composites [[62], [63], [64]]. Korean automakers are implementing a phased strategy to reduce vehicle weight, which includes the use of high-strength steel, lightweight metals such as aluminum and magnesium, expanded use of plastics, and the application of Carbon Fiber Reinforced Polymer (CFRP) [65]. Despite its high cost, CFRP offers over 50 % weight reduction [66], enhanced thermal insulation, reduced noise and vibration [67,68], improved corrosion resistance [[69], [70], [71]], better processability, and increased impact resistance [[72], [73], [74], [75], [76], [77]]. Korean companies are developing high-speed, mass-production technologies to enhance CFRP's cost competitiveness [[78], [79], [80]]. Hyundai's Intrado hydrogen fuel cell concept car [81], using TANSOME carbon fiber from Hyosung, reduced vehicle weight by over 60 %, winning the JEC2015 Innovation Award a shown in Fig. 6a. Another model, the N 2025 Vision Gran Turismo [82], featuring a next-generation hydrogen fuel cell system and CFRP body, reduces total weight to 972 kg, enhancing performance and handling as shown in Fig. 6b. In 2017, Hyundai patented a CFRP front chassis structure in the U.S., enabling a lighter car body with fewer, lighter parts while enhancing rigidity, targeted for high-performance N brand vehicles. Project C, unveiled at the 68th Frankfurt Motor Show, features extensive CFRP application, reducing the car's weight by 50 kg to improve handling dynamics, underscoring the performance benefits of CFRP. KIA Motors mass-produced sunroof parts using carbon fiber composite material for the All New Sorento in 2014 [83,84], lightning the vehicle and enhancing driving stability as shown in Fig. 7. KIA and Hyundai are expanding the application of CFRP to the sunroofs of various models. In collaboration with Dymag, Hankuk Carbon, and Hyundai, a concept carbon fiber hybrid wheel [85] was developed for the Hyundai Ioniq 5 NNPX1 vehicle in July 2023, demonstrating potential for advanced N Performance parts as shown in Fig. 8. The Korean government and private sectors are jointly promoting research to expand CFRP application in automobiles, including developing an AI prediction model to optimize CFRP material properties. Research into CFRP-metal hybrid materials aims to combine the strengths of composites and metals, improving impact resistance and reducing weight [86,87]. As electric vehicles (EVs) [88] tend to be heavier due to their batteries, reducing their weight is crucial. Hyundai's partnership with Japan's Toray Group aims to develop CFRP specifically for EV applications. Despite the significant benefits of CFRP, its high cost remains a barrier to widespread adoption, especially for popular vehicle brands. Reducing CFRP costs through automated processes, low-cost material development, and recycling initiatives is crucial. Continuous innovation in materials, components, and manufacturing processes is essential for CFRP to become a core material in the automotive industry. Some CFRP components have already been commercialized in luxury automobile brands in Korea, but further advancements in material and process technology are needed for broader use.

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Fig. 6. a) Developed CFRP vehicle (Intrado, Hyundai Motors) and b) CFRP applied automotive (HyundaiN 2025 VisionGran Turismo) [89,90].

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Fig. 7. Developed CFRP sunroof frame for all new sorrento [91].

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Fig. 8. Devolved Automotive CFRP Wheel (Hyundai Motors) advanced wheel concept.

4.2. Marine and shipbuilding industry

The International Maritime Organization (IMO) regulations compel the shipbuilding industry to adopt eco-friendly technologies [92], emphasizing lightweight materials with robust properties. Global efforts focus on eco-friendly fuels, regulatory compliance, and efficiency enhancements as shown in Fig. 9. Developing high-performance materials for eco-friendly ship components is ongoing [[93], [94], [95]], driven by the demand for strong, light, and corrosion-resistant hulls and equipment. These materials are expected to reduce weight in automotive and aviation sectors, prioritizing lightweight, eco-friendly designs, and replacing heavy steel with composites to improve fuel efficiency and reduce CO_2 emissions as shown in Fig. 9. The EU's E-LASS network leads research in composite technology for marine applications. The IMO's focus on energy efficiency has boosted lightweight hull technology development [[96], [97], [98], [99]]. Shipbuilding is shifting towards large composite materials, enhancing cargo capacity, reducing weight, and improving efficiency as shown in Fig. 10. This trend underscores composites' importance in shipbuilding, driven by the industry's need for eco-friendly materials amid stringent regulations. Hyundai Heavy Industries has made significant strides in the application of composite materials within the shipbuilding sector, notably securing a patent for a ship propeller and its manufacturing method using composite materials [100] designed specifically for large commercial ships. This innovation aims to enhance propulsion efficiency while reducing weight and maintenance costs, contributing to the overall operational efficiency and environmental performance of modern commercial vessels. Hanwha Ocean leads in marine composite material technology, replacing traditional wind wall materials in offshore plants with lightweight, durable composites, enhancing structural integrity and longevity. They are developing SPS plate composite panels for hatch covers, bulkheads, and other critical ship components, improving strength, efficiency, and reducing emissions. S-com tech develops integrated solutions for large composite radar masts [99], enhancing maritime operations with improved durability, weight reduction, and resistance to harsh environments. Using composite materials, S-com tech aims to boost the performance and lifespan of radar masts, critical for navigation and communication, driving innovation in shipbuilding. To meet greenhouse gas emission regulations and enhance energy efficiency, small and medium-sized ships must use composite lightweight materials. This requires defining product specifications optimized for each ship type. Performance verification and design engineering technologies must meet structural, fire, and saltwater resistance standards. Additionally, optimizing molding methods and developing an integrated value chain are essential.

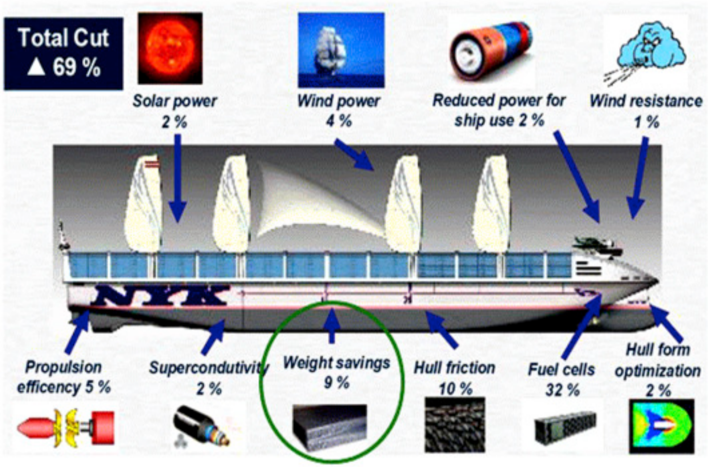

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Fig. 9. Measures to reduce CO2 and improve energy efficiency for eco-friendly ships.

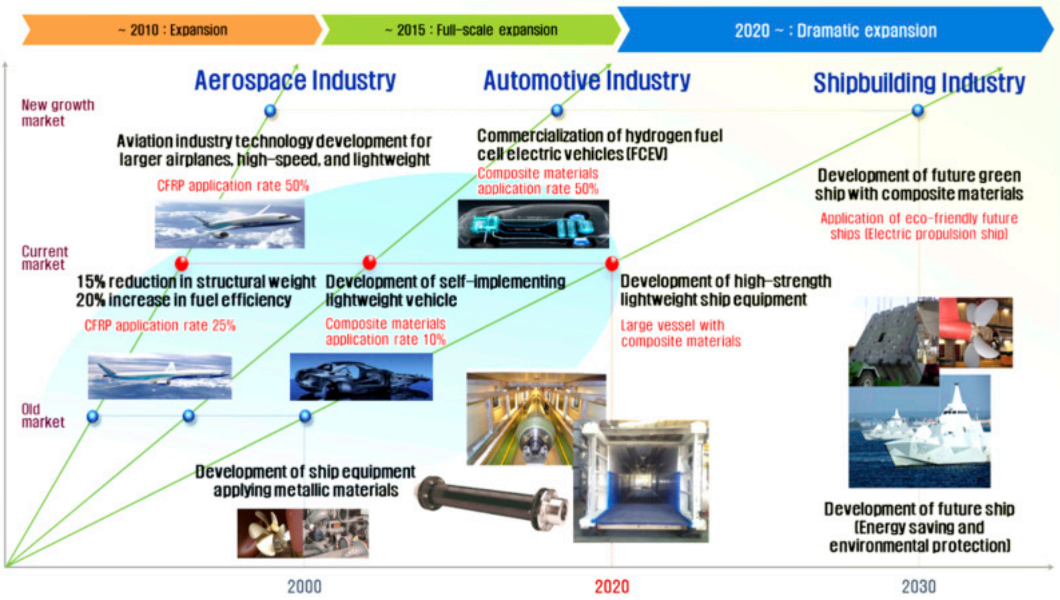

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Fig. 10. Growth trends of composites in different industries.

4.3. Aerospace industry

Korea's aviation industry is diverse [[101], [102], [103]], with companies specializing in airframe manufacturing, aircraft parts, avionics, engines, and Urban Air Mobility (UAM) as shown in Fig. 11. Carbon Fiber Reinforced Polymer (CFRP) is widely used for its high strength-to-weight ratio [[104], [105], [106], [107], [108], [109]]. About 70 % of airframes and parts are exported to Boeing (Fig. 12) and Airbus (Fig. 13). The industry includes 45 airframe companies, 24 avionics companies, 15 parts producers, 5 engine manufacturers, and 5 UAM companies as shown in Table 4. System integration is managed by KAI and KOREAN AIR, highlighting Korea's robust aerospace capabilities.

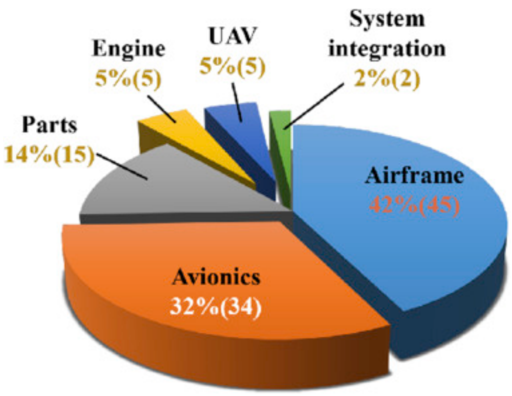

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Fig. 11. Various companies contributing to different aspects of aircraft parts production.

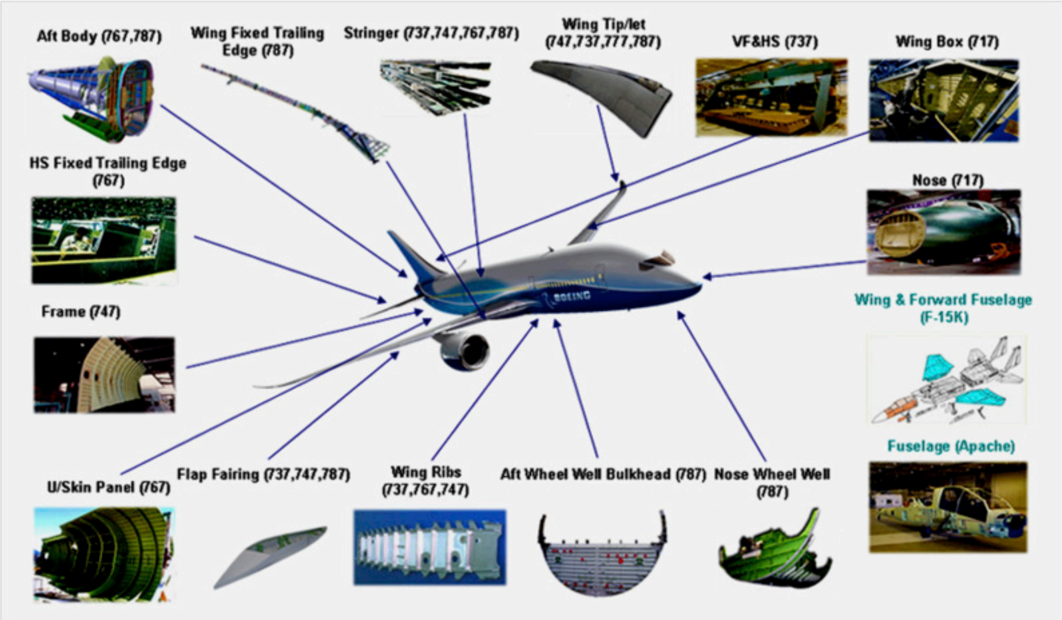

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Fig. 12. Various types of composite materials applied to aircraft parts.

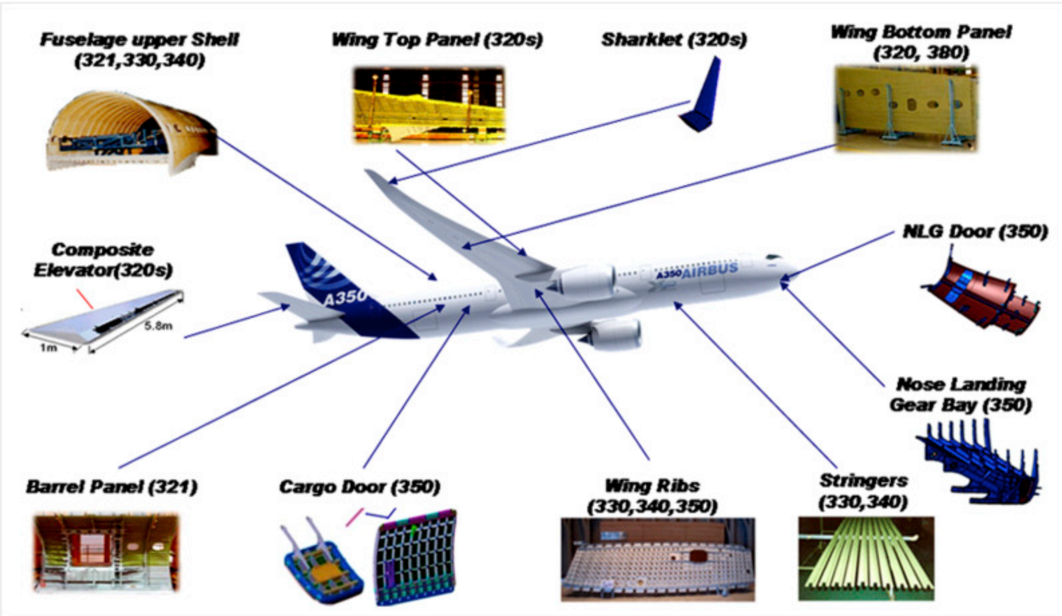

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Fig. 13. Various types of composite materials applied to aircraft parts.

Table 4. The number of Korean companies making aircraft component.

No. of Companies	Part Name	Main Companies
45	Airframe	ASTK, SAMCO, YULKOK, HIZE AERO
24	Avionics	LIG Nex, HANWHA SYSTEM
15	Aircraft Parts	HYUNDAI-WIA, HANWHA
5	Engine	HANWHA TECHWIN, KOREA LOST-WAX

5	UAM	KAI, KOREAN AIR, UNCOSYSTEM
2	System Integration	KAI, KOREAN AIR

The Korean aerospace industry is growing with the use of sustainable carbon fiber composites. Korea aims to be a top-seven global aerospace leader by 2020, focusing on projects like the KF-X fighter jet and LAH/LCH helicopters, which enhance performance and reduce environmental impact [110,111]. Major initiatives include the T-50A bid and KUH-1 Surion helicopter variants. Research emphasizes commercial aircraft parts, leveraging sustainable composites for lighter, stronger components, and the Urban Air Mobility program aims to revolutionize urban transport with advanced materials.

4.4. Hydrogen storage vessel industry

Integrating hydrogen fuel cells into transportation is crucial for reducing carbon emissions, with road transport contributing 75 % of sector emissions [112,113]. Korea began adopting hydrogen fuel-cell vehicles in 2013 with the Hyundai Tucson, transitioning from internal combustion engines [114,115] as shown in Fig. 14. These vehicles use composite materials for hydrogen tanks, primarily carbon fibers for their tensile strength and durability. The Hyundai Nexo, introduced in 2018 (as shown in Fig. 14), features three 52-L hydrogen storage tanks for a total capacity of 156 L [116]. This advancement extends to hydrogen buses and trucks, promoting greener transportation and a sustainable future [117] as shown in Fig. 15.

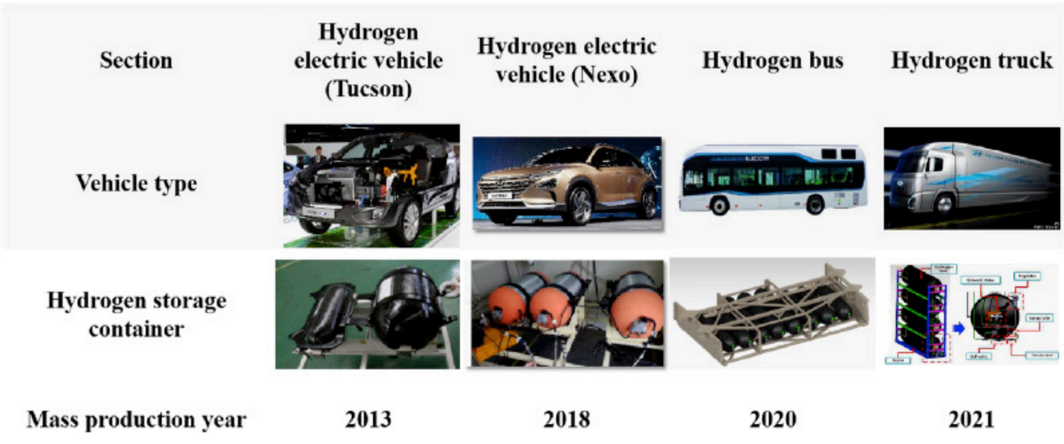

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Fig. 14. The application of the Hyundai Motor's hydrogen vehicle and its mass production plan.

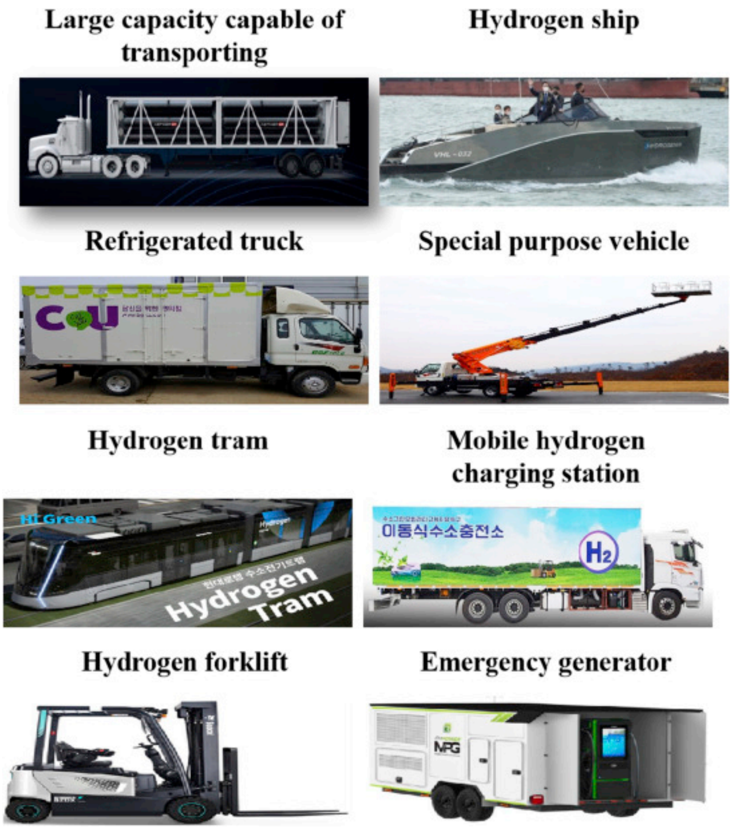

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Fig. 15. Wide range of applications aimed at revolutionizing transportation and infrastructure.

Korea's adoption of CFRP-made hydrogen storage containers [118] spans various sectors, revolutionizing transportation and infrastructure (Fig. 15). These containers ensure safe high-pressure hydrogen transport, promoting eco-friendly advancements. Innovations include hydrogen ships, trams, and mobile charging stations. Hydrogen-powered trucks, forklifts, and emergency generators improve efficiency, reduce emissions, and ensure reliable operations, driving widespread use across diverse industries.

4.5. Past and future technological R&D roadmap for composite materials in Korea based on the applications

Fig. 16 contrasts past development and future directions for various sectors in the composite materials industry based on the on the applications. Domestic Carbon Fiber focused on establishing a foothold in the market, with limited production capacity as a gap, and now aims to enhance production capacity and market share, leveraging technology transfer and partnerships. Domestic Automotive prioritized the adoption of carbon fiber composites, facing high costs and limited adoption, with future directions focusing on optimizing manufacturing technology and addressing market challenges. Marine and Shipbuilding aimed to meet IMO regulations with composite materials, limited by performance verification, and now targets advanced materials for marine applications, aiming for market growth. Aerospace focused on carbon fiber composites for aerospace, with small market share and ongoing investment as gaps, aiming to expand market presence and increase competitiveness. Hydrogen Storage developed hydrogen storage solutions with limited market share and high costs, now focusing on efficiency and safety of hydrogen storage tanks, targeting rapid market growth. Each sector seeks to address past gaps and leverage future opportunities for technological and market advancements.

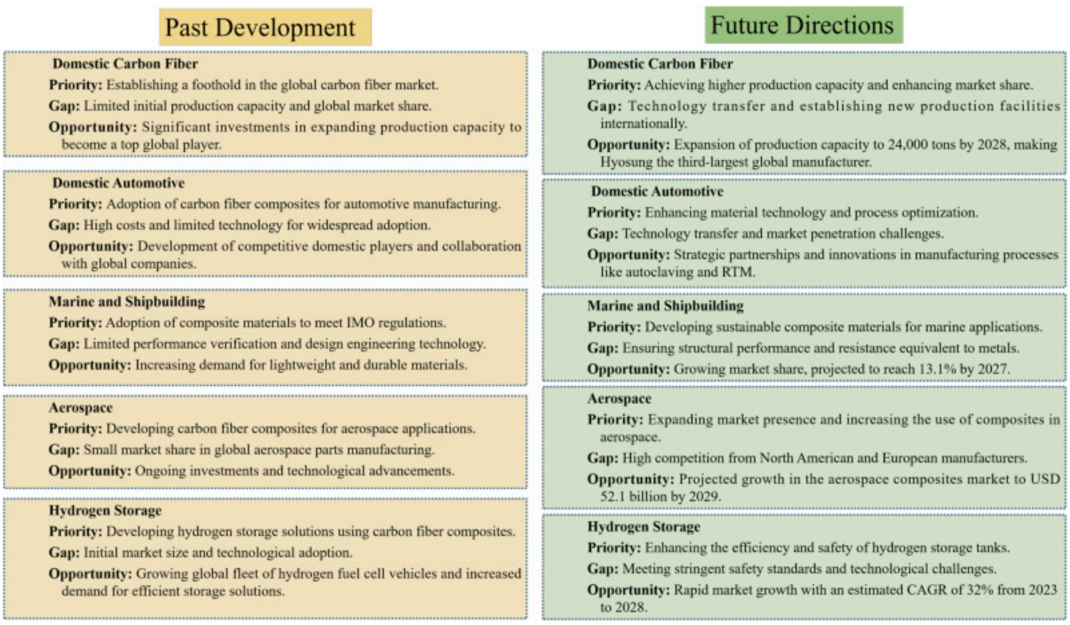

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Fig. 16. Past and Future Technological R&D Roadmap for Composite Materials in Korea based on the applications.

5. Domestic and international carbon fiber and its composites market and industry trends

5.1. Global market and industry trends

In 2023, the global carbon fiber market was valued at USD 7.48 billion and is projected to grow at a CAGR of 12.9 % over the next decade (Fig. 17) [119,120]. This growth is driven by carbon fiber's adoption in aviation, space exploration, energy, automotive, architecture, civil engineering, sports, and recreation. From 2010 to 2019, Toray significantly boosted carbon fiber production and market share, increasing capacity from 17,000 to 57,000 tonnes and market share from 23 % to 35 % [[121], [122], [123]]. Mitsubishi Chemical also expanded, growing from 6150 to 16,000 tonnes and maintaining a 10 % market share. Hexcel increased its production capacity from 7300 to 16,000 tonnes and its market share from 9 % to 10 %. Chinese alliances contributed 14 % of the market with 21,800 tonnes. These companies, particularly Toray, Mitsubishi Chemical, and Hexcel, have been pivotal in the industry's growth, as depicted in Fig. 18.

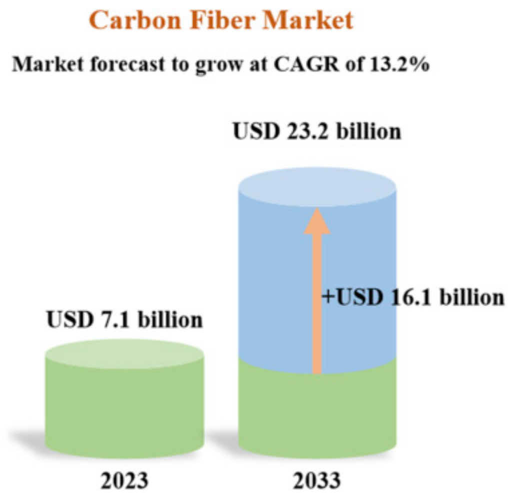

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Fig. 17. Global carbon fiber market forecast from 2023 to 2033 [120].

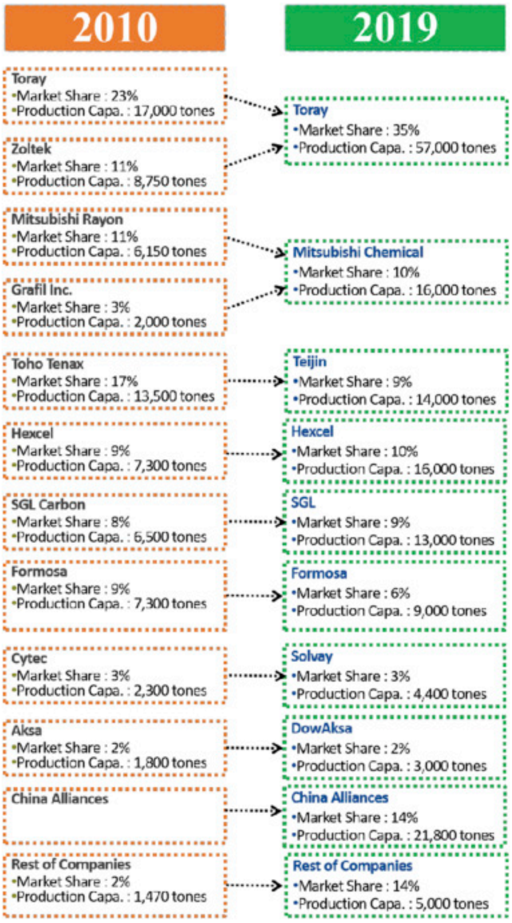

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Fig. 18. Global companies' carbon fiber production capacity and market share.

Segmentation by application reveals distinct categories including automotive, aerospace & defense, wind turbines, sports/leisure, molding & compound, construction, pressure vessel, and others as shown in Fig. 19 [124]. Notably, the aerospace & defense sector dominated with a substantial revenue share of 32.0 % in 2022 and is anticipated to maintain robust growth, projected at a CAGR of 11.3 % throughout the forecast period.

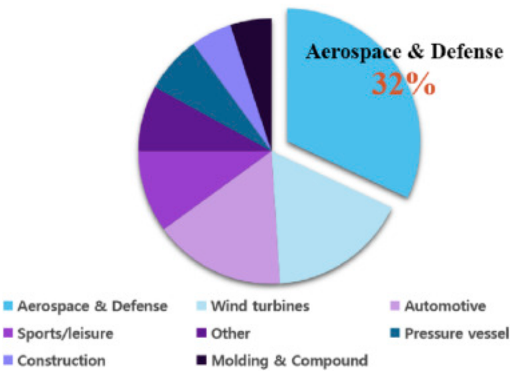

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Fig. 19. Section by carbon fiber application for distinct categories (2022) [124].

In 2020, Wind Turbine Blades and Aerospace emerged as the leading consumers of carbon fiber globally (as shown in Fig. 20), with demand reaching 30.6 kt and 16.5 kt, respectively. Despite challenges faced by the aerospace sector, particularly in civil aviation and business jets, which experienced significant setbacks, the wind power segment continued to exhibit robust growth at 20 %. The effective capacity of the global carbon fiber industry reached 167.9 kt in 2020, marking an increase of approximately 8 kt compared to the previous year, 2019 [119,120,125].

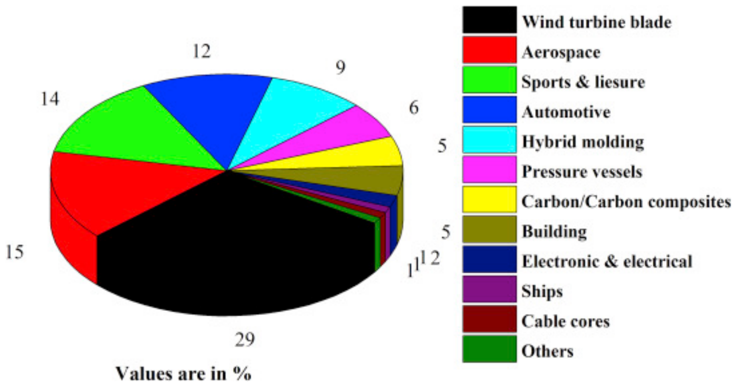

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Fig. 20. Section by carbon fiber application for distinct categories (2020) [125].

In 2022, the Global Carbon Fiber Composites Market achieved remarkable expansion, surging to a value of USD 2.23 billion as shown in Fig. 21. Analysts anticipate this growth trend to persist, with a projected compound annual growth rate (CAGR) of 6.50 % forecasted by 2028 [120]. Renowned for their unparalleled strength-to-weight ratio, these cutting-edge materials are increasingly indispensable across diverse industries such as aerospace, automotive, and wind energy.

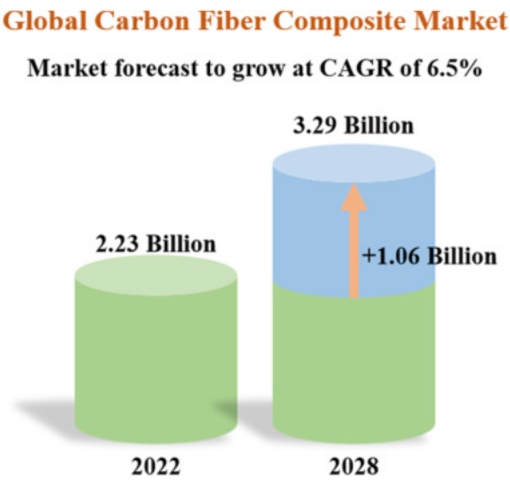

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Fig. 21. Global carbon fiber composites market forecast from 2022 to 2028.

The provided Fig. 22 illustrates the global demand for CFRP composites spanning from 2008 to 2025 [126]. Notably, the utilization of CFRP composites has demonstrated a consistent upward trend since 2014. By 2021, consumption had surged to approximately 181 kt, representing more than a twofold increase from the levels observed in 2014. Projections indicate that demand is poised to further escalate, reaching an estimated 285 kt by 2025.

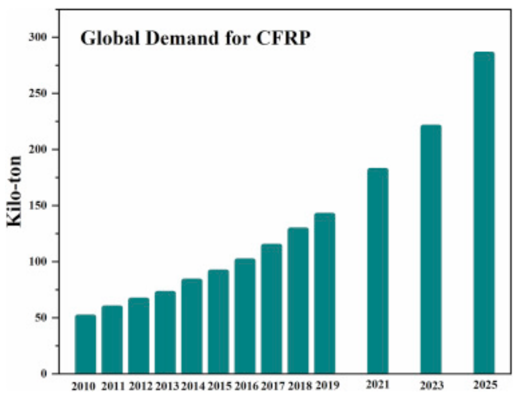

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Fig. 22. Global demand for CFRP composites spanning from 2008 to 2025.

5.2. Domestic market and industry trends

As per the year 2017 as illustrated in Fig. 23, the capacity of the carbon fiber production in the Korea was 6700 tons, by the domestic carbon fiber production companies, the 4700 tons from the Toray Korea's [127] and 2000 tons produced by the Hyosung Advanced Materials [[128], [129], [130]]. It increased to the 8600 tons in the 2018, but due to pandemic the growth was slow to reached 13,700 tons in 2023, but it is expected to grow fastser to reach 24,500 in this year. While Hyosung Advanced Materials is in the early stages of establishing a presence in the global carbon fiber market, Toray Korea's has maintained a leading position for years. In an effort to catch up with Toray Korea's, Hyosung Advanced Materials has embarked on an ambitious expansion strategy. The company plans to invest 1 trillion won to increase its production capacity to 24,000 tons per year by 2028. This new facility, Toray Korea's third carbon fiber production unit, will boost Korea's annual production capacity by 3300 tons, reaching a total of 8000 tons. According to the statics the demand of the carbon fiber in the Korea was 3460 tons in the 2017, however it might increase four times in the recent years.

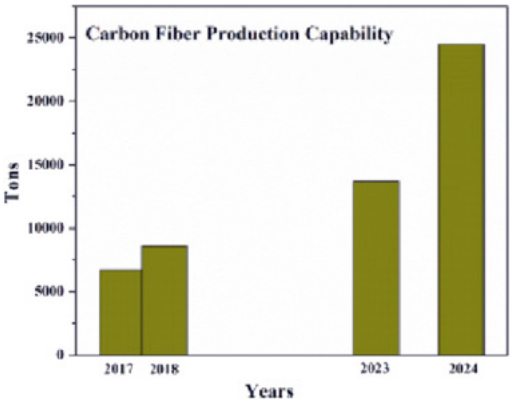

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Fig. 23. The capacity of the carbon fiber production in the Korea.

6. Import and export of carbon fiber and its composites in Korea

6.1. Import and export of carbon fiber

The data highlights Korea's carbon fiber export and import trends from 2017 to 2023, reflecting its evolving role in the global market [[131], [132], [133]]. Exports surged from 4952 units in 2017 to 10,033.6 units in 2023, indicating enhanced manufacturing capabilities and quality. Technological advancements and stronger trade partnerships contributed to this growth. Imports initially rose from 2747 units in 2017 to 2956.9 units in 2022, then declined to 2446.1 units in 2023, showing improved self-sufficiency and production efficiency. This dual trend signifies Korea's competitiveness and increasing self-reliance, marking its transition into a significant carbon fiber exporter, as depicted in Fig. 18.

6.2. Import and export of carbon fiber composites

Korea is a key player in the carbon fiber composites market, both importing and exporting these materials. In recent years (as shown in Fig. 24), Korea has actively engaged in global trade of advanced materials [134,135]. In 2023, Korea imported around 8500 tons of carbon fiber composites, primarily from Japan, the United States, and China. Korea also exported approximately 6200 tons of carbon fiber composites to the United States, Germany, and China, used in aerospace, automotive, and construction industries. The market is expected to grow, driven by demand from high-tech industries. Companies like Toray Advanced Materials Korea are expanding production to meet domestic and international needs.

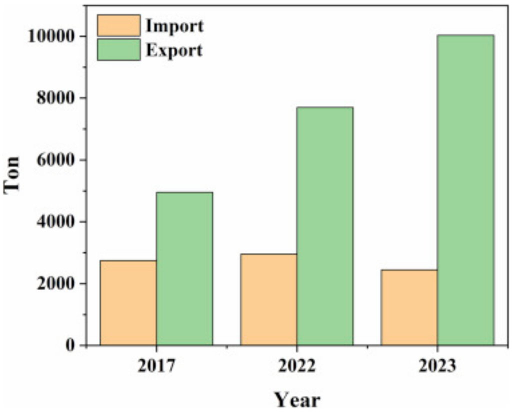

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Fig. 24. Korea's import and export of carbon fiber composites.

7. Technological competitiveness analysis, challenges, and future directions

7.1. Carbon fiber

Hyosung is the only Korean company capable of manufacturing high-intensity, high-strain carbon fiber, crucial for CNG fuel tanks and hydrogen storage tanks in vehicles. Their specialized carbon fiber, TANSOME, launched in 2011 and mass-produced since 2013, ensures strength and durability for critical components (Fig. 25). By 2019, Hyosung produced 2000 tons annually, holding 1 % of the global market. This increased to 9000 tons and a 5.65 % market share by 2023, with projections of 16,500 tons in 2024. Hyosung plans to invest one trillion won by 2028 to expand its Jeonju plant, aiming for an annual capacity of 24,000 tons [129]. This will make Hyosung the world's third-largest carbon fiber manufacturer, commanding about 10 % of the global market.

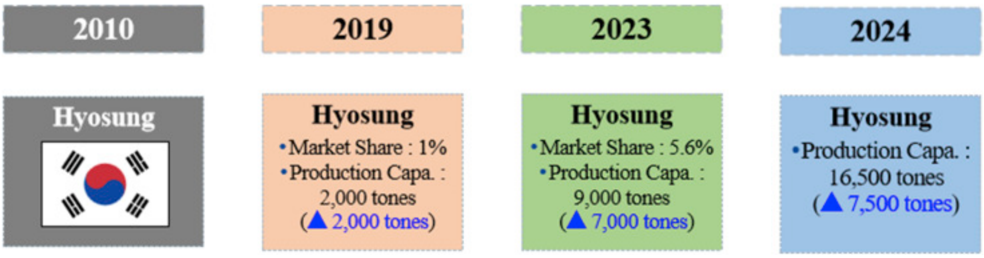

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Fig. 25. Hyosung's carbon fiber production capacity and global market share.

The future of carbon fiber in Korea is set to be shaped by significant investment, technological advancements, and a strong push for self-sufficiency in the industry. The South Korea has committed to investing USD 139.6 million by 2030 to develop carbon composite materials, with a particular focus on carbon fiber, which is critical for the aerospace, defense, and automotive sectors [136]. One of Korea's primary goals is to reduce the cost of carbon fiber, which is currently priced at around USD 20 per kilogram, to USD 10 per kilogram. The aims to achieve this by developing low-cost raw materials and energy-efficient production technologies. By lowering the cost of carbon fiber, Korea hopes to increase its adoption across industries, including aerospace, automotive, and infrastructure, where the demand for lightweight, high-strength materials is growing rapidly. This cost reduction could make carbon fiber more accessible, opening up new opportunities for innovation in manufacturing. The investment also focuses on enhancing the strength and elasticity of carbon fiber. It plans to develop ultra-strong carbon fibers that are 15 times stronger than iron and fibers with ultra-elastic properties 13 times greater than steel. These advancements would position Korea as a leader in producing high-performance carbon fibers, meeting the evolving demands of industries that require materials with superior mechanical properties. In terms of technological innovation, Korea recently became the third country to secure original technology for producing high-strength carbon fiber with a tensile strength of 6.4 GPa. This breakthrough positions the country as a key player in the global carbon fiber market. With plans to establish mass production systems for this material by 2025, Korea aims to meet both domestic and international demand for high-performance carbon fiber in critical sectors like aerospace and defense. Hyosung, a leader in Korea's carbon fiber production, has already made significant strides in developing ultra-strong carbon fibers for use in aerospace and defense applications. However, the company acknowledges the need for further development of a robust industrial ecosystem to fully realize the potential of carbon fiber and compete with global leaders in the U.S. and Japan. By fostering public-private partnerships and investing in technological advancements, Korea is poised to become a global leader in the carbon fiber industry, driving innovation and reducing production costs for this critical material.

7.2. Carbon fiber composites are revolutionizing automotive manufacturing

Carbon fiber composites are revolutionizing automotive manufacturing with their high strength-to-weight ratios. Companies like Mubea CarboTech, TTL Adler Plastic S.p.A, and Multimatic CFT produce BIW structural parts and exterior components. Novation Tech uses braiding and LP-RTM for BIW parts and seats, while HP Composites S.p.A excels in autoclaving exterior parts. Toray Carbon Magic and Cobra International specialize in closures and body panels, respectively. Action Composites, C2i (Hankuk Carbon), and Sparco S.P.A. use autoclaving and prepreg processes. SGL Carbon employs HP-RTM and WCM for pillars and tunnels, while Voith Composite and Teijin focus on exterior panels as shown in Fig. 26, Fig. 27, Fig. 28. Hyundai Steel, SungWoo HiTech, and Kolon Glotech provide competitive domestic options as shown in Fig. 29. Hanwha Advanced Materials and Iljin Hisolus/Aetherct specialize in battery cases and hydrogen tanks. Despite challenges in technology transfer and market penetration, collaboration and innovation drive growth in this sector. Fig. 26 illustrate various manufacturing processes adopted by companies, such as autoclaving, LP-RTM, press molding (as shown in Fig. 27), and in-house factories (as shown in Fig. 28). The autoclave method, including the Vacuum Bag process, is used for high-performance vehicles like the Stinger and G70 EV, producing high-strength, lightweight components ideal for luxury vehicles as shown in Fig. 30. The RTM process, applied in vehicles like the Light Tactical Vehicle and Grandur, involves injecting resin into a mold with dry fibers, yielding complex shapes with good mechanical properties. Filament winding [137,138] is crucial for fuel cell electric vehicles like the Nexo FCEV and Elec City FCEV, creating high-strength, lightweight cylindrical components. Pultrusion, particularly HP-RTM/PCM, is used in vehicles like Solati for rapid production of high-quality parts. CF-SMC, used in the IONIQ 5 SE, molds carbon fiber sheets for automotive body panels and structural components. Korean industries focus on innovation in material technology, process optimization, and advanced technologies like CFRTIP, DAFT, LFT, Injection Molding, and GMT to improve efficiency and minimize environmental impact [139,140]. Emphasizing recyclable and eco-friendly materials ensures sustainable solutions, maintaining a competitive edge while addressing environmental concerns. Future designs for battery housing will incorporate enhanced steel and mixed aluminum/steel/composite structures, emphasizing high strength and reduced weight [141]. For electric motors, future trends involve sinter material compounds, lightweight aluminum stators, CFRP rotors, graphite innovations, and high-temperature superconductivity [142]. BIW structures will increasingly use UHSS, PHS, 7-series aluminum alloys, and hybrid floor structures, with future designs featuring multi-material bodies and active body structures [143,144]. Exterior closures will shift to include composite panels, natural fibers, biopolymers, and recyclable materials. Chassis components will reduce un-sprung mass with plastic and composites, magnesium sub-frames, and forged control arms. Interior designs will emphasize weight reduction and comfort, incorporating natural fiber trims, illuminated surfaces, self-cleaning surfaces, and using aluminum, magnesium, and composites in seat frames. These roadmaps reflect Korea's commitment to sustainability, innovation, and efficiency, paving the way for advanced composite applications.

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Fig. 26. Autoclaving & LP-RTM adopted by various companies to manufacture composite materials for automobile.

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Fig. 27. Press molding adopted by various companies to manufacture composite materials for automobile.

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Fig. 28. In-house factories adopted by various companies to manufacture composite materials for automobile.

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Fig. 29. Manufacturing process and parts of composite materials for automobile of domestic part supplier.

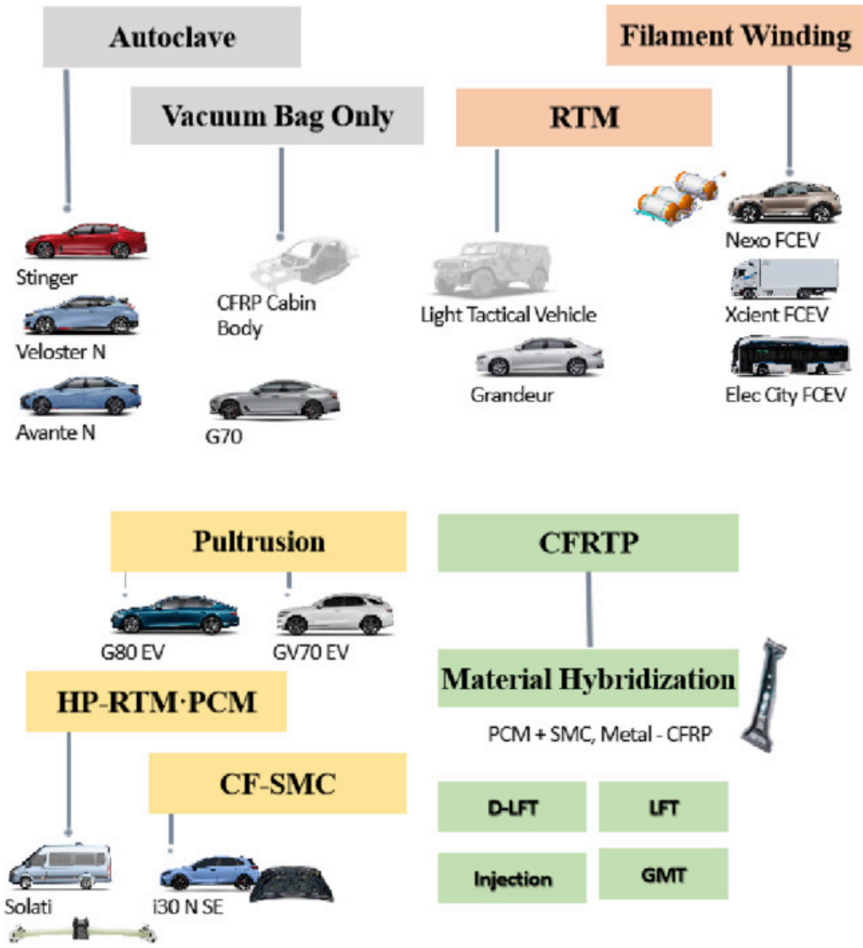

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Fig. 30. Types of domestic automobile according to the manufacturing process.

7.3. Carbon fiber composites are revolutionizing in marine and shipbuilding

The domestic marine composite materials market, accounting for 11 % of the global market in 2023, is expected to grow at an average annual rate of 12.8 % by 2027. Due to IMO regulations, the competitiveness of the composite materials industry is crucial for market growth. The market is projected to grow from KRW 1.5636 trillion in 2021 to KRW 3.4371 trillion by 2027, occupying approximately 13.1 % of the global market by then (Fig. 31). This growth is driven by advancements in composite material technologies that enhance performance and sustainability. The demand for lightweight, durable, and corrosion-resistant materials in the marine industry promotes the use of composites over traditional materials. Emphasis on reducing carbon emissions and improving fuel efficiency aligns with composite properties, making them a preferred choice for shipbuilders. Continuous innovation, investment in R&D, and collaboration among industry stakeholders bolster the domestic market's competitive edge, ensuring strategic growth in the marine sector.

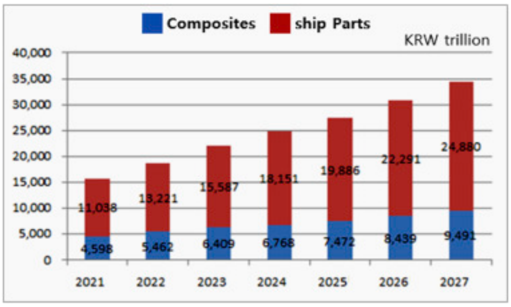

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Fig. 31. Domestic marine composite materials and equipment parts market size.

To meet greenhouse gas emission regulations and improve energy efficiency, small and medium-sized ships must utilize composite lightweight materials. This requires determining optimal product specifications and securing performance verification and design engineering technology suitable for marine environments [145]. Ensuring structural performance, fire resistance, and saltwater resistance comparable to metal materials is essential. Optimizing molding methods for composite parts and developing a value chain from materials to products is crucial, as shown in Table 5. This approach enhances efficiency and compliance with environmental regulations [146].

Table 5. Roadmap for technology development of ship structures using composites [147].

Ship structures using composite materials	Development of materials and systems for lightning ships			
	2020	2025	2030	Final goal
Composite material layered structure hull	O	O	O	Securing technology to manufacture FRP hulls through a lamination process of reinforcing materials such as glass fiber and carbon fiber
Composite material applied deck house	O	O	O	To reduce the weight of ships and improve stability, ship deck houses made of existing metal materials are replaced with composite materials
CFRP applied pressure vessel	O	O	O	Secure technology to design and manufacture fuel storage containers for LNG, LPG, hydrogen, etc. for small and medium-sized coastal ships
CFRP applied rotor sail	O	O	O	Rotor sail lightweight structure manufacturing technology using the Magnus effect to improve the propulsion efficiency of ships
CFRP applied wing sail	O	O	O	Wing sail manufacturing technology using carbon fiber composite material as auxiliary equipment for ship propulsion using wind power

7.4. Carbon fiber composites are revolutionizing in aerospace

The Aerospace Composites Market grew from USD 14.66 billion in 2018 to USD 26.9 billion in 2023, and is projected to reach USD 52.1 billion by 2029 with a CAGR of 12 % [[148], [149], [150]] (Fig. 32). The market is segmented into carbon fiber, ceramic fiber, and glass fiber composites, with carbon fiber composites accounting for over 50 % in 2023 (Fig. 33). Carbon fiber's high stiffness and strength reduce aircraft weight, enhancing efficiency. The National Renewable Energy Laboratory (NREL) reports a 10 % annual growth in carbon fiber demand from 2016 to 2024, potentially constituting over 60 % of the market by 2035.

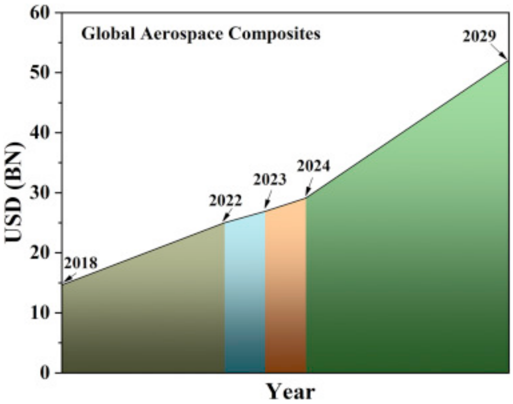

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Fig. 32. Global aerospace composites market from 2018 to 2029.

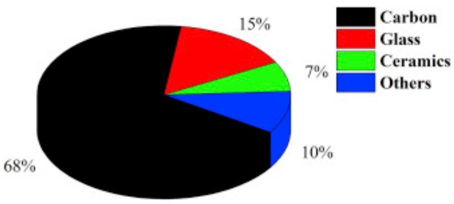

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Fig. 33. Section of fiber making the aerospace composites.

According to the report [151,152], Korea produced 35 % of aircraft parts, mainly from carbon fiber composites. The domestic aircraft parts market was valued at 2078 million USD in 2017, 1911 million USD in 2018, 2111 million USD in 2019, 2009 million USD in 2020, 2256 million USD in 2021, 3025 million USD in 2022, and 3354 million USD in 2023 (Fig. 34). Korea holds a minor share, less than 1 %, of the global composite aircraft parts market due to competition from major North American and European players. However, ongoing investments and technological advancements indicate significant growth potential for Korea in this sector [153].

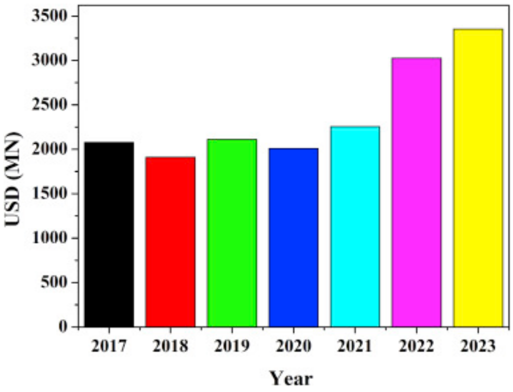

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Fig. 34. Domestic aircraft parts market from 2017 to 2020.

7.5. Carbon fiber composites in hydrogen storage

The estimated value of the worldwide hydrogen energy storage market [154] stands at approximately USD 208.3 million in 2023, with projections indicating a surge to approximately USD 934 million by 2028 as shown in Fig. 35. This growth trajectory signifies a robust Compound Annual Growth Rate (CAGR) of 32 % from 2023 to 2028. The most of the hydrogen storage tank made of the carbon fiber composites. carbon fiber composites are indeed a popular choice for manufacturing hydrogen storage tanks. They offer several advantages such as high strength-to-weight ratio, corrosion resistance, and durability, making them ideal for storing hydrogen safely and efficiently. These tanks play a crucial role in various hydrogen applications, including fuel cell vehicles, stationary power generation, and industrial processes [155].

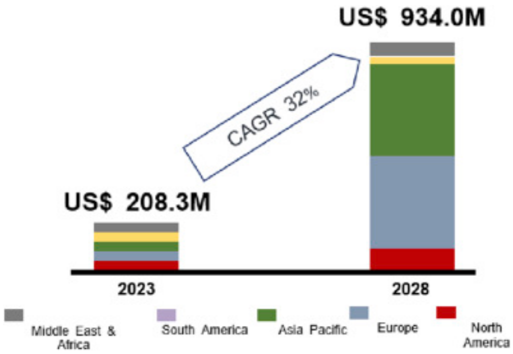

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Fig. 35. The worldwide hydrogen energy storage market from 2023 to 2028.

According to the Global EV Outlook 2023 report [156] by the International Energy Agency (IEA), the global fleet of hydrogen fuel cell electric vehicles (FCEVs) saw a remarkable 40 % surge in 2022, surpassing 72,000 vehicles compared to the previous year. Notably, Korea boasted a significant portion of this global fleet, with 29,623 hydrogen vehicles, accounting for 41 % of the total count as shown in Fig. 36. By 2023, Korea had further increased its FCEV count to 34,258 vehicles, and as of 2024, it stands at 34,872 vehicles, solidifying its position as a major contributor to the global FCEV market [157].

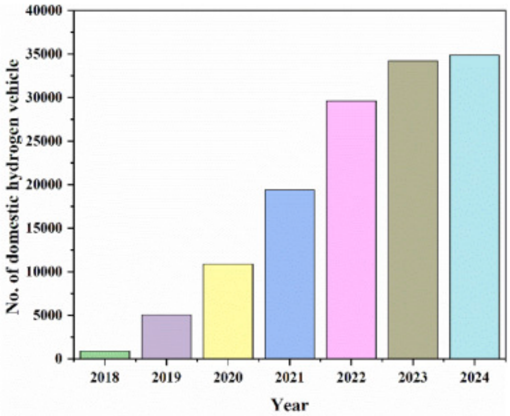

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Fig. 36. The number of domestic hydrogen vehicle.

8. Conclusion

- Korea's carbon fiber industry is robust and diverse, encompassing both large-scale manufacturers like Hyosung, Toray Korea's, and Kolon, and numerous small to medium enterprises specializing in fabrics, prepregs, and applied products across various sectors.
- Major companies are significantly investing in R&D to enhance carbon fiber composites. Innovations are focused on automotive, aerospace, and future mobility applications, emphasizing lightweight, high-performance materials and advanced manufacturing techniques.
- Carbon fiber composites are integral to multiple industries, including automotive, marine, aerospace, hydrogen storage, and sports. Their adoption is driven by their superior strength-to-weight ratio, durability, and ability to meet stringent performance and regulatory standards.
- Korea's carbon fiber production capacity is expanding rapidly, supported by substantial investments. This growth is aimed at meeting increasing domestic and global demand, with production expected to continue rising significantly in the coming years.
- The industry is dedicated to sustainability, focusing on the development of recyclable and bio-based materials, and conducting comprehensive life cycle assessments (LCA). The use of carbon fiber in lightweight structures contributes to fuel efficiency and significant CO2 emission reductions, particularly in the automotive sector.
- Continuous innovation in material technology and process optimization is a hallmark of Korea's carbon fiber industry. This includes the development of new manufacturing techniques, automated processes, and hybrid materials that enhance the performance and cost-effectiveness of carbon fiber composites.
- Korea's carbon fiber industry benefits from strong collaboration between government, research institutes, and private companies. This synergy drives technological advancements and positions Korea as a competitive player in the global carbon fiber market, contributing to its strategic growth and innovation leadership.

CRediT authorship contribution statement

Yun-Hae Kim: Supervision, Resources, Project administration, Funding acquisition. **Sanjay Kumar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kyo-Moon Lee:** Writing – review & editing. **Se-Yoon Kim:** Writing – review & editing. **Sung-Won Yoon:** Writing – review & editing, Data curation. **Sung-Youl Bae:** Writing – review & editing, Data curation. **Do-Hoon Shin:** Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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