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REVIEW

Sustainable Development of Carbon Fiber Industry: An Environmental, Social and Governance Perspective

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Abstract: The growing demand for high-performance materials has expanded the use of carbon fiber in aerospace, automotive manufacturing, sports equipment, and defense technology due to its lightweight, high-strength, and high-stiffness properties. However, the rapid development of the carbon fiber industry poses significant environmental, social, and governance (ESG) challenges that threaten its sustainable development. Environmentally, the production of carbon fiber is energy-intensive and high in emissions, impacting sustainability despite the material's life cycle benefits in reducing energy consumption and greenhouse gas emissions. Additionally, the immature recycling technology for carbon fiber waste presents challenges for environmental protection and circular economy efforts. Socially, the industry's growth demands new labor market skills but also affects worker health and safety, community quality of life, and social equity. Increasing public concern over the environmental and social impacts of carbon fiber products requires the industry to balance economic benefits with social responsibilities. In terms of governance, the rising importance of corporate social responsibility and sustainable development among global investors and consumers makes ESG performance a crucial measure of long-term value. Carbon fiber companies need robust governance structures, improved transparency, enhanced risk management, and a commitment to social responsibilities, all while complying with laws and regulations to bolster their sustainable development capabilities. In view of this, this review aims to deeply analyze the sustainable development status and challenges of the carbon fiber industry from the perspective of ESG, and discuss the future development direction of the industry. Through a comprehensive evaluation of the ESG performance of the carbon fiber industry, this review will put forward strategic suggestions to promote the sustainable development of the industry, in order to provide reference for policy makers, business managers and investors.

Keywords: Carbon fiber industry, Sustainable development, Environment, Society, Governance

1. Overview of Carbon Fiber Industries

Carbon fiber, as one of the advanced materials in the 21st century, has a relatively short development history, but it has shown its indispensable value in many key technology fields. Carbon fiber is a special fiber mainly composed of carbon elements, its carbon content is more than 90%, and it is known for its excellent mechanical properties and chemical stability. Carbon fiber production involves several key steps: precursor production, stabilization, carbonization, and surface treatment. The most common precursor materials are polyacrylonitrile (PAN) and

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pitch. Advanced manufacturing technologies continue to evolve, focusing on improving efficiency and reducing costs [1].

In the realm of fiber-reinforced polymer (FRP) production, the Spray Lay-Up Process (SLU) stands out for its simplicity and efficiency, akin to the Hand Lay-Up (HLU) process. The SLU technique enables faster FRP production and allows for greater shape complexity, making it ideal for creating complex structures, as shown in Figure 1. It utilizes a cost-effective open mold with a single finished part surface, and the curing of the resin is typically carried out at room temperature, although the process can be expedited with the application of moderate heat. This method is particularly well-suited for the manufacturing of large FRP composite components, such as bathroom units, including shower and bathtub parts, as well as ventilation hoods. It is well-adapted for low to moderate volume production, ensuring that the process remains cost-effective while maintaining the high quality of the end product [1].

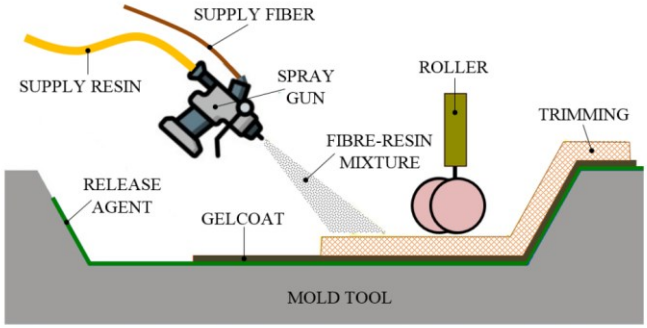

Figure 1. Schematic diagram of the spray lay-up (SLU) manufacturing method [1].

In terms of industrial scale and market distribution, the global carbon fiber market has been growing continuously in recent years, and it is expected to maintain a steady growth trend in the next few years. According to market research reports, the global carbon fiber market is valued at billions of dollars in 2020 and is expected to grow significantly by 2025. At present, the production of carbon fiber is mainly concentrated in Japan, the United States and some European countries, among which Japanese enterprises occupy the leading position in the global high-performance carbon fiber market.

In terms of technological progress, breakthroughs have been made in carbon fiber preparation technology, including new precursors development, more cost-effective production methods and better composite design. The comparison of the traditional and new carbon fiber production methods is given in Figure 2. These technological advances have not only improved the performance of carbon fiber products, but also gradually reduced their production costs, making their application in the civilian field more feasible.

Around the world, the production of carbon fiber is dominated by a few enterprises. Toray, Tobon and Mitsubishi Riyang play an important role in high-performance carbon fiber production. In addition, Hertz and Sigli Group are also important players in the field. These enterprises have promoted the development of the carbon fiber industry through continuous technological innovation and market expansion. The global carbon fiber market is expected to continue growing, driven by increasing demand in various sectors and advancements in manufacturing technologies. The industry is also witnessing a shift towards more sustainable and cost-effective production methods [2].

However, the development of the carbon fiber industry also faces many challenges. Environmental problems are one of them, and the energy consumption and waste disposal

problems in the process of carbon fiber production need to be solved urgently. While carbon fiber offers numerous benefits, its production is energy-intensive and involves significant environmental challenges. The industry is increasingly focusing on sustainable practices, such as recycling and using bio-based precursors to mitigate these impacts [3]. In addition, market competition is becoming increasingly fierce, and competition between new entrants and existing companies may reshape the market landscape. At the same time, the technology threshold and the capital investment are also the important factors restricting the entry of new enterprises into this field.

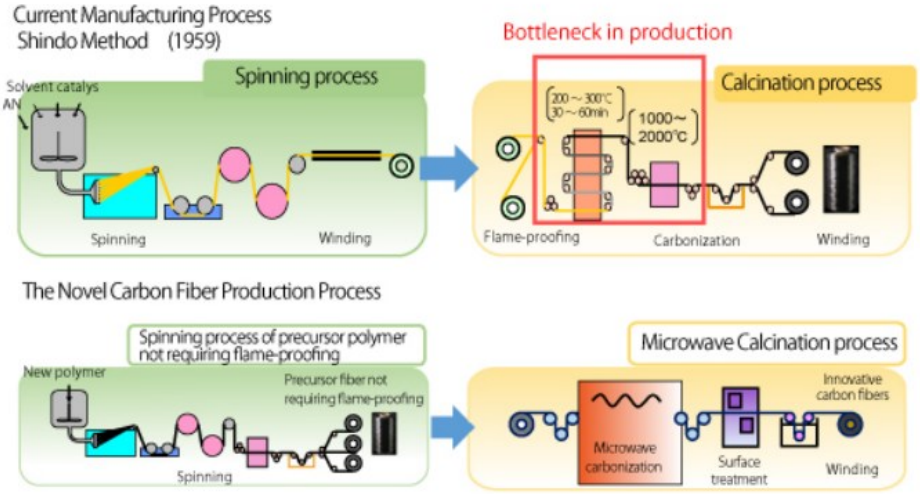

Figure 2. Traditional and New Carbon Fiber Production methods [4].

2. Environmental Dimension: Ecological Footprint and Green Transformation of Carbon Fiber Industry

2.1 Environmental Impact of the Production Process

The environmental impact of the carbon fiber production process is multifaceted. From the collection of raw materials to the manufacture of the final product, every link is accompanied by the consumption of energy and waste production. In particular, the production of carbon fiber requires a high temperature carbonization process, which not only consumes a lot of energy but may also may produce harmful by-products. Therefore, reducing energy consumption and reducing harmful emissions is a major environmental challenge for the carbon fiber industry. Carbon fiber manufacturing is energy-intensive. Improvements in process optimization and the use of renewable energy can significantly reduce the environmental footprint [5].

2.2 Energy Consumption and Efficiency Improvement

The energy consumption problem of carbon fiber manufacturing process is particularly prominent. At present, carbon fiber production mainly depends on fossil fuels, which not only aggravates global greenhouse gas emissions, but also makes production costs more affected by energy price fluctuations. Therefore, the development and utilization of renewable energy sources, such as wind and solar energy, is of great significance for reducing the environmental footprint of the carbon fiber industry.

2.3 Waste Management and Circular Economy

If the waste produced in the carbon fiber production process is not properly treated, it will cause serious pollution to the environment. At present, the recycling and recycling technology

of carbon fiber waste is not mature, resulting in the waste of a large number of valuable materials. Promoting the recycling and utilization of carbon fiber waste and the establishment of a circular economy model are crucial to realizing the sustainable development of the industry.

2.4 Life Cycle Assessment (LCA)

Conducting comprehensive LCAs helps identify and mitigate the environmental impacts from production to disposal [6]. LCA can help us understand the environmental load throughout the product life cycle from raw material acquisition, production, use to waste disposal. Through LCA, enterprises can identify the links with the greatest environmental impact and take corresponding measures to improve them.

2.5 Environmental Regulatory Compliance and Policy Incentives

Globally, more and more countries are beginning to implement strict environmental regulations to reduce the environmental impact of industrial activities. The carbon fiber industry must comply with these regulations or could face heavy penalties. At the same time, the government also encourages enterprises to adopt more environmentally friendly production methods by providing incentives such as tax incentives and subsidies.

2.6 Green Technology Innovation

Technological innovation is the key to promote the green transformation of carbon fiber industry. By developing new production technologies, such as the use of bio-based raw materials and improving carbonization processes, energy consumption and waste production in the production process can be effectively reduced. In addition, the application of cutting-edge technologies such as nanotechnology and 3D printing also provides new possibilities for the green development of the carbon fiber industry. The following Figure 3 shows the mature manufacturing process of carbon fiber with the support of green technology [7].

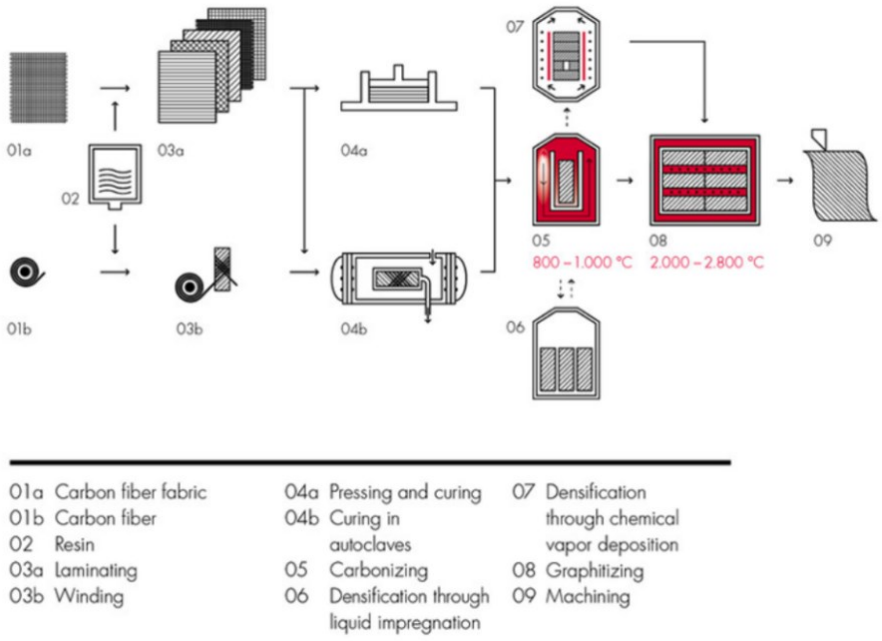

Figure 3. Various stages from raw materials to finished carbon fibers [7].

3. Social Dimension: The Social Responsibility and Public Well-being of The Carbon Fiber Industry

3.1 Working Conditions and Workers' Rights and Interests

The rapid development of the carbon fiber industry has put forward new requirements to the labor market. The expansion of the industry required large numbers of skilled workers and professionals, creating jobs for local communities. However, it also brings a challenge to the protection of workers' rights and interests. The possible exposure of harmful chemicals and high-intensity working pressure in the process of carbon fiber production require enterprises to take effective measures to ensure the health and safety of workers. In addition, providing fair compensation, improving working conditions, and strengthening vocational training and promotion opportunities are important aspects of enterprises in fulfilling their social responsibility.

3.2 Community Influence and Local Development

The establishment of carbon fiber factories has a significant impact on the economic and social development of the surrounding communities. On the one hand, factories can provide employment for local residents and promote economic growth; on the other hand, factory operations may affect the local environment, such as pollution and traffic congestion, which requires a good communication mechanism between enterprises and communities to find solutions together. Ensuring raw materials are sourced sustainably and ethically, considering the impact on local communities and ecosystems [8]. In addition, enterprises should actively give back to the community and promote the sustainable development of the community through community investment projects, such as education and infrastructure construction.

3.3 Consumer Awareness and Market Demand

Consumers are increasingly concerned about the environmental and social impact of the product, which affects their purchasing decisions. The carbon fiber industry needs to pay attention to consumer expectations and meet market demand by improving product sustainability. This includes using more environmentally friendly materials, improved production processes, extended product life, etc. At the same time, enterprises should strengthen communication with consumers, improve transparency, and let consumers understand the social value of their products.

3.4 Social Responsibility and Brand Value

In today's society, corporate social responsibility (CSR) is no longer just a charitable donation, but involves all aspects of business operations. By actively fulfilling their social responsibilities, carbon fiber enterprises can not only enhance their brand image, but also enhance their relationship with consumers, investors and government agencies. The fulfillment of social responsibility can help enterprises to establish long-term competitive advantage and achieve sustainable development.

3.5 Social Impact Assessment (SIA)

Similar to the Life Cycle Assessment (LCA) in the environmental dimension, the social impact assessment (SIA) is an important tool to assessing the social impact of enterprise activities. SIA can help enterprises to identify and evaluate the positive and negative impact of their activities on the society, so as to develop corresponding management strategies. Through SIA, enterprises can better understand their role in the society and improve their social performance.

4. Governance Dimension: Transparency, Accountability, and Long-term Value of the Carbon Fiber Industry

4.1 Corporate Governance Structure

Good corporate governance is the cornerstone of the sustainable development of carbon fiber industry. Enterprises need to establish an efficient and transparent governance structure to ensure the rationality and fairness of the decision-making process. This includes the establishment of an independent board of directors, a shareholder rights protection mechanism, and a transparent financial reporting and audit process. Through these measures, carbon fiber companies can build the trust of investors and other stakeholders and lay a solid foundation for long-term development.

4.2 Transparency and Information Disclosure

Under the framework of the ESG (see Figure 4), transparency and information disclosure are crucial to improving corporate governance. Transparency in the carbon fiber industry involves clear and open communication of information regarding manufacturing processes, environmental impacts, and supply chain practices. Companies that prioritize transparency provide stakeholders with insights into their operations, facilitating informed decision-making and building trust [8]. With this proactive information disclosure, companies can not only demonstrate their commitment to sustainable development, but also attract more ESG investors.

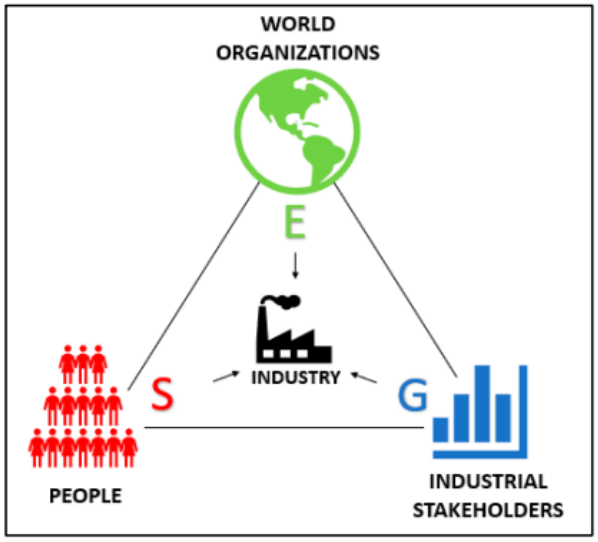

Figure 4. Application of the ESG paradigm with everyone's contributions [9].

4.3 Risk Management and Compliance

Effective risk management and compliance systems are crucial for the stable operation of carbon fiber enterprises. Enterprises need to identify and evaluate the risks they may face in ESG, including environmental regulatory changes, market demand fluctuations, supply chain interruption, etc., and develop corresponding risk management strategies. At the same time, enterprises should ensure that their operating activities comply with the requirements of relevant laws and regulations to avoid punishment or reputation loss for violations.

4.4 Stakeholder Participation

Stakeholder participation is an important part of modern corporate governance. Carbon fiber enterprises should actively communicate and cooperate with stakeholders such as investors, employees, customers, suppliers and communities to understand their needs and

expectations and incorporate them into the corporate decision-making process. Through this inclusive governance, enterprises can better balance the interests of all parties and achieve common development.

4.5 Ethics and Corporate Culture

Corporate culture and moral standards have a profound impact on shaping the governance environment of enterprises. Carbon fiber enterprises should advocate and practice high standards of business ethics, including honest management, fair competition, anti-corruption, etc. In addition, enterprises should also enhance the moral awareness and responsibility through training and education of employees, and create an honest and transparent corporate culture atmosphere.

4.6 Long-term Value

The long-term value of the carbon fiber industry lies in sustainable practices that balance economic prosperity with environmental and social responsibility. Embracing sustainable sourcing, investing in research and development for innovative solutions, and fostering long-term partnerships contribute to the industry's resilience and growth [10].

5. ESG Investment and Market Trends

5.1 Rise and Development of ESG Investment Philosophy

ESG investment, focusing on environmental, social, and corporate governance factors, has gained significant traction worldwide in recent years. Emphasizing sustainable development and social responsibility, ESG investment has become a key trend in the capital markets [11].

5.2 ESG Investment Appeal in the Carbon Fiber Industry

The carbon fiber industry, known for its lightweight and high-strength characteristics, shows significant promise in sectors like wind power and new energy vehicles. These areas align well with ESG investment principles. As the demand for clean energy and low-carbon technologies rises globally, the carbon fiber industry is drawing substantial ESG investments [12].

5.3 ESG Expectations for the Carbon Fiber Market

Investors and consumers are increasingly scrutinizing companies' ESG performance. Carbon fiber companies that demonstrate environmental responsibility, social accountability, and strong corporate governance are more likely to earn market trust and attract capital [13].

5.4 Policy and Regulation Impact on ESG Investment

The influence of policy and regulation on ESG investment is growing globally, with authorities enhancing related oversight. For instance, the EU's Carbon Border Adjustment Mechanism (CBAM) impacts international trade and carbon fiber industry investment by requiring imports to compensate for carbon emissions cost differences [14].

5.5 ESG Risks and Opportunities in the Carbon Fiber Industry

The high energy consumption and carbon emissions are the main ESG risks. However, through technological innovation and improved production processes, the carbon fiber industry can be translated into opportunities, such as reducing the environmental impact of through recycling and development of low-carbon products [15].

5.6 Future Market Trends and Sustainable Development in the Carbon Fiber Industry

The market is anticipated to increasingly prioritize ESG criteria, necessitating that the carbon fiber sectors adapt by enhancing ESG performance to secure its market standing and attract investment. Additionally, the industry must stay vigilant to policy shifts, including advancements in global carbon pricing, and leverage ESG investment to foster its own sustainable transformation [11]. The multiple key areas of action for enterprises in ESG is provided in Figure 5.

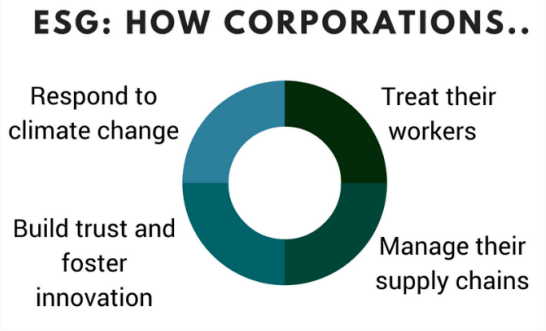

Figure 5. Multiple key areas of action for enterprises in ESG [11].

6. Future Prospects and Suggestions

The sustainable development of the carbon fiber industry faces several key challenges. One significant challenge is reducing the environmental impact of carbon fiber production, including minimizing CO2 emissions and managing waste generated during manufacturing [16]. Ensuring the sustainability of raw materials is another critical issue, with ongoing research focusing on developing carbon fibers derived from lignin and cellulose, which involve complex processing techniques [17]. Economic feasibility remains essential as the industry strives to balance environmental sustainability with maintaining cost-effectiveness, given the high production costs and substantial investments needed for sustainable technologies [18]. Efficient recycling processes and waste management are vital, as the recycled carbon fiber market, although promising, requires further improvements to achieve higher efficiency [17]. Continuous innovation in manufacturing processes to reduce defects and enhance carbon fiber performance is crucial for making these materials more environmentally friendly and cost-effective [18]. Additionally, the industry must navigate market dynamics, including fluctuating demand and the economic implications of transitioning to greener practices [19].

6.1 Innovative Manufacturing Technologies

Continued research into innovative manufacturing technologies can lead to more sustainable production processes, reducing energy consumption and emissions [20].

6.2 Green Raw Materials

Exploration of green and sustainable raw materials for carbon fiber production can minimize environmental impact and enhance the industry's sustainability [9].

6.3 Investment in Research and Development

Increased investment in research and development is crucial for developing alternative materials and processes that enhance environmental sustainability while maintaining or improving performance. Such investments drive innovation, leading to greener solutions that

meet or exceed current efficiency and strength standards [21].

6.4 Circular Economy Practices

Implementing circular economy practices, such as recycling and reusing carbon fiber materials, can reduce waste and contribute to a more sustainable carbon fiber industry [9].

6.5 Regulatory Compliance and Standards

Adhering to regulatory standards and adopting industry best practices for environmental protection and sustainability can ensure responsible business conduct and promote sustainable growth [22].

7. Conclusions

This review comprehensively analyzes the sustainable development status and challenges of carbon fiber industry in the three dimensions of environment, society and governance (ESG), and puts forward corresponding strategic suggestions. This review shows the advanced practices of carbon fiber industry in ESG practice, and points out the key directions for the future development of the industry.

In the environmental dimension, the carbon fiber industry must pay attention to energy consumption and waste disposal in the production process, and reduce the environmental impact of products through tools such as life cycle assessment (LCA). The social dimension requires industries to improve working conditions, promote community development, and respond to consumer demand for sustainable products. The governance dimension emphasizes the need for enterprises to establish a sound governance structure, improve transparency, strengthen risk management, and advocate ethics and corporate culture.

This review also explores ESG investment and market trends, highlighting the need for the carbon fiber industry to accommodate market expectations for ESG performance in order to maintain its market position and attract investment. It is expected that the ESG performance of the carbon fiber industry will be decisive in its long-term development as the global demand for low-carbon solutions grows.

Finally, this review presents a number of suggestions including environmental strategy, social responsibility, mechanisms of governance, risk management, technological innovation, market adaptation, policy participation, cooperation and partnership, training and education, and long-term planning to promote the sustainable development of the carbon fiber industry.

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