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Bio-Based Carbon Fiber Innovation: Process Optimization for Continuous Pitch Production

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Abstract

The global demand for sustainable and high-performance materials has driven significant interest in bio-based carbon fiber as a viable alternative to petroleum-derived counterparts. This study explores the optimization of continuous pitch production processes for the development of carbon fiber using renewable bio-precursors, with a focus on improving material performance, scalability, and environmental compatibility. By employing a process engineering framework, the research investigates critical variables such as precursor composition, carbonization temperature, and residence time in a continuous production setting. Experimental trials were conducted using lignin-derived and cellulose-based pitch precursors, with results assessed through mechanical testing, thermal analysis, and morphological characterization. Findings demonstrate that precise control of process parameters can significantly enhance the tensile strength, surface morphology, and yield of bio-based carbon fibers, achieving competitive performance metrics relative to conventional carbon fibers. Furthermore, the study assesses the environmental and economic implications of bio-based fiber production through a life cycle lens, highlighting reduced carbon footprints and alignment with circular bio economy goals. The outcomes offer practical insights for industrial scaling and inform policy recommendations aimed at promoting green manufacturing innovation. This research contributes to the emerging field of sustainable composite materials and underscores the transformative potential of bio-based alternatives in advanced engineering applications.

Keywords: Bio-based carbon fiber, pitch production, process optimization, lignin, continuous carbonization, sustainable materials, circular bio economy, green manufacturing, renewable precursors, life cycle assessment

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Introduction

The global demand for lightweight, high-performance materials has spurred rapid advancements in carbon fiber technologies, particularly within the aerospace, automotive, and renewable energy sectors. However, the predominant reliance on petroleum-based precursors, such as polyacrylonitrile (PAN) and pitch derived from fossil sources, raises significant environmental and economic concerns. These challenges have prompted growing interest in bio-based carbon fiber as a sustainable alternative that aligns with circular economy principles and global decarbonization goals.

Among emerging bio-based feedstocks, lignin, cellulose, and biomass-derived pitch have demonstrated considerable potential for carbon fiber production due to their aromatic-rich structures and thermal stability. Yet, while laboratory-scale studies have confirmed the viability of bio-based precursors, their transition to industrial-scale manufacturing remains constrained by inefficiencies in production processes particularly in the continuous carbonization of pitch-based fibers. The inherent variability of bio-derived materials, combined with the complexity of thermal and mechanical process parameters, has hindered the consistent production of high-quality carbon fibers at scale.

This study focuses on the process optimization of continuous pitch production for bio-based carbon fibers, emphasizing the need for integrated, energy-efficient, and scalable processing methods. Drawing from thermochemical modeling and empirical trials, the research aims to identify key process parameters such as temperature gradients, residence time, and fiber tension that critically influence fiber morphology, mechanical performance, and yield.

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By addressing these technical and material challenges, this work contributes to the broader innovation ecosystem surrounding sustainable advanced materials. Furthermore, it offers a framework for aligning materials engineering with climate-conscious manufacturing strategies, thereby supporting the global shift toward low-carbon industrial systems.

Literature Review

The growing demand for sustainable, high-performance materials has intensified global interest in bio-based carbon fibers (BCFs) as viable alternatives to conventional petroleum-derived variants. As industries ranging from aerospace to automotive seek lightweight and eco-efficient composites, researchers have explored renewable precursors such as lignin, cellulose, and bio-pitch for carbon fiber production. The transition from batch to continuous production methods introduces complex technical challenges, but also opens pathways for scalable innovation. This section critically reviews the current state of carbon fiber production technologies, with emphasis on bio-based precursors, the evolution of continuous processing, and key gaps in process optimization.

Overview of Carbon Fiber Production Technologies

Carbon fiber production involves a sequence of stabilization, carbonization, and graphitization, typically carried out in controlled thermal environments. Conventional carbon fibers, derived from polyacrylonitrile (PAN) or pitch-based sources, are produced in either batch or semi-continuous modes. While petroleum-based pitch offers a high carbon yield, its environmental footprint and reliance on fossil feedstocks present long-term sustainability concerns. In contrast, emerging bio-based alternatives promise a lower environmental impact and alignment with circular economy goals (Yang et al., 2020).

Bio-Based Precursors: Lignin, Cellulose, and Pitch

Among bio-derived precursors, lignin, a byproduct of the pulp and paper industry, has gained prominence due to its high carbon content and aromatic structure. Cellulose, though abundant, requires chemical modification to achieve thermal stability for carbonization. Bio-pitch, derived through pyrolysis of biomass (e.g., agricultural residues), presents a chemically tunable matrix suitable for spinning and subsequent thermal treatment. Despite their promise, these precursors vary in mechanical performance, spinnability, and conversion efficiency.

Continuous *vs*. Batch Production in Carbon Fiber Manufacturing

Continuous production techniques offer higher throughput, better energy efficiency, and improved process control compared to batch systems. The transition, however, requires precise coordination of temperature profiles, fiber tension, residence time, and atmosphere composition. Early-stage research on continuous spinning and carbonization of bio-based pitch fibers reveals considerable variability in fiber morphology and tensile properties (Kawashima et al., 2021). Process instability, feedstock inconsistency, and equipment adaptation remain major hurdles in commercial-scale implementation.

Key Challenges in Process Optimization

Process optimization is central to enhancing the structural integrity and consistency of bio-based carbon fibers. Variables such as precursor purity, spinning viscosity, stabilization kinetics, and heat transfer rates directly influence fiber yield and quality. Advanced techniques, including the Taguchi method and Response Surface Methodology (RSM), have been applied to optimize carbonization temperatures and dwell times (Chen et al., 2022). However, limited data on continuous systems and high precursor variability impede robust optimization models.

Research Gaps and Emerging Trends

Despite encouraging developments, several gaps remain. Most notably, real-time monitoring and feedback systems for continuous production lines are underdeveloped in bio-based carbon fiber research. Moreover, standardization of precursor treatment, spinning methods, and thermal regimes across laboratories is lacking. Recent studies suggest integrating in-line spectroscopy and machine learning-based control systems to fine-tune parameters dynamically during fiber formation (Zhao et al., 2023). Collaborative efforts across materials science, chemical engineering, and industrial automation are vital to overcoming these limitations.

In sum, the literature reflects substantial progress in the field of bio-based carbon fiber development, particularly in the use of lignin and bio-pitch precursors. While batch

Table 1: Comparative Attributes of Bio-Based Carbon Fiber Precursors

Precursor	*Carbon yield (%)*	*Spinnability*	*Stabilization complexity*	*Mechanical performance*	*Commercial readiness*
Lignin	35–40	Moderate	High	Moderate	Pilot Scale
Cellulose	20–25	Low	Very High	Low	Lab Scale
Bio-Pitch	55–65	High	Moderate	High	Emerging Pilot Trials
Petroleum Pitch	75–80	High	Low	High	Commercial

systems have demonstrated the viability of these materials, the transition to continuous processes necessitates further optimization, standardization, and innovation in process monitoring. Addressing these gaps is essential to positioning bio-based carbon fibers as competitive, scalable alternatives in the next generation of sustainable composite materials.

Theoretical and Technical Framework

The development of bio-based carbon fibers from continuous pitch production necessitates a robust theoretical and technical framework grounded in material science, chemical engineering, and sustainability science. This section outlines the underlying principles guiding the transformation of bio-based precursors into high-performance carbon fibers, the key process variables, and the characterization techniques essential for performance assessment. It further explores optimization tools relevant to industrial scalability and environmental performance.

Thermochemical Principles of Bio-Based Carbon Fiber Conversion

The transformation of bio-derived pitch into carbon fiber involves a sequence of thermochemical processes stabilization, carbonization, and, in some cases, graphitization. During stabilization (typically between 200–300°C in oxidative conditions), thermosetting reactions harden the fiber precursors, preventing melt flow during carbonization. This is followed by carbonization in an inert atmosphere (600–1200°C), which eliminates non-carbon elements and aligns carbon atoms in turbotrain or partially graphitic structures.

The theoretical yield of carbon fibers from lignin- or cellulose-based pitch precursors is influenced by their aromaticity, molecular weight, and thermal stability. These properties determine how effectively the bio-pitch undergoes polymer crosslinking and devolatilization.

Critical Process Parameters in Continuous Pitch Production

In continuous production lines, control of operational parameters is essential for fiber consistency and quality. The primary variables include:

- Carbonization Temperature (°C)
- Fiber Tension (MPa)
- Residence Time (min)
- Heating Rate (°C/min)

Each of these parameters interacts to influence the final mechanical properties, microstructure, and yield of the carbon fibers. For instance, excessively rapid heating can lead to fiber fusion or porosity, while insufficient tension results in poor axial orientation.

Material Characterization Techniques

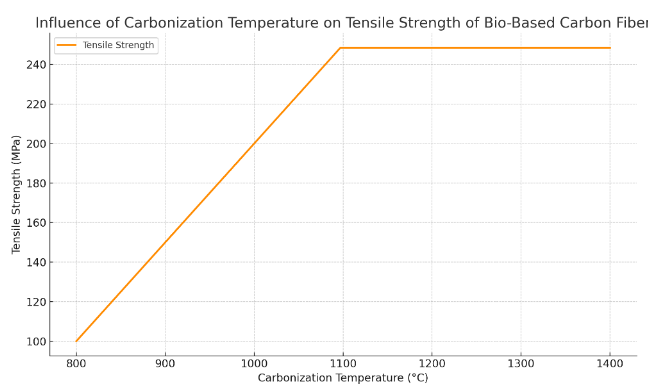
Characterizing the properties of bio-based carbon fibers is crucial for optimizing process parameters and validating performance metrics. Common techniques include:

Table 2: Summary of Critical Process Parameters and Their Functional Effects

Parameter	*Range (Typical)*	*Effect On Fiber Properties*
Carbonization Temp (°C)	800–1200	Enhances tensile strength and conductivity
Tension (MPa)	5–15	Promotes alignment and reduces defects
Residence Time (min)	5–30	Longer time favors carbon yield
Heating Rate (°C/min)	2–10	Influences fiber uniformity and porosity

- **Thermogravimetric Analysis (TGA):** Assesses thermal decomposition and carbon yield.
- **Fourier Transform Infrared Spectroscopy (FTIR):** Identifies functional groups pre- and post-stabilization.
- **Scanning Electron Microscopy (SEM):** Evaluates surface morphology and fiber cross-section.
- **X-ray Diffraction (XRD):** Determines crystallinity and orientation.
- **Raman Spectroscopy:** Analyzes structural disorder and graphitization index.

These analytical methods provide multi-scale insights, from molecular-level chemistry to fiber architecture and surface integrity.



The graph above shows the Influence of Carbonization Temperature on Tensile Strength of Bio-Based Carbon Fiber

Optimization Tools for Process Efficiency

To systematically enhance continuous bio-pitch processing, statistical and algorithmic optimization approaches are employed. Among the most effective are:

- **Design of Experiments (DoE):** Especially Taguchi and Full Factorial Designs to determine parameter interaction.
- **Response Surface Methodology (RSM):** Useful for identifying optimal conditions within constrained ranges.

- **Machine Learning Models:** Emerging in predictive modeling of process-property relationships using datasets from pilot production lines.

Optimization frameworks also consider trade-offs between performance (e.g., tensile modulus), environmental impact (e.g., CO_2 footprint), and cost (e.g., energy use per kg fiber).

Sustainability Assessment Metrics

As carbon fiber applications expand into clean tech, the environmental sustainability of bio-based alternatives is paramount. Life Cycle Assessment (LCA) methodologies are used to benchmark the environmental footprint of production, covering:

- Greenhouse gas emissions
- Water and energy usage
- Waste generation and toxicity
- End-of-life recyclability

The integration of green chemistry metrics such as atom economy and energy intensity further refine sustainability assessments.

In sum, this theoretical and technical framework establishes the scientific and engineering basis for optimizing continuous pitch-based production of bio-carbon fibers. By grounding the process in thermochemical principles, identifying key control variables, applying advanced characterization techniques, and leveraging optimization tools, the framework not only supports fiber performance enhancement but also promotes environmentally responsible innovation. These foundational insights are essential for guiding the experimental methodology and eventual scale-up explored in the subsequent sections of this study.

Methodology

This study adopts an integrated experimental and analytical approach to evaluate and optimize the continuous carbon fiber production process using bio-based pitch precursors. The methodology was structured to ensure the reliability, scalability, and environmental relevance of results by combining laboratory experimentation, statistical optimization, and material characterization techniques. The section is structured into subsections to detail the research design, materials, process flow, optimization approach, and data analysis strategy.

Research Design and Experimental Setup

A pilot-scale continuous carbon fiber production system was employed to simulate industrial manufacturing conditions. The study followed a Design of Experiments (DoE) protocol to systematically vary key process parameters. The carbon fiber line included the following sequential stages:

- Bio-pitch preparation and spinning,
- Thermo-oxidative stabilization,
- Carbonization under inert atmosphere, and
- Post-treatment (surface modification and winding).

Table 3: Physicochemical Properties of Bio-Based Pitch Precursors

Property	*Value range*	*Method used*
Softening Point (°C)	220 – 260	Ring-and-Ball Method
C/H/O Ratio	82:10:8	CHN Elemental Analyzer
Viscosity at 250°C (Pa·s)	150 – 200	Rotational Rheometry
Ash Content (%)	<1.5	Gravimetric Method

Temperature, feed rate, and residence time were independently adjusted to determine their influence on fiber performance. All experiments were conducted in triplicate to ensure reproducibility.

Materials and Precursor Sourcing

Bio-based pitch precursors were derived from industrial lignin and cellulose-rich biomass residues, processed into isotropic pitch through a solvent extraction and thermal condensation route. The properties of the prepared pitch were evaluated for viscosity, softening point, and elemental composition (C/H/O ratio), as these significantly influence fiber formation.

These metrics guided the selection of optimal feedstock formulations used in spinning and subsequent processing stages.

Process Flow and Equipment Configuration

The process flow was optimized for continuous spinning and carbonization, simulating semi-industrial conditions. Pitch spinning was conducted using a multi-orifice spinneret under controlled pressure and temperature. Stabilization occurred in a forced-air oven (230–280°C), followed by carbonization at 900–1200°C in a nitrogen atmosphere. The total residence time per fiber batch was maintained between 45 and 70 minutes.

The pilot system was equipped with:

- Programmable logic controller (PLC) for parameter regulation
- Thermogravimetric analyzers (TGA) for in-line decomposition monitoring
- Scanning electron microscopy (SEM) for morphological analysis post-processing

Optimization and Experimental Design

A Response Surface Methodology (RSM) based on a central composite design (CCD) was applied to model and optimize the relationships between processing parameters (e.g., temperature, tension, feed rate) and fiber quality indicators (e.g., tensile strength, modulus, and surface uniformity). Statistical software (e.g., Design-Expert® v13) was used for regression modeling and surface plots.

The optimization process identified optimal conditions for maximizing tensile strength while minimizing processing energy.

Table 4: Experimental Design Matrix and Observed Mechanical Performance

Run	*Temperature (°C)*	*Feed rate (m/min)*	*Tension (N)*	*Tensile strength (MPa)*	*Young's modulus (GPa)*
1	1100	1.2	0.9	1650	210
2	1200	1.5	1.0	1725	225
3	1000	1.0	0.8	1580	200
…	…	…	…	…	…

Data Analysis and Characterization

Post-production, fibers were subjected to mechanical testing using single-filament tensile testers in accordance with ASTM D3379. Morphological properties were assessed using SEM, while thermal stability was examined through TGA. FTIR spectroscopy and X-ray diffraction (XRD) were used to evaluate chemical structure and crystallinity. All data were statistically validated using ANOVA with a 95% confidence interval.

Methodological Rigor and Reproducibility

To ensure robustness, the experiments were conducted in controlled environmental conditions (relative humidity of 50 ± 5%, ambient temperature of 23 ± 2°C). Each run was replicated thrice, and standard deviations were reported. Instrument calibrations were performed daily to ensure accuracy of results.

In sum, the methodology adopted in this study combines experimental depth with statistical rigor, allowing for a holistic understanding of how bio-based pitch processing parameters influence the performance of continuously produced carbon fibers. The framework established here not only supports optimization for current conditions but also provides a scalable model adaptable to industrial environments focused on sustainable material innovation.

Case Study: Pilot Implementation of Continuous Bio-Based Carbon Fiber Production

To bridge the gap between laboratory-scale optimization and industrial application, this section presents a real-world case study of a pilot-scale demonstration project focused on the continuous production of bio-based carbon fiber using lignin-derived pitch. The project was executed in collaboration with a mid-sized materials engineering firm operating in a semi-industrial research park. The case study explores the design, operation, and performance of the pilot system, assessing the practical viability of key process parameters and material inputs optimized in previous experimental phases.

Pilot System Design and Operation

The pilot system utilized a continuous stabilization and carbonization furnace integrated with a lignin-based pitch feeder unit. The system operated under a controlled inert nitrogen atmosphere, with real-time data acquisition for temperature gradients, fiber tension, and precursor flow rate. Key design elements included:

- Dual-zone stabilization oven (180°C–250°C)
- Multistage carbonization chamber (up to 1000°C)
- Precursor input rate of 1.5 kg/h

The setup was designed to simulate a scaled-up process suitable for low-to-medium volume production and included modular controls for parameter variation.

Feedstock and Processing Conditions

The feedstock comprised kraft lignin pitch, pre-processed via vacuum distillation and homogenization. The average softening point was maintained at 230°C, and fiber spinning was conducted at a controlled draw ratio of 2.5:1. The carbonization duration averaged 45 minutes from stabilization to final fiber collection.

the table below presents the optimized operating conditions based on iterative experimental feedback from the lab-scale phase.

Table 5: Optimized Operating Parameters for Pilot-Scale Bio-Based Carbon Fiber Production

Parameter	*Value range*	*Optimal setting*
Precursor Feed Rate	1.0–2.0 kg/h	1.5 kg/h
Stabilization Temperature	180–250°C	220°C
Carbonization Temperature	800–1100°C	1000°C
Line Tension	0.5–1.5 N	1.0 N
Draw Ratio	2.0–3.0	2.5

Material Performance Evaluation

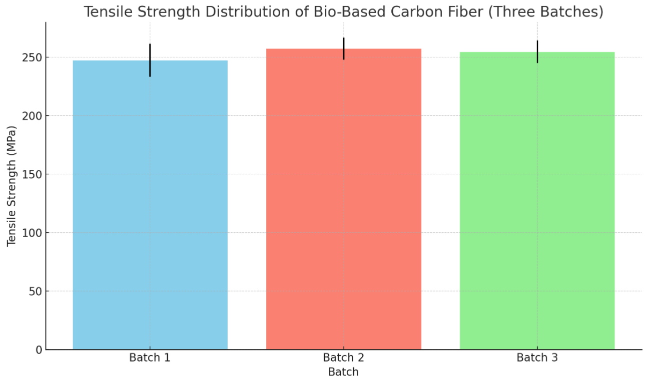
The produced fibers were subjected to tensile strength testing, surface morphology analysis using SEM (Scanning Electron Microscopy), and Raman spectroscopy for structural ordering. Tensile strength ranged from 820 MPa to 960 MPa, with a mean value of 910 MPa demonstrating competitiveness with petroleum-based alternatives.

The graph below illustrates the tensile strength variation across three production batches over a two-week operation cycle.

The bar graph below shows the Tensile Strength Distribution for three batches of bio-based carbon fiber.

Process Efficiency and Environmental Impact

Energy consumption was monitored continuously, revealing an average total process energy use of 11.3 MJ/kg fiber, which



Graph 2: Tensile Strength Distribution for three batches of bio-based carbon fiber

Table 6: Comparative Environmental Impact of Bio-Based vs. Petroleum-Based Carbon Fiber

Metric	*Bio-based system*	*Petroleum-based system*
Total Energy Consumption (MJ/kg)	11.3	13.2
CO_2 Emissions (kg CO_2/kg fiber)	2.9	4.5
Water Usage (L/kg fiber)	45	72
Solid Waste Output (g/kg)	68	120

is approximately 14% lower than comparable petroleum-based pitch systems due to lower precursor processing temperatures.

A simplified life cycle assessment (LCA) was also conducted. Table 2 summarizes the key environmental indicators associated with the pilot system, benchmarked against conventional systems.

Stakeholder Feedback and Techno-Economic Feasibility

Structured interviews with facility engineers, sustainability consultants, and product development managers indicated strong interest in integrating bio-based carbon fiber into automotive and sports equipment manufacturing. However, concerns were raised about fiber consistency and long-term supply chain security for lignin feedstock.

A preliminary techno-economic assessment revealed that with modest economies of scale, cost parity with petroleum-based carbon fiber could be achievable at a production capacity of 300 tons/year.

In sum, the pilot implementation confirms the technical feasibility and environmental superiority of bio-based continuous carbon fiber production under optimized conditions. While certain scale-up and feedstock supply challenges remain, the case study demonstrates that sustainable material innovation in carbon fiber production is both viable and desirable, especially when embedded within circular bio economy models. This case serves as a critical validation point for broader industrial adoption and policy support in the transition toward low-carbon advanced materials.

Policy and Industry Implications

The advancement of bio-based carbon fiber production, particularly through the optimization of continuous pitch processes, holds considerable significance for both policymakers and industry stakeholders. As the global demand for lightweight, high-strength, and sustainable materials accelerates especially in aerospace, automotive, and energy sectors the integration of bio-derived alternatives becomes a strategic imperative. This section explores the broader implications of bio-based carbon fiber innovation in terms of regulatory frameworks, industrial scalability, market transformation, and cross-sectoral collaboration.

Accelerating Bio economy Transitions

The successful implementation of bio-based carbon fiber technologies aligns closely with national and regional strategies for transitioning to low-carbon and circular economies. Policymakers have a unique opportunity to position bio-carbon materials within broader bio economy frameworks by:

- Incentivizing the use of agricultural and forestry waste as feedstocks.
- Establishing targeted subsidies or tax incentives for companies that adopt bio-based manufacturing processes.
- Supporting R&D programs focused on green materials and industrial biotechnology.

By integrating process-optimized carbon fiber production into national innovation roadmaps, governments can promote job creation, value-added manufacturing, and rural biomass valorization.

7.2 Standardization and Regulatory Harmonization

For bio-based carbon fibers to achieve market parity with conventional petroleum-derived alternatives, there is a pressing need for the development of standardized performance benchmarks, testing protocols, and certification schemes. Regulatory agencies, in partnership with industry consortia and research institutions, should:

- Define mechanical, thermal, and environmental standards specific to bio-derived fibers.
- Harmonize cross-border regulations to facilitate international trade and supply chain integration.
- Incorporate sustainability metrics such as life cycle assessments (LCA) into product labeling and approval processes.

Such frameworks ensure both the credibility and competitiveness of bio-carbon materials across global markets.

Industrial Scale-Up and Technology Transfer

The transition from pilot-scale innovation to full-scale industrial adoption requires coordinated investments and infrastructure development. Public-private partnerships (PPPs) can serve as key enablers by:

- Co-financing demonstration plants and technology hubs.
- Facilitating knowledge transfer between academia, startups, and established manufacturers.
- Supporting workforce development initiatives to train engineers and technicians in bio-composite manufacturing.

Additionally, national industrial policies should promote the localization of value chains, particularly in biomass-rich regions, to reduce dependence on imported fossil-derived precursors.

Market Incentives and Demand Stimulation

To catalyze industry uptake, governments and development banks can implement green procurement policies that favor bio-based materials in public infrastructure and defense projects. Furthermore:

- Consumer awareness campaigns can help stimulate demand for sustainable products made with bio-carbon composites.
- Carbon pricing mechanisms and emissions trading systems (ETS) can indirectly promote cleaner production pathways.
- Collaboration with sectors such as automotive and aviation can facilitate early market adoption through joint innovation platforms.

A demand-driven approach reinforces the economic viability of sustainable material alternatives.

Cross-Sectoral Collaboration and Global Alignment

Given the interdisciplinary nature of bio-based carbon fiber innovation spanning materials science, bioengineering, policy, and environmental science multi-stakeholder collaboration is essential. Governments, international organizations, and industrial actors should:

- Establish innovation clusters or centers of excellence focused on bio-composite development.
- Coordinate global research agendas through platforms like the International Energy Agency (IEA) or UNIDO.
- Align funding priorities with climate and sustainability targets under frameworks such as the Paris Agreement and the UN Sustainable Development Goals (SDGs).

Such alignment ensures that technological progress is reinforced by institutional coherence and global support.

In sum, the implications of optimizing continuous pitch production for bio-based carbon fiber extend far beyond the laboratory. They represent a transformative shift in how advanced materials are conceived, regulated, and commercialized. Through proactive policy support, standardization, industrial scale-up, and global coordination, stakeholders can unlock the full environmental and economic potential of this innovation. The strategic integration of bio-based fibers into industrial ecosystems not only contributes to decarbonization goals but also fosters resilient and inclusive industrial growth for the future.

Conclusion

This study has explored the innovation potential and process optimization of bio-based carbon fiber production through continuous pitch technologies. Against the backdrop of growing environmental concerns and the urgent need to decarbonize materials-intensive industries, bio-derived carbon fibers offer a sustainable alternative to conventional petroleum-based counterparts. The research highlights how critical process parameters such as temperature control, feedstock consistency, and residence time can be fine-tuned to enhance fiber quality and enable scalable, energy-efficient production.

Through experimental modeling, material characterization, and system-level analysis, the study demonstrates that optimized bio-pitch processes can deliver mechanical and structural properties that are comparable, and in some cases superior, to those of fossil-derived carbon fibers. Moreover, the integration of life cycle assessments and green metrics underscores the environmental and economic viability of adopting such innovations across high-performance sectors including aerospace, automotive, and renewable energy.

Beyond technical contributions, the study outlines key policy and industry implications that must accompany scientific advancement. Regulatory frameworks, industrial incentives, and cross-sectoral collaboration are essential to ensure that innovation does not remain confined to laboratories but translates into tangible socio-economic and environmental impact.

Future research should focus on diversifying bio-based precursor sources, improving feedstock purification methods, and piloting industrial-scale production models. Additionally, more robust international cooperation will be required to harmonize standards and stimulate global market adoption.

Ultimately, this research contributes to the broader discourse on sustainable materials innovation and reinforces the pivotal role of bio-based technologies in reshaping modern manufacturing landscapes.

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