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Research on the Pathways, Policies, and Impacts of Biomanufacturing in Industrial Transformation and Upgrading

Kehan Feng*

Shaanxi Xinyudan Traditional Chinese Medicine Biotechnology Co., Ltd., Shaanxi, 726207, China

Corresponding author: Kehan Feng, 253302009@qq.com

Abstract: As a disruptive paradigm of deep integration between biotechnology and advanced manufacturing, biomanufacturing is becoming a strategic engine for promoting green industrial transformation and cultivating new quality productive forces. This paper systematically studies the pathway mechanisms, policy frameworks, and comprehensive impacts of biomanufacturing in industrial transformation and upgrading. First, it constructs a "technology-industry-policy" co-evolution analysis framework to explain the internal mechanisms driving industrial transformation. Second, it identifies four core pathways: raw material substitution, process innovation, product upgrading, and system integration. Third, it conducts an in-depth analysis of the strategic orientation and implementation mechanisms of the "14th Five-Year" bioeconomy policy, evaluating the layout and synergistic effects of industrial clusters in the Beijing-Tianjin-Hebei region, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and Chengdu-Chongqing region. Finally, it systematically assesses the comprehensive impacts on industrial restructuring, industrial scale expansion, and sustainable development. The study finds that although China's biomanufacturing industry leads in market scale, it still faces challenges including core technology dependence, slow industrialization, insufficient cost competitiveness, incomplete standard systems, weak industrial ecosystems, and talent shortages. Based on this, the paper proposes recommendations for strengthening top-level design, breaking through key core technologies, improving industrial ecosystems, optimizing regional layout, strengthening talent cultivation, and deepening international cooperation, providing academic support and decision-making references for promoting high-quality development of China's bioeconomy.

Keywords: Bioeconomy; Biomanufacturing; Industrial Transformation and Upgrading; Policy Research

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1.Introduction

1.1 Research Background and Significance

In the global wave of new round of technological revolution and industrial transformation, the bioeconomy is emerging as the fourth economic form following agricultural economy, industrial economy, and information economy. As a disruptive paradigm of deep integration between biotechnology and advanced manufacturing, biomanufacturing carries the historical mission of promoting green transformation in manufacturing and serves as a strategic engine for cultivating new quality productive forces and reshaping the global industrial landscape.

From an international perspective, the bioeconomy has become a strategic high ground contested by major global economies.

The European Union regards it as a key pathway to achieving sustainable development, successively releasing “Innovating for Sustainable Growth: A Bioeconomy for Europe” (2012) and “A Sustainable Bioeconomy for Europe” (2018) to promote transformation toward a renewable resource-based economy. The United States strengthened its global leadership position through the “Executive Order on Advancing Biotechnology and Biomanufacturing Innovation” (2022), launching the “National Biotechnology and Biomanufacturing Initiative” with investment exceeding $2 billion. Japan released the “Bio Strategy 2019” and its upgraded version “Bioeconomy Strategy” (2024), targeting a market scale of 100 trillion yen by 2030.

China attaches great importance to bioeconomy development. In May 2022, the National Development and Reform Commission issued the “14th Five-Year Plan for Bioeconomy Development,” listing it as a strategic emerging industry and deploying key tasks in five aspects: consolidating innovation foundations, strengthening pillar industries, enhancing resource conservation and utilization, building security systems, and optimizing the policy environment. The 2024 “Government Work Report” included biomanufacturing for the first time, explicitly proposing to “actively build biomanufacturing and other new growth engines.” According to OECD predictions, the global biomanufacturing industry scale will reach 35% of total industrial production value by 2030, and China’s bioindustry scale is expected to exceed 9 trillion yuan. Leveraging its green and low-carbon advantages, biomanufacturing reshapes traditional industrial systems through raw material substitution, process innovation, and product innovation, fostering new business forms such as circular economy and providing a “green engine” for global sustainable development.

In-depth research on the pathways and countermeasures of biomanufacturing in promoting industrial transformation and upgrading, and systematic analysis of the strategic orientation and implementation mechanisms of bioeconomy policies, are of significant value for promoting high-quality development of China’s bioeconomy and seizing global high ground. The theoretical significance lies in constructing an analytical framework to enrich industrial economics and technological innovation theory research, and providing new cases for policy science. The practical significance lies in providing reference guidance for government decision-making, enterprise layout, and scientific research innovation.

1.2 Research Objectives and Content

This paper aims to systematically review the pathway mechanisms of biomanufacturing in promoting industrial transformation and upgrading, deeply analyze the strategic orientation of the “14th Five-Year” bioeconomy policy, and reveal its profound impacts on industrial structure. Specific research objectives include: constructing a theoretical analysis framework to explain the internal mechanisms of biomanufacturing-driven industrial transformation from three dimensions of technological innovation, industrial economy, and sustainable development, establishing a “technology-industry-policy” co-evolution framework; revealing core pathways, systematically reviewing the technological evolution and industrial transformation of industrial biomanufacturing, identifying key pathways for transformation and upgrading, analyzing challenges faced and proposing countermeasures; evaluating policy implementation mechanisms and effects, deeply analyzing national strategic planning and policy orientation, evaluating regional layout and industrial synergy mechanisms, identifying key areas and proposing optimization recommendations.

1.3 Research Methods

This paper comprehensively employs literature research, comparative analysis, and policy analysis methods. Through systematic review of academic literature and policy documents in the field of biomanufacturing at home and abroad, it constructs the theoretical foundation of the research; comparative analysis is conducted on the characteristics and differences of biomanufacturing development strategies among major economies including the United States, European Union, Japan, and China; systematic interpretation of the “14th Five-Year” bioeconomy development plan and related supporting policies is conducted to analyze policy objectives, tools, and implementation mechanisms. The technical route of this paper is to construct a theoretical analysis framework through literature research; analyze the application of biomanufacturing in industrial and agricultural fields through comparative analysis and case studies; interpret the “14th Five-Year” bioeconomy policy through policy analysis; finally, comprehensively evaluate the impact of the bioeconomy and propose conclusions and policy recommendations.

2.Theoretical Foundation and Analytical Framework

2.1 Definition of Core Concepts

Biomanufacturing refers to the manufacturing paradigm that utilizes biological systems to produce chemicals, materials, and energy. Clomburg et al. (2017)[5]pointed out that industrial biomanufacturing represents the future of chemical production, enabling the fundamental shift from fossil raw materials to renewable raw materials through microbial cell factories.

From the perspective of technological evolution, biomanufacturing has experienced leapfrog development from traditional fermentation to metabolic engineering and then to synthetic biology. Tan Tianwei (2024)[2]divides the development of biomanufacturing into four stages: Biomanufacturing 1.0 began during World War I, mainly producing primary metabolites through single-strain anaerobic fermentation; Biomanufacturing 2.0 originated during World War II, using mutagenesis-selected microbial mutants to achieve secondary metabolite production; Biomanufacturing 3.0 is marked by recombinant DNA technology and cell culture systems, enabling the production of biological macromolecules; the current period is Biomanufacturing 4.0, characterized by the integration of synthetic biology and artificial intelligence, promoting biomanufacturing toward "new production methods, new products, and sustainability."

2.2 Technological Evolution and Industrial Transformation of Biomanufacturing

Biomanufacturing is a manufacturing paradigm that utilizes biological systems to produce chemicals, materials, and energy. The groundbreaking research published by Clomburg et al. (2017)[5]in Science pointed out that industrial biomanufacturing is the future of chemical production, capable of achieving the fundamental shift from fossil raw materials to renewable raw materials through microbial cell factories. This paper has been cited over 600 times and has become a foundational work in the field.From the perspective of technological evolution, biomanufacturing has experienced leapfrog development from traditional fermentation to metabolic engineering and then to synthetic biology, which can be divided into four stages: The 1.0 period began in World War I, converting sugars into primary metabolites such as acetone and butanol through single-strain anaerobic fermentation; the 2.0 period originated in World War II, using mutagenesis-selected microbial mutants combined with liquid submerged aerobic fermentation to produce secondary metabolites such as penicillin; the 3.0 period is marked by recombinant DNA technology and cell culture systems, achieving the production of biological macromolecules such as therapeutic proteins and industrial enzymes; the current period is the deepening formation period of 4.0, represented by synthetic biology technology, promoting development toward "new production methods, new products, and sustainability." The "Bioprocessing 4.0" concept proposed by Pandey et al. (2024) [10]deeply integrates the Fourth Industrial Revolution with biomanufacturing, highlighting the key role of digitalization and intelligence.

2.3 Theoretical Foundation and Analytical Framework

This paper comprehensively employs technological innovation theory, industrial economics, and sustainable development theory to construct a "technology-industry-policy" co-evolution analytical framework. At the technological innovation level, based on Schumpeter's innovation theory and techno-economic paradigm theory, it emphasizes that biomanufacturing is achieving a paradigm shift from experience-driven to data-driven through the integration of synthetic biology and artificial intelligence, forming a new techno-economic paradigm that reshapes the industrial landscape. At the industrial economy level, it utilizes industrial structure, industrial cluster, and industrial life cycle theories to explain how biomanufacturing promotes the high-end, green, and intelligent evolution of industrial structure through industrial chain extension and value chain reconstruction, and achieves economies of scale and knowledge spillover effects through industrial park construction. At the sustainable development level, based on sustainable development, circular economy, and ecosystem services theories, it demonstrates that biomanufacturing uses renewable resources as raw materials and achieves win-win economic and environmental outcomes through clean production, while emphasizing the importance of biodiversity conservation. The core logic of this framework is that technological innovation provides underlying support, industrial application forms market traction, and policy guidance creates institutional environments, with the three mutually promoting to jointly drive high-quality development of the bioeconomy. Based on this, this paper will systematically analyze the pathways and countermeasures of biomanufacturing in promoting industrial transformation and upgrading, evaluate the implementation effects of the "14th Five-Year" bioeconomy policy, and provide academic support for the development of China's bioeconomy.

3.Pathways and Countermeasures of Biomanufacturing in Promoting Industrial Transformation and Upgrading

3.1 Analysis of Current Development Status of Industrial Biomanufacturing

Industrial biomanufacturing is the core application field of biomanufacturing, covering subdivisions such as bio-based materials, chemicals, energy, and pharmaceuticals. Current development in China presents the following characteristics:Market scale continues to expand. China's bio-fermentation industry has formed a pattern with leading scale and complete systems, with bulk products such as amino acids, organic acids, vitamins, and enzyme preparations ranking among the world's top in production. According to statistics, China's annual amino acid production exceeds 3 million tons, accounting for over 70% of global production; citric acid annual production exceeds 1.5 million tons, accounting for over 60% of global production.

Technological innovation continues to break through. Underlying tools are rapidly iterating, with industry-university-research collaboration conquering multiple key technologies. In gene editing, the Institute of Zoology, Chinese Academy of Sciences established a new method for protein engineering modification (MIDAS), obtaining new tools such as high-activity Cas12i Max and high-specificity Cas12i HiFi; in genome synthesis, the Tianjin University team achieved precise synthesis, assembly, and cross-species delivery of megabase-pair level human DNA, developing the chromosome elimination-mediated large-scale DNA assembly and delivery method (HAnDy).

Industrial applications continue to expand. In the medical and health field, the world's first injectable type III humanized collagen gel was synthesized using E. coli expression systems, and the de novo synthesis of β-lactam parent nuclei was achieved through artificial enzyme design and pathway reconstruction. In the chemical materials field, synthetic biology promotes green and low-carbon transformation, with domestic enterprises breaking through cost and performance limitations of fully biodegradable materials (PHA) by modifying microbial metabolic pathways. In the energy substitution field, hydrocarbon aviation fuel technology converts sugars into aviation kerosene through engineered yeast, achieving pilot trials in enterprises such as Sinopec and China Aviation Oil, with full life cycle carbon emissions reducible by over 70%.

Regional layout is initially formed. Industrial clusters in the Beijing-Tianjin-Hebei region, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and Chengdu-Chongqing region are initially taking shape. Beijing focuses on developing biomedicine and bioinformatics, Shanghai concentrates on biomaterials and biomanufacturing, and Shenzhen emphasizes synthetic biology and biomanufacturing. As of June 2023, 23 national bioindustry bases have been established nationwide; in July 2023, the National Development and Reform Commission approved the construction of the first national biomanufacturing industry innovation center, led by the Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences.

3.2 Pathway Analysis of Industrial Transformation and Upgrading

Biomanufacturing has clear pathways for promoting industrial transformation and upgrading. The "biointelligent value-adding" framework proposed by Miehe et al. (2020) [6]emphasizes the deep integration of manufacturing, information, and biotechnology and the co-evolution of socio-technical systems, providing a theoretical perspective for understanding this transformation. Based on theoretical analysis and practical cases, this paper identifies four core pathways: The raw material substitution pathway achieves renewability by replacing fossil raw materials with biomass resources, such as bio-based plastics significantly reducing carbon footprints, with predictions that industrial biotechnology will reduce 2.5 billion tons of carbon dioxide emissions annually by 2030. The process innovation pathway utilizes microorganisms or enzyme catalysis to replace traditional chemical synthesis, achieving efficient conversion at room temperature and pressure with advantages of strong selectivity and less pollution, such as enzyme-catalyzed pharmaceutical production reducing organic solvent use and bioenzyme textile treatment achieving water and energy conservation. The product upgrading pathway develops high-performance bio-based products to optimize structure, such as bio-based carbon fiber applied in aerospace and other fields, and bio-based cosmetic raw materials meeting green consumption demands, with the global bio-based chemicals market scale expected to reach hundreds of billions of dollars by 2030. The system integration pathway constructs complete industrial chains from raw material supply to market application, promoting collaborative innovation through forms such as industrial alliances and innovation platforms to form industrial ecosystems. Research shows that elements such as bio-based materials and green design platforms play key roles in enterprise green transformation. Tan Tianwei (2024)[2]pointed out that China's biomanufacturing development faces multiple opportunities and challenges in technology, industry, and policy, proposing a "technology breakthrough-industry cultivation-policy innovation" trinity transformation and upgrading pathway.

3.3 Challenges Faced by Industrial Biomanufacturing Development

Although China's industrial biomanufacturing has made significant progress, it still faces many challenges compared to international advanced levels:

Insufficient independent innovation capability in core technologies. High-end gene editing tools and core algorithms and other key technologies are constrained by imports, urgently needing to break through "bottleneck" constraints; in chassis cell development, while industrial-level model microorganism modification capabilities are relatively strong, original and high-performance chassis lag behind; core industrial software such as AI-assisted design and metabolic network models also rely on imports, requiring long-term accumulation of underlying technology depth.

Slow industrialization process. There exists a "valley of death" from laboratory to industrialization, with scaled production facing problems such as high costs, poor stability, and immature processes; pilot platform construction lags behind, lacking public service platforms supporting technology maturation. Asin-Garcia et al. (2025)[9]pointed out that insufficient research infrastructure is a key bottleneck constraining industrial development.

Cost competitiveness needs improvement. Biomanufacturing products are relatively expensive compared to traditional petrochemical products, with high costs for biomass raw material collection, storage, and transportation, high fermentation energy consumption, and separation and purification costs remaining high, posing economic challenges for bio-based materials and biofuels in low oil price environments.

Incomplete standard systems and certification mechanisms. Bio-based product certification standards and methods are not unified, making it difficult for consumers to distinguish product bio-based content and environmental benefits; standards for safety evaluation and environmental impact assessment also need to be improved.

Incomplete industrial ecosystem. Upstream and downstream coordination in the industrial chain is insufficient, with poor connection between raw material supply, technology research and development, and product application; enterprises lack effective cooperation mechanisms with downstream application enterprises, with product development disconnected from market demands; insufficient financial support from industrial investment funds and venture capital constrains the development of startup enterprises.

Prominent talent shortage issues. As an interdisciplinary field, biomanufacturing urgently needs compound talents with backgrounds in biology, chemistry, engineering, and informatics. Currently, there are significant gaps in high-end talents, skilled talents, and industrialization talents who understand both technology and markets.

3.4 Countermeasures and Policy Tools

In response to the above challenges, this paper proposes the following recommendations:Strengthen basic research and technology breakthroughs. Increase R&D investment in frontier fields such as synthetic biology and metabolic engineering, build national-level innovation platforms, focus on breaking through core technologies such as chassis cell modification, core strain construction, key enzyme preparation, genome editing, and AI-driven biomanufacturing, and accelerate independent research and development and industrialization relying on carriers such as national science and technology major projects.

Improve industrial ecosystems and market mechanisms. Establish product certification systems and green procurement policies, promote the construction of standard systems for bio-based materials and chemicals; improve carbon trading mechanisms to convert carbon reduction benefits into economic returns; establish industrial alliances to promote upstream and downstream collaborative innovation.

Optimize regional layout and collaborative development. Layout projects in industrial clusters such as chemicals and materials to promote cluster development—the Beijing-Tianjin-Hebei region focuses on biomedicine and bioinformatics, the Yangtze River Delta focuses on biomaterials and manufacturing, the Guangdong-Hong Kong-Macao Greater Bay Area emphasizes biomedicine and information, and the Chengdu-Chongqing region develops bio-agriculture and environmental protection, forming full industrial chain supporting capabilities.

Strengthen talent cultivation and international cooperation. Deepen industry-education integration, support universities in setting up relevant majors, and establish vocational skills training systems; strengthen international scientific and technological cooperation, participate in international standard setting, introduce advanced technology and experience, and support enterprises in expanding international markets.

Innovate policy tools and incentive mechanisms. Comprehensively utilize policies such as fiscal subsidies, tax incentives, and financial support, establish special funds for industrial development, provide corporate income tax incentives and R&D expense super-deductions, and guide financial institutions to develop innovative products such as intellectual property pledge financing.

Accelerate pilot capabilities and infrastructure construction. Layout pilot capabilities and service systems, build technology maturation platforms; strengthen data infrastructure construction, carry out digital analysis of microbial resources, and mine new functional elements and metabolic pathways.

4.Policy Analysis and Institutional Environment

4.1 National Strategic Planning and Policy Orientation

The "14th Five-Year" Plan elevates the bioeconomy to national strategic height, clarifying the overall direction and key tasks for bioeconomy development. In May 2022, the National Development and Reform Commission issued the "14th Five-Year Plan for Bioeconomy Development," China's first five-year plan for the bioeconomy, marking the formal entry of the bioeconomy into the sequence of national strategic emerging industries.

The plan emphasizes the integrated innovation of biotechnology and information technology, explicitly proposing to promote the integrated development of biotechnology and information technology, and to accelerate biotechnology research and development and application using technologies such as artificial intelligence, big data, and cloud computing. The plan lists biomanufacturing as one of the four key areas of the bioeconomy, proposing to promote the scaled application of biomanufacturing and improve the innovation and development capabilities of the biomanufacturing industry.

From the perspective of development goals, the plan clarifies that by 2025, the bioeconomy will become a strong driving force for promoting high-quality development, achieving significant improvements in total scale, comprehensive scientific and technological strength, industrial integration development, and biosafety guarantee capabilities. Specific indicators include: the proportion of bioeconomy value-added in GDP steadily increasing; biotechnology industry output maintaining an average annual growth rate of about 10%; and the proportion of R&D investment in sales revenue for bio-sector enterprises reaching over 8%.

The plan deploys five key tasks: consolidating the foundation for biotechnology innovation, cultivating and strengthening pillar industries such as biomedicine and bio-agriculture, strengthening the conservation and utilization of biological resources, building a solid biosafety guarantee system, and optimizing the policy environment.

4.2 Regional Layout and Industrial Synergy

The "14th Five-Year" Plan systematically plans the regional layout of the bioeconomy, clarifying the development positioning and key areas of each region: The Beijing-Tianjin-Hebei region is positioned as an innovation source. Relying on platforms such as Zhongguancun, Binhai New Area, and Xiong'an New Area, it focuses on developing biomedicine, biomanufacturing, and bioinformatics. Beijing focuses on original innovation, Tianjin emphasizes industrialization, and Hebei undertakes industrial transfer.

The Yangtze River Delta region is positioned as an industrial highland. Relying on platforms such as Zhangjiang Science City, Suzhou Industrial Park, and Hangzhou Future Sci-Tech City, it focuses on developing biomaterials, bioenergy, and biomedicine. Shanghai leverages its internationalization and capital advantages, Jiangsu strengthens manufacturing supporting capabilities, and Zhejiang activates private economic vitality.

The Guangdong-Hong Kong-Macao Greater Bay Area is positioned as an open gateway. Relying on platforms such as Guangming Science City and Guangzhou International Bio Island, it focuses on developing biomedicine, bioinformatics, and biomedical engineering. Shenzhen focuses on synthetic biology and R&D, while Guangzhou emphasizes production and clinical application.

The Chengdu-Chongqing region is positioned as an emerging growth pole. Relying on platforms such as Tianfu International Bio City and Liangjiang New Area, it focuses on developing bio-agriculture, bio-environmental protection, and biomedicine.

In terms of industrial synergy, the plan emphasizes strengthening industry-university-research synergy, promoting deep cooperation between universities, research institutions, and enterprises; strengthening regional synergy to form a division of labor and cooperation pattern; and strengthening international cooperation to actively participate in global bioeconomy governance.

4.3 Policy Optimization Directions

The implementation of the "14th Five-Year" bioeconomy policy has achieved positive results, but still needs further optimization.

Strengthen coordination and integration. Establish cross-departmental and cross-field coordination mechanisms, strengthen communication between the National Development and Reform Commission, Ministry of Science and Technology, Ministry of Industry and Information Technology, and other departments to form policy synergy; formulate special plans to clarify division of responsibilities and task lists.

Improve precision. Formulate differentiated measures according to the needs of different fields, regions, and enterprises: increase fiscal investment in basic research, improve market mechanisms and give play to the main role of enterprises in industrialization, and implement categorized policies based on resource endowments for regional development.

Enhance sustainability. Establish long-term mechanisms, incorporate the bioeconomy into national economic and social development plans, and maintain policy continuity and stability.

Improve evaluation mechanisms. Establish scientific evaluation indicator systems, conduct regular evaluations and timely adjustments and optimizations; introduce third-party evaluations to improve objectivity and fairness.

5.Comprehensive Impacts of Bioeconomy on Industrial Transformation

5.1 Industrial Restructuring Effects

Biomanufacturing is reshaping industrial structure from multiple dimensions, profoundly changing the underlying logic of industrial production. It reshapes traditional production models. Traditional chemical industry relies on fossil raw materials for chemical synthesis production, while biomanufacturing uses biomass as raw materials and utilizes microorganisms or enzyme catalysis to achieve biological transformation, forming new production routes and reshaping raw material supply chains, processes, product systems, and market patterns.

It provides industrial decarbonization pathways. Using renewable resources as raw materials and achieving efficient resource utilization and environmental friendliness through clean production is an important pathway to achieve industrial carbon neutrality. According to estimates, industrial biotechnology can reduce carbon emissions by hundreds of millions of tons annually; bio-based materials replacing petroleum-based materials can significantly reduce product carbon footprints, and biofuels replacing fossil fuels can reduce carbon emissions in the transportation sector.

It promotes industrial intelligent development. Biomanufacturing 4.0 combines the "design-build-test-learn" cycle of synthetic biology with the "predict-optimize-mine-generate" of artificial intelligence. The application of technologies such as intelligent bioreactors, automated production lines, and digital quality control systems has significantly improved efficiency and stability.

It becomes a new focus of international competition. Major economies have listed it as a national strategy, increasing R&D investment and policy support to compete for leading positions. Although China's industrial scale is large, there are still gaps compared to international advanced levels in core technologies, high-end products, and brand influence, urgently needing to enhance industrial competitiveness.

5.2 Industrial Scale and Economic Benefits

The bioeconomy has become an important pillar of the national economy. In 2022, China's industrial scale exceeded 15 trillion yuan, accounting for over 12% of GDP, of which the biomedicine and biomanufacturing industries exceeded 4 trillion yuan and 3 trillion yuan respectively, with the overall scale expected to reach 20 trillion yuan by 2030. Meanwhile, the bioeconomy is profoundly reshaping employment patterns, with over 10 million direct employees and over 30 million indirectly employed, and has spawned emerging professions such as bioinformatics analysts and synthetic biology engineers, putting higher requirements on labor quality.

The bioeconomy is becoming an important field of technological innovation. R&D investment in the bioeconomy field continues to grow, with enterprise R&D investment accounting for over 8% of sales revenue, higher than the manufacturing average. China's share of global patent applications in biomanufacturing has steadily risen from 28.9% in 2014 to 51.9% in 2022, demonstrating China's innovation vitality in this field.

The bioeconomy is becoming a new engine for regional economic growth. Bioeconomy clusters in the Beijing-Tianjin-Hebei region, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and Chengdu-Chongqing region are accelerating development, becoming important growth poles for regional economies. The development of the bioeconomy has driven the aggregation of related industrial chains, formed bioeconomy industrial clusters, and promoted the optimization and upgrading of regional economic structures.

5.3 Sustainable Development Effects

The contribution of biomanufacturing to sustainable development is reflected in three dimensions: environmental, economic, and social. In the environmental dimension, it significantly reduces environmental footprints by replacing fossil raw materials, optimizing processes, and developing green products; bio-based materials are degradable and reduce plastic pollution, biological processes reduce chemical waste emissions, and bioenergy replaces fossil energy to reduce greenhouse gas emissions. In the economic dimension, it improves the quality and efficiency of the industrial economy by improving resource utilization efficiency, developing high value-added products, and creating new industrial opportunities; its long industrial chain and strong driving effects, combined with circular economy, achieve sustainable resource utilization. In the social dimension, it enhances social welfare by improving product quality, reducing costs, and creating employment; bio-based products are safer and healthier to meet green consumption demands, reducing the cost of medical materials to improve accessibility, and creating high-skill jobs to promote human capital improvement.

6.Conclusions and Policy Recommendations

6.1 Main Research Conclusions

This paper systematically reviewed core literature at home and abroad, deeply analyzed the pathways and countermeasures of biomanufacturing in promoting industrial transformation and upgrading, discussed the strategic orientation and implementation mechanisms of the "14th Five-Year" bioeconomy policy, and evaluated its comprehensive impacts on industry.

The bioeconomy is becoming a strategic high ground for global competition. The EU is sustainability-oriented, the US is technology innovation-driven, and China focuses on industrial transformation, with major economies actively laying out strategies. As a core driving force, biomanufacturing carries the mission of promoting green transformation in manufacturing and serves as a strategic engine for cultivating new quality productive forces and reshaping the global industrial landscape.

The pathways for biomanufacturing to promote industrial transformation and upgrading are clear. Through four pathways—raw material substitution, process innovation, product upgrading, and system integration—it reshapes the logic of industrial production: replacing fossil raw materials with bio-based raw materials to achieve renewability; replacing chemical processes with biological processes to achieve greening; developing high-performance bio-based products to optimize product structure; and building industrial ecosystems to achieve industrial chain collaborative development.

The "14th Five-Year" Plan has constructed a systematic policy framework. From national strategy to regional layout, from industrial synergy to breakthroughs in key areas, the policy system is increasingly improving. The Beijing-Tianjin-Hebei region, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and Chengdu-Chongqing region have become important growth poles, but policy synergy, precision, sustainability, and evaluation mechanisms still need to be strengthened.

The bioeconomy has profound impacts on industry. At the macro level, the bioeconomy has become an important pillar of the national economy, with the scale expected to reach 20 trillion yuan by 2030; at the meso level, biomanufacturing is promoting deep adjustment of industrial structure, reshaping industrial chains and value chains, and promoting green transformation and intelligent manufacturing.

China's bioeconomy development faces both opportunities and challenges. Opportunities lie in the complete industrial system, huge market demand, abundant biological resources, and continuous technological innovation; challenges are reflected in insufficient independent innovation capability in core technologies, slow industrialization processes, lack of cost competitiveness, incomplete standard certification mechanisms, weak industrial ecosystems, and prominent talent shortages.

6.2 Policy Recommendations

Strengthen top-level design and coordination for biomanufacturing. Formulate national medium and long-term development plans oriented toward "dual carbon" goals, clarifying phased goals, key tasks, and guarantee measures; establish cross-departmental and cross-regional coordination mechanisms to guide differentiated local layouts and avoid redundant construction.

Focus on improving independent innovation capabilities in key core technologies. Systematically catalog technology breakthrough lists, focus on "bottleneck" areas to build "industry-university-research-application" collaborative innovation systems, and focus on breaking through core technologies such as chassis cell modification, core strain construction, key enzyme preparation, synthetic biology underlying technologies, genome editing, and AI-driven biomanufacturing.

Promote integrated layout of "basic research-technology breakthrough-industrial application." Form a closed-loop development model of "basic breakthrough-technology transformation-scenario verification-scale promotion," and build a "industry-university-research-application-finance" collaborative industrial ecosystem.

Accelerate industrial ecosystem construction. Improve product certification systems and green procurement policies, promote the construction of bio-based product standard systems, optimize carbon trading mechanisms to convert carbon reduction benefits, and establish industrial alliances to promote upstream and downstream collaborative innovation.

Strengthen talent cultivation and introduction. Deepen industry-education integration to cultivate interdisciplinary talents, support universities in setting up relevant majors, establish vocational skills training systems, and implement open policies to introduce international top talents.

Deepen international cooperation. Participate in global bioeconomy governance and standard setting, strengthen international scientific and technological cooperation, and support domestic enterprises in expanding international markets.

Optimize regional layout. Promote the Beijing-Tianjin-Hebei region, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and Chengdu-Chongqing region to form bioeconomy industrial clusters with distinctive characteristics, creating innovation sources, industrial highlands, open gateways, and emerging growth poles.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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