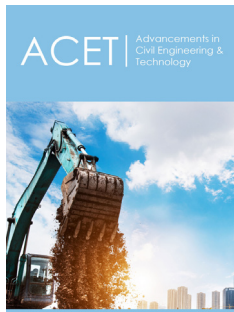


Current Situation, Problems and Solutions for Low-Carbon Transformation in China's Pharmaceutical Industry

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Abstract

In the context of escalating global climate change, the pharmaceutical industry, being energy-intensive and high-emitting, bears significant responsibility for low-carbon transformation. China's "dual-carbon" goals further promote green and sustainable development in this sector. This study aims to explore the paths, challenges, and policy support for low-carbon transformation in China's pharmaceutical industry. Through literature analysis, it systematically reviews the current status of carbon emissions, technological pathways, policy support, and challenges faced by the industry. The study finds that carbon emissions mainly originate from production processes, with notable regional variations and imperfections in monitoring and evaluation systems. Key pathways for promoting low-carbon transformation include green pharmaceutical technology, clean energy application, circular economy models, and digital technology. However, major obstacles remain, such as dual challenges of technology and cost, insufficient corporate transformation motivation, and supply chain coordination issues. Therefore, the study proposes policy recommendations including strengthening national policy support, improving financial mechanisms, and enhancing regulatory systems, while outlining future directions for technological innovation, international cooperation, and long-term strategic planning.

Keywords: Pharmaceutical industry; Low-Carbon transformation; Policy support

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Introduction

Global climate change, one of the gravest challenges in the 21st century, impacts economies, societies, and the environment. The Intergovernmental Panel on Climate Change (IPCC) report highlights that global warming is closely linked to human-induced greenhouse gas (GHG) emissions, primarily due to the continuous increase in CO₂ and other GHGs [1]. Under this backdrop, all sectors face pressure to reduce emissions. The pharmaceutical industry, a significant player in the global economy, involves substantial energy and resource inputs in production processes, encompassing raw material extraction, drug manufacturing, packaging, and transportation. These processes consume considerable energy and generate notable carbon emissions [2]. Specifically, pharmaceutical processes such as autoclaving and freeze-drying require substantial electricity, while solvents and reagents used in chemical synthesis generate greenhouse gases [3]. Additionally, the logistics sector, particularly cold chain transportation, significantly contributes to carbon emissions [4]. Carbon emissions from the pharmaceutical industry not only exert environmental pressure but also conflict with its social responsibility. As a crucial industry for human health, the pharmaceutical industry should lead by example in addressing climate change. Globally, more pharmaceutical companies are recognizing the importance of low-carbon transformation and adopting measures like optimizing production processes, enhancing energy efficiency, and using clean energy [5]. However, challenges remain, including high costs of technological innovation, complexity in supply chain coordination, and uncertainty in policy support [6]. In the context of global climate change, low-carbon transformation is not only an environmental responsibility for the pharmaceutical industry but also an inevitable choice for its sustainable

development. By reducing carbon emissions, the industry can mitigate environmental impact, enhance competitiveness, and meet growing green consumer demand [7]. Future efforts should focus on technological innovation, policy support, and international cooperation to achieve low-carbon transformation goals and contribute to global climate governance.

China's "Dual Carbon" goals, aiming for carbon peaking by 2030 and carbon neutrality by 2060, demonstrate its proactive stance and responsibility in global climate governance. These goals are not only China's strategic choice in addressing global climate change but also a crucial driver for green transformation of its domestic economic structure. As one of the high-energy-consumption and high-emission industries, the pharmaceutical industry faces profound policy guidance and transformation pressure under the "Dual Carbon" goals, while also embracing new opportunities for low-carbon development. The "Dual Carbon" goals set clear carbon reduction requirements for the pharmaceutical industry, promoting its transformation towards green and low-carbon directions. According to the "14th Five-Year Plan," China aims to accelerate the development of a green, low-carbon, and circular economy, with key industries required to formulate carbon peaking action plans and implement emission reduction measures [8]. The pharmaceutical industry, as a crucial component of the national economy, is increasingly facing scrutiny regarding energy consumption and carbon emissions during production. Processes such as raw material extraction, chemical reactions and equipment operation in drug manufacturing, as well as the production and logistics of medical devices, involve significant energy use and high carbon emissions. Thus, pharmaceutical enterprises must reduce carbon emission intensity per unit product through technological innovation and process optimization to meet the policy requirements of the "dual-carbon" goals. These goals promote the R&D and application of low-carbon technologies in the pharmaceutical industry through policy incentives and market mechanisms. Mechanisms such as green finance and carbon trading provide financial support and market impetus for the low-carbon transformation of pharmaceutical enterprises. Green credit policies encourage the adoption of clean energy and energy efficiency improvements by directing capital flows toward low-carbon projects [9]. The establishment of carbon trading markets offers platforms for pharmaceutical enterprises to trade carbon emission quotas, promoting carbon reduction through market-based means. These policies and mechanisms not only reduce the costs of low-carbon transformation but also create new economic growth points. The "dual-carbon" goals accelerate the green collaborative development of the pharmaceutical industry chain. Low-carbon transformation in the pharmaceutical industry involves not only production processes but also the full lifecycle management of upstream raw material supply and downstream product distribution. Pharmaceutical enterprises need to collaborate with suppliers to promote the R&D and application of green raw materials, while optimizing logistics networks and packaging designs to reduce carbon emissions in product distribution [10]. This synergistic effect within the industry chain enhances overall

carbon reduction efficiency and strengthens the international competitiveness of the pharmaceutical industry. The "dual-carbon" goals promote the deep integration of the pharmaceutical industry with digital technologies, providing new technological pathways for low-carbon transformation. The application of digitalization and intelligence technologies, including big data, AI and IoT, can optimize production processes, improve energy utilization efficiency, and enable real-time monitoring and management of carbon emissions [11]. Through intelligent manufacturing technologies, pharmaceutical enterprises can achieve precise control over production processes, reducing energy waste and carbon emissions. Additionally, digital technologies support the tracking of the full lifecycle carbon footprint of pharmaceutical products, providing consumers with transparent information on low-carbon products.

China's "dual-carbon" goals provide clear policy guidance and transformation momentum for the pharmaceutical industry, promoting low-carbon development across technology, markets, industrial chains, and digitization. In this process, pharmaceutical companies must not only address emission reduction pressures but also seize new opportunities from green transformation to contribute to the industry's sustainable development.

Analysis of Low Carbon Transformation Status in China's Pharma Industry

Driven by global climate change and China's "dual carbon" targets, the low-carbon transformation of the pharmaceutical industry, a high-energy-consumption and high-emission sector, has emerged as a crucial issue for sustainable development. After discussing its background and significance, this chapter focuses on the current carbon emission status and issues in China's pharmaceutical industry. By analyzing industry distribution, primary sources, monitoring and evaluation systems, and regional differences, it reveals the challenges faced by the industry in carbon emissions, laying the foundation for subsequent exploration of technical pathways and policy support for low-carbon transformation. This research aims to provide data support and problem-oriented solutions for the green and low-carbon development of the pharmaceutical industry.

Industry carbon emissions distribution in pharmaceutical industry

The carbon emissions of China's pharmaceutical industry are distributed across production, logistics, waste disposal, and exhibit significant sectoral variations, mainly concentrating in sub-sectors such as pharmaceuticals, medical devices, and biomedicine. The pharmaceutical sector, as the core, dominates carbon emissions. Major sources include energy consumption and chemical synthesis reactions, particularly in the production of APIs and chemical formulations, which are energy-intensive and high-emission processes [12]. Traditional Chinese medicine (TCM) manufacturers also face carbon emission issues from energy consumption and waste disposal [13]. In the medical device sector, emissions concentrate on manufacturing and logistics, involving energy-

intensive processes like metalworking and plastic molding, as well as high-emission logistics, especially cross-border transportation [14,15]. Sterilization and packaging also contribute significantly to emissions due to energy use and material consumption. In the biomedicine sector, particularly biopharmaceuticals and genetic engineering, emissions stem from energy consumption in R&D and production processes, including fermentation and purification, which require substantial electricity and produce greenhouse gases. Cold chain logistics further increases energy consumption and emissions due to strict temperature control requirements. Regionally, eastern China exhibits higher carbon emissions than the west due to higher industrial agglomeration and production scale, while the west, though smaller in scale, has a coal-dominated energy structure leading to high emission intensity per unit output [16,17].

The carbon emission distribution in China's pharmaceutical industry is influenced by industry characteristics, regional energy structures, production scales and technological levels. The pharmaceutical manufacturing sector, as a major contributor, has the greatest potential for emission reduction. Medical device and biopharmaceutical industries, due to the specificity of their production processes, require more aggressive measures in technological innovation and energy structure adjustment.

The main source of carbon emissions in the pharmaceutical industry

The carbon emissions of China's pharmaceutical industry mainly originate from production, logistics, and waste disposal, closely related to industry characteristics. Production, a significant emission source, is greatly influenced by manufacturing processes and technology levels. Complex chemical reactions and energy consumption are involved, especially in the production of APIs and intermediates, where extensive fossil fuel use directly leads to greenhouse gas emissions [18]. Stringent temperature and humidity control further increases energy consumption and emissions [19]. Logistics emissions are linked to the specificity of pharmaceutical products, requiring specific conditions during transportation, particularly for cold chain products like vaccines and biologics, consuming substantial energy to maintain [20]. Brett et al. [21] indicate that carbon emissions in pharmaceutical logistics stem mainly from road transport and warehousing, with road transport emissions varying by vehicle type, loading rate and empty running rate. Warehouse energy consumption, especially cold storage operations, also significantly impacts emissions [21]. Waste disposal emissions are related to pollutants from production, including wastewater, exhaust gas and solid waste containing organic solvents and heavy metals, which require energy-intensive treatment to meet discharge standards. Incineration of pharmaceutical waste directly releases CO₂ and other harmful gases, exacerbating emissions [18].

These emission characteristics indicate that the pharmaceutical industry's low-carbon transition requires a focus on green production technology, enhanced logistics efficiency and innovative waste treatment technology. This aligns with previously discussed

industry differences and regional distribution features, providing a foundation for subsequent challenges in carbon emission monitoring and assessment.

Monitoring and evaluation of carbon emissions in the pharmaceutical industry

China's pharmaceutical industry faces multiple challenges in carbon emission monitoring and assessment, posing significant obstacles to precise carbon emission management and optimization. A comprehensive monitoring system has not been fully established, lacking unified standards and methodologies. Many pharmaceutical companies struggle with incomplete and inaccurate data in collection, organization, and reporting processes, compromising the reliability of carbon emission assessments [12]. These data quality issues stem from limitations in monitoring technology and inadequate awareness of carbon emission management among enterprises.

The standardization of carbon emission assessment methods in the pharmaceutical industry remains unestablished. Significant variations exist among enterprises in terms of emission accounting boundaries, calculation methodologies, and data sources, hindering horizontal comparisons of assessment results. For instance, some enterprises solely focus on production-related emissions while neglecting contributions from logistics, waste disposal, and other stages [22]. This limited scope impedes comprehensive carbon emission assessments. Current methods largely rely on traditional static accounting models, lacking real-time monitoring and predictive capabilities for dynamic carbon emission changes, which are inadequate for the rapid development of the pharmaceutical industry. The application of carbon emission monitoring technologies in this industry is also underdeveloped. Although IoT, AI, and Machine Learning (ML) exhibit great potential in carbon emission monitoring, their application in the pharmaceutical industry is still in its infancy [23]. IoT-based real-time monitoring systems can collect data on electricity consumption, fuel use, and transportation activities through sensors and predict future emission trends using ML models. However, the adoption of such systems in the pharmaceutical industry is low. This technological lag not only constrains the accuracy of emission monitoring but also affects enterprises' abilities to formulate scientific emission reduction strategies.

Lack of transparency in carbon emission data within the pharmaceutical industry hinders effective disclosure and monitoring mechanisms. Firms selectively disclose carbon emission information, impeding stakeholders' access to comprehensive and authentic data [24]. This opacity undermines public trust in the industry's low-carbon transition and obstructs policymakers from formulating effective reduction strategies based on accurate data. Additionally, the carbon emission assessment framework in the pharmaceutical industry fails to account for regional disparities. Significant variations exist in energy structures, technological levels and developmental stages across China's pharmaceutical sectors; however, current assessment systems often apply a one-size-fits-all approach, neglecting regional characteristics' impact

on carbon emissions [25]. This limitation hinders carbon emission optimization at the regional level.

In summary, China's pharmaceutical industry faces multiple issues in carbon emission monitoring and assessment, including data quality, evaluation methods, technological application, transparency and regional variations. To address these issues, comprehensive measures encompassing technology, standards, and policies are needed to improve and optimize the carbon emission monitoring and assessment system in the pharmaceutical industry.

Regional differences in carbon emissions of the pharmaceutical industry

China's pharmaceutical industry exhibits significant regional variations in carbon emissions, primarily due to an uneven distribution across eastern, central, and western regions. Eastern regions, with developed economies and high industrial concentration have relatively larger total carbon emissions. In contrast, central and western regions, characterized by smaller industrial scales and relatively backward technologies have lower total emissions but potentially higher emission intensities per unit of output. These differences reflect not only disparities in regional economic development levels but are also closely related to factors such as energy structures, technological levels and policy enforcement efforts.

The eastern region of China, a major hub for the pharmaceutical industry, exhibits significantly higher carbon emissions than other areas, due to the large-scale and intensive production activities in Beijing, Shanghai and Guangdong. However, eastern regions also lead in energy structure optimization and technological innovation, with some enterprises adopting clean energy and green production technologies, thereby mitigating carbon emission growth [26]. The central region displays transitional characteristics in pharmaceutical carbon emissions. While gradually expanding the scale of the pharmaceutical industry through the transfer of industries from the east, the region faces high carbon emission intensity per unit output due to technological and energy structural constraints. The rapid development of the pharmaceutical industry in Henan and Hubei relies heavily on coal consumption, resulting in low carbon emission efficiency. Additionally, policy implementation and technology promotion in the central region lag, exacerbating carbon emission issues [27]. The western region, economically less developed, has a smaller pharmaceutical industry and lower total carbon emissions but potentially higher emission intensity per unit output. This region's heavy reliance on coal, low application of clean energy, and limited technological capacity contribute to inefficient carbon emissions. Prominent carbon emission problems in energy consumption and waste disposal exist in the pharmaceutical industry of Shaanxi and Sichuan. Furthermore, inadequate policy support and funding in the western region hinder the promotion and application of low-carbon technologies [28]. Regional differences are influenced by local policies, energy structures, technological levels, among others. Eastern regions are advanced in policy implementation and technological innovation, while central and western regions face challenges such as inadequate

policy enforcement and technology promotion. Moreover, regional variations in energy structures are key drivers of carbon emission differences, with eastern regions actively adopting clean energy, while central and western regions predominantly use coal, leading to higher carbon emission intensities [29].

In summary, regional variations in carbon emissions from China's pharmaceutical industry reflect the complex influences of economic development, energy mix, technological level, and policy implementation. Future efforts should focus on regional coordinated development, optimizing energy structure, and promoting low-carbon technologies to gradually narrow regional disparities and facilitate the low-carbon transformation of the pharmaceutical industry [30].

Tech Path for Low-Carbon Transformation in China's pharmaceutical Industry

Based on the current carbon emission status and issues of China's pharmaceutical industry, exploring effective technological pathways has become a core task for achieving low-carbon transformation. As an energy-intensive and high-emission sector, the low-carbon transformation of the pharmaceutical industry relies not only on policy drives but also on technological innovation. This chapter delves into key pathways such as green pharmaceutical technology, energy efficiency enhancement, circular economy models, and digitalization and intelligent technologies, analyzing their potential and practices in reducing carbon emissions and optimizing resource utilization. It provides technological solutions and forward-thinking for the low-carbon transformation of China's pharmaceutical industry. As a strategic industry vital to national economy and people's livelihood, the low-carbon transformation of the pharmaceutical industry exhibits distinct characteristics compared to other manufacturing sectors. From an industrial perspective, pharmaceutical manufacturing is typically energy-intensive and high-emission. An empirical analysis by Zhang et al. (2023) on traditional Chinese medicine preparation production shows that the energy utilization rate of traditional decoction and alcohol precipitation processes is less than 40%, while modern countercurrent extraction technology can increase it to 65%, but with an average equipment retrofitting cost increase of RMB 3.2 million per production line. This techno-economic characteristic often traps small and medium-sized enterprises in a dilemma of "retrofitting leading to losses," forming a barrier to transformation. The rigid requirements for drug quality control impose institutional constraints on the application of low-carbon technologies.

Innovation and application of green pharmaceutical technology

Innovations and applications in green pharmaceutical technology represent a pivotal pathway for advancing the low-carbon transformation of China's pharmaceutical industry. By optimizing production processes, reducing harmful substance use, and enhancing resource utilization efficiency, this technology significantly decreases carbon emissions during pharmaceutical production. The application of green chemistry principles,

particularly through the reduction or substitution of toxic solvents, has emerged as a crucial means of mitigating carbon emissions. The use of green solvents such as water and ethanol, as alternatives to traditional organic solvents, not only minimizes environmental pollution but also reduces energy consumption [31]. The introduction of biocatalysis has also markedly elevated the greenness of pharmaceutical processes. Biocatalysts efficiently react at ambient conditions, decreasing energy demand while avoiding the formation of toxic byproducts [32]. Continuous manufacturing offers new possibilities for the low-carbon transformation of the pharmaceutical industry. Compared with traditional batch production, continuous manufacturing significantly reduces energy consumption and waste emissions by optimizing reaction conditions and minimizing intermediate steps. The use of continuous-flow reactors for the production of pharmaceutical intermediates enhances production efficiency while decreasing solvent use and carbon emissions [33]. Additionally, continuous manufacturing supports real-time monitoring and process optimization, further improving resource utilization efficiency. Innovations in green pharmaceutical technology also encompass waste recycling. By developing efficient waste recovery and reuse technologies, pharmaceutical companies can convert waste generated during production into valuable resources, thereby reducing carbon emissions. For instance, advanced solvent recovery technologies enable the efficient recovery and reuse of solvents used in pharmaceutical processes, lowering raw material costs and reducing the environmental burden of waste disposal. Organic waste produced during pharmaceutical processes can also be converted into biofertilizers or other useful products through biodegradation technologies, further promoting the development of a circular economy. In practice, the application of green pharmaceutical technology has achieved remarkable results. One pharmaceutical company successfully reduced carbon emissions by 30% and energy consumption by 25% in the production process of a key drug by introducing green chemistry processes and continuous manufacturing technologies [34]. Some enterprises have achieved zero-waste emission targets and significantly lowered production costs by optimizing waste management processes [35].

Innovations and applications in green pharmaceutical technology have not only provided technical support for the low-carbon transformation of China's pharmaceutical industry but also promoted sustainable development by optimizing production processes and enhancing resource utilization efficiency. With continued technological advancements and policy support, green pharmaceutical technology is expected to be widely adopted, injecting new impetus into the low-carbon transformation of China's pharmaceutical industry.

Energy efficiency improvement and clean energy application

Energy efficiency enhancement and clean energy application constitute a pivotal technological pathway for the low-carbon transformation of China's pharmaceutical industry. As an energy-intensive sector, pharmaceutical production, particularly in

manufacturing pharmaceuticals and medical devices, consumes substantial energy, accounting for a major portion of carbon emissions. Building upon innovations in green pharmaceutical technology, improving energy efficiency enables enterprises to reduce energy consumption without compromising production capacity, thereby decreasing carbon emissions. Additionally, the widespread adoption of clean energy fundamentally diminishes reliance on fossil fuels, further advancing the industry's low-carbon transition.

In enhancing energy efficiency, pharmaceutical companies can achieve energy-saving goals by optimizing production processes and introducing efficient equipment and technologies. Adoption of high-efficiency motors, variable frequency technology, and heat recovery systems can significantly reduce energy consumption during production. Deployment of Intelligent Energy Management Systems (EMS) enables real-time monitoring of energy use and optimizes energy allocation through data analysis, minimizing unnecessary energy waste [36]. Xu et al. [37] indicated that integrated application of these technologies can improve energy efficiency by over 20% in pharmaceutical enterprises, while reducing carbon emission intensity per unit product. The utilization of clean energy represents another crucial direction for the low-carbon transformation of the pharmaceutical industry. Traditional pharmaceutical production mainly relies on fossil fuels such as coal and natural gas, which not only generate significant carbon emissions but also pollute the environment. By incorporating clean energy sources like solar, wind, and biomass, pharmaceutical companies can markedly decrease carbon emissions. Solar photovoltaic power generation systems applied in pharmaceutical production provide factories with clean electricity, reducing dependence on grid power [38]. Biomass energy, as a renewable resource, can supply thermal and electrical energy for pharmaceutical production through gasification or combustion technologies, while also achieving waste resource utilization [39].

This technological pathway complements the circular economy model, forming a comprehensive system for the low-carbon transformation of the pharmaceutical industry. By optimizing energy use, introducing efficient equipment and technology, and promoting clean energy, pharmaceutical companies can reduce carbon emissions while maintaining production efficiency and competitiveness. This transformation aligns with China's "dual-carbon" goals and provides valuable insights for the sustainable development of the global pharmaceutical industry.

Low-carbon transformation support for DI technologies

Digitalization and intelligence serve as pivotal supports for the low-carbon transformation of the pharmaceutical industry, advancing it toward green development through optimizing production processes, enhancing energy efficiency, and reducing resource waste. Digital technologies establish intelligent production management systems for precise monitoring and optimization of entire pharmaceutical production. IoT and big data analytics-based smart factory systems collect real-time data on production equipment, energy consumption, and environmental emissions,

optimizing production parameters via algorithms to decrease energy consumption and carbon emissions [40]. Digital Twin technology simulates and predicts carbon emissions in various production scenarios by creating virtual factory models, providing a scientific basis for low-carbon production decisions [41]. AI application in pharmaceutical R&D and production significantly improves resource utilization efficiency, reducing unnecessary carbon emissions. AI-driven drug screening platforms optimize experimental designs through algorithms, minimizing experiment trials and chemical usage, thereby lowering the carbon footprint in R&D [42]. In production, AI utilizes machine learning algorithms to optimize scheduling, reducing equipment idling and energy waste, while predicting equipment failures to avoid energy inefficiencies due to downtime [43]. Blockchain application in pharmaceutical supply chain management enhances transparency, decreasing carbon emissions in logistics. By tracing and monitoring raw material procurement, production, transportation and sales, blockchain optimizes logistics routes, minimizing unnecessary transport steps and energy consumption [44]. Additionally, blockchain promotes pharmaceutical waste recycling by establishing waste trading platforms, improving resource recycling rates, and reducing carbon emissions [45].

In summary, digitalization and intelligence technologies provide robust technical support for the low-carbon transformation of the pharmaceutical industry by optimizing production processes, enhancing resource utilization efficiency, improving supply chain management, and strengthening energy monitoring. In the future, with continuous technological advancements and expanded application scenarios, these technologies will play an increasingly crucial role in the low-carbon transformation of the pharmaceutical industry [46].

Policy & Institutional Support for China's Pharmaceutical Industry's Low-carbon Transformation

In the low-carbon transformation of China's pharmaceutical industry, policy and institutional support are crucial drivers. With intensifying global climate change and China's "dual carbon" targets, the high-energy-consumption and high-emission pharmaceutical industry faces unprecedented transformation pressure. While previous discussions focused on technical pathways and carbon emission statuses, this chapter further examines policy and institutional frameworks, analyzing national and local policy landscapes, financial support mechanisms, and the establishment of regulatory evaluation systems. By reviewing policy trends and institutional innovations, this chapter aims to provide systematic policy recommendations for the low-carbon transformation of China's pharmaceutical industry, facilitating its sustainable development goals [47].

Current situation & Trend of national low-carbon policies

China's national policy framework for low-carbon transformation in the pharmaceutical industry has gradually taken shape and deepened under the guidance of the "dual-carbon"

targets. In 2020, China clearly proposed "carbon peaking" and "carbon neutrality" goals, providing top-level design guidance for the low-carbon transformation of the pharmaceutical industry. Against this backdrop, the National Development and Reform Commission, the Ministry of Industry and Information Technology and other departments have successively issued a series of policy documents aiming to promote the transformation of the pharmaceutical industry towards green and low-carbon development. The "14th Five-Year Plan for Pharmaceutical Industry Development" explicitly proposes accelerating the construction of a green manufacturing system, promoting clean production technologies and circular economy models, and reducing resource consumption and pollution emissions.

Under China's "dual carbon" goals, local governments, as crucial drivers for the low-carbon transformation of the pharmaceutical industry, have established a multi-layered support system through policy innovation and practice. This system encompasses five key dimensions: Policy guidance, where local governments align with national goals to formulate special plans for low-carbon transformation in the pharmaceutical industry, setting regional carbon emission caps and outlining implementation paths such as energy structure adjustment and green technology innovation [48]. Incentive mechanisms, which include fiscal subsidies and preferential tax policies to reduce the cost burden of low-carbon transformation. Specific measures involve establishing special funds for green pharmaceutical technology R&D and clean energy application, as well as tax incentives like corporate income tax and VAT reductions to enhance enterprises' internal drive for transformation [49]. Spatial layout optimization, through the establishment of low-carbon industrial parks to promote clustered and low-carbon development of the pharmaceutical industry. These parks adopt circular economy models, encouraging resource, energy, and waste treatment facility sharing among enterprises, improving resource utilization efficiency and fostering collaborative innovation through policy guidance and technical support [50]. Technological innovation support, achieved through cooperation with universities and research institutions to establish low-carbon technology R&D centers for the pharmaceutical industry. These platforms provide technical consulting and talent support, accelerating the development and promotion of low-carbon technologies, and significantly enhancing pharmaceutical enterprises' innovation capabilities through industry-university-research collaboration [51]. Improvement of the regulatory system, involving the establishment of carbon emission data platforms for pharmaceutical enterprises to enable real-time monitoring and periodic assessments. These measures enhance data transparency and accuracy, providing a scientific basis for policy formulation and adjustment [48]. Additionally, local governments actively promote green financial innovation, collaborating with financial institutions to introduce green credit, green bonds, and other financial products. These instruments reduce financing costs, guide capital flows towards low-carbon sectors through market mechanisms, and provide crucial support for the sustainable development of the pharmaceutical industry [52].

Through multi-dimensional policy innovations and practices, local governments have systematically supported the low-carbon transformation of the pharmaceutical industry, effectively promoting its upgrade towards greenness and low carbon [53].

Regulatory & Evaluation system for pharmaceutical industry's low-carbon transformation

In facilitating the low-carbon transition of the pharmaceutical industry, establishing a comprehensive regulation and evaluation system is crucial for achieving industry low-carbon goals. Currently, one of the major challenges faced by China's pharmaceutical industry in this transition is the lack of a systematic regulatory framework and evaluation standards. To effectively promote the low-carbonization of the pharmaceutical industry, constructing a scientific and comprehensive regulation and evaluation system is vital.

A regulatory framework for the low-carbon transition in the pharmaceutical industry necessitates clarifying regulatory bodies, objects, and contents. Regulatory bodies should encompass government departments, industry associations, and third-party independent institutions, forming a multi-layered and multi-dimensional regulatory network [54]. Regulatory objects should cover all stages of the pharmaceutical industry, including R&D, production, logistics and waste disposal, ensuring effective carbon emission control throughout the entire lifecycle [55]. Regulatory contents should include key indicators such as carbon emission standards, energy efficiency, and the proportion of clean energy use, ensuring targeted and operable regulation [56]. The establishment of an evaluation system is a crucial part of the regulatory framework. It should include both quantitative and qualitative indicators to comprehensively reflect the low-carbon transition effectiveness of the pharmaceutical industry. Quantitative indicators can include carbon emissions per unit of output, the proportion of clean energy use and waste recycling rates, while qualitative indicators can include the formulation and implementation of corporate low-carbon strategies and the level of R&D and application of low-carbon technologies [57]. The evaluation system should also introduce a dynamic evaluation mechanism, regularly updating evaluation indicators and methods to adapt to the rapid development of the low-carbon transition in the pharmaceutical industry [58]. In the implementation of the regulatory and evaluation system, the application of digital technology is particularly important. Through technologies such as big data, IoT and blockchain, real-time monitoring, precise accounting and transparent management of carbon emission data can be achieved, improving regulatory efficiency and evaluation accuracy [59]. Blockchain technology ensures the immutability and traceability of carbon emission data, providing reliable data support for the operation of the carbon trading market [60]. The regulatory and evaluation system for the low-carbon transition in the pharmaceutical industry needs to align with international standards to promote the coordinated low-carbon development of the global pharmaceutical industry. By drawing on international advanced experiences, China can further improve its regulatory framework and evaluation

system, enhancing its competitiveness in the global low-carbon pharmaceutical industry [61]. Simultaneously, China should actively participate in the formulation of international standards, promoting standardization and normalization of the low-carbon transition in the global pharmaceutical industry [62].

In summary, the establishment and improvement of a regulation and evaluation system for the low-carbon transformation of the pharmaceutical industry are crucial for achieving low-carbon goals. By clarifying the regulatory framework, constructing a scientific evaluation system, applying digital technologies, and aligning with international standards, China's pharmaceutical industry will take solid steps towards low-carbon transformation.

Prospects for China's Pharmaceutical Industry's Low-Carbon Transformation

As global climate change intensifies and China advances its "dual carbon" goals, the pharmaceutical industry, being energy-intensive, faces an inevitable strategic issue of low-carbon transformation. Building on previous discussions of technical pathways, policy support, and challenge response, this chapter outlines future trends and potential opportunities for low-carbon transformation in China's pharmaceutical industry. By analyzing technological innovation, international cooperation, global health contributions, and long-term strategic planning, this chapter aims to provide a forward-looking perspective for the sustainable development of the pharmaceutical industry, enabling it to take a leading position in the global low-carbon economy.

The technological innovation trends in the low-carbon transformation of the pharmaceutical industry will center around green pharmaceutical technology, clean energy application, circular economy models and the deep integration of digitalization and intelligence. As the core innovation, green pharmaceutical technology significantly reduces carbon emissions in chemical reaction processes through biocatalysis while enhancing drug synthesis efficiency and selectivity. Advances in gene engineering and enzyme immobilization will further optimize biocatalysis, lowering energy consumption and waste emissions. Clean energy application will accelerate the low-carbon transformation, with renewables like solar and wind gaining popularity in pharmaceutical production, drastically reducing fossil fuel use and carbon emissions. Additionally, innovations in energy efficiency, such as high-efficiency heat exchange systems and intelligent energy management systems, will optimize energy utilization and minimize waste. Digitalization and intelligence will be crucial supports, with AI and big data analytics optimizing production processes, enhancing resource utilization, and reducing unnecessary energy consumption. Furthermore, blockchain technology will enhance supply chain transparency and traceability, facilitating green procurement and low-carbon logistics. The integrated application of these technologies will steer the pharmaceutical industry towards greater efficiency and environmental friendliness. In summary, the technological innovation trends in the low-carbon transformation of the pharmaceutical industry will focus on green pharmaceutical

technology, clean energy application, circular economy models, and the deep integration of digitalization and intelligence, significantly reducing carbon emissions and driving the industry towards greater efficiency and environmental friendliness.

In advancing the low-carbon transformation of China's pharmaceutical industry, international cooperation plays a pivotal role. Technological cooperation provides crucial support by introducing and absorbing advanced green pharmaceutical technologies, clean energy applications, and circular economy models, accelerating technology upgrades and reducing carbon emission intensity. Specifically, international technology transfer has significantly enhanced low-carbon innovation, particularly in green pharmaceutical R&D. Policy-level cooperation also offers important safeguards, with international organizations and multilateral mechanisms facilitating global scientific collaboration and promoting cross-border cooperation in low-carbon technology R&D and application. Institutions like the WHO and the UN set policy frameworks to support industrial transformation. Additionally, EU-China cooperation in the low-carbon economy provides technical support and policy insights, enriching transformation pathways. Industrial chain-level cooperation injects continuous momentum, emphasizing global supply chain collaboration. International pharmaceutical firms and academic institutions play a key role in green pharmaceutical R&D, sharing resources and accelerating commercialization. Multinational companies introduce low-carbon standards in supply chain management, driving low-carbon transformation in raw material sourcing, manufacturing, and logistics. Market-level international demand offers external impetus. As global consumers increasingly demand low-carbon products, the international pharmaceutical market's demand for low-carbon technologies rises. Chinese companies, competing internationally, adopt low-carbon standards, driving technological upgrades. Furthermore, mature international carbon trading markets offer new opportunities, incentivizing low-carbon technology R&D and application. Through technology transfer, policy support, industrial chain collaboration and market demand, international cooperation systematically supports China's pharmaceutical industry's low-carbon transformation. Moving forward, China must deepen international partnerships, leverage global resources, accelerate low-carbon goals, and contribute to the sustainable development of the global pharmaceutical industry.

The low-carbon transition in the pharmaceutical industry contributes to global health in several ways: Firstly, it mitigates environmental impacts, indirectly enhancing global public health. As an energy-intensive sector, the industry's carbon emissions exacerbate climate change and pose health risks through air and water pollution. By promoting green manufacturing, improving energy efficiency and adopting clean energy, the industry can significantly reduce emissions and pollution, fostering a cleaner and more sustainable environment for global health. Secondly, it enhances the stability and resilience of the global pharmaceutical supply chain. Climate-induced extreme weather and resource scarcity pose severe threats, particularly during public health

emergencies, where supply chain disruptions can lead to drug shortages impacting global health. By transitioning to a low-carbon model, the industry optimizes resource use and reduces fossil fuel dependence, strengthening supply chain sustainability and resilience. Thirdly, it promotes equity in global health. Developing and underdeveloped regions face greater environmental pollution and public health issues, with limited capacity to address climate change and access medical resources. Through international cooperation and technology transfer, the low-carbon transition can help these regions establish more sustainable healthcare systems, improving drug accessibility and affordability, thereby narrowing the global health gap. Lastly, it provides innovative impetus for global health. The development and application of low-carbon technologies not only reduce emissions but also spur new medical technologies and products. For instance, innovations in green pharmaceutical manufacturing may lead to more efficient and eco-friendly production methods, while digital and intelligent technologies enhance healthcare service efficiency and quality. These innovations contribute to the sustainable development of the pharmaceutical industry and provide advanced, reliable solutions for global health.

Long-term strategic planning for the low-carbon transformation of China's pharmaceutical industry requires systematic design encompassing technological innovation, policy support, industrial chain collaboration, and international cooperation. Technological innovation serves as the core driver. The R&D and application of green pharmaceutical technologies will significantly reduce carbon emissions during production by replacing traditional energy-intensive and polluting processes with green chemistry techniques like enzymatic catalysis and biosynthesis. Additionally, the integration of digital and intelligent technologies optimizes production processes, enhances energy efficiency, and achieves precise energy management through AI and big data analysis. Policy and institutional support are crucial safeguards. At the national level, it is necessary to improve the policy framework for low-carbon transformation, incentivizing enterprises to reduce emissions through carbon trading mechanisms and green financial instruments. Local governments should formulate differentiated support measures based on regional characteristics, promoting clean energy applications in energy-rich areas and establishing low-carbon technology R&D centers in regions with strong R&D capabilities. Industrial chain collaboration is key. The low-carbon transformation necessitates participation from upstream and downstream enterprises, such as establishing a green supply chain management system to encourage joint carbon emission reductions among raw material suppliers, manufacturers, and logistics service providers. Furthermore, promoting a circular economy model can effectively reduce waste, for instance, by recycling and reusing discarded pharmaceuticals to lessen environmental burdens. International cooperation accelerates this transformation. China's pharmaceutical industry should actively engage in global low-carbon technology exchanges and cooperation, introducing advanced technologies and management experiences by joining international green pharmaceutical alliances and participating in global carbon

reduction initiatives. Simultaneously, leveraging international cooperation platforms like the Belt and Road Initiative can propel Chinese low-carbon pharmaceutical technologies and products into global markets, enhancing international competitiveness.

During implementation, the long-term strategic planning for low-carbon transformation in the pharmaceutical industry requires phased progression. Short-term goals should focus on technology R&D and pilot demonstrations, conducting trials of green pharmaceutical technology applications in key enterprises. Mid-term goals emphasize policy improvement and industrial chain coordination, promoting upstream and downstream enterprises to jointly participate in low-carbon transformation through policy guidance. Long-term goals aim for comprehensive industrial decarbonization, achieving carbon neutrality in the pharmaceutical industry through the synergistic effect of technological innovation and policy support.

Declarations

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Availability of data and materials

The data supporting the findings of this study are in the supplementary materials.

Ethics approval

Not applicable.

Author contribution

Zimin Cao: Validation, Formal analysis, Writing - original draft & review & editing. Yalin Lei: Writing - review & editing.

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