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Research on Environmental Resource Protection and Sustainable Paths in Pharmaceutical Development

—A Case Study of Taiji Group

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Abstract: Under the background of the "dual-carbon" strategy, the pharmaceutical industry, as an important industry related to public health and ecological security, is facing the dual challenges of high resource consumption and high environmental load. From the perspective of environmental resource protection and sustainable development, this paper systematically sorts out the environmental impact mechanism of the entire life cycle of the pharmaceutical industry, reveals its characteristics of "high energy consumption, high pollution, and high risk", and combines the national policy system to analyze the institutional guarantee for green transformation. Taking Taiji Group as a typical case, this paper deeply analyzes its practical paths in green planting, energy conservation and carbon reduction, clean technology, resource recycling, and ESG governance, and summarizes its replicable green development model. On this basis, it puts forward hierarchical and classified enterprise green transformation strategies and policy suggestions, such as green drug evaluation, green financial incentives, and multi-regulatory collaboration. The study believes that we should adhere to systematic thinking and whole-process management to promote the organic unity of environmental friendliness, efficient resource utilization, and responsibility fulfillment in the pharmaceutical industry.

Keywords: Green pharmaceuticals; Sustainable development; Environmental resource protection; Taiji Group

1 Introduction

At present, China's domestic economy is transforming towards high-quality development, and sustainable and healthy development has become a common proposition for the development of various industries in the new era. People are also increasingly pursuing a healthy and positive lifestyle（Zhang Yuan et al., 2021）. As an important field directly related to national health and indirectly affecting the environment and ecology, the development of the pharmaceutical industry must not only ensure the safety and effectiveness of drugs but also take into account resource conservation, pollution prevention and control, and environmental and ecological responsibilities. However, traditional pharmaceutical manufacturing links generally have problems such as high energy consumption and complex emissions, and there is an

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urgent need to promote green transformation through technological innovation and management upgrading, and take a path of high-quality development with low environmental costs（Hua Ying, 2017; Zhang Kun & Huang He, 2025）.

In recent years, the Chinese government has attached great importance to the green development of the pharmaceutical industry. Through formulating a series of policies such as the "14th Five-Year Plan for the Development of the Pharmaceutical Industry", "Guidelines for Zero-Carbon Planning and Management Practices in the Pharmaceutical Industry", and "Guiding Opinions on Promoting the Green Development of the API Industry", it has clearly proposed to build a green pharmaceutical manufacturing system and promote the environment-friendly transformation of the entire life cycle of drugs to help achieve the "dual-carbon" goal （Kong Fei et al., 2023; Xue Xiaojuan et al., 2023）. Against this background, more and more pharmaceutical enterprises have begun to actively practice the concept of sustainable development, incorporating energy conservation and emission reduction, pollution control, ecological protection, etc. into enterprise strategic management and technological innovation, such as Yunnan Baiyao Group and Yiling Pharmaceutical （Bai Xin, 2024）. As a large enterprise group integrating pharmaceutical research and development, the pharmaceutical industry, and the pharmaceutical distribution industry in China, Taiji Group has actively responded to the "dual-carbon" strategy and explored a green pharmaceutical development path covering green planting, clean production, recycling, and social responsibility （Li Yangchun et al., 2022）. It has accumulated relatively mature experience in the protection of traditional Chinese medicine resources, greening of processes, collaborative governance of waste, and construction of ESG management systems, demonstrating the feasibility and leadership of traditional pharmaceutical enterprises in transforming to green and low-carbon development. This paper takes "pharmaceutical environmental resource protection and sustainable paths" as the core theme, focuses on key issues in the green development of the pharmaceutical industry, sorts out Taiji Group's green practice paths, and discusses the internal logic, implementation paths, and policy implications of green transformation in the pharmaceutical industry from both theoretical and practical dimensions, aiming to provide theoretical support and practical reference for the high-quality development of China's pharmaceutical industry.

2 Theoretical Basis of Pharmaceuticals and Sustainable Development

2.1 Environmental Impact Mechanism of the Pharmaceutical Industry

The impact of the pharmaceutical industry on the environment runs through the entire process of "resource extraction - production and manufacturing - circulation and use - waste disposal", showing the composite characteristics of the whole life cycle, multi-media, and high risk. In the upstream stage, a large amount of fossil energy and rare metals are consumed, bringing significant resource pressure; in the middle manufacturing link, there is a concentrated emission of high COD wastewater, VOCs, drug dust, and hazardous wastes such as bacterial residues, accompanied by high-intensity consumption of steam and electricity, leading to multiple pollutions such as water ecological toxicity, atmospheric photochemical smog, and the greenhouse effect. In the downstream use stage, after metabolism in the human body, drugs enter sewage, soil, and the food chain in their original form, inducing the spread of drug-resistant genes; if expired drugs, aluminum-plastic/PVC packaging, and medical wastes are improperly disposed of, they may cause long-term deposition of dioxins and heavy metals, and affect the microbial community structure, biological sex ratio, and overall biodiversity through ecological cascade effects. At the same time, insufficient disclosure of enterprise

environmental information and high end-of-pipe treatment costs lead to frequent problems such as regulatory blind spots and illegal discharge and dilution, constituting a systematic environmental pressure of "high energy consumption, high pollution, high risk, and non-degradability".

2.2 Core Concepts and Goals of Sustainable Development

The pharmaceutical industry internalizes the core concept of sustainable development as "meeting global health needs without exceeding the earth's ecological boundaries and preserving equal health and resource opportunities for future generations". This means that in terms of the environment, the pharmaceutical industry takes net-zero emissions and positive natural benefits as rigid constraints, and through technologies such as green chemistry, micro-reaction, and enzymatic methods, transforms the high-energy consumption and high-pollution mode of APIs into a green factory with closed-loop resources and ultra-low emissions; at the same time, establishes a residue control system in the entire chain of drug use to prevent and control drug resistance and environmental hormone pollution（Cai Chun & Lu Xiangyang, 2025）. In terms of the economy, it takes green processes, digital supply chains, recycled packaging, and waste resource utilization as new growth points, reduces transformation costs through green finance and carbon trading, and eliminates high-pollution and low-cost modes. In terms of society, it ensures the universal accessibility of vaccines and essential drugs, promotes fair pricing and localized production, improves occupational health and information transparency, and promotes public co-governance and sharing. The goal is to achieve in-depth alignment with SDG3, SDG6, SDG12, and SDG13 by 2030, promoting the coordinated win-win of health and well-being and ecological protection (Table 1).

Table 1 Sustainable development paths of the pharmaceutical industry

Sustainable Development	Dimension Key Goals	Paths/Technical Tools	Corresponding SDGs (United Nations Sustainable Development Goals)
Environmental Dimension	Pollution reduction and carbon reduction	Green chemistry, continuous flow micro-reaction, enzymatic substitution, centralized pollution control systems in parks, carbon footprint accounting and life cycle assessment, full-process monitoring of drug residues	SDG6 (Clean Water and Sanitation)SDG12 (Responsible Consumption and Production) SDG13 (Climate Action)
Economic Dimension	Reduce green transformation costs and stimulate new growth poles: Green process redesign.	Digital supply chain and traceability system, recycled packaging and green logistics, resource utilization of medical waste, ESG information disclosure, green bonds/ carbon market financing	SDG9 (Industry, Innovation and Infrastructure)、SDG12 (Responsible Consumption and Production)、SDG17 (Partnerships for the Goals)
Social Dimension	Universal healthcare, fair health, safe work, Essential	drug supply guarantee mechanism, technology transfer and localized production, occupational health and safety system (OHS), transparent management of drug life cycle, public participation in green supervision platforms	SDG3 (Good Health and Well-being) SDG10 (Reduced Inequalities) SDG16 (Peace, Justice and Strong Institutions)

2.3 Resources and Environmental Elements in the Entire Life Cycle of Drugs

In their "cradle-to-grave" life cycle, drugs are closely intertwined with resource consumption and environmental impacts, forming a complex and dense ecological network. The upstream link relies on raw materials such as fossil energy, precious metals, and corn steep liquor. Their extraction and planting processes occupy a large amount of land and consume water resources, fertilizers, and agricultural chemicals, forming significant resource pressure; the middle stage includes high-energy-consuming processes such as synthesis, fermentation, extraction, and purification. While using a large amount of electricity, steam, and organic solvents, it emits high-salt and high-COD wastewater, VOCs waste gas, and hazardous solid waste, constituting multi-media pollution loads; the packaging link widely uses aluminum-plastic blisters, PVC materials, and cold chain transportation systems, further increasing the product carbon

footprint. In the downstream use stage, 30% to 90% of the active ingredients of drugs taken by patients are discharged into the environment in their original form with domestic sewage, inducing the spread of drug-resistant genes; improper incineration or landfilling of expired drugs and medical wastes will release dioxins and heavy metals, bringing long-term ecological risks. It is estimated that the pharmaceutical industry already accounts for 20% to 25% of the total carbon emissions of the medical system, but the environmental data of downstream drug use and waste disposal links have been missing for a long time, making pollution identification and source control difficult.

3 Environmental Challenges and Green Transformation: Background of China's Pharmaceutical Industry

3.1 Industry Emission Status and Typical Pollutants

The pharmaceutical industry generates a large amount of pollutants during production, mainly characterized by large wastewater discharge and complex composition, involving multiple links such as synthesis, fermentation, and extraction, containing refractory pollutants such as high-concentration organic matter, solvent residues, antibiotics, and hormones; waste gas emissions are intermittent and highly toxic, mainly from links such as reaction, distillation, and drying, containing harmful gases such as VOCs, ammonia, sulfides, and hydrogen chloride; solid wastes are diverse and harmful, including waste activated carbon, waste solvents, reaction residues, and sludge, most of which are hazardous wastes; at the same time, some small and medium-sized pharmaceutical enterprises have imperfect construction or unstable operation of pollution prevention and control facilities, with problems such as insufficient governance capacity and low compliance emission rate, and prominent environmental risks. Among them, wastewater contains refractory substances such as high-concentration organic matter, antibiotics, and hormones; waste gas is rich in toxic and harmful components such as VOCs, ammonia gas, and sulfides; solid wastes including waste solvents, residues, and sludge are mostly hazardous wastes, and some small and medium-sized enterprises have incomplete pollution treatment facilities and unstable operation, leading to high environmental pollution risks (Table 2) （Yao Guangyuan et al., 2021）.

Table 2 Types of typical pollutants in the pharmaceutical industry

Type	Main Pollutants	Characteristics
Wastewater	COD, BOD5, ammonia nitrogen, antibiotics, organic solvents, heavy metals	High concentration, strong toxicity, poor biodegradability
Waste Gas	VOCs (benzene series, alcohols, ketones, ethers), HCl, NH_3, hydrogen sulfide	Strong volatility, difficult to collect, and obvious odor
Solid Wastes	Waste solvents, reaction residues, waste activated carbon, sludge, expired drugs.	Mostly hazardous wastes, requiring standardized treatment
Noise	Generated by the operation of pumps, compressors, reaction kettles and other equipment	Impact on communities and surrounding residents

3.2 National Policy Promotion and Regulatory System Construction

To promote the green transformation and pollution prevention and control of the pharmaceutical industry, the state has, on the one hand, successively issued documents such as the "14th Five-Year Plan for Ecological and Environmental Protection", "14th Five-Year Plan for the Development of the Pharmaceutical Industry", and "Guiding Opinions on the High-Quality Development of the Pharmaceutical Industry", clearly proposing to promote green manufacturing

of pharmaceutical enterprises, strengthen the whole-process control of pollution, and improve resource utilization efficiency. On the other hand, environmental protection departments have continuously improved the regulatory system, established a regulatory mechanism centered on the pollutant discharge permit system, and implemented measures such as enterprise environmental credit evaluation, whole-process supervision of hazardous wastes, and special rectification of VOCs. At the same time, the Ministry of Ecology and Environment has promoted clean production audit and performance grading management in key industries, included the pharmaceutical industry in the key supervision list, and improved enterprises' awareness of environmental protection responsibilities and governance capabilities through differentiated law enforcement, online monitoring, mandatory disclosure of environmental information, etc., building a relatively systematic policy support and supervision management system.

3.3 Evolution of Industry Green Certification and Environmental Protection Standards

With the in-depth advancement of the concept of green development, the green certification system and environmental protection standard system in the pharmaceutical industry have been continuously improved. The state has vigorously promoted certification work for green factories, green supply chains, and green products, encouraged pharmaceutical enterprises to participate in the construction of green manufacturing systems, and included them in important bases for policy support, fund support, and project approval. At the same time, industry environmental protection standards have continued to iterate and upgrade, and normative documents such as the "Water Pollutant Discharge Standards for Pharmaceutical Industry" and "Standards for Volatile Organic Compounds Emission Control" have been issued, further refining pollutant discharge limits and control requirements, and enhancing operability and mandatory compliance. In addition, the ecological and environmental departments have promoted the implementation of clean production standards and technical guidelines, covering multiple subcategories such as chemical drugs, biopharmaceuticals, and proprietary Chinese medicines, gradually realizing the transformation from "end-of-pipe treatment" to "source control" and "whole-process management", and accelerating the construction of a green, efficient, and low-carbon pharmaceutical industry standard system.

4 Development Overview and Green Pharmaceutical Practice of Taiji Group

4.1 Enterprise Development History and Business Layout

Taiji Industrial (Group) Co., Ltd. is a member enterprise of China National Pharmaceutical Group Co., Ltd. Its predecessor was Sichuan Fuling Traditional Chinese Medicine Factory, established in 1972. It was listed on the Shanghai Stock Exchange in 1997 and completed strategic restructuring in 2021 to become a holding subsidiary of Sinopharm Group. With modern traditional Chinese medicine intelligent manufacturing as the core and anesthetic and psychotropic characteristic chemical drugs as a supplement, the company has built a whole industry chain system covering pharmaceutical research and development, industrial manufacturing, commercial distribution, Chinese medicinal material resource development, and international business, with 12,000 employees and dozens of subsidiaries. Its R&D system has a national postdoctoral research workstation and multiple academician teams, having undertaken more than 90 major scientific research projects and obtained more than 300 patents. In terms of industrial

manufacturing, it has built multiple national-level green factories and intelligent workshops, with the capacity of processing 100,000 tons of Chinese medicinal materials per year and producing 3 billion oral liquid preparations per year, and has won national honors in greening and intellectualization. In terms of pharmaceutical commerce, it has formed a modern pharmaceutical logistics system with an annual throughput capacity of 35 million pieces, covering more than 100,000 terminals. In terms of Chinese medicinal material resources, the company has built more than 200,000 mu of standardized planting bases and a whole-chain traceable digital system, and is a national key leading enterprise in agricultural industrialization. Its international business has expanded to more than 20 countries and regions, with more than 120 brand registrations. As a national intellectual property demonstration enterprise and an intangible cultural heritage inheritance unit, Sinopharm Taiji continues to promote the modernization, industrialization, and internationalization of traditional Chinese medicine, committed to building a world-class traditional Chinese medicine enterprise with global influence. As a core enterprise under Sinopharm Group, relying on a complete industrial chain and strong R&D strength, it has created a "Taiji Green Plan" with demonstration and leading significance through building a sound environmental management system, intelligent energy-saving technologies, resource recycling models, and green R&D practices, providing replicable experience for the green transformation and high-quality development of the traditional Chinese medicine industry.

4.2 Environmental Management System and Pollution Control Technology

Taiji Group has established a systematic ESG management system and organizational structure, including a board decision-making mechanism, a full-time leading group, and a collaboration mechanism among various departments. It has a strategic committee, a management leadership working group, and an executive team to ensure the synergy between top-level design and grass-roots implementation, and strengthen the responsibility implementation of subsidiaries and departments at all levels in ESG matters. It aims to build a scientific, systematic, and standardized sustainable development work system, fully implement the responsibilities in the three fields of environmental protection, social responsibility, and corporate governance. The system clearly takes the development concept of innovation, coordination, greenness, openness, and sharing as guidance, integrates ecological environmental protection, safe production, scientific and technological innovation, employee care, and compliance governance into the entire chain operation of the enterprise, and promotes environmental governance and sustainable development simultaneously. The company actively implements the concept of green development, emphasizes clean production, incorporates it into strategic planning, strictly implements the requirements for "three wastes" management, pollution control, and resource conservation, and has successively obtained ISO 14001 environmental management system and ISO 50001 energy management system certification. In 2025, its Wind rating was upgraded to A-level, ranking 11th in the pharmaceutical industry, demonstrating its benchmarking significance in green transformation.

4.3 Cases of Energy Conservation, Emission Reduction, and Resource Recycling

Taiji Group has established a green practice system covering the entire industrial chain in terms of energy conservation, emission reduction, and resource recycling, forming a multi-dimensional collaborative mechanism centered on intelligent manufacturing, clean energy substitution, efficient utilization of water resources, and extension of environmental protection technologies. In intelligent manufacturing, the Group has realized production line automation and energy efficiency optimization through systems such as SCADA, DCS, and MES. For instance, the

oral liquid production line saves over 80 million yuan in costs annually, and the efficiency of traditional Chinese medicine extraction has doubled. Supporting technologies like magnetic levitation refrigerators, cloud-intelligent controlled air compressors, MVR concentration equipment, and electric heat pump technology have been applied to comprehensively improve energy efficiency, with energy savings exceeding 75% in some processes. In energy and resource substitution, the Group has promoted the implementation of photovoltaic + energy storage projects. Sichuan Taiji Pharmaceutical generates 1.6 million kWh of electricity annually, reducing carbon emissions by approximately 2,000 tons. It has also built a resource closed-loop of "traditional Chinese medicine residue–biomass fuel," achieving over 95% reuse of medicine residues. In water resource management and pollution control, Fuling Pharmaceutical Factory has an annual water reuse rate of 86%. Boiler waste heat recovery has significantly reduced steam consumption, and multiple subsidiaries have advanced in-depth wastewater treatment and low-carbon boiler transformation, resulting in a marked reduction in COD and VOCs emissions. In the extension of environmental protection technologies, Ningbo Taiji Environmental Protection Company has innovated a "waste-to-treat-waste" model, providing ultra-low emission solutions for high-emission industries such as steel and electric power, and realizing flue gas treatment and waste resource utilization. To date, Taiji Group has built four national-level green factories, five provincial-level green factories, and one green supply chain management enterprise. Through technological innovation, energy structure optimization, and ecological closed-loop construction, it has successfully achieved a win-win situation in economic and ecological benefits for green and low-carbon development, offering a replicable and promotable model for the green transformation of the traditional Chinese medicine industry.

4.4 Practices in Green Transformation of Drug R&D

Taiji Group has actively advanced green transformation in drug R&D, systematically reducing environmental impacts throughout the R&D process through source control, process optimization, and collaboration with digital platforms. In raw material management, relying on the "Three Noes and One Full" standard system (no pesticide residues, no heavy metals, no genetically modified organisms, and full-process traceability) and the Chinese medicinal material GAP traceability platform, the Group has established a green medicinal material management system covering planting environment monitoring, pesticide residue control, and full-process traceability. It has also built a visualized and collaborative green supply chain through supplier access mechanisms. In R&D processes, the concept of "green manufacturing process design" has been introduced to promote process modularization and energy efficiency optimization in core links such as extraction, with some systems achieving 20% energy savings. Additionally, risk visualization and error-proofing mechanisms have been adopted to achieve "first-time qualification," effectively reducing resource waste and pollutant generation. In platform empowerment, the Group has collaborated with academic teams to build the "Herbal Medicine Think Tank" large model, accelerating the transformation of green process research achievements. It has also established a green-oriented R&D investment mechanism: in 2024, R&D investment reached 282 million yuan, accounting for 2.28% of revenue, including 61 low-carbon technology R&D projects, 10 of which have obtained green drug registration standards. In downstream extension, the Group has promoted resource reuse of medicine residues, with over 95% converted into biomass fuel. It has also improved the GVP pharmacovigilance system to strengthen environmental risk control during drug use, forming a green closed-loop covering the entire process of R&D, production, use, and waste disposal. In 2024, Taiji Group added four green factories, with CO_2 emissions per 10,000 yuan of output value decreasing by 33.7% compared to 2020. Its Wind ESG rating rose to A, ranking among the

top 11 in the pharmaceutical industry. This represents a dual breakthrough in green R&D and ecological benefits, setting a benchmark for sustainable innovation in the traditional Chinese medicine industry.

5 Exploration of Green Innovation Paths in Pharmacy

Driven by global sustainable development strategies and China's "dual-carbon" goals, the pharmaceutical industry is undergoing a profound green transformation. Shifting from the traditional "high resource consumption and high environmental load" model to an "ecologically friendly and circularly efficient" one has become an era requirement and core proposition for the pharmaceutical sector. The essence of green pharmacy is to achieve resource conservation, pollution reduction, and ecological protection while ensuring drug quality and safety, based on the concept of the whole life cycle. This chapter systematically analyzes the mainstream paths of current green innovation in pharmacy from four dimensions—green raw materials, green processes, end-of-pipe treatment, and corporate responsibility—and corroborates them with typical practices （He Binsheng et al., 2022）.

5.1 Green Sourcing of Raw Materials and Protection of Traditional Chinese Medicine Resources

The starting point of green pharmacy lies in green raw materials. In China, especially in the traditional Chinese medicine industry, long-term reliance on natural medicinal resources has led to prominent issues such as resource depletion, quality fluctuations, and lack of traceability. Many authentic medicinal materials, such as Fritillaria cirrhosa, antelope horn, and Phellodendron chinense, have been listed in the National Key Protected Wild Plants List due to over-harvesting. Resource protection has thus become the primary link in the industry's green transformation. To address resource bottlenecks, the industry generally promotes the "base-oriented, standardized, and ecological" construction of medicinal material cultivation. For example, Taiji Group has established tens of thousands of mu of green medicinal material planting bases in Liangping (Chongqing) and Nanjiang (Sichuan), implementing the "Three Noes and One Full" standard (no pesticide residues, no heavy metals, no genetically modified organisms, and full-process traceability). Through the introduction of remote sensing monitoring and IoT terminals, dynamic monitoring of environmental factors such as soil, water quality, and climate during medicinal material growth is realized, ensuring the ecological safety of production areas and the stable quality of medicinal materials. In addition, enterprises have collaborated with research institutions to build "authentic medicinal material germplasm resource banks" for domestication, cultivation, and protection of the genetic diversity of endangered species. For instance, Taiji Group, in conjunction with the China Center for Chinese Materia Medica Resources and Southwest University, has conducted research on germplasm evaluation and artificial propagation of species such as Coptis chinensis and Scrophularia ningpoensis, promoting the protection of authentic medicinal materials and enhancing green supply capacity, thereby laying a solid foundation for green drug manufacturing.

5.2 Optimization of Clean Production Processes and Application of Green Chemistry

The pharmaceutical industry is typically energy- and resource-intensive. Traditional processes are plagued by frequent solvent use, generation of harmful intermediates, and low energy conversion efficiency, which severely hinder the simultaneous improvement of environmental performance and production efficiency. The introduction of green

chemistry concepts has provided theoretical support and technical directions for cleaner and more sustainable drug synthesis processes. Currently, enterprises are promoting process greening through the following paths:

First, the construction of green solvents and solvent recovery systems. Some enterprises have replaced traditional high-pollution substances such as chloroform, DMF, and DMSO with low-toxicity solvents like ethanol and water, and built supporting multi-stage distillation and membrane separation systems to improve the recovery rate of organic solvents. For example, Taiji Group has achieved a solvent recovery rate of over 85% in multiple API projects, significantly reducing total VOCs emissions.

Second, the application of green catalysis and continuous flow reaction technologies. In API synthesis, catalytic reactions are the core of green processes. Enterprises are experimenting with green technologies such as biological enzymes, nano-catalysts, and photocatalysis to replace traditional heavy metal catalytic systems, reducing residual pollution and reaction by-products. Meanwhile, continuous flow synthesis technology enables precise temperature control, automatic regulation of reaction time and dosage, which not only improves yield but also effectively reduces batch pollution risks. For example, through continuous process transformation, Huahai Pharmaceutical shortened the reaction time of a core intermediate by 50% and reduced energy consumption by 30%.

Third, whole-process quality control and green design. Incorporating mechanisms such as green process screening, EHS risk assessment, and process safety evaluation in the early stage of drug R&D to avoid high-pollution and high-risk paths from the design source has become part of the standard R&D process for most large pharmaceutical enterprises.

5.3 Waste Management and Synergistic Disposal of "Three Wastes"

The "three wastes" (wastewater, waste gas, and solid waste) emitted by the pharmaceutical industry are both complex and hazardous. In particular, wastewater from antibiotics, steroids, and chemically synthesized drugs contains a large amount of refractory organic matter, hormone residues, and heavy metals, posing potential threats to ecosystems. Therefore, end-of-pipe treatment remains an important technical barrier for green pharmacy.

In wastewater treatment, enterprises generally adopt a multi-stage treatment model of "pretreatment + biochemical treatment + advanced oxidation." For example, Taiji Group's API production park is equipped with MBR membrane bioreactors and ozone-ultraviolet synergistic advanced oxidation devices, enabling effluent COD to be reduced to below 50 mg/L, which is far better than national discharge standards. In waste gas treatment, the focus is on VOCs recovery and harmless treatment. Current mainstream technologies include combined systems of condensation recovery + activated carbon adsorption + catalytic combustion (RTO), which are widely used in reaction sections with intensive organic solvent use. Meanwhile, some enterprises have built closed feeding, metering, and reaction systems to reduce unorganized emissions and control gas leakage from the source. In solid waste management, resource-oriented synergistic disposal of hazardous wastes such as medicinal residues, waste adsorbents, and heavy metal-containing residues has become a trend. Some pharmaceutical enterprises have established long-term cooperation mechanisms with cement kilns and hazardous waste incineration plants to achieve a closed-loop of "reduction, harmlessness, and resource utilization." For example, CSPC Pharmaceutical Group has collaborated with China United Cement to synergistically utilize hazardous wastes, handling over 10,000 tons of pharmaceutical hazardous wastes annually.

5.4 Corporate ESG Practices and Fulfillment of Social Responsibility

Green development is not only a technical path but also a governance model and value orientation （Luo Zhiyong,

2018）. As ESG (Environmental, Social, and Governance) becomes a new global capital market standard, the green transformation of pharmaceutical enterprises is shifting from "pollution control and emission reduction" to "systematic responsibility fulfillment." First, corporate ESG strategies are becoming more systematic. Large pharmaceutical enterprises generally establish ESG committees led by the board of directors, formulate annual ESG action plans covering carbon auditing, green procurement, green finance, and employee safety. Taiji Group has released an Enterprise ESG Report annually since 2022, with the 2024 edition disclosing core indicators such as total greenhouse gas emissions, water reuse rate, and total environmental protection investment, strengthening public supervision and responsibility tracing. Second, the creation of green factories continues to advance. According to statistics from the Ministry of Industry and Information Technology, as of 2023, over 60 pharmaceutical enterprises have been rated as national-level green factories, covering various sectors such as chemical drugs, biopharmaceuticals, and traditional Chinese medicines. Through the introduction of intelligent manufacturing systems, energy management systems, and green building standards, overall energy efficiency and environmental performance have been improved. Third, the concept of whole-life-cycle green management is gradually being popularized. Pharmaceutical enterprises are establishing green auditing mechanisms throughout the entire process from drug design, raw material procurement, production and manufacturing to packaging and logistics. For example, some enterprises use biodegradable packaging materials, build green supply chain rating systems, and assess the environmental performance of upstream enterprises to achieve collaborative ecological responsibility.

6 Case Insights and Policy Recommendations

As one of China's leading proprietary Chinese medicine enterprises, Taiji Group has made systematic arrangements and practical explorations in green pharmaceutical development. Its valuable experience in raw material cultivation, process optimization, pollution control, and ESG construction not only provides a solid foundation for its own green transformation but also offers a model and path reference for the green and high-quality development of China's pharmaceutical industry （Xu Zhiling, 2023）. Based on the above analysis, this paper further puts forward systematic thinking and countermeasures from three aspects: case summary, industry recommendations, and policy guarantees.

6.1 Analysis of the Replicability and Promotability of Taiji Group's Experience

Taiji Group has formed a systematic path in green pharmaceutical development, covering four sectors: "green source–green process–green end–green governance," with the following three key characteristics that make it highly replicable and promotable:

(1) Integration of systematic planning and strategic orientation

Taiji Group has elevated green development to the core corporate strategy, embedding environmental protection concepts into corporate governance through the establishment of a dedicated ESG committee and the formulation of green factory promotion plans, achieving synergy between top-level design and implementation mechanisms. This "strategy + organization" dual embedding mechanism provides institutional guarantees for green practices and is suitable for promotion among other pharmaceutical enterprises with a certain scale and organizational foundation.

(2) Parallel advancement of technology-driven and ecological synergy

In green technology, Taiji has adopted a "single-point breakthrough–overall integration" path, implementing key technological transformations around core nodes such as solvent recovery, biological catalysis, membrane separation, and intelligent environmental protection facilities, and collaborating with research institutes to promote synergistic innovation in medicinal material germplasm protection and clean process R&D. This "enterprise-led + research support + industrial chain collaboration" model helps form regional green pharmaceutical industry ecosystems and is suitable for replication and promotion in traditional Chinese medicine industrial clusters.

(3) Sound whole-process supervision and visualized traceability mechanisms

In medicinal material cultivation, Taiji has built a whole-process supervision system through "remote sensing + IoT + traceability systems"; in emission control, it has introduced AI + data platforms for dynamic monitoring of wastewater and waste gas. This "technology + data + platform" integrated governance model can be widely applied to pollution control and green management in medium and large pharmaceutical enterprises, with strong operability and promotability.

However, the replication of Taiji's experience requires a differentiated path design based on factors such as enterprise scale, process type, and financial strength. Small and medium-sized pharmaceutical enterprises need to focus on exploring adaptive strategies for "low-cost and high-efficiency" technological transformation paths.

6.2 Strategic Recommendations for Green Development of Other Pharmaceutical Enterprises

For the green transformation paths of different types of pharmaceutical enterprises, strategies should be tailored to specific circumstances and implemented in a hierarchical manner.

Small and medium-sized enterprises can start with "end-of-pipe treatment + basic standardization," prioritizing the improvement of "three wastes" treatment facilities, alleviating financial pressure through fiscal interest subsidies and equipment leasing, and promoting the establishment of environmental management systems such as ISO 14001 to lay the foundation for green management.

Large enterprises should focus on "source innovation + process reengineering," increasing R&D investment in green raw material substitution, clean processes, and green catalytic technologies, collaborating with research institutions to establish green manufacturing platforms, and promoting industrial chain restructuring.

The entire industry should advance "digital empowerment + intelligent supervision", introducing environmental protection digital systems and AI analysis tools to achieve real-time monitoring of energy consumption and emissions, performance evaluation, and refined management.

Additionally, a "green industry alliance" should be built, especially in major production areas of traditional Chinese medicinal materials, to realize the co-construction and sharing of green resources through cooperatives and standardized cultivation, forming a whole-chain green ecological system from medicinal material sources to circulation.

6.3 Optimization Paths at the Policy and Regulatory Level

Promoting green development in pharmacy not only relies on spontaneous exploration by enterprises but also requires continuous improvement of institutional design, policy incentives, and regulatory systems. Therefore, it is recommended to optimize the policy and regulatory system from the following three aspects:

(1) Improve the green drug evaluation and access system

Currently, China lacks clear evaluation standards and market incentive mechanisms for green drugs. It is suggested that the National Medical Products Administration and the Ministry of Ecology and Environment jointly formulate a green drug standard system, incorporate environmental impact assessment indicators of the preparation process, and introduce green assessment elements in drug review. Positive incentives such as priority registration, priority inclusion in medical insurance, and authorization of green labels should be given to environmentally friendly drugs.

(2) Establish special funds and credit channels for green pharmaceuticals

It is recommended that the National Development and Reform Commission and the Ministry of Finance jointly establish a "Special Fund for Green Pharmaceutical Development" to support enterprise technological transformation, demonstration project construction, and protection of traditional Chinese medicine resources. Meanwhile, policy banks and green financial institutions should be encouraged to launch "green pharmaceutical credit products", implementing interest-subsidized loans or risk compensation mechanisms for green projects to reduce the financing cost of green transformation.

(3) Improve diversified supervision and public participation mechanisms

It is suggested to further strengthen environmental supervision over drug production, especially for special pollution links involving antibiotics and hormones, implementing key list supervision and dynamic information disclosure. At the same time, promote the establishment of a mandatory ESG information disclosure system for enterprises, expand public supervision channels, and enhance the attention and participation of all sectors of society in the green development of the pharmaceutical industry.

6 Conclusions and Prospects

Against the backdrop of the "dual-carbon" strategy, the pharmaceutical industry is undergoing a fundamental shift from "prioritizing development" to "prioritizing greenness." Green and low-carbon practices are no longer optional but a necessary path for the survival and development of pharmaceutical enterprises. From raw material cultivation and production manufacturing to emission management and corporate governance, the concept of green development has gradually permeated all links in the entire life cycle of drugs, driving the industry to accelerate the construction of a new development pattern characterized by ecological friendliness, efficient resource utilization, and responsibility orientation. Through a systematic review of green innovation paths in pharmacy, this paper focuses on analyzing Taiji Group's practical experience in green raw materials, clean processes, pollution control, and ESG governance. It is found that its green development model of "strategic leadership - technical support-mechanism synergy" boasts strong systematicness, operability, and promotional value. Meanwhile, it also points out practical problems in the current industry's green transformation, such as unbalanced regional development, weak transformation capabilities of small and medium-sized enterprises, and the lack of green technical standards.

Looking ahead, the green development of pharmacy must adhere to the principles of "multi-stakeholder collaboration, whole-chain coordination, and policy guidance." On one hand, enterprises need to continuously enhance their green governance capabilities and integrate green concepts into strategic decision-making and daily operations. On the other hand, the government should provide systematic guarantees in terms of policy support, standard formulation, and financial incentives, promoting the establishment of a green drug evaluation system and the building of a green

supply chain ecosystem. Additionally, public participation and information transparency should be strengthened to foster social consensus and supervisory synergy for the industry's green transformation. Green pharmacy is not only a crucial fulcrum for achieving environmental friendliness and the "Healthy China" strategy but also a key window for China's pharmaceutical industry to move toward high-quality development. Only by taking greenness as the foundation, technology as the engine, and systems as the guarantee can we build sustainable competitive advantages and drive China's pharmaceutical industry to achieve a dual leap in ecological and economic value in the global industrial chain.

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