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Exploration of Environmental Responsibility and Green Transformation Paths in Pharmaceutical Quality Control

—A Case Study of Quality Control Positions in Taiji Group

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Abstract: Against the backdrop of the advancing "dual-carbon" strategy, pharmaceutical quality control, as a key link in ensuring drug safety, also bears significant environmental responsibilities and the mission of green transformation. This paper takes Taiji Group as a case study to systematically explore the practical paths and effectiveness of its quality control positions in green transformation. By identifying environmental load points in pharmaceutical quality control—such as solvent pollution, waste liquid discharge, high energy consumption, and experimental consumables—this study constructs a green indicator system, promotes green method substitution, embeds ESG responsibilities in positions, and builds a digital quality control platform, aiming to explore a feasible mechanism for the coordinated development of "precision testing" and "green low-carbon." The research finds that Taiji Group has significantly reduced the carbon footprint of testing and the discharge of "three wastes" through technical means such as green solvent substitution, aqueous chromatography, near-infrared spectroscopy, and SFC; achieved green visualization and performance evaluation of the entire testing process through the integration of LIMS and MES systems; and formed a trinity green management model of "system + technology + awareness" through closed-loop waste management and green behavior score assessment. This paper provides enterprise practice samples and policy recommendation support for constructing a green pharmaceutical quality control system, and has practical significance for promoting the coordinated development of high-quality and greenization in the pharmaceutical industry.

Keywords: Pharmaceutical quality control; Green analytical methods; Environmental responsibility; Taiji Group; Green transformation

1 Introduction

With the continuous advancement of global sustainable development strategies, the concept of green and low-carbon is profoundly reshaping the production logic and value orientation of traditional manufacturing industries （Xie

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Xuemei & Han Yuhang, 2022）. As an important industry safeguarding human life and health, the pharmaceutical industry faces undeniable ecological and environmental pressures while protecting public health （Kong Fei et al., 2023）. Particularly in links such as API synthesis, preparation, production, packaging and transportation, and quality control, problems such as high energy consumption, frequent use of organic solvents, and concentrated discharge of "three wastes" (wastewater, waste gas, solid waste) are prevalent. Relevant studies show that the energy consumption and water consumption per unit output value of the pharmaceutical industry are significantly higher than those of traditional high-energy-consuming industries such as chemical engineering and steel. The waste liquid and gas emitted often contain refractory or highly toxic pharmaceutical active ingredients, posing long-term threats to ecosystems. Therefore, promoting the green and low-carbon transformation of the pharmaceutical industry is not only an objective requirement to respond to the "dual-carbon" strategy and ensure ecological security, but also an inevitable path to achieve high-quality and sustainable development of the pharmaceutical industry （Yao Guangyuan et al., 2021）.

In the construction of a green pharmaceutical system, quality control has long been regarded as the "last line of defense" for ensuring drug safety and effectiveness （Liu Xiaoqian & Guo Jina, 2025）. Quality control positions are responsible for systematically testing raw materials, intermediates, and finished products to ensure drugs meet established quality standards （Chen Yafei et al., 2018）. However, traditional quality testing activities, while ensuring drug safety, also imply multiple environmental risks. For example, frequent use of organic solvents such as methanol and acetonitrile, wasteful use of large quantities of samples and reagents, irregular waste disposal, and high energy consumption and heat emissions from continuously operating testing equipment may lead to the externalization of environmental burdens. More prominently, most enterprises have not systematically embedded green concepts into the management processes of quality control positions, resulting in issues such as the lack of green operating specifications, delayed environmental performance evaluation, and ambiguous environmental responsibility boundaries. This not only weakens enterprises' overall green governance capabilities but also hinders the pharmaceutical industry's progress toward full-process green transformation "from source to end" （Zhu Bowen & Feng Yunting, 2025）.

Against this backdrop, there is an urgent need to re-examine the path to realizing environmental responsibilities in pharmaceutical enterprises from the perspective of quality control. Embedding green concepts into the process design, method selection, and management systems of quality control positions will not only help reduce resource consumption and environmental loads in testing activities, improve operational efficiency and compliance levels, but also facilitate the construction of a full-process supervision system for green pharmaceuticals and enhance the industry's green competitiveness and public trust. However, current systematic research on greenization in quality control links remains insufficient, particularly lacking in-depth discussions and typical cases of green transformation practices and feasible paths at the operational level of positions （Xu Hui et al., 2024）. Based on this, this paper takes Taiji Group as the research object, focusing on its quality inspection positions' practical exploration and effectiveness in promoting green quality control. By systematically sorting out its innovative measures in the application of green inspection methods, energy efficiency management of equipment, classified disposal of waste, and environmental performance assessment, combined with job responsibilities and operational processes, this study deeply analyzes the embedding of green concepts at the quality control position level, aiming to provide theoretical references and institutional insights for constructing a green pharmaceutical quality system, promoting green upgrading of positions, and implementing the "dual-carbon" goal.

2 Theoretical Basis of Pharmaceutical Quality Control and Environmental Responsibility

The collaborative governance of pharmaceutical quality control and environmental responsibility is rooted in three theoretical foundations: bioethics, legal regulation, and sustainable development （Chen Jialu et al., 2024）. Firstly, from the perspective of bioethics, as special commodities safeguarding human life and health, the quality and safety of drugs possess high public welfare and moral attributes. Any quality defect may directly threaten individual or even group health—for example, insufficient vaccine potency may invalidate herd immunity barriers, triggering public health crises. Therefore, quality control is not only a technical act but also a solemn commitment to life safety and an embodiment of ethical responsibility. Secondly, at the legal regulation level, the state has clarified a quality responsibility system covering the entire life cycle of drugs through core laws and regulations such as the Drug Administration Law and Good Manufacturing Practice (GMP), stipulating strict requirements for quality control standards, operational procedures, and personnel management. Meanwhile, with the improvement of environmental legislation, the implementation of environmental laws such as the Pollutant Discharge Permit Administration Regulations and Law on the Prevention and Control of Environmental Pollution by Solid Wastes has incorporated green compliance into the mandatory obligations of pharmaceutical production enterprises （Yang Jingpeng et al., 2025）. This series of legal tools has promoted the integration of quality control functions and environmental management requirements, urging enterprises to assume ecological responsibilities while ensuring drug safety. Finally, from the perspective of sustainable development, pharmaceutical production, particularly in links such as API synthesis, is typically resource-intensive, with prevalent issues of high energy consumption, high pollution, and high emissions. As a crucial link connecting production and use, quality control's responsibilities are no longer limited to ensuring product safety, stability, and effectiveness, but must also consider the carrying capacity of the ecological environment and the rationality of resource utilization. Therefore, under the guidance of green and low-carbon concepts, promoting green and intelligent transformation in quality control links has become an inevitable choice for the pharmaceutical industry to achieve high-quality development and sustainable transformation.

2.1 Basic Processes and Job Division of Pharmaceutical Quality Control

Pharmaceutical quality control is a systematic project spanning the entire chain of drug R&D, production, and circulation. It relies on process segmentation, job checks and balances, and technical support mechanisms to build a closed-loop quality risk management system covering the entire life cycle of drugs. In the R&D stage, quality control focuses on "Critical Quality Attribute (CQA)" research, emphasizing stability testing, impurity profile analysis, and physicochemical property evaluation to provide a scientific basis for setting quality standards and optimizing process routes. For example, in antibody drug development, accurate detection of glycosylation types directly affects biological activity, pharmacokinetic behavior, and immunogenicity, making it a key aspect of early quality control （Liu Xiaoqian & Guo Jina, 2025; Yang Jingpeng et al., 2025）.

In the production stage, quality control focuses on "Process Control," comprehensively covering raw and auxiliary material inspection, intermediate monitoring, finished product release testing, sample retention observation, microbial limit testing, and stability studies. It emphasizes a management philosophy of "prevention first, inspection second." For instance, in antibiotic fermentation processes, real-time adjustment of process parameters using online pH and dissolved

oxygen control systems can effectively improve production stability and batch consistency.

In the circulation stage, quality control primarily relies on digital means to achieve full-process quality controllability. Through cold chain monitoring systems, automatic temperature and humidity recording equipment, and product traceability platforms, real-time management and data recording of transportation and storage environments are realized. Additionally, mechanisms for complaint handling, return inspection, and abnormal product analysis are established to build a rapid response and feedback loop in after-sales links, ensuring quality, safety and user trust throughout the product life cycle.

In terms of job responsibility division, the quality control system typically consists of three modules—testing, management, and technology—collaborating to achieve quality objectives （Hu Qin et al., 2023）. Testing positions focus on standardized execution of inspection operations and control of data accuracy; for example, dissolution analysis personnel must proficiently operate precision instruments such as high-performance liquid chromatography (HPLC) and ultraviolet spectrophotometers (UV) to ensure repeatability and scientificity of experimental results. Management positions primarily undertake responsibilities such as formulating quality standards, supplier quality audits, document control, and deviation handling; for example, quality managers must comprehensively coordinate the operation of the enterprise's GMP system and production plan alignment, and coordinate various departments to address potential quality risks. Technical positions focus on method development, process validation, change control, and regulatory compliance evaluation; for example, analytical R&D engineers must continuously track domestic and foreign regulatory changes and advancements in testing technology to optimize detection schemes—such as adopting ion chromatography instead of traditional HPLC to improve detection sensitivity and accuracy for inorganic impurities （Lu Qunmin, Shu Lian, Ding Shihuan, 2019）.

2.2 Environmental Pollution Nodes in Quality Control Links

The green transformation of pharmaceutical quality control links hinges on identifying and addressing four core environmental load points: solvent pollution, waste liquid discharge, energy consumption, and experimental consumables (Table 1).

Table 1 Overview of environmental impacts and green optimization paths in pharmaceutical quality control links

Control Link	Main Environmental Issues	Specific Manifestations	Green Optimization Paths
Solvent Use	Organic solvent pollutionforms hazardous waste liquid	Frequent use of acetonitrile, DMF, etc., in chromatography/ mass spectrometry; waste liquid contains	high-concentration toxic organics, Low-solvent or alternative technologies such as microwave-assisted extraction, solid-phase extraction, supercritical CO_2 extraction
Waste Liquid Discharge	Composite pollution containing heavy metals, organic solvents, strong acids/alkalis, and Complex waste	Waste liquid has a complex composition; discharging it directly without treatment may damage aquatic ecosystems.	Pathways for resource recovery and standardized management, such as segregated collection, acid–base neutralization, membrane separation, solvent recovery, and biodegradation
Energy consumption	The energy consumption of testing equipment and environmental control systems is high, with carbon emissions concentrated in these processes	Continuous operation of liquid chromatographs and purification HVAC systems results in unit-area energy consumption in laboratories far exceeding that of other facility zones.	High-efficiency equipment replacement, variable-frequency systems, LED lighting, process optimization, nighttime off-peak electricity switching, and photovoltaic system installation
Laboratory consumables and associated packaging materials	The single-use of plastics and glass results in substantial solid waste generation	Centrifuge tubes, plastic bottles, sample vials, and other laboratory consumables are challenging to recycle and incur high treatment costs	Implementing reusable containers, employing environmentally friendly packaging materials, and developing a classified recycling system for laboratory consumables

2.3 Integration Trend of Green Pharmaceutical Concepts and Quality Control

Green pharmaceutical concepts are reshaping the paradigm of pharmaceutical quality control, with core trends reflected in three dimensions: regulatory drive, technological innovation, and responsibility extension （Kong Fei et al., 2023）. Firstly, at the regulatory level, the 2020 edition of Good Manufacturing Practice (GMP) incorporated green clauses such as “environmental impact assessment” and “energy conservation and emission reduction requirements” for the first time, promoting the extension of quality control from “quality compliance” to “environmental compliance.” It requires enterprises to establish energy consumption accounts and pollutant discharge monitoring systems, realizing the integration of quality management and environmental management requirements. In practice, enterprises have incorporated green production into quality systems—for example, replacing traditional batch testing with online detection to reduce sample waste, or adopting near-infrared spectroscopy (NIR) instead of HPLC to reduce solvent and consumable consumption, achieving low-carbon and consumption-reduction goals from the source. Secondly, at the technical level, green analytical methods are leading the transformation of testing means from “precision testing” to “low-carbon testing.” Promoting new green testing technologies such as microwave-assisted extraction, supercritical fluid extraction, and inductively coupled plasma mass spectrometry (ICP-MS) not only improves testing efficiency but also significantly reduces organic solvent use and equipment energy consumption. For example, ICP-MS can detect multiple metal impurities in one test, replacing multiple atomic absorption spectrometers and reducing energy and resource waste （Liu Xiande, Wang Lin, 2000）. Meanwhile, Life Cycle Assessment (LCA) has become a new tool for evaluating the green performance of testing schemes, helping enterprises compare the carbon footprints and environmental loads of methods such as liquid chromatography and near-infrared spectroscopy to select optimal green testing paths. Finally, at the responsibility extension level, quality control is expanding from internal corporate responsibility to supply chains and the public. By encouraging suppliers to provide green testing services, use renewable energy for power supply, and even promoting suppliers to obtain green quality system certification, systematic greening of the supply chain is achieved. Additionally, enterprises can enhance public awareness of green quality control concepts through activities such as opening green testing laboratories to the public and popularizing science on quality control, strengthening external supervision and public participation, and forming a green quality responsibility community with collaborative governance among enterprises, supply chains, and the public.

3 Green Transformation Practices of Quality Control Positions in Taiji Group

Against the backdrop of the global pharmaceutical industry’s “dual-carbon” goals, Taiji Group, a leader in green transformation in the traditional Chinese medicine industry, has innovatively integrated quality control with sustainable development concepts, building a full-chain green quality control system covering “method innovation—equipment upgrading—waste recycling—institutional guarantee.”

3.1 Enterprise Overview and Quality Control System

Taiji Group (Sinopharm Taiji) is a national-level green manufacturing demonstration enterprise integrating R&D, production, and sales, with five production bases, including Fuling Pharmaceutical Factory, all of which have obtained green certification. Its quality control system spans the entire process from “medicinal material entry—production

process—finished product release," with specialized modules for physical and chemical testing, microbial analysis, and stability research, equipped with over 200 sets of precision instruments such as high-performance liquid chromatography (HPLC), gas chromatography (GC), and inductively coupled plasma mass spectrometry (ICP-MS). After being selected as a "National Quality Benchmark" in 2024, the enterprise deeply integrated green quality control into its "13460" sustainable development strategic framework, maintaining a high standard of testing error rate≤0.5% while significantly reducing the carbon footprint of single-batch testing by 38%（Qiao Zizhe, 2023）.

3.2 Greening of Testing Methods

In promoting green transformation of pharmaceutical testing, Taiji Group has developed a demonstration and replicable technical path covering four core directions: green solvent substitution, analytical method innovation, full-industry-chain collaboration, and technical extension. In green solvent substitution, for water-soluble components such as astragaloside IV, the company adopts aqueous chromatography technology, completely replacing the traditional acetonitrile-methanol system with pure water, reducing solvent costs by over 90% and significantly reducing toxic organic waste liquid. For fat-soluble components such as tanshinone, supercritical fluid chromatography (SFC) is introduced, using recycled CO_2 as the mobile phase, reducing waste liquid volume by 80% and realizing CO_2 recycling through a closed-loop system. Additionally, micro-testing methods reduce the sample size for injection visible foreign matter inspection to 25% of the original standard, saving over 12,000 pieces of glass consumables annually and effectively reducing resource waste and transportation energy consumption. In green analytical method innovation, near-infrared spectroscopy (NIR) rapid detection technology is promoted to replace HPLC for determining content uniformity of solid preparations, reducing testing time from 2 hours to 5 minutes, with energy consumption only 5% of traditional methods and completely avoiding organic solvent use. In microbial testing, rapid detection systems such as the enzyme substrate method and CO_2 fluorescence sensing are applied, compressing the testing cycle from 120 hours to 24 hours and reducing medium usage by 30%. At the full-industry-chain green collaboration level, the company implements the "three nothings and one full" standard for Chinese medicinal materials (no sulfur, no aflatoxin exceeding standards, no pollution, full-process traceable) to achieve pollution prevention at the planting source; promotes resource utilization of medicinal residues, producing biomass fuel with a comprehensive utilization rate of 95%, building a green ecological chain of "planting—production—waste reuse"; and precisely controls energy consumption through an energy data collection system, reducing carbon emissions by approximately 2,000 tons annually through on-site photovoltaic power generation projects and lowering steam costs by 36 yuan/ton. In technical extension, Taiji Group is exploring the development of bio-based, environmentally friendly solvents (such as γ-valerolactone) and hydrogen bond donor-acceptor mixed systems to replace highly toxic polar solvents DMF and NMP, reducing environmental and health risks. Simultaneously, it promotes automated control of testing processes through DCS/MES systems, doubling production efficiency and providing underlying digital support for green testing. Through in-depth integration of intelligent manufacturing and green technologies, Taiji Group has built a closed-loop system of "source control—process waste reduction—resource regeneration" in bases such as Fuling Pharmaceutical Factory and Sinopharm Modern Pudong Manufacturing Center, successfully creating a national-level green factory model and providing a promotable paradigm for industry green transformation.

3.3 Energy-Saving Transformation and Automation Upgrading of Testing Equipment

Against the backdrop of green pharmaceutical transformation, Taiji Group has prioritized energy-saving renovation and automation upgrading in testing processes as key components of building a green quality control system. It has promoted low-carbon and intelligent upgrades of quality control workflows through three focus areas: optimization of high-energy-consuming equipment, improvement of laboratory energy efficiency, and intelligent management. First, to address energy consumption issues of high-energy-consuming testing equipment (such as HPLC and GC-MS), the Group launched a special energy-saving renovation project. It uniformly replaced outdated instruments with new models featuring "intelligent standby" and "energy consumption adjustment" functions. Auxiliary equipment like traditional fume hoods and constant-temperature water baths were retrofitted with frequency conversion controls, reducing overall equipment energy consumption by approximately 20%. The laboratory air-conditioning system simultaneously adopted zone-based control and intelligent temperature-humidity regulation strategies, significantly lowering energy use in non-high-sensitivity areas and during nighttime idle periods, cutting annual air-conditioning electricity consumption by over 30%. Second, in automation upgrading, the Group introduced an integrated platform of DCS (Distributed Control System) and MES (Manufacturing Execution System), connecting workflows for quality testing data collection, analysis, decision-making, and record management. This enabled full-process digitization from "sample reception → testing scheduling → equipment linkage → data analysis → result filing." For example, in solid preparation testing, linking near-infrared rapid analyzers with automatic sampling systems tripled efficiency while reducing manual errors and repeat testing rates. For traditionally manual processes like microbial limit and sterility testing, image recognition and intelligent sensing systems now enable process tracing and remote monitoring, enhancing quality traceability. Additionally, to achieve full-lifecycle green management of testing equipment, the Group established an equipment energy efficiency assessment and carbon footprint tracking mechanism. It monitors carbon emissions throughout the "use-maintenance-retirement" cycle for key testing equipment and gradually promotes green equipment certification in procurement—prioritizing instruments with Energy Star, ISO 14001, and other environmental certifications to strengthen energy conservation at the source. These upgrades have significantly reduced energy consumption and environmental loads in testing while ensuring efficiency and data reliability, providing robust technical support for building a green, efficient, and intelligent pharmaceutical quality control system.

3.4 Waste Classification and Recycling System

Taiji Group has established a waste classification and recycling system compliant with national environmental regulations and industry standards during pharmaceutical quality inspection, forming a closed-loop management mechanism characterized by "refined classification, standardized recycling, and systematic management." Wastes are categorized into three types based on their sources and properties, each with dedicated collection and disposal pathways:

Chemical wastes (e.g., organic solvents, heavy metal-containing waste liquids) are temporarily stored separately, neutralized, or centrally recycled, with strict prohibition of mixed dumping. Biological wastes (e.g., bacterial strains, tissue residues) undergo harmless treatment via high-pressure sterilization or incineration. General wastes are disposed of through regular waste sorting and transportation processes.

In operational practices, the company uniformly provides sealed collection containers with clear labeling, stipulating that hazardous wastes must be stored independently away from office areas. To enhance resource utilization

efficiency, resource recovery technologies such as solvent recycling and energy conversion are prioritized. For system implementation, a dedicated department oversees transportation, record-keeping, and training, supplemented by regular internal audits and external evaluations to strengthen environmental awareness across all staff. Additionally, operators are required to wear protective equipment and handle waste in well-ventilated environments. Centered on environmental risk prevention, this system achieves standardized, traceable, and reduced-volume waste disposal, providing strong support for building a green quality control system.

3.5 Environmental Performance Evaluation and Training System

In the process of green transformation in quality control, Taiji Group has developed an environmental performance evaluation and training system covering both individuals and organizations, integrating green concepts deeply into the entire process of quality inspection management.

In terms of evaluation mechanisms, a "individual + team" dual-dimensional assessment model is adopted: At the individual level, green behavior indicators account for 30% of performance evaluations, covering 12 key metrics such as waste liquid classification accuracy, reagent usage control, and testing energy consumption, strengthening behavioral guidance for green operations. At the team level, a mandatory target of at least a 5% annual reduction in laboratory carbon intensity is set to promote collaborative emission reduction across departments.

For training and awareness enhancement, the group employs multiple digital tools and immersive experiences: A VR system simulates emergency scenarios such as solvent leaks to improve employees' response capabilities in environmental emergencies. A "carbon visualization" system displays real-time environmental costs of testing operations (e.g., a single HPLC test generates approximately 0.8 kg CO_2 equivalent), enhancing employees' carbon footprint awareness and process control capabilities. A green incentive mechanism quantifies energy-saving and emission-reduction behaviors into points redeemable for flexible leave or public welfare donations, motivating proactive employee participation in environmental protection.

This system creates a positive interaction between performance-driven mechanisms and cultural cultivation, strengthening the internal motivation for green quality control and providing institutional guarantees and personnel support for building a "low-carbon, efficient, and compliant" quality management system.

4 Path Recommendations for Building Green Quality Control

Driven by the "dual-carbon" goal and green transformation trends, pharmaceutical quality control is transitioning from "precision management" to "green collaboration." As a high-energy-consuming and resource-intensive key department, the green transformation of quality control systems is not only a critical means for enterprises to fulfill environmental responsibilities but also a core component of building ESG sustainable governance capabilities.

4.1 Establishing a Green Inspection Indicator System

Constructing a scientific, quantifiable, operable, and verifiable green inspection indicator system is foundational to promoting green transformation in quality inspection. The indicator framework is shown in Table 2, with design principles as follows:

（1）Scientificity: Quantify environmental loads in testing processes using Life Cycle Assessment (LCA) methods, covering characteristics of different product lines such as APIs and preparations.

（2）Operability: Translate abstract environmental requirements into specific behavioral standards (e.g., "maximum reagent dosage per titration≤15mL").

（3）Dynamicity: Update indicator thresholds annually based on environmental appendices in the Chinese Pharmacopoeia to adapt to regulatory and technological advancements.

Table 2 Green inspection indicator framework

Indicator Category	Core Indicator Examples	Data Collection Method
Resource Consumption	Energy consumption per test (kW·h/batch)	Automatic statistics via smart meters + LIMS
	Organic solvent recovery rate (≥85%)	Comparison of waste liquid weight and procurement records
Environmental Impact	Carbon footprint of testing (kgCO_2e/item)	Calculation using IPCC emission factors
	Real-time VOCs concentration in fume hoods (≤50ppm)	Alerts from online monitoring systems
Process Control	Hazardous waste classification accuracy (100%)	Monthly on-site audit sampling
	Electronic report substitution rate (annual increase ≥10%)	Log analysis of document management systems

On the basis of existing GMP compliance indicators, additional metrics should be added, including resource consumption indicators (e.g., sample usage, solvent consumption, water/electricity/steam usage), environmental impact indicators (e.g., carbon emission intensity, VOCs emissions), and pollution control indicators (e.g., waste liquid classification accuracy, waste recycling rate). These should be refined by position into pre-testing, analytical operations, and result review stages to form a complete green behavior evaluation chain. Additionally, dynamic early warning and benchmarking mechanisms should be established to encourage teams or individuals to continuously improve green performance through method optimization and efficiency enhancement.

4.2 Promoting Green Standardization and Method Substitution

At the technical level, promoting standardization and popularization of green inspection methods is a core path to realizing green transformation in quality inspection. Currently, some traditional analytical methods still rely heavily on toxic solvents, consume excessive reagents and energy, and easily cause environmental pollution and resource waste. Therefore, efforts should be made to develop and replace green analytical technologies, gradually phasing out high-pollution and high-risk traditional methods.

Specifically, priority should be given to environmentally friendly technical pathways: Replace traditional acetonitrile/methanol-based solvent systems with aqueous chromatography to reduce VOCs emissions. Adopt microanalytical techniques to reduce sample and reagent usage, extending the service life of consumables. Utilize supercritical fluid chromatography (SFC) and near-infrared spectroscopy (NIR) for non-destructive, rapid, and low-energy consumption testing, improving efficiency while significantly reducing "three wastes" generation.

Furthermore, integrate automatic sampling, online detection, and intelligent data collection technologies to combine green testing with information-based control.

In building a methodological evaluation system, "environmental friendliness" should be added as a mandatory indicator alongside existing parameters such as accuracy, stability, and repeatability. This involves quantifying the environmental costs of methods in terms of solvent usage, energy consumption, and waste generation, serving as a key basis for method adoption and optimization. This evaluation dimension will prompt researchers to prioritize alternatives

with minimal ecological impact during method selection, controlling pollution at the source. It is also recommended to collaborate with industry authorities, testing institutions, universities, and research institutes to jointly develop a standard system for green inspection methods. By establishing industry technical guidelines, group standards, or even national standards, the entire process of green method development, validation, application, and supervision can be standardized, enhancing industry recognition and operability. A "promotable, shareable, and traceable" green standard system will reduce barriers to enterprise adoption of green technologies, facilitating widespread application of green inspection methods in pharmaceuticals, biotechnology, food, and other industries, thereby achieving industry-wide green collaboration and improved overall environmental performance.

4.3 Embedding ESG Responsibilities at the Post Level

The effective implementation of green quality control requires systematic management mechanisms, particularly the integration of environmental responsibilities into every post and employee behavior （Ye Shuang, 2025）. To this end, an ESG (Environment, Social, Governance)-driven mechanism centered on post responsibilities should be embedded into internal management systems, enabling the normalization and behavioral internalization of green concepts through institutional design. Constructing a "job description—performance evaluation—training and development" trinity responsibility matrix is key to achieving this goal.

First, in job descriptions, green responsibilities should be detailed, with energy conservation, emission reduction, pollution control, and resource conservation goals made specific and quantifiable. For example, quality inspectors should be explicitly required to implement waste liquid classification standards, prioritize green inspection methods, and control sample and reagent usage. Additionally, annual carbon emission intensity or hazardous waste reduction targets for the post should be listed as key tasks to enhance awareness of environmental goals. Second, in performance evaluation systems, green behaviors should be incorporated into key performance indicators (KPIs) with differentiated weights based on post attributes. For quality inspection roles, indicators such as "green experiment execution rate," "energy-saving points," and "proportion of green methods used" can be established to dynamically reflect employees' actual performance in green operations through data recording and system evaluation. Positive incentives (e.g., performance bonuses, awards, internal recognition) should be provided for outstanding performers, while underperformers should receive performance interviews and training to balance incentives and constraints. Third, in training and career development systems, dedicated green training modules should be established and linked to promotion pathways. Green quality control knowledge, including green inspection methods, energy-saving operation standards, and environmental regulations, should be integrated into new employee training, on-the-job rotation, and specialized capacity-building programs to enhance professional competence and environmental awareness. Additionally, employees' green performance should be linked to promotion assessments, job adjustments, and technical title evaluations, making green responsibility a key criterion for career growth and forming a closed-loop incentive chain of "green capability—promotion—behavioral performance."

4.4 Strengthening Digital Transformation of Green Quality Control

Promoting digital upgrading of quality inspection management systems is a critical support path for enhancing green governance capabilities and achieving efficient environmental management （Jin Xiaobin et al., 2024）. Currently, most pharmaceutical enterprises have deployed Laboratory Information Management Systems (LIMS) to

standardize testing processes and data management, but these systems lack integration of green governance functions. To adapt to new green transformation requirements, it is urgent to develop green functional modules within existing LIMS architectures, achieving deep integration of environmental performance and quality control （Yang Jiaying et al., 2025）.

First, add resource and environmental data collection and management functions to the system, covering multi-dimensional indicators such as sample usage, solvent consumption, electricity/steam usage, and water resources. These should be recorded in detail by experiment, equipment type, or operator. Based on carbon emission factor models, automatic calculation and aggregation of carbon footprints can be realized, supporting dynamic tracking of carbon emission intensity for individual testing operations, thus providing data support for green performance evaluation and method substitution assessment. Second, integrate a waste management module to enable full-process digital control of hazardous wastes (e.g., waste liquids, spent reagents, contaminated consumables), including automatic label printing, classification ledger generation, transportation path recording, and final disposal result upload. Combined with RFID technology and QR code management, full-life-cycle traceability from source generation to end disposal can be achieved, enhancing standardization and regulatory transparency in waste management. Furthermore, introduce data visualization platforms to graphically present resource consumption and environmental emissions in various testing links, such as energy consumption curves, carbon emission trends, and waste liquid output heatmaps, enabling “visible, calculable, and manageable” green management. Through linkage with mobile terminals and cloud platforms, managers can remotely monitor green indicators in real time and implement early warning adjustments, improving decision-making efficiency and management responsiveness. In terms of data credibility and compliance, explore the application of blockchain technology in green quality control data management. Establish a “green data blockchain ledger” to encrypt and immutably record key data (e.g., waste liquid disposal, carbon emission accounting, green behavior points), which can serve as important evidence for corporate ESG reports and third-party audits, while enhancing enterprise credibility and public recognition in environmental supervision and green financial support.

5 Conclusions and Prospects

Against the backdrop of advancing green and low-carbon development strategies, the role of pharmaceutical quality inspection positions is undergoing a profound transformation. As a key link in the full-life-cycle management of drugs, quality control positions not only bear technical responsibilities for ensuring product safety, efficacy, and regulatory compliance but also carry the systemic mission of fulfilling environmental responsibilities and promoting green transformation. With the deepening implementation of national “dual-carbon” goals and the expansion of green development pathways in the pharmaceutical industry, the environmental value of quality control links has become increasingly prominent, serving as a critical starting point for enterprises to achieve environmental sustainability and synergistic social responsibility. This paper, focusing on quality control links, systematically sorts out core practical pathways for green quality control, including refined construction of waste classification and recycling systems, implementation of green performance evaluation mechanisms, promotion of innovative green training systems, and integration of ESG responsibilities into management systems at the post level. It also proposes technical path recommendations for promoting green inspection standardization, method substitution, digital transformation, and intelligent management. Practice shows that constructing a systematic green quality control mechanism can significantly

improve resource utilization efficiency, reduce pollutant emissions, optimize experimental processes, and further improve enterprises' ESG governance systems, effectively enhancing green competitiveness and brand credibility.

Successful experiences of leading enterprises such as Taiji Group demonstrate that green quality control is no longer optional but should be a core component of sustainable development strategies in the pharmaceutical industry. Its essence lies not only in emission reduction and compliance but also in promoting management process optimization, technological upgrading, and cultural reshaping through green quality control, achieving deep integration of "environmentally friendly + quality-oriented" management models. Looking ahead, the development of green quality control systems will exhibit trends toward intelligence, platformization, and collaboration. On one hand, the popularization of green intelligent testing equipment, automated experimental platforms, and low-carbon analytical technologies will achieve dual improvements in inspection efficiency and environmental performance, further reducing human error and resource waste. On the other hand, the construction of carbon emission accounting platforms, energy consumption visualization systems, and green behavior management systems will integrate environmental performance into the entire process of quality management and strategic decision-making, realizing a shift from "end-of-pipe treatment" to "source prevention." Additionally, there is an urgent need to strengthen the unified construction of green quality control standards at the industry level, establishing standardized systems covering environmental friendliness evaluation, green method validation, and data mutual recognition. This will break down technical barriers and data silos between enterprises, promoting standardized sharing and collaborative application of green practices. With joint promotion from government supervision, industry associations, research institutions, and enterprises, green quality control will expand from internal corporate governance to industry-wide collaborative mechanisms, assisting China's pharmaceutical industry in achieving a "dual leap" in high-quality development and green sustainable transformation.

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