

Article

How Does Industrial Robot Application Promote Sustainable Green Innovation of Enterprises?

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Abstract

As digital technologies continue to evolve, intelligent manufacturing technology represented by industrial robots has been increasingly integrated into various stages of enterprise production and operational activities. This trend has created new opportunities for enterprises to advance green transformation and enhance the level of sustainable green innovation. Based on data from Chinese A-share listed firms, this study empirically examines the effect of industrial robot application on sustainable green innovation of enterprises. The study finds that industrial robot application significantly enhances sustainable green innovation of enterprises. The underlying mechanisms mainly operate through the optimization of human capital structure and government-specific subsidies. Meanwhile, industrial robot application exhibits significant peer spillover effect, which can generate demonstration and pressure transmission effects among enterprises within the same industry and region, thereby promoting the coordinated improvement of sustainable green innovation. Heterogeneity analysis further reveals that the promoting effect of industrial robot application on sustainable green innovation is more pronounced in non-state-owned enterprises, labor-intensive enterprises, enterprises whose executives have an environmental background, and enterprises in regions with stricter environmental regulation. Furthermore, the establishment of regional environmental courts can strengthen the positive effect of industrial robot application on sustainable green innovation of enterprises. The results of the extended analysis further demonstrate that the contribution of industrial robot application to sustainable green innovation mainly stems from its “leverage effect” on overall corporate innovation activities, rather than from the “crowding-out effect” caused by compressing other technological innovation activities. This study not only enriches the literature on the environmental effects of industrial robot application but also provides new insights into how enterprises can leverage intelligent technologies such as industrial robots to achieve green transformation.



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1. Introduction

Alongside China’s sustained high-speed economic growth, environmental pollution and energy scarcity have become increasingly severe (Jin et al., 2022) [1], making it imperative to accelerate the green transformation of the economic development model and progressively move toward a low-carbon, sustainable growth path. At the 2020 United Nations General Assembly, China announced its “dual-carbon” goals, committing to peak

carbon emissions before 2030 and achieving carbon neutrality by 2060. Sustainable green innovation, which integrates economic growth with environmental stewardship, aligns closely with China's "dual-carbon" goals (Zhou & Gao, 2025) [2] and serves as an important driver of corporate green transformation and high-quality development. However, in contrast to traditional green innovation, sustainable green innovation requires enterprises to consistently allocate resources to long-term green innovation projects, such as green product R&D and green process improvement. The long-term nature of R&D, coupled with considerable failure risks and uncertain payoffs, poses substantial challenges to the sustained implementation of green innovation activities, thereby limiting the overall level of sustainable green innovation in Chinese enterprises. Moreover, the environmental externalities and knowledge spillover effects generated during the process of sustainable green innovation may weaken the exclusive benefits that innovators can obtain from their outcomes, thereby further reducing the enthusiasm of enterprises to carry out relevant innovation activities (Li et al., 2024) [3]. Consequently, effectively promoting sustainable green innovation of enterprises has become an important issue to be solved urgently.

The promotion of corporate green innovation has received sustained scholarly interest. Existing research suggests that both internal organizational resources and external environmental pressures play important roles in shaping corporate green innovation activities. From the internal perspective, the basic attributes of enterprises and the characteristics of the executive team exert significant influence on green innovation activities. On the one hand, state-owned enterprises and large-scale enterprises typically possess stronger resource endowments, economies of scale, and risk-bearing capacity, which can provide sustained support for corporate green innovation (Leonidou et al., 2017; Li & Wang, 2025) [4,5]. On the other hand, the upper echelons theory holds that executives' personal characteristics significantly influence strategic decision-making. Prior studies have shown that female CEOs and board members with experience in environmental governance or ecological protection are more inclined to carry out green innovation projects, thereby promoting quantity increase and quality improvement of green innovation (Wang et al., 2023; Javed et al., 2023) [6,7]. From the external perspective, scholars generally regard environmental regulations and regulatory pressures faced by enterprises as important drivers of green innovation. Cai et al. (2020) [8] found that the implementation of China's new Environmental Protection Law increased environmental compliance costs of enterprises and strengthened their environmental responsibilities, thereby forcing enterprises to engage in green technological innovation to some extent. Sun et al. (2024) [9] demonstrated that different stages of the Central Environmental Protection Inspection program can effectively promote corporate green innovation activities and improve green innovation level of enterprises. Overall, although the existing research has deeply explored the influencing factors of enterprise green innovation, the research on enterprise sustainable green innovation considering the time dimension is relatively scarce.

Meanwhile, as digital technologies continue to evolve, intelligent manufacturing technologies represented by industrial robots have been increasingly integrated into various stages of enterprise production and operational activities. While significantly improving production efficiency and optimizing resource allocation, industrial robots also create new opportunities for enterprises to advance green transformation and enhance the level of sustainable green innovation. China's demographic dividend continues to weaken, and labor costs have continued to rise, accelerating the popularization of industrial robots in the field of industrial production. Evidence from the International Federation of Robotics indicates that China remained the largest consumer of industrial robots globally for several consecutive years, and since 2021, China's industrial robot installations have exceeded the combined total of all other countries. Specifically, in 2024, China's industrial robot stock

reached 2.027 million units, representing a 7% year-on-year increase. The newly installed robots in the same year amounted to 295,000 units, increasing by 21.25% compared with 2021. This figure far exceeded that of Japan and the United States, accounting for more than half of the global total new installations of 524,000 units.

In fact, the accelerated application of industrial robots has long attracted wide attention from scholars. Relevant studies indicate that industrial robot application not only plays a significant role in promoting economic growth and industrial upgrading (Afonso et al., 2025) [10] but also has a profound impact on employment structure and wage income (Li et al., 2021) [11]. In addition, while a few studies have examined the environmental effects of industrial robots, most have focused on their impact on current green production or green transformation of enterprises (Yuan et al., 2024) [12], lacking direct investigation into sustainable corporate green innovation behavior. So, as an important carrier of advanced technology and a key terminal device in intelligent production, can industrial robot application generate “green dividends” and thereby promote corporate sustainable green innovation? Through what mechanisms does industrial robot application affect corporate sustainable green innovation? Can industrial robot application generate the peer spillover effect and further improve the overall level of sustainable green innovation within industry and region? The systematic discussion of the above questions not only contributes to a comprehensive understanding of the logical relationship between industrial robot application and corporate sustainable green innovation but also provides important policy implications for China to achieve the carbon peaking and carbon neutrality goals.

In view of this, this study uses micro-level data from Chinese A-share-listed firms to empirically examine the impact of industrial robot application on corporate sustainable green innovation. This study contributes to the literature in several ways. Firstly, this study advances research on corporate sustainable green innovation. Although existing studies have extensively explored corporate green innovation (Wang & Wang, 2021; Xue et al., 2026) [13,14], most of them focus on short-term innovation activities, with insufficient attention paid to corporate sustainable green innovation. Based on the research idea of innovation sustainability, this study incorporates both technological progress and the sustained dimension of green innovation into a unified analytical framework and focuses on the impact of industrial robot application on corporate sustainable green innovation. This improves the theoretical framework of corporate green innovation. Secondly, this study clarifies the mechanisms through which industrial robot application impacts corporate sustainable green innovation. By introducing human capital structure and government-specific subsidies as mediating variables, this study further uncovers the mechanisms through which industrial robot application promotes sustainable green innovation. This not only opens the “black box” of how industrial robot application empowers corporate sustainable green innovation but also provides new insights for how enterprises can leverage intelligent technologies such as industrial robots to achieve comprehensive green transformation.

Thirdly, this study verifies the peer spillover effects of industrial robot application. Existing studies on the impact of industrial robots on green innovation have largely relied on firm-level static analyses, paying little attention to the interactions between enterprises. This study finds that industrial robot application generates significant peer spillover effects: While enhancing enterprises’ own sustainable green innovation, it also encourages other enterprises in the same region or industry to adopt industrial robot technology through demonstration driving and pressure transmission mechanisms, thereby improving their sustainable green innovation levels. This provides new empirical evidence for understanding how inter-enterprise interactions impact sustainable green innovation. Fourthly, this study enriches the contextual factors that industrial robot application impacts sustainable green innovation of enterprises. By incorporating factors such as corporate ownership type,

executives' environmental background, capital intensity, and the stringency of regional environmental regulations into the research model, this study systematically examines the heterogeneous influence of industrial robot application on sustainable green innovation. This provides valuable policy insights for government departments to promote differentiated digital and intelligent transformation of enterprises, thereby supporting high-quality green development.

2. Theoretical Analysis and Research Hypotheses

Sustainable green innovation refers to a series of long-term and coherent innovation activities aimed at achieving low-carbon development, environmental protection, energy conservation, and emission reduction, while balancing economic and environmental benefits. It includes green product innovation, green process innovation, and other related innovation activities. Sustainable green innovation emphasizes embedding the concept of green development into the core values of enterprises, thereby improving overall environmental and economic performance and achieving high-quality green development. Distinct from traditional green innovation, sustainable green innovation emphasizes the continuity of innovation activities; that is, sustainable green innovation is not a temporary expedient or a short-term initiative, but rather a long-term strategic choice made by enterprises in pursuit of their long-term development objectives. This requires enterprises to sustain stable investments in green innovation over time, thereby institutionalizing green innovation as a regular component of business operations. However, sustainable green innovation is generally characterized by long R&D and payback periods, as well as high levels of complexity and uncertainty, which tend to weaken enterprises' incentives to engage in such innovation activities. The resource-based theory suggests that sustained and stable resource investment is essential for maintaining innovation activities. Among various strategic resources, human capital, as the most important strategic asset within the enterprise, provides the knowledge foundation and capability support necessary for the continuous implementation of green innovation and plays a critical role in enhancing green innovation. Moreover, government-specific subsidies serve as an important external financing channel and can alleviate enterprises' funding constraints and reduce the marginal costs of R&D, thereby encouraging enterprises to engage more actively in innovation activities.

In recent years, intelligent manufacturing technologies represented by industrial robots have been widely applied by enterprises. It not only helps to enhance the level of human capital and attract highly skilled talent through both substitution and creation effects but also helps to increase government-specific subsidies obtained by enterprises through the signal effect, thereby broadening the sources of funding for innovation investment and promoting sustainable green innovation. In view of this, based on resource-based theory, this study explores the underlying mechanisms through which industrial robot application impacts sustainable green innovation from two perspectives: the optimization of enterprises' internal human capital structure and the acquisition of external government-specific subsidies. The specific theoretical framework is presented in Figure 1.

2.1. Human Capital Structure

An industrial robot is an intelligent mechanical device applied in automated production processes, which can independently perform part or all of production tasks according to preset programs and control instructions. Therefore, industrial robot application not only reshapes corporate production organization modes but also profoundly impacts their labor demand structure, thereby driving adjustments in human capital structure. Meanwhile, the theoretical framework of "task substitution and creation" proposed by Acemoglu and Restrepo [15] suggests that technological progress generates both substitution effect and

creation effect on labor. As a typical form of skill-biased technological progress, industrial robots can not only efficiently perform repetitive, standardized, and highly intensive routine tasks, thereby replacing low-skill and high-risk jobs, but also create a series of new positions related to emerging technologies that complement high-skill labor, thereby increasing enterprises' demand for high-skill labor. Accordingly, this study systematically analyzes how industrial robot application impacts the human capital structure of enterprises from the two dimensions of substitution effect and creation effect.

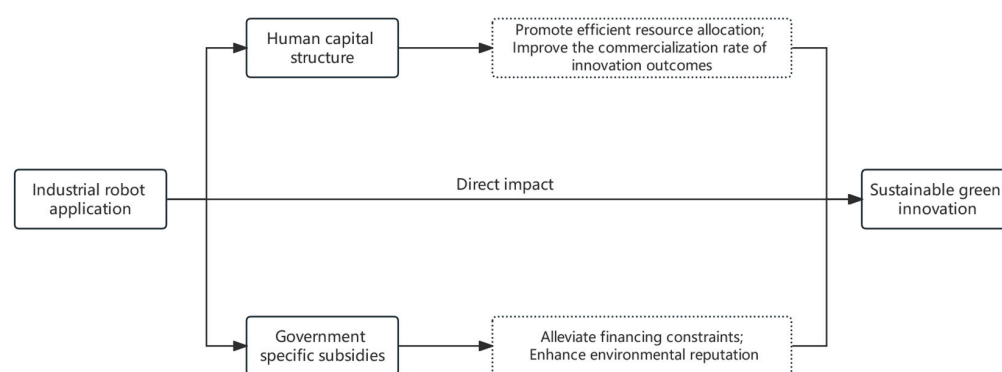


Figure 1. Theoretical framework.

In terms of the substitution effect, as labor costs continue to rise and the cost advantages of industrial robots and other production factors become increasingly apparent, enterprises are more inclined to replace traditional labor with industrial robots in performing production tasks (Graetz & Michaels, 2019) [16]. Firstly, compared with low-skill labor, industrial robots possess significant comparative advantages in performing standardized and repetitive production tasks. They are capable of continuously and efficiently undertaking work that requires relatively low technical skills but involves prolonged physical effort and a high degree of concentration (Xie et al., 2025) [17]. Acemoglu and Restrepo (2020) [15] found that the increase in industrial robot application significantly reduces labor demand for occupations involving routine manual tasks, particularly among blue-collar workers, machine operators and assemblers, and transportation workers. Wang and Dong (2020) [18] further showed that the substitution effect of industrial robots on labor is most pronounced in labor-intensive industries, such as the paper manufacturing and furniture manufacturing sectors.

Secondly, industrial robots exhibit a significant substitution effect in hazardous occupations, enabling the replacement of human labor in high-risk fields such as power-line inspection, high-altitude welding, and medical waste treatment, thereby achieving “machine substitution for labor”. For example, in maintenance operations at a power substation, the application of a live-line working robot eliminates the need for workers to enter high-voltage hazardous areas and substantially reduces operation time. This not only helps decrease workers’ occupational exposure to hazardous environments but also improves production efficiency to a certain extent. Finally, with the continuous advancement of automation technology, the acquisition and maintenance costs of industrial robots have steadily declined, effectively reducing the corresponding threshold for enterprises to apply industrial robots. As a result, enterprises are more motivated to deploy industrial robots in manufacturing processes and further accelerate the substitution of low-skill labor in hazardous occupations.

In terms of the creation effect, the widespread application of industrial robots in the production process has reshaped the production model of enterprises, altered the task structure of enterprises, and given rise to a variety of new technology-related occupations that are complementary to skilled labor, which in turn has increased enterprises’ need for

high-quality human capital. For example, the operation and maintenance of industrial robots has generated new positions, such as systems integration engineer, technical commissioning engineer, and virtual scenario simulation specialist (Wang & Han, 2025) [19]. These positions generally require higher levels of digital literacy and professional skills of employees, thereby driving enterprises to shift their employment structure toward more knowledge intensity and higher skill levels.

Moreover, industrial robots have a pronounced skill-biased characteristic. Compared with low-skill labor engaged in routine tasks, high-skilled labor performing non-routine tasks is better able to adapt to the rapid iteration of industrial robots and achieve more effective collaboration with robot equipment. Therefore, to fully leverage the complementary effect between human and robot and enhance productivity and competitiveness, on the one hand, enterprises are motivated to intensify their efforts to attract and recruit high-quality talent, thereby facilitating the agglomeration of skilled labor. On the other hand, enterprises also tend to strengthen the professional skills and job competencies of their existing employees through systematic training, enabling them to adapt to the changing skill requirements brought about by industrial robot application, thereby building a pool of high-quality talent for intelligent transformation and upgrading of enterprises. In addition, to meet the demand for new knowledge and skills arising from industrial robot application and alleviate employment anxiety that their jobs may be replaced by automation technology, existing employees often take the initiative to enhance their digital literacy and skill levels through various learning approaches. This process contributes to the continuous accumulation of human capital and promotes the optimization and upgrading of the human capital structure (Shen et al., 2025) [20].

A well-developed human capital structure is instrumental in enabling enterprises to maintain long-term engagement in green innovation activities. Firstly, the knowledge, skills, and experience embodied in human capital can not only significantly enhance enterprises' ability to identify, absorb, and apply green technologies, but can also aid in continuously exploring new green technologies and solutions through independent research and development, which helps improve the quality of green innovation and strengthens the core competitiveness of enterprises. Meanwhile, with the deepening of intelligent transformation of enterprises, communication and learning among human capital become increasingly frequent. This facilitates the acquisition and integration of heterogeneous knowledge and information, thereby improving the efficiency of green innovation resource allocation and further enhancing the level of sustainable green innovation of enterprises.

Secondly, high-quality human capital possesses strong capabilities in information acquisition and analysis, which can help enterprises accurately identify opportunities in green markets and develop green products that meet market demand, thereby reducing the uncertainty and failure risk associated with sustainable green innovation activities and improving the conversion rate of sustainable green innovation outcomes. Finally, high-quality human capital tends to possess stronger environmental awareness and is more capable of aligning individual interests with long-term development objectives of enterprises. By improving enterprise knowledge networks and strengthening the knowledge spillover effect, high-level human capital helps to promote the diffusion and internalization of the sustainable development concept within enterprises, thereby enhancing employees' overall environmental awareness (Dai et al., 2025) [21]. This helps foster a positive green innovation atmosphere, encourages enterprises to engage more actively in environmentally friendly activities, and continues to increase investment in green innovation activities, ultimately promoting sustainable green innovation.

2.2. Government-Specific Subsidies

As a kind of fixed capital investment with high technological content, the introduction of industrial robots by enterprises can convey a positive signal to external stakeholders that they have strong innovation ability and technological level (Wang et al., 2025) [22]. This signal not only reflects the investment and strategic commitment of enterprises in digital transformation and intelligent upgrading but also helps enhance the cognition of government departments and other external investors on the development potential and innovation ability of enterprises, thereby improving the ability of enterprises to obtain external resources to a certain extent. Therefore, for enterprises, the greater the number of robots deployed in production processes and the higher the expenditure on robot equipment, the stronger the signal of digital transformation and intelligent upgrading they convey. Under existing policy incentive mechanisms, enterprises are better positioned to obtain special subsidies and policy support from the government in the field of intelligent manufacturing. For example, Cui et al. (2025) [23] reported that the signal effect of industrial robots significantly enhances both the scale and proportion of government intelligent subsidies and effectively alleviates financing constraints of enterprises.

Meanwhile, the widespread application of industrial robot technology is highly consistent with the policy orientation of local government to promote industrial intelligent and green transformation. By introducing industrial robots, enterprises not only demonstrate active responsiveness to regional industrial policies but are also more likely to be included in the scope of key government support, thereby further increasing government-specific subsidies obtained by enterprises. For example, the “Anhui Province Action Plan for the Development of the Intelligent Robot Industry (2025–2027)” explicitly encourages enterprises to increase their procurement of industrial robots and implements tiered and differentiated subsidy schemes based on enterprises’ annual expenditures on industrial robot purchases. In 2026, Longgang District of Shenzhen plans to launch a “robot voucher” program with a total budget of 100 million yuan, under which enterprises can receive special subsidies of up to 50% of the contract value for the purchase and application of industrial robots.

Government-specific subsidies can significantly improve the level of sustainable green innovation. On the one hand, in contrast to green innovation, sustainable green innovation requires enterprises to maintain sustained and stable capital investment over a long period; higher R&D investment cost has become a key reason for restricting enterprises from taking the initiative to implement sustainable green innovation activities. As financial support granted to enterprises without repayment obligations, government-specific subsidies can provide necessary funding for sustainable green innovation, effectively reducing the green R&D cost and innovation risk of enterprises and thereby increasing their willingness to continuously engage in green innovation. For example, Wang et al. (2024) [24] pointed out that government-specific subsidies can significantly alleviate financial pressures in the R&D process of enterprises, thereby continuously improving the quality and efficiency of green innovation. Shi and Zhou (2024) [25] further found that government-specific subsidies significantly increase the number of applications for green patents, highlighting the important role of public financial support in improving sustainable green innovation.

On the other hand, obtaining government-specific subsidies signifies a favorable cooperative relationship between enterprises and the government, which can convey an implicit signal of government endorsement to external stakeholders. This helps enhance the reputation of enterprises and attract the favor of external investors, thereby further alleviating financing constraints and stimulating the intrinsic motivation of enterprises to continuously engage in green innovation. In addition, obtaining government special subsidies can also enhance the innovation confidence and sense of honor of enterprises, encouraging them to proactively optimize and reallocate innovation resources (Cui et al.,

2025) [23] and actively carry out innovation activities such as green products and green production processes, thereby promoting sustainable green innovation. In summary, this study proposes the following hypotheses:

Hypothesis 1. *Industrial robot application can improve sustainable green innovation of enterprises.*

Hypothesis 2. *Industrial robot application can promote enterprises' sustainable green innovation by optimizing human capital structure and increasing the scale and proportion of government-specific subsidies obtained by enterprises.*

3. Research Design

3.1. Data

Given the rapid growth of industrial robots in China since 2011, and considering data availability, this study takes China's A-share-listed firms from 2012 to 2023 as the research sample. The sample is screened according to the following criteria: (1) excluding enterprises designated as ST or *ST; (2) excluding enterprises in the financial industry; (3) excluding enterprises with missing key data.

The data used in this study mainly include enterprise-level industrial robot stock data, green patent data, enterprise characteristics, and operational and financial data. Among them, the industrial robot stock data are obtained from IFR, which covers information on the stock and installations of industrial robots across 17 major industries in nearly 100 countries and regions worldwide. Given its authority and extensive coverage, it has been widely used in related studies (Acemoglu & Restrepo, 2020) [15]. Based on China's National Economic Industry Classification Nodes and the industry classification standards provided by IFR, this study matches listed enterprises with industrial robot data. Enterprise green patent data are obtained from CNRDS. Except for the industrial robot stock data and green patent data, all other enterprise data are collected from CSMAR. Furthermore, enterprises' industry classifications are primarily based on the Industry Classification Guidelines for Listed Companies issued by the China Securities Regulatory Commission (CSRC).

3.2. Selection of Variables

3.2.1. Dependent Variable

Sustainable green innovation (SGI). Unlike traditional green innovation, sustainable green innovation is characterized by two core characteristics: the continuity of innovation activities and the dynamic accumulation of innovation outcomes. The former emphasizes that sustainable green innovation is not a temporary or stage-specific initiative but rather a long-term strategic choice made by enterprises in pursuit of sustainable development objectives. It requires enterprises to maintain continuous and stable investments in green product development and green process improvement, thereby transforming green innovation from a sporadic behavior into a routine and ongoing action. The latter reflects the dynamic evolution of green innovation outcomes over time. In essence, sustainable green innovation takes into account both green innovation capability and its growth trajectory, thereby capturing not only the scale of green innovation but also its dynamic development over time. Following the approach of Zhou and Gao (2025) [2], this study uses the before-and-after comparison method based on the green patent output index to measure the level of sustainable green innovation of enterprises. The specific calculation formula is as follows:

$$SGI_{i,t} = \frac{GI_{i,t} + GI_{i,t-1}}{GI_{i,t-1} + GI_{i,t-2}} * (GI_{i,t} + GI_{i,t-1}) \quad (1)$$

Among them, *GI* represents the total number of green patent applications, while *SGI* represents the level of sustainable green innovation of enterprises.

3.2.2. Independent Variable

Industrial robot application (*Robot*). Drawing on the instrumental variable construction approach proposed by Bartik (1991) [26] and following the research of Acemoglu and Restrepo (2020) [15], this study transforms industry-level industrial robot stock data into an enterprise-level measure of industrial robot penetration to measure the extent of industrial robot application among China's listed enterprises.

Firstly, based on industry-level industrial robot stock data, this study constructs the industry industrial robot penetration index:

$$PR_{c,t}^{CH} = \frac{MR_{c,t}^{CH}}{Labor_{c,t=2010}^{CH}} \quad (2)$$

Among them, subscripts *c* and *t* represent industry and year, respectively, $MR_{c,t}^{CH}$ represents industrial robot stock of industry *c*, *Labor* represents the total employment of industry *c* in 2010, and $PR_{c,t}^{CH}$ represents industrial robot penetration of industry *c*.

Second, based on the industry industrial robot penetration index, this study further constructs the enterprise-level industrial robot penetration index:

$$Robot_{i,c,t} = \frac{PWP_{i,c,t}}{PWP_{t=2010}} * PR_{c,t}^{CH} \quad (3)$$

Among them, subscript *t* represents enterprise. The first term on the right-hand side represents the ratio based on the median employment of all enterprises in industry *c*, while the second term represents industrial robot penetration of industry *c*, and $Robot_{i,c,t}$ represents industrial robot penetration of enterprise *i*.

3.2.3. Control Variables

To alleviate potential omitted variable bias in the model estimation as much as possible, this study refers to Wang and Cai (2025) [27] and includes the following control variables: enterprise age (*Age*); Squared enterprise age (*Age2*); Enterprise size (*Size*); Revenue growth rate (*Growth*); Cash flow ratio (*Cashflow*); Return on equity (*ROE*); Board size (*Board*); Ownership concentration of the top five shareholders (*Top5*); CEO duality (*Dual*); and Ownership type (*SOE*).

3.3. Model Construction

To examine the direct impact of industrial robot application on corporate sustainable green innovation, this study sets the following baseline regression model:

$$SGI_{i,t} = \alpha_1 + \alpha_2 Robot_{i,t} + \sum controls + \sum year + \sum industry + \varepsilon_{i,t} \quad (4)$$

where *SGI* represents the level of corporate sustainable green innovation, while *Robot* represents the degree of industrial robot application. *Controls* represents control variables that may impact sustainable green innovation of enterprises, including enterprise age, enterprise size, ownership concentration of the top five shareholders, and other characteristics. *Year* and *Industry* represent time and industry fixed effects, respectively, and ε represents the random disturbance term. α_2 is the estimated coefficient of the independent variable. If α_2 is significantly positive, it indicates that industrial robot application can significantly enhance the level of sustainable green innovation of enterprises.

Additionally, to test the underlying mechanism through which industrial robot application impacts sustainable green innovation of enterprises, this study employs the classical mediating effect model proposed by Li et al. (2023) [28]. The specific mediating effect model is set as follows:

$$Me_{i,t} = \beta_1 + \beta_2 Robot_{i,t} + \sum controls + \sum year + \sum industry + \varepsilon_{i,t} \quad (5)$$

$$SGI_{i,t} = \delta_1 + \delta_2 Me_{i,t} + \sum controls + \sum year + \sum industry + \varepsilon_{i,t} \quad (6)$$

In Models (5) and (6), *Me* represents the mediating variable, including human capital structure and the scale of government-specific subsidies.

3.4. Descriptive Statistics

The descriptive statistics results of the main variables in this study are reported in Table 1. The value of sustainable green innovation (SGI) of enterprises ranges from 0 to 5.4940, and the mean value is 1.0807. The results imply that sustainable green innovation is still at a relatively early stage among Chinese enterprises, and there exist significant disparities in sustainable green innovation across enterprises. The value of industrial robot application (*Robot*) ranges from 0.1286 to 2.9035, and the mean value is 1.8978. This suggests that industrial robots have been widely applied in Chinese enterprises. For most control variables, standard deviations remain below 1, with the exceptions of the squared enterprise age (*Age2*) and enterprise size (*Size*). This suggests that the majority of control variables exhibit limited dispersion and are relatively concentrated within the sample.

Table 1. Descriptive statistical results.

Variables	Observations	Mean	Std. Dev	Min	Max
SGI	31,940	1.0807	1.4669	0.0000	5.4940
Robot	31,940	1.8978	0.6588	0.1286	2.9035
Age	31,940	2.9494	0.3269	0.6931	4.2905
Age2	31,940	8.6796	1.8798	0.4805	17.4255
Size	31,940	7.6876	1.2751	2.3979	13.2535
Growth	31,940	0.1081	0.2899	−0.8809	1.2541
Cashflow	31,940	0.0468	0.0740	−0.7443	0.8385
ROE	31,940	0.0502	0.1248	−0.6786	0.2705
Board	31,940	2.1229	0.1986	1.3863	2.8904
Top5	31,940	0.5286	0.1546	0.0081	0.9923
Dual	31,940	0.2860	0.4519	0	1
SOE	31,940	0.3446	0.4752	0	1

4. Empirical Analysis

4.1. Baseline Results

Table 2 presents the baseline regression results. Across all model specifications, the coefficient on industrial robot application remains positive and statistically significant. Specifically, the coefficient is 0.0325 in Column (1), which excludes both control variables and fixed effects. After progressively introducing control variables and year and industry fixed effects in Columns (2)–(4), the estimated coefficient ranges from 0.0190 to 0.0434 and remains statistically significant. These findings indicate that industrial robot application consistently promotes corporate sustainable green innovation, thereby providing support for Hypothesis 1.

Table 2. Baseline regression results.

Variables	(1)	(2)	(3)	(4)
Robot	0.0325 *** (3.3003)	0.0190 ** (2.2265)	0.0434 *** (4.9411)	0.0213 *** (3.1791)
Age			0.3628 * (1.7714)	0.3722 ** (2.7373)
Age2			−0.0720 ** (−2.7354)	−0.0747 *** (−3.5750)
Size			0.3906 *** (5.4924)	0.3711 *** (5.5487)
Growth			0.3739 *** (5.8419)	0.1810 *** (5.1379)
Cashflow			−0.2124 (−0.6513)	−0.1737 (−1.0176)
ROE			0.0689 (1.1527)	0.1283 ** (2.6094)
Board			0.3701 *** (3.5329)	0.4797 *** (5.7115)
Top5			−0.2987 (−0.9865)	−0.2587 (−0.9873)
Dual			−0.0097 (−0.2054)	−0.0372 (−0.8436)
SOE			0.1840 ** (2.3414)	0.2907 *** (3.8252)
Cons	1.0196 *** (5.8604)	1.0449 *** (5.0453)	−0.2754 (−0.5295)	−0.4970 (−1.3080)
Year	No	Yes	No	Yes
Industry	No	Yes	No	Yes
Obs	31,940	31,940	31,940	31,940
R ²	0.0212	0.2044	0.1767	0.2756

Note: *, **, and *** represent that the estimated results are significant at the 10%, 5%, and 1% levels.

4.2. Endogenous Treatment and Robustness Test

4.2.1. Instrumental Variable Method

The baseline regression model in this study may face two endogenous issues. Firstly, although the baseline model incorporates a set of variables related to sustainable green innovation of enterprises and controls fixed effects, there may still exist other unobservable factors that potentially impact sustainable green innovation of enterprises. Secondly, there may be a reverse causal relationship between industrial robot application and sustainable green innovation of enterprises. On the one hand, industrial robot application can enhance the level of sustainable green innovation of enterprises by optimizing human capital structure and obtaining government-specific subsidies. On the other hand, enterprises with higher levels of sustainable green innovation usually have obvious advantages in terms of technology accumulation and R&D capacity, making them more inclined to expand both the breadth and depth of industrial robot application to achieve intelligent upgrading and green low-carbon transformation.

To address the above endogeneity concerns, this study re-estimates the baseline regression model using the 2SLS method to mitigate potential estimation bias caused by endogeneity. Following the approach of Fishman and Svensson (2007) [29], this study

employs the leave-one-out group mean as an instrumental variable. Specifically, enterprises are grouped by region, and the average level of industrial robot application among all other enterprises within the same region, excluding the focal enterprise itself (*IV*), is used as an instrumental variable. The rationale for selecting this instrumental variable is that enterprises located within the same region are generally exposed to similar external environments and industry-related risks in a long period of time. The improvement of industrial robot applications in other enterprises can impact the application decision of the focal enterprise through demonstration and competitive effects, thereby satisfying the relevance requirement of the instrumental variable. Secondly, the level of industrial robot application by other enterprises within the same region is unlikely to impact sustainable green innovation of the focal enterprise through other ways. Therefore, this instrumental variable meets the exogeneity requirement to a certain extent.

Columns (1) and (2) of Table 3 report the results of 2SLS. In the first stage, the F-statistic is 29.143, which exceeds the conventional threshold of 10. In addition, the LM-statistic is significantly positive, rejecting the unidentifiable hypothesis. Meanwhile, the coefficient of the instrumental variable (*IV*) is 0.1918 and passes the 1% significance test, suggesting a significant positive relationship between industrial robot application by other enterprises within the same region and that of the focal enterprise. This finding is consistent with our expectations. In the second stage, the coefficient of the independent variable is significantly positive, indicating that after addressing potential endogeneity concerns, industrial robot application still significantly promotes sustainable green innovation of enterprises.

Table 3. Endogenous treatment.

Variables	(1)	(2)	(3)	(4)
	First Stage	Second Stage	Heckman	PSM
Robot		0.4212 * (2.0442)	0.0209 *** (3.1023)	0.0180 ** (2.4414)
IV	0.1918 *** (5.3642)			
IMR			−6.7410 *** (−3.0099)	
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
F-statistic		28.77		
LM-statistic		5.24 **		
Obs		31,940	31,940	29,029
R ²		0.1504	0.2757	0.2755

Note: *, **, and *** represent that the estimated results are significant at the 10%, 5%, and 1% levels.

4.2.2. Heckman Two-Step Model

When examining the impact of industrial robot application on the level of sustainable green innovation of enterprises, the issue of sample selection bias cannot be ignored. The decision of whether to apply industrial robots is often a self-selection behavior made by enterprises based on their own development conditions, which has certain tendentious characteristics. For example, large enterprises and enterprises in heavily polluting industries are generally more capable and motivated to leverage industrial robot technology to enhance their sustainable green innovation. This may lead to the overestimation of the impact of industrial robot application on sustainable green innovation of enterprises.

In view of this, this study follows Wang and Wang (2025) [30] and uses the Heckman two-step model to alleviate potential sample selection bias. In the first stage, this study uses the Probit model to estimate the probability of enterprises applying industrial robots and calculates the inverse Mills ratio (*IMR*). In the second stage, industrial robot application, *IMR*, and all control variables are included as independent variables in the baseline regression model for re-estimation. The corresponding results are reported in Table 3. Moreover, the coefficient on *IMR* is significantly negative, indicating the presence of negative sample selection bias in this data. Therefore, failure to correct for this selection issue may lead to biased and inconsistent estimation results. Meanwhile, the coefficient of industrial robot application is significantly positive. Taken together, these findings indicate that after correcting sample selection bias, industrial robot application can significantly enhance sustainable green innovation of enterprises.

4.2.3. Propensity Score Matching

This study further uses the PSM method to further alleviate sample selection bias in the baseline regression model. Firstly, the sample is divided into treatment group and control group according to the level of industrial robot application in enterprises. Among them, enterprises with industrial robot application above the median are classified as treatment group, while those below the median are classified as control group. Secondly, this study selects all control variables as covariates and uses the 1:3 nearest neighbor matching method to match the samples. Finally, based on the baseline regression model, this study re-estimates using the matched sample. Column (4) of Table 3 shows that the coefficient of industrial robot application is significantly positive. This indicates that after addressing potential sample selection bias using propensity score matching, industrial robot application still significantly promotes sustainable green innovation of enterprises.

4.2.4. Replacing Dependent Variable

Distinct from green utility model patents, green invention patents generally involve higher application thresholds and greater technological value, which can more accurately reflect the green innovation level of enterprises (Jaffe et al., 2000) [31]. Therefore, this study substitutes the total number of green invention patent applications into Equation (1) to remeasure corporate sustainable green innovation. The corresponding regression results are listed in Column (1) of Table 4. The results show that industrial robot application can still promote corporate sustainable green innovation.

Table 4. Robustness test of replacing dependent variable and regression model.

Variables	Replace Dependent Variable		Replace Regression Model	
	(1)	(2)	(3)	(4)
Robot	0.0227 *** (3.2333)	0.0172 ** (2.7835)	0.0213 *** (3.1802)	0.0327 ** (2.0594)
Cons	−0.6741 * (−1.8271)	−0.5399 (−1.5153)	−1.0425 *** (−2.7628)	−1.3008 * (−1.9245)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Obs	31,940	31,940	31,940	31,940
R ²	0.2407	0.2680	0.1049	0.1405

Note: *, **, and *** represent that the estimated results are significant at the 10%, 5%, and 1% levels.

Meanwhile, this study further employs the natural logarithm of the total number of green patent applications as another alternative proxy for sustainable green innovation

of enterprises and re-estimates Model (4) using this measure. Column (2) of Table 4 shows that industrial robot application continues to exert a significantly positive effect. In summary, these findings indicate that the positive effect of industrial robot application on sustainable green innovation of enterprises is still valid after replacing the measurement of the dependent variable.

4.2.5. Replace Regression Model

Given that sustainable green innovation is a left-censored variable, the use of ordinary least squares (OLS) estimation may incorporate nonlinear disturbances into the error term, thereby resulting in biased and inconsistent estimates. Therefore, following the research of Zhang et al. (2023) [32], this study employs the Tobit model based on the maximum likelihood estimation (MLE) approach as a robustness check. Column (3) of Table 4 reports the corresponding regression results. It can be seen that industrial robot application can significantly enhance sustainable green innovation of enterprises.

Furthermore, considering that some enterprises in the sample did not apply for any green patents in certain years, resulting in a substantial number of zero observations for sustainable green innovation, this study further constructs a dummy variable (*SGI_Dum*). Specifically, *SGI_Dum* is assigned a value of 1 if sustainable green innovation in the current period is greater than zero, and 0 otherwise. This study then uses the Logit model as an additional robustness check. The results in Column (4) show that under the Logit model setting, the coefficient and significance of industrial robot application do not change substantially, which further enhances the robustness of the research conclusions.

4.2.6. Control of Fixed Effect

Due to the significant regional differences in the regions where enterprises belong, the impact of industrial robot application on sustainable green innovation may be disturbed by factors such as regional policy environments and resource allocation. To alleviate the above issues, this study further controls the regional fixed effect in addition to controlling the time and industry fixed effects, thereby testing the robustness of the baseline regression results. The corresponding results are shown in Column (1) of Table 5. The results show that after introducing the regional fixed effect, industrial robot application remains significantly and positively associated with sustainable green innovation of enterprises, providing support for the research conclusions.

Table 5. Robustness test of controlling fixed effect and excluding special samples.

Variables	Control Regional Fixed Effect		Exclude Special Samples	
	(1)	(2)	(3)	(4)
Robot	0.0210 *** (3.0557)	0.0164 *** (2.8845)	0.0193 * (2.6667)	0.0242 ** (2.6461)
Cons	−0.4008 (−1.0781)	−0.2804 (−0.7558)	0.1299 (0.2863)	−0.2964 (−0.8809)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Region	Yes	Yes	No	No
Region × Year	No	Yes	No	No
Industry × Year	No	Yes	No	No
Obs	31,940	31,940	20,943	23,466
R ²	0.2819	0.2998	0.2771	0.2563

Note: *, **, and *** represent that the estimated results are significant at the 10%, 5%, and 1% levels.

Furthermore, to eliminate potential time trend differences of different industries and regions, this study controls industry $\times$ year and region $\times$ year interaction fixed effects in the baseline regression model. As shown in Column (2), although the coefficient of industrial robot application slightly decreases, it remains significantly positive. These results indicate that after fully accounting for the potential impact of macro-level factors, the positive impact of industrial robot application on sustainable green innovation remains robust.

4.2.7. Exclude Special Samples

As a critical component of industrial modernization, intelligent manufacturing not only promotes the transformation and upgrading of manufacturing enterprises but also contributes significantly to their sustainable green innovation. In recent years, industrial robots have been increasingly widely applied in the manufacturing industry. According to data from IFR, the density of industrial robots in China's manufacturing industry reached 470 units per 10,000 employees in 2024, significantly higher than in other industries. Based on this, this study only retains manufacturing industry samples in the robustness test. The results of Column (3) in Table 5 show that the coefficient of industrial robot application is significantly positive. This indicates that in the manufacturing industry, which is more closely aligned with the actual application context of industrial robots, industrial robot application can still promote sustainable green innovation, once again supporting the research conclusions of this study.

Furthermore, given that municipalities directly under the central government are characterized by relatively concentrated social resources, higher administrative status, and larger economic scale, they exert a stronger promoting effect on sustainable green innovation, which may weaken the validity of the baseline regression results. Therefore, to reduce the potential adverse impact of such samples on the regression results, this study excludes enterprises located in municipalities directly under the central government and re-examines the impact of industrial robot applications on sustainable green innovation of enterprises. According to Column (4), the research conclusions have not changed substantially.

4.3. Peer Spillover Effect Test

According to social psychology, individuals' decision-making within a specific group is impacted by other group members' decisions, resulting in a tendency toward behavioral convergence. This phenomenon is referred to as the peer spillover effect (Zhao & Wang, 2024) [33]. The peer spillover effect is primarily manifested in two aspects: industry peer spillover effect and regional peer spillover effect. As information technology continues to evolve, the application of intelligent technologies such as artificial intelligence and industrial robots not only impacts enterprises' own production processes and environmental governance capability but may also encourage enterprises in the same industry or region to accelerate their intelligent manufacturing transformation and upgrading and actively enhance environmental governance capability through the peer spillover effect, thereby promoting sustainable green innovation level of enterprises in the same industry or region.

4.3.1. Industry Peer Spillover Effect

From the industry perspective, enterprises in the same industry often face similar technological environments, market opportunities, and growth prospects, resulting in intense competitive relationships. According to dynamic competition theory, to maintain existing market position and prevent the erosion of competitive advantages, enterprises in competitive markets closely monitor the innovation behavior of other enterprises and respond accordingly. Therefore, this study believes that industrial robot application can exert an indirect effect on other enterprises in the same industry through the peer effect, thereby promoting the improvement of the sustainable green innovation level of other enterprises.

Firstly, when some enterprises in the same industry gain competitive advantages from industrial robot application, such as improving production efficiency, optimizing human capital structure, and enhancing environmental governance capability, they can encourage other enterprises to engage in technological catch-up through the demonstration effect. As a result, these enterprises are more likely to accelerate the introduction and application of industrial robot technology to strengthen their own technological capability and market competitiveness, thereby avoiding competitive disadvantages arising from lagging behind in green innovation.

Secondly, enterprises are generally less willing to engage in green innovation because persistent green innovation is characterized by substantial investment requirements, high uncertainty, and a long R&D cycle. The successful experiences of some enterprises in the industry in achieving continuous improvement of environmental governance capability and green innovation level through industrial robot application can enhance the cognition and benefit expectation of other enterprises on industrial robot technology and reduce the trial-and-error cost and uncertainty risk associated with sustainable green innovation, thereby encouraging other enterprises to actively leverage industrial robot technology to improve their own levels of sustainable green innovation, ultimately promoting simultaneous improvement in the overall level of sustainable green innovation in the industry.

To identify whether industrial robot application impacts sustainable green innovation of other enterprises in the same industry through the peer spillover effect, this study follows Leary and Roberts (2014) [34], uses the mean value of sustainable green innovation of other enterprises in same industry as dependent variable, and incorporates it into the baseline regression model for empirical analysis. According to the regression results of Column (1) in Table 6, industrial robot application is significantly positive. In addition, to alleviate potential endogeneity concerns, this study further employs the 2SLS method for robustness testing. As reported in Column (2), the coefficient of the endogenous explanatory variable remains significantly positive. These results suggest that industrial robot application exhibits a pronounced industry peer spillover effect, which can encourage other enterprises in the same industry to actively apply industrial robot technology through the demonstration effect and diffusion effect and enhance the level of sustainable green innovation, thereby improving the overall level of sustainable green innovation in the industry.

Table 6. Peer spillover effect.

Variables	Industry Peer Spillover Effect		Regional Peer Spillover Effect	
	(1)	(2)	(3)	(4)
Robot	0.0056 *** (2.8927)	0.6684 ** (2.2711)	0.0047 ** (2.1184)	1.7513 *** (3.4206)
Cons	1.0033 *** (4.7476)	−0.7935 ** (−2.1481)	1.0615 *** (3.4197)	−2.4998 *** (−2.8214)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Obs	31,940	31,940	31,940	31,940
R ²	0.8976	0.4867	0.6009	0.1164

Note: **, and *** represent that the estimated results are significant at the 5%, and 1% levels.

4.3.2. Regional Peer Spillover Effect

In today's socio-economic context characterized by significant technological spillovers, the relevance of enterprises in the same region has been continuously strengthened, and interactions among them have become increasingly evident (Wu et al., 2024) [35]. Based on consideration of economic rationality and the pursuit of gains while avoiding losses,

enterprises tend to closely monitor the operational behavior and strategic choices of other enterprises in the same region to obtain valuable information and private resources, thereby avoiding situations in which competitors establish barriers first and place themselves at a disadvantage in market competition. Therefore, this study speculates that industrial robot application can exert an indirect impact on other enterprises in the same region through the peer spillover effect, thereby promoting the sustainable green innovation level of other enterprises.

Firstly, local governments play a guiding and regulatory role in the behavior decision-making of local enterprises. In general, enterprises with better environmental performance are better able to obtain policy support such as environmental subsidies and tax incentives, while enterprises with poor environmental performance may face stricter tax burdens and more intensive administrative regulatory penalties. Therefore, when local enterprises obtain key scarce resources needed for development by advancing intelligent manufacturing and green transformation, this will undoubtedly generate a significant demonstration and leading effect on other enterprises in the same region, encouraging these enterprises to accelerate the application of industrial robots, actively engage in green practices, and improve the level of environmental governance to obtain more policy support and development opportunities.

Secondly, industrial robot application aligns with the regional green development concept and helps enterprises improve production efficiency and sustainable green innovation levels, thereby achieving the coordinated advancement of economic development and environmental protection. When the environmental protection level of enterprises is inconsistent with the overall level in the region, enterprises may suffer losses in reputation, legitimacy, and competitive advantage (Wang et al., 2022) [36]. Therefore, to maintain environmental reputation and legitimacy, as well as sustain competitive advantage, enterprises tend to pay closer attention to the technological application and innovation decision-making of other enterprises in the region, enhance the ability to access and extract private resources and information of other enterprises, and improve their sustainable green innovation levels by learning and imitating the practical experience of other enterprises, ultimately contributing to the overall enhancement of sustainable green innovation in the region.

To examine how industrial robot application impacts sustainable green innovation of other enterprises in the same region through the peer spillover effect, this study draws on Sun et al. (2024) [37], uses the mean value of sustainable green innovation of other enterprises in same region as the dependent variable, and incorporates it into Model (3) for re-estimation. The results obtained from both the OLS estimation in Column (3) and the 2SLS estimation in Column (4) indicate that industrial robot application exhibits a pronounced peer spillover effect at the regional level, which can promote other enterprises in the same region to use industrial robot technology to improve sustainable green innovation through the demonstration effect and the competitive pressure effect, thereby strengthening the overall level of sustainable green innovation in the region. Hence, the above hypothesis proposed in this study is empirically supported.

4.4. Mediating Effect Test

The baseline regression and robustness test results presented above indicate that industrial robot application can significantly enhance the sustainable green innovation level of enterprises. To further clarify the mechanism through which industrial robot application impacts sustainable green innovation, this study employs the mediating effect for testing. Focusing on human capital structure and government-specific subsidies, we conduct empirical tests from multiple perspectives, including average employee compensation, the

share of employees with at least a bachelor's degree, the share of non-production personnel, and the scale of government-specific subsidies.

4.4.1. Human Capital Structure Mechanism

According to the theoretical analysis, industrial robot application generates both a significant substitution effect and a creation effect, which help improve the human capital level of enterprises and optimize human capital structure, thereby enhancing sustainable green innovation of enterprises. In terms of the substitution effect, this study refers to Xie et al. (2025) [17] and employs average employee compensation (*Wage*) as a proxy variable of the substitution effect. The reason is that an upward trend in average employee compensation typically indicates that industrial robot application has led to structural adjustments in labor costs of enterprises; that is, industrial robot application increases the overall average compensation level of employees by reducing the proportion of low-skill or low-entry-barrier positions.

Column (1) of Table 7 reports the regression results with average employee compensation as the dependent variable. There is a significantly positive relationship between industrial robot application and average employee compensation. The above results show that industrial robot application exerts a certain substitution effect on low-skill labor, thereby helping optimize human capital structure of enterprises. On the one hand, industrial robots have a comparative advantage in performing codifiable, repetitive, and routine tasks, thereby posing a direct threat to low-skill labor. On the other hand, with the continuous advancement of digital technology, the acquisition and maintenance costs of industrial robots have steadily declined, which reduces the corresponding threshold for enterprises to apply industrial robots to a certain extent, promotes their widespread application in production processes, and accelerates the substitution of low-skill labor.

Table 7. Substitution effect mechanism test.

Variables	(1)	(2)
Robot	0.0084 ** (2.7134)	
Wage		0.3078 ** (2.4074)
Cons	1.4689 *** (8.9677)	−3.9903 ** (−2.4160)
Year	Yes	Yes
Industry	Yes	Yes
Obs	31,940	31,940
R ²	0.3564	0.2840

Note: **, and *** represent that the estimated results are significant at the 5%, and 1% levels.

Column (2) presents the regression results with sustainable green innovation as the dependent variable and average employee compensation as the independent variable. The coefficient of average employee compensation is 0.3078, which is significantly positive at the 5% level. When the average compensation level of employees continues to increase, it often indicates a rising proportion of high-skill and high-knowledge employees within enterprises, accompanied by a relative decline in the share of low-skill employees. The knowledge, skills, and experience embodied in high-skill and high-knowledge employees not only enhance the ability of enterprises to identify, absorb, and apply green technologies but also facilitate the exploration of new green technologies and solutions through continuous research and development activities. As a result, enterprises are better positioned to

improve the quality of green innovation on a sustained basis and strengthen their long-term competitive advantage. The above results suggest that industrial robot application can optimize human capital structure through the substitution effect, thereby enhancing the level of sustainable green innovation of enterprises.

In terms of the creation effect, this study follows Wang and Han (2025) [19] and selects the share of employees with at least a bachelor's degree (EDU) and the share of non-production personnel (NPR) as proxy variables of the creation effect. As shown in Columns (1) and (3) of Table 8, the coefficients of industrial robot application are 0.0068 and 0.0349, respectively, both of which are statistically significant at least at the 10% level. These results indicate that industrial robot application can improve labor quality through the creation effect, thereby promoting the optimization of the human capital structure of enterprises. While replacing certain low-skill labor, industrial robots also create new occupations that match automation, such as robot trainers, data analysts, and maintenance engineers, thereby increasing enterprises' demand for high-skill labor. Meanwhile, the large-scale application of industrial robots imposes new requirements on enterprises' human resource allocation. Enterprises are compelled not only to recruit high-skill talent but also to enhance the professional skills and job competencies of existing employees through systematic training, enabling them to adapt to changes in job requirements brought about by industrial robot application and to collaborate effectively with robotic systems. This process inevitably improves the overall labor quality, thereby promoting the optimization and upgrading of enterprises' human capital structure.

Table 8. Creation effect mechanism test.

Variables	(1)	(2)	(3)	(4)
Robot	0.0068 ** (2.8370)		0.0349 * (1.8309)	
EDU		0.3557 ** (2.5862)		
NPR				0.0658 *** (19.6192)
Cons	1.4685 *** (8.8142)	−4.5399 ** (−2.5798)	1.4814 *** (5.3413)	−0.5574 *** (−4.0006)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Obs	31,940	31,940	31,940	31,940
R ²	0.3827	0.2856	0.1577	0.2857

Note: *, **, and *** represent that the estimated results are significant at the 10%, 5%, and 1% levels.

The results reported in Column (2) show that the coefficient of the share of employees with at least a bachelor's degree is significantly positive. The results in Column (4) indicate that the coefficient of the share of non-production personnel is significantly positive. Highly educated employees and non-production personnel generally possess strong professional knowledge, technical expertise, and innovative capabilities. An increase in their proportion can enhance enterprises' efficiency in green technology research and development, facilitate the accumulation and diffusion of green knowledge, and provide stable human capital support for sustainable green innovation. Moreover, highly educated employees and non-production personnel have stronger capabilities in information acquisition, processing, and analysis. These capabilities enable enterprises to identify and capitalize on green market opportunities more effectively and to develop green products that better meet market demands. Consequently, enterprises can reduce the uncertainty and risk of failure associated

with sustainable green innovation activities and improve the conversion efficiency of green innovation outcomes. The above results suggest that industrial robot application promotes enterprises' sustainable green innovation by optimizing human capital structure.

4.4.2. Government-Specific Subsidies Mechanism

The previous theoretical analysis points out that a higher level of industrial robot application can help enterprises obtain more government-specific subsidies, thereby promoting sustainable green innovation. To identify this potential mediating mechanism, this study follows Cui et al. (2025) [23] and extracts subsidy programs containing keywords such as “robot” and “artificial intelligence” from the government subsidy data in the CSMAR database. The amounts of these subsidies are then aggregated to measure the scale of government-specific subsidies obtained by enterprises. Meanwhile, to alleviate the impact of enterprise size and operating capacity on the estimation results, this study uses year-end total assets and operating revenue of enterprises to standardize the scale of government-specific subsidies, which are denoted as GS and GSA, respectively. According to Columns (1) and (3) of Table 9, industrial robot application helps enterprises obtain greater amounts of government-specific subsidies. Industrial robots have a significant spotlight effect and can attract wide attention from government departments and various stakeholders. Therefore, the larger the scale of industrial robot application and the higher the investment in robotic equipment, the stronger the signal of digital transformation and intelligent upgrading conveyed by enterprises. Under the existing policy incentive mechanism, such enterprises are more likely to obtain government subsidies and policy support targeted at intelligent manufacturing. Moreover, the introduction of industrial robots into production processes is generally regarded as an important initiative for promoting intelligent manufacturing and technological upgrading, which is highly consistent with the policy orientation of local governments to promote industrial intelligence and green transformation, thereby further increasing both the scale and proportion of government-specific subsidies available to enterprises.

Table 9. Government-specific subsidies mechanism test.

Variables	(1)	(2)	(3)	(4)
Robot	0.0017 *** (2.9844)		0.0028 *** (2.9238)	
GS		0.3510 ** (2.4510)		
GSA				0.0585 ** (2.6380)
Cons	0.0883 *** (3.1621)	−0.4876 (−1.2519)	0.3098 ** (2.5969)	−0.4739 (−1.2225)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Obs	31,940	31,940	31,940	31,940
R ²	0.1056	0.2761	0.0643	0.2757

Note: **, and *** represent that the estimated results are significant at the 5%, and 1% levels.

Columns (2) and (4) report the results in which government-specific subsidies are included. The coefficients of government-specific subsidies are both significantly positive. Government-specific subsidies, as non-repayable financial support provided by the government to enterprises, can offer the necessary funding for sustainable green innovation, effectively reducing the costs and risks associated with green R&D activities and

thereby enhancing enterprises' willingness to engage in sustainable green innovation. In addition, the acquisition of government-specific subsidies can strengthen the innovation confidence and sense of honor of enterprises, encourage them to optimize and reallocate innovation resources, and actively carry out green product and green process innovations, thereby enhancing the level of sustainable green innovation. These findings indicate that industrial robot application can increase the scale of government-specific subsidies available to enterprises, thereby enhancing their sustainable green innovation. In other words, government-specific subsidies play an important mediating role in the relationship between industrial robot application and sustainable green innovation of enterprises.

4.5. Heterogeneity Test

4.5.1. Ownership Structure

In China's market environment, state-owned enterprises and non-state-owned enterprises differ significantly in terms of labor structure, business objectives, and competitive pressures. As the cornerstone of national economic development, the operations of SOEs are greatly impacted by government policies, and they need to undertake social and policy-oriented responsibilities, such as "stabilizing employment" and "maintaining growth". Even when industrial robots are introduced on a large scale, it is still difficult for SOEs to achieve efficient reallocation of labor resources within a short period (Wang et al., 2023) [38]. Therefore, the promoting effect of industrial robot application on sustainable green innovation of enterprises may be relatively limited in SOEs. Meanwhile, SOEs often obtain greater policy support, tax incentives, and financial resources, which may reduce their incentives to engage in R&D activities and lead to relatively lower innovation efficiency, thereby reducing the effectiveness of industrial robot application in promoting sustainable green innovation to a certain extent.

In contrast, non-SOEs generally have more flexible employment systems and lower implementation costs for "machine substitution for labor", allowing them to fully realize the substitution effect of industrial robot application and optimize and upgrade their human capital structure. In addition, non-SOEs are typically exposed to greater competitive pressure in the marketplace. To maintain competitive advantages, they have stronger incentives to leverage industrial robot technology to enhance sustainable green innovation. Taken together, this study speculates that compared with SOEs, the positive relationship between industrial robot application and sustainable green innovation will be more evident in non-SOEs.

To explore the heterogeneous effect of industrial robot application across different ownership structures, this study classifies the sample enterprises into state-owned and non-state-owned enterprises and conducts group regression based on Model (4). The results are reported in Table 10. In the sample of SOEs, the coefficient of industrial robot application is 0.0104, but it is not statistically significant. In the sample of non-SOEs, the coefficient of industrial robot application is significantly positive. It can be seen from the above that the innovation-enhancing effect of industrial robot application is stronger among non-state-owned enterprises.

4.5.2. Environmental Background of Executives

Imprint theory suggests that individuals' educational background or work experience can be regarded as a formation process of "imprinting", which has a persistent impact on executives' decision-making behavior by shaping their cognitive structures and behavioral preferences (Wei et al., 2025) [39]. As a unique imprint, an environmental background can strengthen executives' environmental ethical cognition, thereby enhancing their ability to identify, evaluate, and promote green projects. Meanwhile, as key managers of enter-

prises, executives typically hold high organizational status and substantial decision-making authority, enabling them to exert an important impact on other members of enterprise through supervision, management, and strategic planning. In this process, executives can transmit their concern for environmental issues throughout enterprise, thereby forming a certain pressure and incentive mechanism at the organizational level and encouraging enterprise as a whole to place greater emphasis on environmental governance and green innovation practices. Existing studies also indicate that executives with an environmental background tend to place greater emphasis on ecological protection and have a stronger willingness to promote sustainable innovation activities of enterprises (Wang and Han, 2025) [19]. Therefore, it can be expected that industrial robot application is likely to exert a greater promoting effect on sustainable green innovation in enterprises whose executives have an environmental background.

Table 10. Heterogeneity test: ownership structure and environmental background of executives.

Variables	SOEs	Non-SOEs	Executives Who Have Environmental Background	Executives Who Do Not Have Environmental Background
	(1)	(2)	(3)	(4)
Robot	0.0104 (1.0485)	0.0223 ** (2.5915)	0.0261 * (1.9165)	0.0093 (1.1510)
Cons	−0.4968 (−0.6681)	0.0158 (0.0444)	0.6019 (1.3393)	−0.7738 ** (−2.1152)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Obs	11,007	20,933	8998	22,942
R ²	0.3497	0.2466	0.3214	0.2822

Note: *, and ** represent that the estimated results are significant at the 10%, and 5% levels.

To verify the above speculation, this study follows Fang and Zhang (2024) [40] and divides the sample into two groups: enterprises with executives who have an environmental background and enterprises with executives who do not have an environmental background. Specifically, if an executive's resume contains keywords such as "sustainability", "energy conservation", or "environmental protection", the executive is identified as having an environmental background; otherwise, the executive is identified as not having an environmental background. According to Table 10, in enterprises with executives who have an environmental background, the coefficient of industrial robot application is significantly positive. In contrast, in enterprises with executives who do not have an environmental background, the positive relationship does not hold. The above results show that executives' environmental background plays an important role in the process through which industrial robot application improves sustainable green innovation of enterprises.

4.5.3. Capital Intensity

The difference in capital intensity of enterprises may lead to heterogeneous effects of industrial robot application on sustainable green innovation. Compared with capital-intensive enterprises, labor-intensive enterprises generally have a higher proportion of labor input and lower technological requirements for many job tasks, making them more likely to implement "machine substitution for labor". As China's demographic dividend has gradually diminished and labor costs have continued to rise, labor-intensive enterprises have increasingly turned to industrial robots to replace low-skill labor, optimize human resource allocation, improve human capital structure, and facilitate the absorption and

application of green technology, thereby promoting sustainable green innovation in labor-intensive enterprises.

In contrast, capital-intensive enterprises typically possess more advanced production systems and well-established technological infrastructure, making them less dependent on low-skill labor in production processes. Moreover, the fixed assets of capital-intensive enterprises are mostly concentrated in large-scale mechanized production equipment. Such assets generally exhibit low mobility and are difficult to transfer or reallocate within a short period (Wang et al., 2023) [38]. As a result, the scope for technological improvement and the marginal substitution effect generated by industrial robot application are relatively limited in capital-intensive enterprises, making its impact on sustainable green innovation less pronounced. Taken together, this study speculates that industrial robot application has a stronger positive effect on sustainable green innovation among labor-intensive enterprises.

To examine whether the impact of industrial robot application on sustainable green innovation of enterprises varies across enterprises with different capital intensity, this study follows Ye et al. (2023) [41] and classifies the sample into capital-intensive enterprises and labor-intensive enterprises based on the industry-year median of the ratio of net fixed assets to the number of employees. Sub-sample regressions are then conducted to test for heterogeneity. The results in Table 11 show that in capital-intensive enterprises, the coefficient of industrial robot application is 0.0087, but it is not statistically significant. In contrast, in labor-intensive enterprises, the coefficient of industrial robot application is significantly positive. These findings suggest that industrial robot application significantly enhances sustainable green innovation of labor-intensive enterprises, while its effect on sustainable green innovation of capital-intensive firms is relatively limited.

Table 11. Heterogeneity test: capital intensity and regional environmental regulation intensity.

Variables	Capital-Intensive	Labor-Intensive	Strong Environmental Regulation	Weak Environmental Regulation
	(1)	(2)	(3)	(4)
Robot	0.0087 (0.6133)	0.0252 ** (2.4037)	0.0242 ** (2.4091)	0.0181 (1.5550)
Cons	−1.1277 (−1.4518)	−0.2339 (−0.5898)	−0.4519 (−1.1093)	−0.6016 (−1.4873)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Obs	10,277	21,663	18,139	13,801
R ²	0.2122	0.2992	0.2863	0.2631

Note: ** represent that the estimated results are significant at the 5% level.

4.5.4. Regional Environmental Regulation Intensity

Environmental regulation refers to a series of rules and measures formulated by government with the objectives of protecting the ecological environment and reducing environmental pollution and resource waste. Given the significant difference in the intensity of environmental regulation across different regions of China, the effect of industrial robot application on sustainable green innovation of enterprises may exhibit significant regional heterogeneity. As an important institutional arrangement for government to advance ecological governance, environmental regulation can constrain and guide enterprises' production and operational activities, encouraging them to proactively develop and adopt new technologies, improve resource utilization efficiency, and achieve cleaner production and green transformation while maintaining economic performance. Meanwhile, the Porter Hypothesis suggests that moderate environmental regulation can strengthen the awareness

of social responsibility of enterprises, compel them to actively take green actions, and realize the green transformation from passive to active, thereby enhancing sustainable green innovation of enterprises. In summary, this study speculates that the stronger the environmental regulation in a region, the more significant the positive impact of industrial robot application on sustainable green innovation of enterprises.

To verify this speculation, following Shao et al. (2024) [42], this study first measures the intensity of regional environmental regulation by counting the frequency of environment-related keywords appearing in local government work reports. The sample is then divided into high- and low-environmental-regulation groups based on the industry-year median of environmental regulation intensity in the region where enterprises are located. As reported in Table 11, in regions with relatively strong environmental regulation, industrial robot application is positively associated with sustainable green innovation of enterprises. In contrast, the coefficient of industrial robot application is 0.0181 in regions with relatively weak environmental regulation, but it does not reach statistical significance. Overall, the above findings show that the moderate strengthening of environmental regulation by local governments can effectively encourage enterprises to actively apply industrial robot technology, thereby enhancing the level of sustainable green innovation.

4.5.5. Establishment of Environmental Courts

The establishment of environmental courts may be an important factor impacting the relationship between industrial robot application and corporate sustainable green innovation. As an important institutional arrangement for promoting the specialization of environmental justice and strengthening ecological governance, environmental courts improve the environmental governance system, enhance the enforcement of environmental laws, and increase the costs of environmental violations, thereby effectively making up for the limitations of traditional administrative regulation in environmental governance (Chu & Chen, 2026) [43]. At the same time, environmental courts strengthen the awareness of corporate environmental responsibility through a judicial constraint mechanism and encourage them to proactively pursue green transformation, thereby providing a strong foundation for enterprises to continuously conduct green innovation activities with the help of industrial robot technology.

Moreover, environmental courts are typically established in densely populated areas, where public and media attention toward environmental issues is relatively higher, resulting in greater environmental compliance pressure and reputational pressure on enterprises. To maintain a favorable social image and reduce potential risk associated with environmental litigation, enterprises have stronger incentives to leverage industrial robot technology to further enhance their environmental governance capabilities and improve sustainable green innovation performance. In summary, this study proposes that the establishment of environmental courts can strengthen the positive effect of industrial robot application on corporate sustainable green innovation.

To verify the above speculation, this study follows Deng et al. (2024) [44] and constructs a dummy variable based on whether an environmental court has been established in the region where the enterprise is located. Specifically, if an environmental court has been established in an enterprise's location in year t , the value is assigned as 1; otherwise, it is assigned as 0. Accordingly, the sample is divided into two groups for regression analysis, with the results reported in Table 12. The findings show that in regions with established environmental courts, industrial robot application significantly promotes corporate sustainable green innovation. However, this relationship does not hold in regions without environmental courts. These results suggest that the establishment of environmental courts

helps strengthen the positive effect of industrial robot application on corporate sustainable green innovation.

Table 12. Heterogeneity test: establishment of environmental courts.

Variables	Regions with Environmental Courts	Regions Without Environmental Courts
	(1)	(2)
Robot	0.0317 * (1.9531)	0.0117 (0.8340)
Cons	−0.5983 ** (−2.4650)	−0.1881 (−1.0604)
Year	Yes	Yes
Industry	Yes	Yes
Obs	13,951	17,989
R ²	0.3229	0.2513

Note: *, and ** represent that the estimated results are significant at the 10%, and 5% levels.

4.6. Leverage Effect and Crowding-Out Effect Test

The previous results indicate that industrial robot application can significantly enhance sustainable green innovation of enterprises. However, due to the generally long R&D cycles, high complexity, and substantial uncertainty associated with sustainable green innovation, coupled with enterprises' relatively limited available resources (Karpenko et al., 2025) [45], enterprises often need to make trade-offs among different innovation activities when pursuing sustainable green innovation. The first choice is to further increase R&D and human capital investment on the basis of existing green innovation investment, thereby enhancing the overall innovation capability of enterprises and forming a “leverage effect” on sustainable green innovation. The second choice is to reallocate internal resources under the impact of resource constraints and concentrate resources originally allocated to general innovation projects on long-term green innovation projects, thereby generating a certain “crowding-out effect” on non-green innovation activities.

In view of this, to test the “leverage effect”, following the research of Chen et al. (2024) [46], this study first examines the impact of industrial robot application on the overall innovation of enterprises. The overall innovation indicator of enterprises is measured by the logarithm of the total number of patent applications and the logarithm of the total number of patents granted, respectively. The results reported in Table 13 show that the coefficients of industrial robot application are 0.0216 and 0.0254, respectively, both of which are statistically significant. These findings indicate that industrial robot application can promote enterprises to carry out innovation activities and enhance the overall level of innovation.

Secondly, this study uses human capital investment of enterprises as the dependent variable in the baseline regression model to examine the impact of industrial robot application on human capital investment of enterprises. The human capital investment indicator is measured by the logarithm of cash payments to employees. According to Table 13, the coefficient of industrial robot application is 0.0185 and is significantly positively associated with human investment of enterprises, that is, industrial robot application helps to increase human capital investment of enterprises.

Finally, this study further examines whether industrial robot application impacts R&D investment of enterprises. The R&D investment indicator is measured by the logarithm of total R&D expenditures. Based on Table 13, industrial robot application has a significant positive effect on R&D investment of enterprises. Overall, these results suggest that

industrial robot application generates an ideal “leverage effect” by enhancing the overall innovation level and increasing human capital investment and R&D investment.

Table 13. Leverage effect and crowding-out effect test.

Variables	(1) Patent Application	(2) Patent Granted	(3) Human Capital Investment	(4) R&D Investment	(5) Cash Flow
Robot	0.0216 * (1.7939)	0.0254 ** (2.2273)	0.0185 ** (2.1302)	0.0604 ** (2.3659)	0.0381 (0.8202)
Cons	0.2364 (1.5286)	0.1785 (1.2103)	1.1652 *** (6.6769)	−1.3750 *** (−4.2688)	−1.5342 ** (−2.4726)
Year	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes
Obs	31,940	31,940	31,940	31,940	31,940
R ²	0.3991	0.4052	0.4351	0.1075	0.4916

Note: *, **, and *** represent that the estimated results are significant at the 10%, 5%, and 1% levels.

To test the “crowding-out effect”, this study uses the cash flow of enterprises as a dependent variable in the baseline regression model and measures cash flow by the ratio of monetary funds to total assets. To provide a more intuitive illustration of the impact of industrial robot application on cash flow of enterprises, this study divides the sample into high- and low-application groups based on the median of industrial robot application. The results are presented in Figure 2. The difference in cash flow between the two groups is relatively small, providing preliminary evidence that a higher level of industrial robot application does not lead to resource constraints within enterprises.

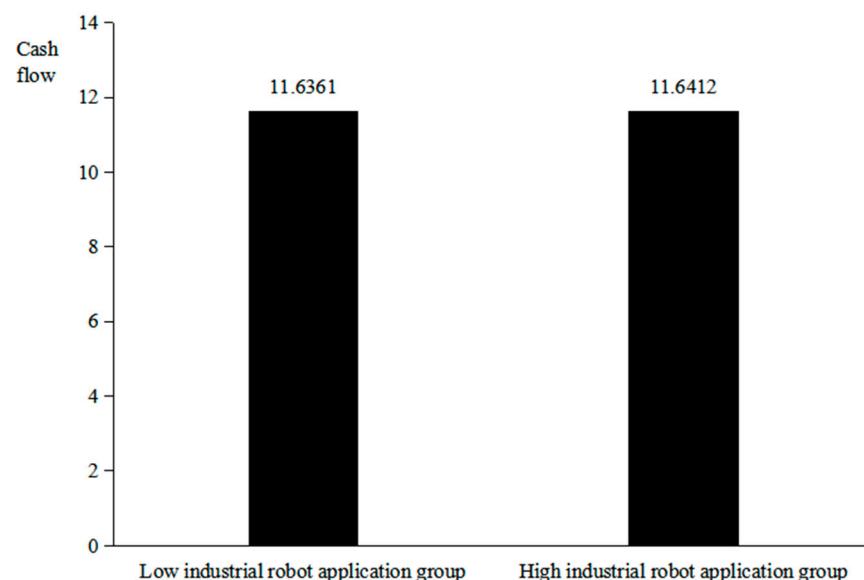


Figure 2. Industrial robot application and cash flow of enterprises.

The regression results reported in Table 13 show that the coefficient of industrial robot application is 0.0381, but it is not statistically significant. This suggests that industrial robot application does not intensify internal resource constraints or lead to a decline in the cash flow of enterprises. Overall, the positive impact of industrial robot application on sustainable green innovation of enterprises mainly stems from the “leverage effect” on overall corporate innovation activities rather than from the “crowding-out effect” caused by compressing other non-green innovation activities.

5. Conclusions and Implications

As the core technology driving digital transformation and intelligent upgrading of enterprises, industrial robots are quietly impacting corporate production and operation modes and R&D innovation ability. Against the backdrop of increasingly prominent “dual carbon” goals and the concept of green development, how to fully leverage the environmental governance effect of industrial robots and improve sustainable green innovation of enterprises has become a key issue for corporate green and low-carbon transformation and the ultimate realization of green development. In view of this, this study empirically examines the impact of industrial robot application on sustainable green innovation of enterprises. The results show the following:

Firstly, industrial robot application significantly enhances sustainable green innovation of enterprises. Secondly, the mechanism analysis indicates that industrial robot application promotes sustainable green innovation by optimizing human capital structure and increasing the scale of government-specific subsidies available to enterprises. Thirdly, the peer spillover effect analysis indicates that industrial robot application exhibits a pronounced peer spillover effect, which can generate a demonstration effect and a competitive pressure effect among enterprises in the same industry and region, encourage other enterprises to accelerate the introduction of industrial robot technology, and simultaneously improve sustainable green innovation and environmental responsibility. Fourthly, the heterogeneity analysis indicates that the effect of industrial robot application on sustainable green innovation varies substantially across different types of enterprises. Specifically, the promoting effect is stronger among non-state-owned enterprises, labor-intensive enterprises, enterprises with executives who have an environmental background, labor-intensive enterprises, and enterprises in regions with stricter environmental regulations. Furthermore, the establishment of regional environmental courts can strengthen the positive effect of industrial robot application on sustainable green innovation of enterprises. Fifthly, the promoting effect of industrial robot application on sustainable green innovation of enterprises is primarily driven by the “leverage effect”, which enhances the overall innovation level, as well as increases human capital investment and R&D investment, rather than the “crowding-out effect” on existing non-green innovation activities. In light of the empirical results, several recommendations are presented as follows:

(1) Government departments should adhere to the development direction of high-end and intelligentization and accelerate the promotion and application of industrial robot technology. To this end, government departments should formulate reasonable fiscal and tax policies and increase subsidies for industrial robot application, reduce the application cost, and enhance the willingness of enterprises to apply industrial robot technology by setting up special subsidy funds, providing tax incentives and discounts, and implementing accelerated depreciation of fixed assets. In particular, greater support should be given to the intelligent transformation of non-state-owned enterprises, enterprises with executives who have an environmental background, and labor-intensive enterprises, so as to provide material guarantees for fully leveraging the positive role of industrial robot application in improving environmental governance and promoting green development. Furthermore, government departments should establish specialized consulting and training institutions to systematically provide technical advisory and training services aimed at addressing the technological bottlenecks and implementation barriers that enterprises encounter during intelligent transformation and environmental governance, thereby enhancing both the breadth and sophistication of industrial robot application within enterprises.

(2) Government departments should fully leverage the peer spillover effect of industrial robot application to promote the overall improvement of intelligent transformation and environmental governance capabilities among enterprises within same industry and region.

At the industry level, government departments can establish industrial robot application alliances or collaborative platforms to strengthen production cooperation and information exchange among enterprises, facilitate knowledge spillover and technological integration, and foster a virtuous cycle of demonstration, diffusion, and coordinated advancement in industrial robot application, thereby encouraging more enterprises to achieve sustainable green innovation by utilizing industrial robot technology. At the regional level, government departments should accelerate the construction of industrial robot demonstration parks and industrial clusters, while regularly organizing experience-sharing forums, matchmaking events, and other exchange activities on intelligent development. These initiatives can help create benchmark examples for local enterprises, enhance the demonstration effect of leading industrial robot adopters in fulfilling environmental responsibilities, and ultimately promote the coordinated advancement of regional intelligent and green development.

(3) Government departments should strengthen the role of environmental regulation and create a favorable external environment for industrial robot application to empower corporate green development. The Porter Hypothesis suggests that moderate environmental regulation can improve corporate production efficiency and strengthen their sense of social responsibility. Therefore, government departments should build a diversified environmental regulation system that integrates command control, market incentive and public participation, and pay attention to the coordination and complementarity among different environmental regulatory tools rather than relying solely on mandatory environmental regulation, thereby more effectively playing the comprehensive effect of technological progress and green transformation.

(4) Enterprises should accelerate the deployment of industrial robot technology and expand the application scenarios. By introducing industrial robots into key business processes such as production and manufacturing, operational management, and product R&D, enterprises can achieve comprehensive, full-chain intelligent transformation and leverage technological advancement to empower green transformation. Meanwhile, enterprises should strengthen communication and information exchange with government departments and pay close attention to their expectations and policy priorities regarding environmental governance and green development. By improving both the content and methods of information disclosure and comprehensively presenting their industrial robot application practices and environmental governance achievements, enterprises can build trust with government departments and strive for more policy support.

(5) Enterprises should optimize human capital allocation to meet the demand for high-quality talent. The core of enterprise digital and intelligent transformation is not simply “machine substitution for labor” but rather achieving higher-quality human–machine collaboration. Therefore, enterprises should strengthen vocational education and training through online learning, targeted on-the-job training, skills competition and other ways to improve the human capital and professional competencies of the existing labor, particularly low-skill labor, enabling them to better understand and operate emerging technologies such as industrial robots and helping them achieve job transformation.

This study investigates the impact of industrial robot application on corporate sustainable green innovation and its underlying mechanisms, contributing to both theory and practice. However, several limitations still warrant further attention. On the one hand, due to constraints in data availability and accuracy, this study focuses on A-share-listed firms in China. However, whether the findings derived from listed firms can be generalized to the broader population of firms remains to be further verified. Future studies can expand the scope of samples and data sources by incorporating questionnaire surveys, semi-structured interviews, and field investigations, thereby providing more comprehensive and robust empirical evidence on how industrial robot application impacts corporate sustainable green

innovation. On the other hand, different from existing studies, this study clarifies the mechanisms by which industrial robot application impacts corporate sustainable green innovation from the perspectives of human capital structure and government-specific subsidies. However, the impact of industrial robot application on corporate sustainable green innovation is inherently complex, and other potential mechanisms may still exist. Future studies can further explore the deeper underlying mechanisms linking industrial robot application to corporate sustainable green innovation, thereby enriching and refining the research framework in this field and providing stronger theoretical support and practical insights for enterprises to leverage industrial robot technology to promote sustainable green innovation.

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