ISSN 2409-2665
Journal of Logistics, Informatics and Service Science
Vol. 12 (2025) No. 5, pp. 68-85
DOI:10.33168/JLISS.2025.0504

The Impact of Intelligent Manufacturing on Corporate Environmental Performance of High-tech Manufacturing Enterprises in the Pearl River Delta Region of China

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Abstract. Against the backdrop of China's "dual carbon" goals and the accelerating green transformation of the manufacturing industry, this study investigates the impact of Intelligent Manufacturing (IM)—the deep integration of digital technologies and advanced manufacturing—on Corporate Environmental Performance (CEP) in high-tech manufacturing enterprises in the Pearl River Delta region. Drawing on survey data from 413 employees, the study employs SPSS and SmartPLS to examine direct, mediating, and moderating effects within a multidimensional analytical framework. The results show that IM significantly improves CEP ($\beta = 0.147$, $p < 0.01$). Green Innovation (GI) positively influences CEP ($\beta = 0.178$, $p < 0.01$), and Green Supply Chain Collaboration (GSCC) also has a significant positive impact ($\beta = 0.219$, $p < 0.01$). Mediation analysis confirms that GI ($\beta = 0.071$, $p < 0.001$) and GSCC ($\beta = 0.061$, $p < 0.001$) serve as critical mediators, indicating that IM enhances CEP primarily by strengthening innovation capability and advancing supply chain collaboration. Moreover, Top Management's Environmental Awareness (TMEA) positively moderates the IM–CEP relationship ($\beta = 0.138$, $p < 0.01$), amplifying the effectiveness of IM when executives demonstrate stronger environmental commitment. Overall, the study highlights IM's dual role as both a technological driver and a sustainability enabler, offering robust theoretical support and practical guidance for enterprises seeking the synergistic development of intelligent manufacturing and green transformation under the national low-carbon strategy.

Keywords: Intelligent manufacturing; Corporate Environmental Performance; Green innovation; Green supply chain collaboration; Executives' environmental awareness.

1. Introduction

Amid escalating challenges such as climate change, resource depletion, and ecological degradation, Corporate Environmental Performance (CEP) has emerged as a critical issue for global sustainable development. As one of the world's largest economies, China has achieved significant economic growth but faces mounting environmental pressures. Rapid industrialization and resource-intensive development have led to widespread pollution, affecting ecosystems and public health (Chen et al., 2024; Hu et al., 2023).

The Pearl River Delta (PRD), as one of China's most economically dynamic regions, is home to dense manufacturing industries and severe environmental stress. Air monitoring data show that ozone levels in the region rose by 39% from 2006 to 2022, highlighting the urgency of environmental governance and industrial upgrading (Qin et al., 2024). The Chinese government has issued a series of policies to support smart manufacturing, including development roadmaps, standardization systems, and regional coordination initiatives. Under the carbon neutrality agenda, IM is regarded not only as a driver of economic efficiency but also as a strategic enabler of low-carbon transformation.

Manufacturing firms in the PRD region have taken the lead in adopting IM technologies, showing promising outcomes in green innovation, resource optimization, and environmental performance (Chen et al., 2021). Existing research suggests that IM can enhance CEP by optimizing resource use, reducing energy consumption, and enabling cleaner production (Jin et al., 2024; Yang et al., 2022). It strengthens firms' green innovation capabilities and energy efficiency, while also promoting green supply chain collaboration and upstream–downstream integration to reduce redundancy and waste (Cheng et al., 2024; Xu et al., 2024). In addition, top management's environmental awareness (TMEA) plays a pivotal role in firms' green transition, shaping decisions related to environmental investment and sustainability strategies (Cheng et al., 2024).

Despite the growing literature on IM and environmental outcomes, most studies remain at the macro level and lack micro-level, firm-based analyses—especially for high-tech enterprises. While previous studies have independently explored green innovation (Rahmani et al., 2024), green supply chain collaboration (Sadiq et al., 2024), and TMEA (Cheng et al., 2024), little is known about how these factors jointly interact with IM to influence CEP.To fill this gap, this study conducts an empirical investigation using survey and interview data from high-tech manufacturing firms in the PRD. It develops a triadic framework that integrates green innovation, green supply chain collaboration, and TMEA, aiming to explore how their interaction under IM contributes to environmental performance improvement.

This research contributes to the literature by providing a micro-level perspective on how IM enhances CEP through organizational, technological, and managerial mechanisms. It also offers practical implications for firms in the PRD seeking to accelerate digital transformation and implement IM strategies to achieve both environmental and economic goals.

2. Literature Review

2.1. Intelligent manufacturing

Intelligent manufacturing is a new production model that integrates advanced manufacturing technologies with new-generation information technologies such as big data analysis, the Internet of Things, artificial intelligence (AI), and automation technology into all aspects of research and development, production, sales, and service. It enables the production and service processes to have self-perception, self-learning, self-applicability, self-determination, and other functions (Xu et al., 2024). Intelligent manufacturing mainly consists of five dimensions: First, "Automation Level", which focuses on measuring the extent to which enterprises adopt automated equipment and technologies in the production process (Kamble et al., 2020); Second, "Smart Data Analytics Capability", which refers to the ability of enterprises to enhance operational efficiency and decision-making quality by collecting, analyzing, and utilizing big data (Stornelli et al., 2024); Third, "Flexible Manufacturing Capability", which measures the ability of enterprises to adjust production according to changes in market demand, and can respond to rapidly changing market demands through modular design and intelligent scheduling (Zhang et al, 2024); Fourth, "Intelligent Monitoring and Feedback Systems", which comprehensively uses IoT devices and real-time data analysis to conduct real-time monitoring and optimization of the production process (Zhao & Lyu, 2024); Fifth, "Human-Machine Collaboration Capability", which reflects the ability of enterprises to achieve efficient collaboration between humans and intelligent devices in the production process (Li et al., 2024).

In the related research on intelligent manufacturing, scholars mainly explore the impact of intelligent manufacturing from macro and micro perspectives. At the macro level, existing studies mainly discuss the impact of intelligent manufacturing on regional innovation (Ying et al., 2021), regional environmental pollution management (Lv et al., 2022; Shen & Zhang, 2023), green innovation (Lee et al., 2022), and employee structure (Fu et al., 2021). Specifically, intelligent manufacturing can promote regional innovation and drive the coordinated development of the regional innovation system (Ying et al., 2021). Lv et al. (2022) found that intelligent manufacturing significantly reduced carbon dioxide emissions in the industrial sector. Shen and Zhang (2023) empirically tested the impact of intelligent manufacturing on the environment, and green technological innovation played a positive mediating role in the impact of intelligent manufacturing on improving air quality. At the micro level, some scholars have deeply explored the impact of intelligent manufacturing implementation on the effects of enterprises. Xu et al. (2024) used China's intelligent manufacturing pilot and demonstration projects as a natural experiment to empirically test that intelligent manufacturing helps promote green innovation in enterprises, and the improvement of enterprises' green innovation levels helps promote the sustainable development of enterprises (Feng et al., 2023), further improving the environmental performance level of enterprises (Jin et al., 2024).

2.2. Corporate environmental performance

In recent years, growing attention from the Chinese government and academia to environmental issues — especially the goals of "carbon neutrality" and "carbon peaking" — has made Corporate Environmental Performance (CEP) a research hotspot. According to ISO14001, CEP refers to an organization's performance in achieving environmental goals by managing environmental factors across all operational stages. Ren et al. (2019) divide CEP into two dimensions: operational environmental performance (focused on outcomes of environmental activities) and managerial environmental performance (focused on the environmental management process). Similarly, China's ISO14031 (2021) categorizes CEP into Operational Performance Indicators (OPIs) and Managerial Performance Indicators (MPIs), reflecting environmental outcomes related to operations and management respectively (International Organization for Standardization, 2021). Alnaim et al. (2024) adopt a similar classification.

As a key element of corporate sustainability, CEP has drawn extensive attention regarding its driving factors. Internally, ownership structure (Liu et al., 2024) and green M&A (Lu et al., 2021) positively affect CEP. Externally, regulatory and institutional factors—such as environmental laws (Lin & Zhang, 2023), government subsidies (Wang & Zhang, 2020), GDP growth targets (Zhong et al., 2022), and regulatory distance (Tang et al., 2024)—play significant roles.

Recently, the relationship between digital technologies and CEP has gained traction. Lin et al. (2024) show that AI enhances CEP through green product and process innovation. Wei et al. (2024) find that intelligent manufacturing improves CEP via increased environmental investment, human capital, and green technologies. Other studies highlight the roles of green innovation, green supply chain collaboration, and top management’s environmental awareness. Green innovation significantly improves CEP, with process innovation having a stronger effect than product innovation (Rahmani et al., 2024). It also enables coordinated reduction of pollution and carbon emissions (Liu et al., 2025). Green supply chain collaboration supports improved CEP (Sadiq et al., 2024). Moreover, managers with strong environmental awareness actively leverage digital tools for green innovation and pollution reduction (Cheng et al., 2024).

In summary, most existing studies focus on macro-level economic impacts of intelligent manufacturing, while micro-level evidence remains limited. As firms are the direct implementers of intelligent manufacturing, its actual impact at the enterprise level needs further exploration. Although a few studies link intelligent manufacturing to green innovation and sustainability, research explicitly examining its effects on CEP and underlying mechanisms is scarce. Therefore, this study aims to investigate the impact of intelligent manufacturing on CEP from a firm-level perspective and to explore its internal mechanisms and transmission pathways.

3. Theoretical Basis and Research Hypotheses

Unlike conventional technical means, intelligent manufacturing is a holistic concept that encompasses all aspects of design, production, logistics, sales, and service (Zhou et al., 2018). It can effectively promote complementary innovation and often has greater potential value than individual technological products, and can be applied to all aspects of production and various fields, thereby changing the economic operation model. With the advanced intelligent monitoring system and external sensing technology of intelligent manufacturing, enterprises can quickly identify pollution sources during the production process, thereby achieving a shift from end-of-pipe pollution control to source pollution control, effectively avoiding energy waste and pollutant generation (Shen & Zhang,, 2023). As public expectations for a good ecological environment increase and people's environmental awareness strengthens, industrial enterprises, considering the maintenance of their own image and social reputation, will accordingly increase capital investment to introduce or develop green technologies, achieving the transformation from "end-of-pipe pollution control" to "source pollution control", thereby obtaining a leading advantage and occupying a favorable position in the market, greatly facilitating the improvement of the enterprise's environmental performance level (Shen & Zhang, 2023). Secondly, the implementation of intelligent manufacturing helps enterprises utilize industrial robots, intelligent measurement and control instruments, CNC machines, as well as new-generation information technologies such as cloud computing, big data, Internet of Things, and mobile Internet, through data analysis and optimization algorithms, to improve information processing capabilities (Lv et al., 2022). This enables enterprises to accurately assess their production capacity and predict market demand, better achieve intelligent scheduling and utilization of resources, achieve optimal resource allocation, reduce resource waste and environmental pressure, and thereby improve the enterprise's environmental performance level. Additionally, the application of intelligent manufacturing also promotes the intelligence of the production process, enabling real-time capture of production process information of various departments, promoting point-to-point transmission of management information between different departments, and thereby enhancing the overall management efficiency of the enterprise during the production process (Xu et al., 2024). At the same time, the improvement of management efficiency can drive enterprises to adopt more efficient production decision-making models, effectively avoiding high-pollution production phenomena caused by inefficient production processes, and ultimately reducing the pollution emission scale of the enterprise in the production process (Zhu et al., 2024), thereby improving the enterprise's environmental performance. Therefore, based on the above analysis, the following hypotheses are proposed.

H1: Intelligent manufacturing has a significant positive impact on Corporate environmental performance

The implementation of intelligent manufacturing by enterprises promotes the exchange and sharing of data and knowledge elements within and between the enterprise and the outside world, increases the opportunities for green innovation integration among different innovation entities, and enhances the efficiency of green innovation. During the process of implementing intelligent manufacturing, enterprises have promoted green innovation in various aspects such as research and development, production, sales, and services (Cao et al., 2024). For instance, in the research and development trial stage of intelligent manufacturing, digital technologies are utilized to conduct simulation tests and trial-and-error experiments for different product development plans, so as to determine the best research and development plan under different circumstances in the shortest time, reducing waste caused by trial-and-error and effectively saving resources, and significantly improving the efficiency of green product innovation. In the sales process of enterprises, through digital technologies such as intelligent manufacturing, market and user information can be obtained through multiple channels, greatly expanding the radiation range of the market for green products, opening up new market opportunities, and thereby prompting enterprises to produce more green products (Jin et al., 2023). Additionally, the process of intelligent manufacturing inevitably involves the upgrading of manufacturing enterprises' technologies and equipment, thereby optimizing the production operation process, improving the efficiency of product design and manufacturing processes, and promoting enterprise green process innovation (Zhu et al., 2024). And the improvement of the enterprise's green innovation level helps to enhance the environmental performance level of the enterprise. The research by Singh et al. (2020) indicates that the improvement of the enterprise's green innovation level helps to enhance the enterprise's environmental performance level. Thus, it can be seen that intelligent manufacturing has a significant positive impact on the enterprise's environmental performance by improving the enterprise's green innovation level. Based on the above analysis, the following hypothesis is proposed:

H2: Green innovation has a significant positive impact on corporate environmental performance

H4: Intelligent manufacturing has a significant positive impact on corporate environmental performance by improving green innovation .

Supply chain collaboration (SSC) relies on close inter-organizational cooperation, requiring all parties to work together across design, R&D, procurement, production, and marketing functions(Burinskienė et al.,2023). Intelligent manufacturing plays a critical role in promoting green supply chain collaboration (GSCC). First, it provides an efficient platform for the sharing of information, knowledge, and resources. By leveraging digital technologies such as big data and artificial intelligence, firms can break down information barriers, enable rapid and effective transmission of green information and resources, mitigate information asymmetry, and enhance mutual trust and understanding among partners. This, in turn, strengthens cooperative relationships and improves GSCC performance (Li et al., 2023; Cheng et al., 2024).Second, intelligent manufacturing offers abundant knowledge and technological resources to support GSCC. From the perspective of the resource-based view, data has become a key strategic asset for gaining competitive advantage. Through data mining and joint decision-making, intelligent manufacturing technologies assist supply chain partners in precisely filtering information, generating new knowledge, and enhancing green innovation efficiency, thereby transforming data resources into valuable knowledge and technology (Tian et al., 2022; Cheng et al., 2024).Third, intelligent manufacturing fosters a stable strategic alliance environment. By integrating upstream and downstream data resources, it breaks organizational boundaries and facilitates strategic coordination between manufacturers, suppliers, and retailers. This reduces transaction costs, improves collaboration efficiency, and enhances the feasibility of inter-organizational interaction (Annarelli et al., 2021).

Importantly, GSCC has been widely recognized for its role in improving firms' environmental performance. Through its internal optimization mechanisms, GSCC reduces resource waste and lowers operational costs, becoming a key path to enhancing competitiveness (Ahmed et al., 2020; Mishra et al., 2022; Wu et al., 2022). By implementing green practices throughout the supply chain—from raw material procurement to production and waste treatment—firms can monitor resource consumption and environmental impacts more accurately, and take targeted actions for improvement(Liu et al.,2025). Moreover, GSCC encourages resource sharing and technological exchange, enhancing firms' environmental capabilities and resource efficiency, and broadening the path toward green development(Li et al.,2025).In summary, intelligent manufacturing significantly enhances GSCC through its technological strengths, and the deep implementation of GSCC, in turn, effectively promotes improvements in corporate environmental performance.Therefore, based on the above analysis, the following hypothesis is proposed:

H3: Green supply chain collaboration.has a significant positive impact on corporate environmental performance

H5: Intelligent manufacturing has a significant positive impact on corporate environmental performance by improving the level of green supply chain collaboration.

Upper echelons theory posits that the background characteristics, cognitive styles, and core values of top management teams (TMT) exert a profound influence on organizational strategy and decision-making. Within this theoretical framework, Top Management's Environmental Awareness (TMEA) reflects the depth of executives' understanding of environmental issues and their sense of environmental responsibility. Executives with a strong sense of environmental accountability are typically more adept at identifying environmental risks and regulatory trends, recognizing the strategic importance of green transformation for long-term corporate sustainability. These executives actively guide their firms toward adopting intelligent manufacturing technologies to promote green innovation and pollution control (Karatekin et al., 2014; Cheng et al., 2024).Such top managers are skilled at leveraging intelligent manufacturing technologies to seize green market opportunities, optimize production processes, and achieve environmental goals such as energy conservation and emissions reduction through technological means (Wei et al., 2024). Moreover, environmentally aware managers tend to possess a more forward-looking perspective, enabling them to comprehend the strategic potential of intelligent manufacturing in enhancing operational efficiency, developing green products, and facilitating low-carbon transitions. They are more willing to invest resources in intelligent manufacturing and proactively drive the enterprise toward a green, efficient, and circular development model (Cheng et al., 2024), thereby improving the firm's environmental performance.Therefore, based on the above analysis, the following hypothesis is proposed:

H6: Top management's environmental awareness plays a positive moderating role in the impact of intelligent manufacturing on corporate environmental performance.

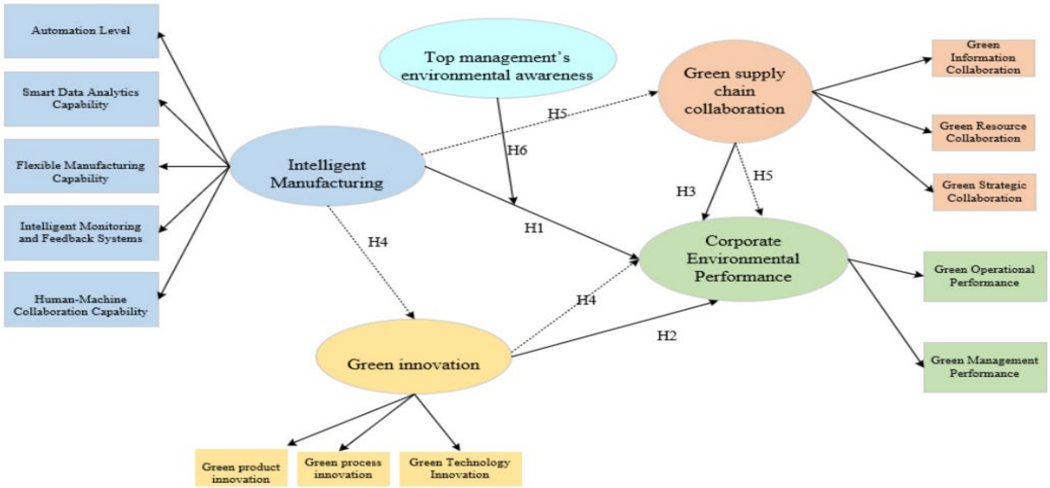

Fig. 1: Conceptual Framework of the Study

4. Conclusion and Suggestion

4.1. Research sample and data collection

The focus of this study is on the high-tech industrial enterprises in the manufacturing sector in the Pearl River Delta region (Guangzhou, Foshan, Shenzhen, Dongguan, Huizhou, Zhuhai, Zhaoqing, Zhongshan, Jiangmen). The Pearl River Delta is the forefront of China's reform and opening up, with a solid manufacturing foundation. It has long been a typical area for studying the transformation of Chinese enterprises. The high-tech enterprises in this region not only have representativeness in terms of quantity and scale, but also demonstrate strong momentum in intelligent manufacturing and green transformation. The respondents are managers of high-tech manufacturing enterprises, including those related to procurement, processing, operation, or environmental, health and safety management. They are familiar with the intelligent manufacturing technologies used in production and operation, as well as the collaborative business with upstream and downstream enterprises in the supply chain, and the performance of the enterprises in terms of environment and innovation.

The research data was collected through random sampling. The questionnaires were distributed through various channels, including government departments, research institutions, and the academic network within universities in the Pearl River Delta region. Specifically, the respondents included alumni related to these universities, EMBA and MBA students, and individuals in the personal social network of the author. The dissemination was carried out through instant messaging platforms such as We Chat and QQ. The main respondents were front-line, middle-level, and senior managers of the enterprises. To ensure the authenticity of the responses, anonymity was ensured during the survey, and confidentiality statements were provided to the participants. The data collection process lasted approximately three months, from March to May 2025.

A total of 492 questionnaires were received for this survey. To ensure the quality and reliability of the research data, several steps were taken to verify the questionnaires. Firstly, all questionnaires underwent completeness checks, and any missing responses to key questions were considered invalid. Secondly, the internal consistency of the items was evaluated using Cronbach's alpha coefficient to analyze the consistency of the questionnaire responses. Any questionnaire with a Cronbach's alpha value below 0.7 was excluded to ensure data reliability. Finally, statistical methods were used to check for outliers in the data, such as using the Z-score method to identify and handle extreme values. These steps ensured the efficiency and reliability of 413 questionnaires, with a response rate of 84.11%.

Table 1 provides a detailed statistical overview of the sampled enterprises. From the basic information of the respondents, there are more females (54.7%) than males, and the number of those with a bachelor's degree or above is the highest (42.8%). In terms of the technical fields of the affiliated enterprises, enterprises in electronic information technology accounted for 23.7%, new materials technology enterprises accounted for 24.0%, new energy and energy-saving technology enterprises accounted for 30.3%, enterprises for the high-tech transformation of traditional industries accounted for 12.8%, other industries accounted for 9.2%, and the sample covers a wide range of technical industry types. In terms of the total asset size of the enterprises, enterprises with assets ranging from 30 to 100 billion yuan and above occupied the majority of the sample (53.2%), and large and medium-sized enterprises accounted for a relatively high proportion. In terms of the establishment years of the enterprises, enterprises established for less than 3 years accounted for 25.7%, those established for 3 to 5 years accounted for 24.7%, those established for 6 to 10 years accounted for 27.4%, those established for 11 to 20 years accounted for 13.1%, and those established for 20 years or more accounted for 9.2%, indicating that the sample enterprises are generally in the growth and maturity stages. In terms of the positions of the respondents, senior managers accounted for 63.7%, middle-level managers accounted for 18.9%, and grassroots employees accounted for 17.4%. The majority of the respondents are enterprise executives, ensuring the decision-making reference value of the data. In summary, the sample is reasonably distributed in terms of gender, education, technical fields, enterprise asset size, establishment years, and positions, and has good representativeness, providing a reliable data basis for subsequent empirical analysis.

Table 1. Basic information of the respondents

Characteristic	**Category**	**Frequency**	**Percentage**	**Valid percent**	**Cumulative percentage**
Gender	Male	187	45.3	45.3	45.3
	Female	226	54.7	54.7	100
Qualification	High school and below	103	24.9	24.9	24.9
	junior college	133	32.2	32.2	57.1
	undergraduate	107	25.9	25.9	83.1
	graduate and above	70	16.9	16.9	100
	Electronic Information Technology	98	23.7	23.7	23.7
	New Materials Technology	99	24	24	47.7
	New Energy and Energy-Saving Technology	125	30.3	30.3	78
	High-tech Transformation of Traditional Industries	53	12.8	12.8	90.8
	other	38	9.2	9.2	100
Total Asset Scale of Your	2—10	92	22.3	22.3	22.3
	10—30	101	24.5	24.5	46.7

Company	30—100	130	31.5	31.5	78.2
	100—300	51	12.3	12.3	90.6
	Above 300	39	9.4	9.4	100
Age of your enterprise	Less than 3 years	106	25.7	25.7	25.7
	3–5 years	102	24.7	24.7	50.4
	6–10 years	113	27.4	27.4	77.7
	11–20 years	54	13.1	13.1	90.8
	More than 20 years	38	9.2	9.2	100
Your Position in enterprise	Senior managers	263	63.7	63.7	63.7
	Middle managers	78	18.9	18.9	82.6
	Frontline Employee Perspective	72	17.4	17.4	100
	Aggregate	413	100	100	

4.2. Variable measurements

The questionnaire survey is used to collect data to verify the proposed hypotheses. To ensure the validity of the content, we used the following steps to design the measurement scale. Initially, an extensive literature review was conducted on relevant studies on intelligent manufacturing, corporate environmental performance, green innovation, green supply chain collaboration, and top management's environmental awareness. Then, senior experts from high-tech manufacturing enterprises were invited to review and modify the initial questionnaire based on the literature. The measurement scale for intelligent manufacturing variables was designed according to the studies of Kamble et al. (2020), Mittal et al. (2020), Liu et al. (2024), Zhang et al. (2025), Zhao and Lyu (2024). The measurement scale for green innovation was designed based on the studies of Wang and Zhang (2020), Rehman et al. (2024), Liu et al. (2025), etc. The measurement scale for green supply chain collaboration was designed based on the study of Cheng et al. (2024), and the measurement scale for corporate environmental performancewas designed based on the studies of Cheng et al. (2024) and Xin et al. (2022). The measurement scale for top management's environmental awareness was designed based on the study of Cheng et al. (2024) and Xin et al. (2022). After the questionnaire design was completed, a pre-survey was conducted to verify the reliability and validity of the questionnaire. Based on the test results, the questionnaire was adjusted and modified to form the final formal questionnaire.

The final questionnaire consists of two parts. The first part is the basic information of the surveyed enterprises and individuals, including gender, highest educational attainment, main product categories of the company, total asset scale of the company, years of establishment of the company, and the position of the respondent in the company. The second part includes five sections: intelligent manufacturing, green innovation, green supply chain collaboration, corporate environmental performance, and top management's environmental awareness. There are a total of 59 assessment questions. Intelligent manufacturing is measured from five dimensions: automation level, intelligent data analysis ability, flexible manufacturing ability, intelligent monitoring and feedback system, and human-machine collaboration ability; green innovation is measured from three dimensions: green product innovation, green process innovation, and green technological innovation; green supply chain collaboration is measured from three dimensions: green information collaboration, green resource collaboration, and green strategic collaboration; corporate environmental performanceis measured from two dimensions: green operating performance and green management performance. Each dimension has multiple measurement questions. The questionnaire for this study adopts a 5-point Likert scale, ranging from 1 ("Strongly Disagree") to 5 ("Strongly Agree"), to facilitate precise measurement of respondents' attitudes and perceptions. In this study, SPSS and SmartPLS4 were used for data analysis.

5. Data Analysis

5.1. Reliability and validity analysis

Firstly, in terms of reliability analysis, Cronbach's alpha greater than 0.7 is used as the reliability (credibility) test indicator. The results show (Table 2), the Cronbach's α values of each variable are all between 0.842 and 0.902, all exceeding 0.7, indicating that the internal consistency of each scale is good. Among them, GRC (0.902), GOP (0.894), and GIC (0.893) have higher reliability coefficients, indicating that there is a strong correlation among the internal items of the scale. From the comprehensive reliability (rho_a and rho_c), the rho_a values of all variables are above 0.845, and the rho_c values are above 0.905, far exceeding the recommended standard of 0.7, further verifying the stability and reliability of the scale. Secondly, in terms of convergent validity analysis, the average variance extracted (AVE) test was conducted. The results show (Table 2), the AVE values of each variable are all between 0.656 and 0.781, all above the standard threshold of 0.5, indicating that the scale has good convergent validity. Among them, GMP (0.781), Prodict (0.761), and Tch (0.765) have higher AVE values, indicating that the items can better reflect the measurement characteristics of the corresponding latent variables. Finally, in terms of discriminant validity, the analysis results are shown in Table 3. The square roots of the AVE of each latent variable are all greater than the absolute value of its correlation coefficient with other variables, indicating that there is good discriminant validity among the variables. In summary, the scale of this study has good internal consistency reliability and validity, and is suitable for subsequent structural equation model analysis or other multivariate statistical analysis.

Table 2. Results of reliability and validity analysis

	Cronbach's alpha	**Comprehensive reliability (rho_a)**	**Comprehensive reliability (rho_c)**	**Average variance extraction（AVE）**
AL	0.891	0.893	0.925	0.755
FMC	0.873	0.874	0.913	0.725
GIC	0.893	0.894	0.921	0.701
GMP	0.859	0.864	0.914	0.781
GOP	0.894	0.898	0.919	0.656
GRC	0.902	0.904	0.928	0.72
GSC	0.882	0.883	0.914	0.681
HCC	0.864	0.864	0.908	0.711
IMaFS	0.876	0.88	0.916	0.731
Process	0.885	0.888	0.921	0.745
Prodict	0.842	0.845	0.905	0.761
SDAC	0.882	0.883	0.919	0.74
Tch	0.846	0.848	0.907	0.765

W	0.885	0.903	0.915	0.684

Note: AI= Automation Level; FMC= Flexible Manufacturing Capability; GIC=Green Information Collaboration; GMP= Green Management Performanc; GOP= Green Operational Performance; GRC= Green Resource Collaboration; GSC= Green Strategic Collaboration; HCC=Human-Machine Collaboration Capability; IMaFS=Intelligent Monitoring and Feedback Systems; Process=Green Process Innovation; Prodict=Green Product Innovation; SDAC=Smart Data Analytics Capability; Tch=Green Technological Innovation; W=Top management's environmental awareness

Table 3. The results of the discriminant validity analysis

	AL	FMC	GIC	GMP	GOP	GRC	GSC	HCC	IMaFS	Process	Prodict	SDAC	Tch	W
AL	0.869													
FMC	0.539	0.851												
GIC	0.136	0.184	0.837											
GMP	0.19	0.268	0.164	0.884										
GOP	0.22	0.259	0.279	0.431	0.81									
GRC	0.2	0.189	0.495	0.15	0.236	0.849								
GSC	0.181	0.153	0.494	0.214	0.206	0.492	0.825							
HCC	0.522	0.507	0.186	0.17	0.223	0.174	0.16	0.843						
IMaFS	0.535	0.566	0.203	0.241	0.278	0.159	0.227	0.495	0.855					
Process	0.246	0.237	0.083	0.211	0.253	0.083	0.101	0.244	0.235	0.863				
Prodict	0.277	0.255	0.08	0.176	0.254	0.189	0.111	0.253	0.246	0.429	0.872			
SDAC	0.611	0.521	0.19	0.165	0.235	0.171	0.174	0.535	0.525	0.218	0.222	0.86		
Tch	0.272	0.265	0.08	0.201	0.205	0.143	0.075	0.258	0.256	0.384	0.446	0.225	0.875	
W	0.181	0.214	0.023	0.212	0.245	0.016	0.084	0.234	0.215	0.182	0.129	0.241	0.178	0.827

Note: represents the square root of the AVE value, while the others are correlation coefficients.

5.2. Main effect analysis

According to the results in Table 4 and Figure 2, Intelligent Manufacturing (IM) has a significant positive effect on Corporate Environmental Performance (CEP) ($\beta = 0.147$, $t = 2.906$, $p < 0.01$), indicating that the implementation of Intelligent Manufacturing helps to improve the level of Corporate Environmental Performance. Therefore, Hypothesis H1 is supported. Intelligent Manufacturing (IM) also has a significant positive effect on Green Innovation (GI) ($\beta = 0.396$, $t = 8.625$, $p < 0.01$), suggesting that the adoption of Intelligent Manufacturing promotes the advancement of Green Innovation. Similarly, Intelligent Manufacturing (IM) shows a significant positive effect on Green Supply Chain Collaboration (GSCC) ($\beta = 0.396$, $t = 8.625$, $p < 0.01$), demonstrating that Intelligent Manufacturing contributes to strengthening Green Supply Chain Collaboration. Furthermore, Green Innovation (GI) significantly and positively influences Corporate Environmental Performance (CEP) ($\beta = 0.178$, $t = 3.802$, $p < 0.01$), thus supporting Hypothesis H2. Green Supply Chain Collaboration (GSCC) also significantly and positively affects Corporate Environmental Performance (CEP) ($\beta = 0.219$, $t = 4.959$, $p < 0.01$), thereby supporting Hypothesis H3. Table 2 presents the results of the reliability and validity analysis.

Table 4. Results of Structural Model Path Analysis

	Original sample (O)	Sample mean（M）	Standard deviation (STDEV)	T-statistical data (|O/STDEV|)	P
GI -> CEP	0.178	0.177	0.047	3.802	0
GSCC -> CEP	0.219	0.22	0.044	4.959	0
IM -> CEP	0.147	0.146	0.051	2.906	0.004
IM -> GI	0.396	0.397	0.046	8.625	0
IM -> GSCC	0.278	0.278	0.049	5.635	0

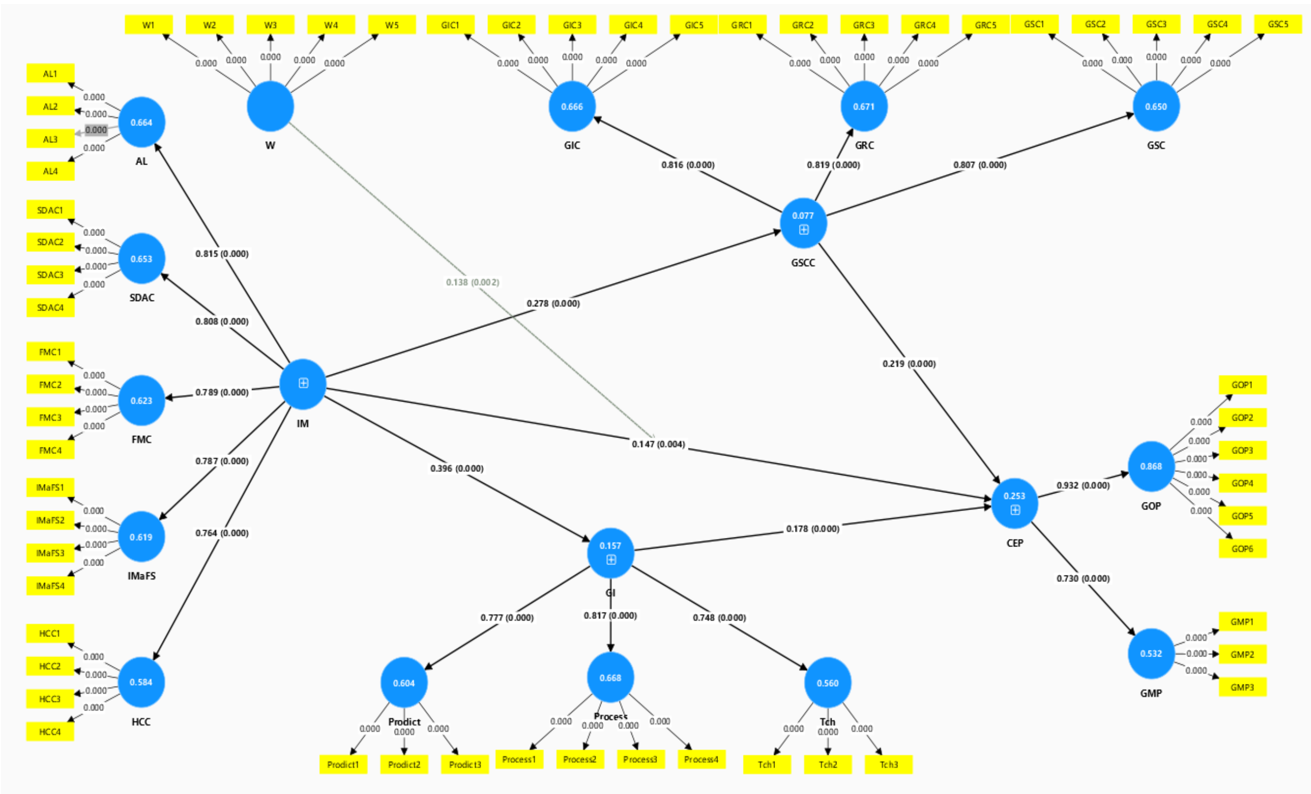

Fig. 2: Path relationship diagram of the structural model

5.3. Analysis of Mediating Effects

This study further examined the mediating effects of Intelligent Manufacturing (IM) on Corporate Environmental Performance (CEP) through Green Innovation (GI) and Green Supply Chain Collaboration (GSCC). The results are shown in Table 5.Firstly, the mediating path from IM → GI → CEP has a coefficient of 0.071, with a T-value of 3.513 and a P-value < 0.001. This indicates that the mediating effect is statistically significant, suggesting that the implementation of Intelligent Manufacturing promotes Green Innovation, which in turn enhances Corporate Environmental Performance. Therefore, Hypothesis H4 is supported. Secondly, the mediating path from IM → GSCC → CEP has a coefficient of 0.061, with a T-value of 3.545 and a P-value < 0.001. This result confirms that the mediating effect is statistically significant, indicating that the implementation of Intelligent Manufacturing improves Corporate Environmental Performance by strengthening Green Supply Chain Collaboration. Therefore, Hypothesis H5 is supported.

Table 5. Analysis of Mediating Effects

	Original sample (O)	**Sample mean （M）**	**Standard deviation (STDEV)**	**T-statistical data (|O/STDEV|)**	**P**
IM -> GI -> CEP	0.071	0.07	0.02	3.513	0
IM -> GSCC -> CEP	0.061	0.061	0.017	3.545	0

5.4. Analysis of Moderating Effect

This study employed the PROCESS macro in SPSS to examine the moderating effect of Top Management's Environmental Awareness (W) on the relationship between Intelligent Manufacturing (IM) and Corporate Environmental Performance (CEP). As shown in Table 6, the interaction term between IM and W has a path coefficient of 0.138, with a T-value of 3.092 and a P-value of 0.002, which reaches a significant level ($P < 0.01$). This finding indicates that Top Management's Environmental Awareness exerts a significant positive moderating effect on the relationship between Intelligent Manufacturing and Corporate Environmental Performance. Specifically, when enterprises exhibit higher levels of Top Management's Environmental Awareness, the positive impact of Intelligent Manufacturing on Corporate Environmental Performance becomes more pronounced. Therefore, Hypothesis H6 is supported.

Table 6. Analysis of Moderating Effect

	Original sample (O)	**Sample mean（M）**	**Standard deviation (STDEV)**	**T-statistical data (|O/STDEV|)**	**P**
W × IM -> CEP	0.138	0.138	0.045	3.092	0.002

6. Research Conclusions and Countermeasure Suggestions

6.1. Research conclusions

In recent years, the integration of digital technology and environmental governance has become a prominent field in academic research. High-tech manufacturing enterprises in China play a dual role, being both the key drivers of implementing intelligent manufacturing technologies and the important supporters of environmental governance for the enterprises. Therefore, based on the perspective of digital technology, this paper takes high-tech manufacturing enterprises in the Pearl River Delta region of China as the research sample, to study the impact of intelligent manufacturing on enterprises' environmental performance and its mechanism of action, and further explore the moderating effect of the environmental awareness of enterprise executives on the positive promotion effect of intelligent manufacturing on enterprises' environmental performance. The research findings show that the implementation of intelligent manufacturing by enterprises helps to improve the environmental performance of enterprises. Intelligent manufacturing mainly enhances the environmental performance of enterprises by improving their green innovation and the level of green supply chain collaboration. Moreover, the stronger the environmental awareness of enterprise executives, the stronger the positive promotion effect of intelligent manufacturing on the environmental performance of enterprises.

6.2. Countermeasure and suggestion

The government should strengthen policy guidance and continuously promote enterprises to implement intelligent manufacturing. Firstly, the government can encourage enterprises to accelerate the implementation of intelligent manufacturing technologies by providing financial subsidies and tax incentives. Secondly, a number of green intelligent manufacturing pilot and demonstration projects should be established to select representative enterprises for pilot experiments, explore the path of green intelligence integration, accumulate replicable and scalable experiences, and provide models for improving enterprises' green performance. Finally, a multi-departmental collaborative mechanism for promoting green intelligent manufacturing should be established, coordinating capital investment, standard formulation and policy implementation, to form a synergy for the transformation of green intelligent manufacturing. Through precise policy implementation and systematic mechanism coordination, the government will play a key guiding role in promoting the improvement of enterprises' environmental performance and accelerate the formation of a new green and low-carbon manufacturing development pattern.

Enterprises should strengthen their own initiative and actively promote the transformation of intelligent manufacturing. High-tech manufacturing enterprises should recognize the core position of intelligent manufacturing in improving environmental performance from a strategic perspective, actively shift from "external policy-driven" to "internal active innovation" governance logic, and strengthen the internal driving mechanism. On one hand, enterprises should clearly incorporate intelligent manufacturing into their medium- and long-term development strategies and environmental management systems, and use it as a core path for achieving green transformation and enhancing market competitiveness. They should establish an integrated transformation model of "technology empowerment - process reengineering - performance improvement", promoting the integration of production, management and environmental governance, and forming a full-process green operation mechanism. On the other hand, enterprises should increase investment in key intelligent manufacturing technologies, including industrial Internet of Things (IIoT), digital twins, edge computing, automation control and green manufacturing software systems, through technological upgrading to improve resource utilization efficiency, reduce energy consumption and pollution emissions, and build a green manufacturing system characterized by intelligent perception, dynamic control and continuous optimization.

Enterprises should strengthen the green innovation effect and green supply chain collaboration effect of intelligent manufacturing to improve their environmental performance. On one hand, green innovation is the key mechanism by which intelligent manufacturing affects environmental performance. Enterprises should rely on intelligent manufacturing platforms to promote green technological research and application in production processes, product design, and emission control. First, establish a digitalized green R&D system to achieve real-time monitoring and optimization of energy consumption and emissions; second, use big data analysis and artificial intelligence means to identify green innovation opportunities and form green patent achievements; third, promote the construction of green technology standards to enhance the recognition and competitiveness of green products in the market, thereby achieving a synergistic win-win effect of environmental performance improvement and brand value enhancement. On the other hand, extend intelligent manufacturing to the entire supply chain system, promote the participation of upstream and downstream enterprises in environmental governance, and build a green and low-carbon industrial ecosystem. Enterprises should actively form green manufacturing alliances, and the main bodies of supply chain upstream and downstream enterprises should utilize intelligent manufacturing technologies to jointly build and share green technology platforms, collaboratively formulate green standards, promote the diffusion of green technologies, and form a collaborative mechanism of shared responsibility, value creation and performance improvement, to comprehensively enhance the environmental performance level and sustainable development ability of the entire supply chain.

Strengthen the environmental awareness of senior management and enhance the driving effect of intelligent manufacturing on environmental performance. Studies have shown that in enterprises with stronger environmental awareness of senior management, the improvement effect of intelligent manufacturing on environmental performance is more significant. Therefore, enterprises should attach importance to the cultivation and institutionalization of environmental awareness of senior management. On one hand, they should establish an environmental performance assessment and incentive system for senior management, incorporate key indicators such as carbon emission control, green technology adoption and environmental compliance into the assessment system of senior management, and link them with salary, promotion and other aspects, to strengthen the sense of responsibility for green governance. On the other hand, through organizing special training sessions on green transformation, industry forums, and international green standard-setting activities, the comprehensive decision-making capabilities of senior executives in areas such as environmental strategies, integration of intelligent technologies, and governance of green supply chains should be continuously enhanced. The improvement of top management's environmental awarenessnot only enhances the execution ability of enterprises in green transformation strategies, but also further releases the governance efficiency of intelligent manufacturing in improving environmental performance.

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