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RESEARCH ARTICLE

Pathways to corporate green technological innovation: An analysis from the perspective of dynamic capabilities

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ABSTRACT

Green technological innovation has become a pivotal tool for driving economic restructuring and achieving environmental sustainability. However, in the face of complex and volatile market and policy environments, a critical question remains: how can enterprises effectively select and implement innovation pathways to address environmental turbulence? Drawing on data from 14,751 Chinese listed companies from 2012 to 2022, this study employs dynamic capabilities theory and a fixed-effects panel model to examine the impact of dynamic capabilities on firms' choice of green innovation pathways. Results show a significant positive influence of dynamic capabilities on green innovation, although this effect varies depending on the research and development model and the level of environmental turbulence. Firms with high dynamic capabilities tend to favor independent research and development, with an effect coefficient of 0.778 ($p<0.01$); firms with moderate dynamic capabilities benefit more from cooperative research and development, with a coefficient of 0.045 ($p<0.01$); and firms with lower dynamic capabilities primarily pursue green innovation through technology transactions, with a coefficient of 0.052 ($p<0.01$). Furthermore, environmental turbulence significantly moderates the relationship between dynamic capabilities and green innovation negatively, with an interaction coefficient of -0.088 ($p<0.05$), indicating that environmental uncertainty weakens the positive impact of dynamic capabilities.

These findings suggest that firms can select suitable research and development models aligned with their level of dynamic capabilities and adopt flexible innovation strategies to effectively manage environmental turbulence. This study proposes the following policy recommendations: enterprises should strengthen their dynamic capabilities, particularly in knowledge acquisition, resource integration, and adaptability to environmental changes, to enhance their green innovation capacity. Additionally, the government should increase policy support for green technological innovation by offering financial subsidies, tax incentives, and intellectual property protections, helping enterprises maintain their innovation momentum amid environmental turbulence.

Keywords: dynamic capabilities; green technological innovation; environmental turbulence

1. Introduction

As the world enters the era of the green economy, China is facing the dual challenges of economic

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restructuring and environmental sustainability. In this context, corporate green technological innovation becomes a key force in promoting sustainable development.

In recent years, with the support of Chinese policies, corporate green technological innovation has become an important driving force for the development of enterprises[1,2]. However, as the economy develops, the contradiction between economic growth rate and the carrying capacity of resources and environment has become increasingly prominent[3].

How enterprises in developing countries, represented by China, achieve rapid green technological innovation in turbulent market environments has become a critical topic in current sustainable development research[4]. Compared to firms in developed countries, enterprises in developing nations often face relative deficiencies in financial resources, technology, and management expertise, leading their green innovation pathways and strategic choices to be more influenced by external factors[5]. At the same time, however, enterprises in developing countries are advancing sustainable ecological development through green technology innovation while fostering economic coordination on multiple levels[6].

Specifically, these firms have made substantial progress in the design of green products, the improvement of production processes, and the end-of-life management throughout the product lifecycle. Such innovations not only reduce resource consumption and pollutant emissions but also optimize resource allocation and enhance production efficiency, thereby achieving higher economic returns[7]. Moreover, green technological innovation enables enterprises to expand into green markets, meeting growing consumer demand for environmentally friendly products, and thus strengthening their market competitiveness[8]. By implementing circular economy models and measures for energy conservation and emissions reduction, these firms further enhance economic and environmental synergy, achieving a win-win for corporate profit growth and environmental protection, thereby injecting new momentum into sustainable development.

Enhancing corporate competitiveness through green technological innovation, truly achieving a 'win-win' for technological innovation and the ecological environment, is the harmonious unity of corporate profits and environmental greening[9,10],and is the inevitable choice facing Chinese enterprises under the current context[11,12].

In the pursuit of technological advancement and improved living standards, excessive resource consumption has led to a series of environmental challenges, including pollution, ecosystem degradation, and climate change. Addressing these issues has elevated the importance of achieving efficient resource utilization and promoting green technologies, making these critical factors central to advancing sustainable development[13].These organizations are striving to find new methods and pathways, attempting to combine the economic objectives of businesses with addressing environmental issues and ensuring human survival. Therefore, the choice of environment-related strategies by businesses, making environmental sustainability an important strategic decision, enables businesses to seize significant opportunities[14].The external environment significantly promotes the efficiency of green technological innovation, while government support and the R&D capabilities of the businesses themselves also play an important role .

The theory of dynamic capabilities offers an essential framework for understanding how companies achieve green innovation under uncertain conditions. Dynamic capabilities enable companies to adapt to external changes and secure a sustained competitive advantage through resource integration and knowledge reconfiguration[15]. Subsequent studies have examined the specific effects of dynamic capabilities on firms' green innovation pathways. For instance, the digital literacy of top management can enhance the effectiveness of dynamic capabilities in driving green innovation[16]. In contrast, other scholars have highlighted the bridging role of internet development between dynamic capabilities and green innovation.

From an external pressure perspective, stakeholder demands and societal influences further strengthen the role of dynamic capabilities in green innovation[17].

Environmental turbulence is a critical factor impacting the relationship between dynamic capabilities and green innovation. In environments of increasing uncertainty, the interaction between dynamic capabilities and political relationships can effectively boost firms' green innovation performance, although this effect may be attenuated under high turbulence. Additionally, a humble leadership style can facilitate resource integration and knowledge sharing in turbulent environments, enhancing resilience in green innovation. This finding underscores the significance of corporate culture and leadership style in the efficacy of dynamic capabilities[18].

In fast-changing environments, collaboration between firms and governments is crucial for green innovation. The coordinated development of green finance and digital technology requires governmental policy support, especially through financial incentives, tax benefits, and intellectual property protection to promote green technological innovation[19].Experiences from Nordic countries indicate that government support extends beyond financial subsidies to encompass regulatory frameworks and market guidance, fostering long-term green innovation development. This body of research suggests that firms must leverage dynamic capabilities to navigate environmental turbulence, while governmental policy incentives and financial support provide a solid foundation for advancing green innovation[20].

Despite progress in understanding the role of dynamic capabilities in green technology innovation, several research gaps remain. Helfat and Peteraf (2009) explore the role of dynamic capabilities in corporate resource integration; however, there is a lack of in-depth analysis of how dynamic capabilities specifically influence firms' green technology innovation pathways[21,22] examine the impact of environmental uncertainty on corporate innovation but lack clarity on the moderating role of environmental turbulence in the relationship between dynamic capabilities and green innovation. Porter and van der Linde (1995)[23] and Ambec and Barla (2006)[24] emphasize the role of policy incentives in fostering green innovation. Nevertheless, the specific strategies that firms and governments should adopt to enhance green innovation capacity in fast-evolving environments remain underexplored. Addressing these questions is theoretically and practically significant for achieving green transformation and enhancing firms ’ environmental adaptability.

In this study, while previous literature has provided a foundation for understanding the role of dynamic capabilities in green technology innovation, notable research gaps persist concerning the specific influence of dynamic capabilities on green innovation pathways, the moderating effect of environmental turbulence, and the collaborative strategies between firms and governments in uncertain environments. Existing literature primarily focuses on the overarching impact of dynamic capabilities[15] but lacks detailed analysis of how dynamic capabilities manifest along distinct innovation pathways. This research contributes to the field by examining how dynamic capabilities operate within autonomous R&D, cooperative R&D, and technology transactions in green technology innovation, offering a new perspective.

Although Gao et al. (2016)[22] investigate the effects of environmental uncertainty on corporate innovation, they do not explore how environmental turbulence specifically moderates the relationship between dynamic capabilities and green innovation. This study systematically analyzes how environmental turbulence influences the selection of green innovation pathways, whether positively or negatively. Moreover, while Porter and van der Linde (1995)[23] and Ambec and Barla (2006)[24] underscore the role of policy incentives, existing research has yet to refine strategies for effective firm-government collaboration. Based on the varying levels of dynamic capabilities and the differential impacts of environmental turbulence, this study proposes specific measures for firms and governments to enhance green innovation in dynamic environments, helping firms to achieve green transformation in complex policy and market contexts.

To bridge these research gaps, this study employs qualitative research methods, utilizing secondary data from 14,751 Chinese listed companies to empirically analyze innovation pathways, environmental turbulence, and policy impacts. Through in-depth examination of secondary data, this research aims to reveal the intricate relationships between dynamic capabilities, green technology innovation pathways, and external environments more comprehensively. The findings will enrich the theoretical understanding of dynamic capabilities in green innovation and offer actionable strategic insights for firms and policymakers. Specifically, this study explores how firms with different levels of dynamic capabilities choose among three main pathways: collaborative R&D, technology transactions, and independent R&D. It also investigates the moderating role of environmental turbulence in shaping these relationships. By presenting a strategic framework for green technology innovation, this research contributes theoretically and practically, offering evidence-based recommendations for fostering sustainable innovation in dynamic environments.

2. Literature Review

2.1. The mechanism of dynamic capabilities' impact on corporate green technological innovation

The earliest research on dynamic capabilities described it as the ability of a firm to maintain a competitive advantage in a constantly changing external environment, specifically manifested in the firm's integration and reconfiguration of its own resources, and the timely launch of new products, among other methods, to address problems brought about by environmental changes[25]. Subsequent research further expanded the concept and scope of dynamic capabilities, considering them as organizational forces that integrate and reconfigure resources in response to changes in the external environment.

The mechanisms by which dynamic capabilities influence green innovation are particularly evident in resource integration and adaptive decision-making. Aragón-Correa and Sharma (2003)[26], from a resource-based perspective, analyzed the role of dynamic capabilities in corporate environmental strategies, finding that resource restructuring and capability reconfiguration facilitate green technological innovation. Eisenhardt and Martin (2000)[27] highlighted that dynamic capabilities enhance firms' innovative capacities across diverse market environments by optimizing resource allocation and enabling agile decision-making, particularly within the green technology sector. Teece (2018)[28] expanded the theoretical framework of dynamic capabilities, proposing a management system-supported dynamic capability architecture that fosters long-term growth in green innovation. Additionally, Ambrosini et al. (2009)[29] explored how firms leverage dynamic capabilities to reshape their resource base, thereby enhancing the adaptability and sustainability of green innovation. Collectively, these studies clarify how dynamic capabilities support green technological innovation through resource integration, learning, and adaptive decision-making.

Recent studies demonstrate the varied effects of dynamic capabilities across different contexts. Li et al. (2023)[30] investigated how digital transformation, through dynamic capabilities, drives green innovation, showing that enhanced digital capabilities significantly improve firms' resource integration efficiency and responsiveness. Yang and Ruan (2023)[31] found that under stringent environmental regulations, dynamic capabilities further promote green innovation by enhancing firms' environmental, social, and governance (ESG) performance. Feng (2023)[32] identified environmental regulation as a positive moderating factor between dynamic capabilities and green innovation, allowing firms to better meet green technology innovation requirements through resource optimization and risk management. Furthermore, Sun et al(2023)[33] emphasized the role of management, showing that a humble CEO leadership style fosters green innovation by facilitating the interplay between dynamic capabilities and green innovation. Wang et al

(2023)[34]examined how fiscal incentives activate firms' green innovation potential through dynamic capabilities, and Yin (2023)[35], based on a case study of low-carbon pilot cities, found that policy support significantly accelerates green technological innovation when dynamic capabilities are effectively leveraged.

Through resource integration, environmental adaptability, strategic pathway selection, and managerial support, dynamic capabilities provide a robust theoretical and practical foundation for green technological innovation in rapidly changing environments. These studies uncover the multi-layered mechanisms of dynamic capabilities, offering substantial theoretical and empirical support for firms' strategic choices in green technological innovation. Future research could further explore the interplay between dynamic capabilities and green technological innovation, particularly within various industry and market contexts, to furnish more management insights for sustainable development. Thus, the following hypothesis is proposed:

H1: Dynamic capabilities positively enhance firms' level of green technological innovation.

2.2. The moderating role of environmental turbulence

Environmental turbulence refers to 'the temporary, unpredictable disturbances to an organization by its environment, which have a destructive impact on the organization' (Meyer, 1982)[36]. Every enterprise and social organization exists within an environment, and the impact of the environment on the survival and development of enterprises cannot be ignored. The enterprise environment includes the macro environment, meso environment, and micro environment (Hodge Johnson, 1970)[37]. The macro-environment refers to a broad range of factors that indirectly impact an organization's operations, including demographics, economy, technology, politics, and natural resources. These factors not only shape the business context but also influence market demand fluctuations and the direction of technological innovation (Porter & Reinhardt, 2007)[14]. For instance, advancements in the technological environment drive the development and application of green technologies, while increasingly stringent environmental regulations prompt firms to prioritize sustainability in their innovations (Eisenhardt & Martin, 2000)[38]. The meso-environment encompasses industry, business, and regional factors closely related to corporate operations. These elements determine the competitive structure within which firms operate and impact their access to resources and policy support for innovation. Aragón-Correa and Sharma (2003) suggest that a firm's position within industry and regional environments affects its resource acquisition capabilities and promotes green innovation through collaboration and network relationships. For example, the level of green technology standardization within an industry and the green technology demands of business partners can influence a firm's investment in green technologies. Competitive pressure within the industry also drives firms to increase their green technology investments to maintain a competitive edge (Teece, 2018).

The micro-environment includes factors that directly influence a firm's innovation activities, such as customers, suppliers, and competitors, and these elements are closely linked to achieving the firm's objectives. Customer demand is one of the primary drivers of green technological innovation; when consumer preference for green products rises, firms often adjust their innovation strategies to meet market demand (Chen et al., 2022)[39]. Suppliers also play a crucial role by providing raw materials and technological support, especially when specific resources or materials required for green technologies are involved. Supplier collaboration is essential to developing green technologies. Additionally, competitors' innovation dynamics push firms toward green innovation to maintain their market position (Wang & Ahmed, 2007)[40]. Among these environmental factors, the micro-environment is not only influenced by but also often governed by the macro-environment. For instance, changes in macroeconomic conditions can affect customer consumption behaviors, which, in turn, alter a firm's green innovation direction through shifts in customer demand. Similarly, policy changes in the macro-environment, such as updates in environmental regulations, can indirectly impact firms by influencing supplier and competitor actions within the green technology domain (Duncan, 1972; Helfat & Peteraf, 2009).

Some scholars analyze these environments from both internal and external perspectives (Duncan, 1972)[41], considering that the internal environment consists of entities and social factors within the organization or decision-making unit, including organizational structure, corporate culture, human resource allocation, etc., with individual behaviors and attitudes also taken into account. The external environment includes relevant entities and social factors outside the organization or specific decision-making unit, such as customers, suppliers, competitors, economic and technological factors, etc. Tan and Litschert (1994) divided the organizational environment into the task environment (the environment closely related to the setting and achievement of organizational goals) and the institutional environment (social, demographic, economic, political, etc., environments)[42].

Research on environmental turbulence and dynamic capabilities shows that when enterprises are affected by external consistency pressure, dynamic capabilities play an important role in the survival and development of enterprises. On one hand, existing studies focus on the impact of macro policies on innovation capability, adaptability, organizational learning ability, and dynamic capabilities (Guo Hai et al., 2012)[43]. On the other hand, research focuses on the uniqueness of the external environment faced by enterprises. When enterprises interact with a favorable external environment and government, it can bring more resources to the enterprises.

The political connections of company executives are valuable institutional resources, and enterprises with high political connections with the government gain benefits such as tax incentives, financing convenience, and government support (Amezcua et al., 2013)[44]. By utilizing the unique resources obtained through political connections, enterprises can better implement innovative differentiation strategies, strengthen R&D investment, increase complementary resources, and improve the resource base of dynamic capabilities. However, existing research rarely discusses the compensatory effects of government-business relations and unique dynamic capabilities from an external environment perspective.Xiong Huibing et al. (2021) pointed out that a good relationship with the government is a main way to obtain legitimacy. Therefore, the turbulence of the external environment, such as rapid changes in the market, policies, and laws, has a significant impact on the survival and development of enterprises. This turbulence requires enterprises to have sufficient dynamic capabilities to adapt to and cope with environmental changes[45].

Therefore, in the relationship between corporate dynamic capabilities and green technological innovation, the turbulence of the external environment acts as a moderating variable, as it affects the extent and manner in which corporate dynamic capabilities are exercised, thereby influencing the effectiveness of corporate green technological innovation.

Hence, this paper proposes:

H_2: Environmental turbulence serves as a negative moderating variable in the mechanism by which dynamic capabilities influence corporate green technological innovation.

2.3. The mechanism of impact of different R&D models on corporate green technological innovation

Choosing the appropriate R&D model is a crucial means for modern enterprises to quickly achieve technological innovation in a highly competitive and rapidly changing market environment. The different R&D models in the process of corporate green technological innovation mainly include: collaborative R&D, technology transactions, and independent R&D. However, these aspects are not isolated but are interdependent and mutually reinforcing, together constituting the core of corporate R&D models.

Independent innovation, cooperative research and development (R&D), and technology transactions each serve as distinct pathways for corporate green technological innovation, impacting corporate performance in green innovation through unique mechanisms. Independent innovation primarily fosters green innovation by building internal technological capabilities and enhancing core competitiveness. In this approach, firms rely on their own resources for R&D activities, gaining proprietary knowledge and technology, thereby improving responsiveness to market demands and establishing technological barriers and competitive advantages. For example, Liang et al. (2022) found that independent innovation helps companies develop core green technologies, enhancing the uniqueness and inimitability of environmental technologies[46], as well as their adaptability and resilience in the face of environmental changes (Helfat & Winter, 2011)[47]. This self-directed R&D model enables firms to flexibly adjust their innovation strategies based on their technological foundations and resource conditions, responding effectively to dynamic market and policy demands in the green technology sector (Aragón-Correa & Sharma, 2003).

Cooperative R&D, on the other hand, lowers risks and costs in green technological innovation through resource sharing and technical collaboration, also reducing development cycles. This model allows firms to combine resources and knowledge from various organizations to achieve higher levels of green technological innovation. Wang et al (2022)[48] found that firms can expand the depth and breadth of their green innovation by partnering with universities and research institutions, gaining access to the latest research outcomes and expertise. Furthermore, Geng and Zhu (2022)[49] noted that cooperative R&D enhances a firm's learning capabilities and knowledge accumulation, accelerating both technological development and market application through knowledge transfer and resource sharing among organizations. Complementary resources among partners improve green innovation efficiency, allowing companies to conduct green technology innovation more effectively under resource constraints (Feng et al., 2027)[50].

Technology transactions, in contrast, achieve green innovation efficiency by rapidly incorporating external technological advancements. This approach allows firms to acquire ready-to-use green technologies through purchases, licensing, or transfers, saving on innovation-related time and costs. He et al. (2023)[51] highlighted that technology transactions enable firms to quickly adopt advanced environmental technologies, offering flexibility in adapting to shifting market and policy demands for green technology. Eisenhardt and Martin (2000)[52] observed that technology transactions are particularly suitable for companies lacking internal technological capabilities, providing a means to overcome innovation limitations and bridge technical gaps effectively (Cui et al., 2023)[53].

These three aspects together constitute the R&D model of a company. Autonomous innovation provides the foundation of technology and knowledge for the company, collaborative R&D expands the company's resource and capability range, and technology transactions offer the company ways to acquire and commercialize technology. These three aspects complement each other and jointly promote the company's continuous innovation and growth. In a highly competitive and rapidly changing market environment, choosing different R&D models becomes an essential path for companies to achieve green technological innovation.

Autonomous innovation is the foundation of the R&D model, reflecting the company's sensitivity to market demands and its ability to absorb new technologies. Through innovative activities with internal resources, companies can develop new products, services, or processes. Collaborative R&D, on the other hand, allows companies to share resources, knowledge, and skills to achieve more efficient and cost-effective innovation. Technology transactions are a way for companies to fully utilize their financial advantages to quickly acquire methods of green technological innovation. In the context of globalization and networking, different R&D models can all become key strategies to accelerate green technological innovation. Therefore, the author proposes the following hypothesis:

H3a: The Partial Mediating Role of Collaborative R&D between Dynamic Capabilities and Green Technological Innovation

H3b: The Partial Mediating Role of Technology Transactions between Dynamic Capabilities and Green Technological Innovation

H3c: The Partial Mediating Role of Independent R&D between Dynamic Capabilities and Green Technological Innovation

2.4. The pathways of corporate green technological innovation under different dynamic capabilities vary

Considering the interplay among environmental turbulence, dynamic capabilities, and R&D models, firms' green technology innovation pathways exhibit notable differentiation. Faced with unstable and unpredictable market environments, firms experience significantly heightened uncertainty, necessitating robust dynamic capabilities to swiftly adjust strategies and tackle the multifaceted challenges brought about by external shifts (Teece, 2018). Dynamic capabilities endow firms with flexibility and adaptability, enabling them to integrate and reorganize both internal and external resources, thereby enhancing resilience across every phase of the innovation process (Eisenhardt & Martin, 2000)[57]. Through this adaptable mechanism, dynamic capabilities not only support firms in optimizing resource allocation under complex conditions but also allow rapid adjustments to innovation pathways at critical junctures, ensuring the continuity and efficacy of green technological innovation.

Specifically, firms with high dynamic capabilities tend to demonstrate greater acuity in recognizing market demands and technological shifts, enabling them to identify emerging needs for green technology and proactively adjust innovation strategies. These firms often excel in resource reconfiguration, allowing them to optimize pathways for technology development and application, thereby gaining a leading position in green technology innovation (Helfat & Peteraf, 2009). Moreover, such firms exhibit higher resilience in the face of environmental turbulence, adeptly navigating policy changes or market fluctuations through efficient resource and technology integration, which enhances innovation efficiency (Ambrosini et al., 2009)[54]. For instance, when environmental regulations tighten or market preferences shift, firms with strong dynamic capabilities can swiftly reorganize resources and adjust processes to meet new market and regulatory requirements.

In contrast, firms with weaker dynamic capabilities struggle to adapt swiftly to environmental turbulence and technological shifts, often lacking the necessary agility and resilience to modify resource allocations and innovation strategies to support green technological innovation (Liang et al., 2022)[55]. These firms face significant obstacles in resource mobilization and technology absorption, limiting their competitive standing in green technology innovation. Research indicates that this disparity in dynamic capability levels directly influences firms' choice of innovation pathways and the eventual effectiveness of their green technology initiatives (Wang et al., 2022)[56]. Thus, while firms with robust dynamic capabilities are better equipped to adapt and lead in green technological innovation within complex environments, those with insufficient dynamic capabilities may struggle to achieve similar outcomes on the innovation path, ultimately losing competitive ground in a rapidly evolving market landscape.

Due to the differences in dynamic capabilities of enterprises, the main consideration in choosing R&D models is the maximization of benefits. Therefore, enterprises need to select different R&D models based on the differences in their dynamic capabilities. Hence, the author proposes the following hypotheses:

H_{4a}: For enterprises with higher levels of dynamic capabilities, choosing an independent R&D path has a more significant effect on enhancing green technology.

H_{4b}: For enterprises with moderate levels of dynamic capabilities, choosing a cooperative R&D path has a more significant effect on enhancing green technology.

H_{4c}: For enterprises with lower levels of dynamic capabilities, choosing a technology transaction path has a more significant effect on enhancing green technology.

In summary, the path of corporate green technological innovation is moderated by environmental turbulence, with dynamic capabilities and R&D models playing a crucial role in this process. Therefore, under different environmental and capability conditions, the effects of different R&D models on enhancing the level of green technological innovation for companies with different dynamic capabilities vary, and the overall mechanism of action is as follows:

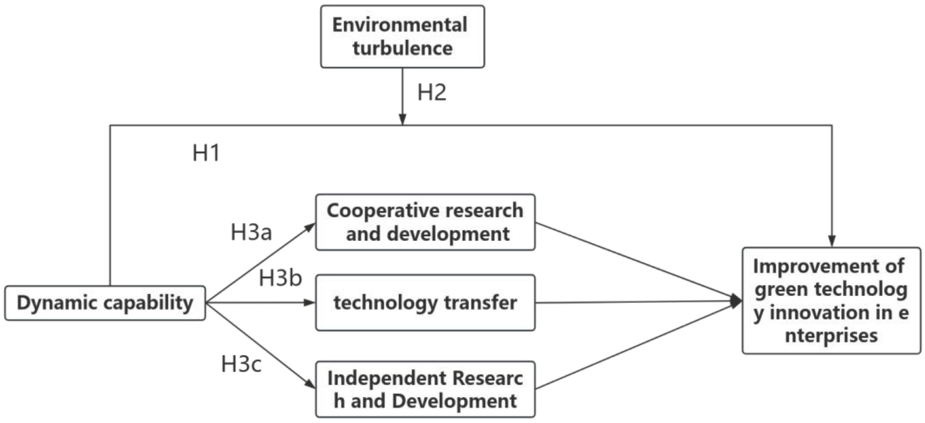

Figure 1. The triple path of corporate green technological innovation from the perspective of dynamic capabilities.

3. Research Design

3.1. Data source and sample selection

To ensure the comprehensiveness, representativeness, and comparability of the data, this study selected companies listed on China's A-share market from 2012 to 2022 as the initial research sample, utilizing data obtained from the CSMAR database to analyze the impact of dynamic capabilities on green technological innovation and its specific mechanisms. To enhance the accuracy and consistency of data analysis, the sample data underwent the following processing steps: first, companies flagged as ST, *ST, PT, newly listed, or exhibiting abnormal financial data during the study period were excluded to reduce bias arising from unstable corporate status[57]; second, firms with significant missing data in key variables were removed to improve data completeness and the reliability of the analysis[58]; third, financial institutions, banks, and insurance companies—which rarely engage in technological innovation and have unique financial reporting structures—were excluded to avoid the interference of industry heterogeneity on the results[59]. Additionally, to control for the impact of extreme values on the results, a 1% and 99% winsorization was applied to the relevant variables. This process yielded 14,751 valid sample data points, ensuring the robustness and credibility of the study's conclusions[60].

3.2. Variable Selection

3.2.1 Dependent variable

In examining corporate green technological innovation, this study adopts the "IPC Green Inventory" classification system released by the World Intellectual Property Organization (WIPO), categorizing green technology innovation into seven fields, including transportation, nuclear power, energy conservation, alternative energy, among others. This classification method effectively delineates the scope of green technological innovation, ensuring systematic and comprehensive analysis[61]. Based on this classification standard, data on green patent applications in these fields were collected for each listed company from the State Intellectual Property Office (SIPO) patent search database, quantifying corporate investment and output in green technological innovation through specific patent data[62].

Furthermore, to ensure accuracy and representativeness, this study follows the methodological approach of Ren et al[63],selecting the total number of authorized green invention patents and green utility model patents to represent both the intensity and breadth of green technological innovation. This choice of patent data not only reflects firms' accumulation of technology in green innovation but also reveals their contributions to environmental sustainability. To avoid heteroscedasticity arising from differences in patent counts, a natural logarithmic transformation was applied to all patent data after adding one, a widely adopted approach in existing research that enhances data normalization and improves the robustness and interpretability of results[64,65].This multi-tiered data processing approach, integrating authoritative classification standards with appropriate patent data indicators, provides a precise and representative foundation for measuring green technological innovation. It strengthens empirical support for analyzing the relationship between corporate dynamic capabilities and green innovation[66].

3.2.2. Explanatory variables

Existing literature often employs surveys to measure corporate dynamic capabilities, but this approach, relying on cross-sectional data, struggles to capture the evolution of these capabilities over time. It is particularly limited in reflecting how firms accumulate and adjust capabilities to innovate within continuously changing environments[67]. To overcome this limitation, this study adopts a more dynamic measurement approach based on panel data to comprehensively illustrate the temporal changes and development trajectory of corporate dynamic capabilities. Drawing on the frameworks of Zhao Feng (2016)[68], Yang Lin (2020)[69], and Li Jun (2022)[70], this study divides dynamic capabilities into five core dimensions: knowledge acquisition, environmental adaptability, technological innovation, knowledge integration, and resource reconfiguration. These dimensions effectively capture the diverse capability expressions and innovation potential firms exhibit when responding to external changes.

To quantify each dimension specifically, this study follows the measurement strategy developed by Song Zhe and Sheng Yuhua (2016)[71],selecting five key indicators. First, mainstream opinion counts and positive feedback frequency are extracted via text analysis to assess knowledge acquisition and environmental adaptability, capturing firms' sensitivity to market and environmental changes and their learning capacity[72]. Second, R&D investment, widely used in the literature to gauge innovation input, serves as the indicator for technological innovation capabilities[73]. Third, patent counts represent knowledge integration, reflecting the firm's capacity to assimilate and leverage knowledge through patent accumulation[74]. Lastly, leverage ratio in capital structure is used to measure resource reconfiguration, indicating flexibility in resource allocation and financial management[75].

To ensure measurement accuracy and reliability, this study applies factor analysis and dimensionality reduction on these indicators using SPSS 26, extracting representative factors to minimize redundancy and measurement error. This multidimensional quantification strategy not only captures the full scope of corporate dynamic capabilities but also reveals the mechanisms through which these capabilities impact green technological innovation, providing a solid empirical foundation for this study. The details are shown in the table below:

Table 1. Dynamic capability coefficient table.

Primary Indicator	Secondary Indicator	Weight
Dynamic Capabilities	Knowledge Learning Ability (Mainstream View in Text)	24.15%
	Environmental Adaptation Ability (Positive Feedback in Text)	24.70%
	Innovative Technological Ability (R&D Investment)	0.99%
	Knowledge Integration Ability (Number of Individual Patents)	26.13%
	Resource Reconfiguration Ability (Capital Structure)	24.03%

3.2.3. Moderating variables

The concept of environmental turbulence and its dimensional division have been explored and researched maturely. The standard error of regression coefficients under the time window[76-78] is specifically calculated according to the studies by Tan et al (1994): using the sales volume at the industry level (total sales of all companies in the industry) and technical information (total patents obtained by all companies in the industry to measure the fluctuation degree of product and technology markets. This method yields standardized indicators and, due to the use of publicly standardized data, has strong reproducibility and a wider application field than other questionnaire and interview methods, making it more suitable for the issues concerned in this study (Tan et al,1994). The technological environmental dynamism of enterprises is also measured in the same way. This calculation method is based on industry-level data, which means it reflects the common environmental characteristics faced by participants in the industry.

3.2.4. Mediating variable

Independent innovation generally refers to research and development activities carried out by enterprises independently. Its measurement standard is the number of patents, particularly the number of invention patents, which reflects the actual technological output of the enterprise in terms of independent R&D. Collaborative R&D emphasizes innovation activities conducted jointly by enterprises and external organizations. Its measurement standard includes the number of patents jointly applied for with other enterprises or research institutions. The measurement standard for technology transactions includes the number of times technology is transferred to external parties or the number of contracts signed.

3.2.5. Control variables

To ensure the reliability and accuracy of this study's conclusions, key variables influencing corporate green technological innovation were rigorously controlled. Drawing from existing literature, this study includes firm size (Size), firm age (Age), firm growth (Growth), R&D investment (R&D), asset-liability ratio (Asset), and ownership concentration (Concen) as control variables to mitigate the risk of bias due to omitted variables[79]. The data for this analysis is sourced from the CSMAR (China Stock Market & Accounting Research) database. Specifically, firm size (Size) is represented by the natural logarithm of year-end total assets, reflecting the potential influence of firm resources and scale on green innovation. Firm age (Age) is measured by the number of years since the company's registration, indicating the potential impact of firm maturity and experience on innovation pathways. Firm growth (Growth) is calculated as the ratio of annual total asset growth to the total assets at the beginning of the year, reflecting the potential divergent impacts of expansion or contraction on innovation decisions[80]. Additionally, R&D investment (R&D) is measured as the ratio of R&D expenditure to operating income, capturing the level of commitment to technological and research innovation[81]. To assess financial stability, the asset-liability ratio (Asset) is represented by the year-end debt-to-total assets ratio, highlighting the role of financial structure in supporting corporate green innovation, while ownership concentration (Concen) is gauged by the shareholding percentage of the largest shareholder, analyzing the influence of equity structure and corporate governance on innovation decisions[82]. These control variables were selected based on empirical research and aligned with the specific data characteristics of this study to ensure comprehensive measurement and robust results.

Table 2. Variable definition table.

Variable Type	Variable Name	Variable Symbol
Dependent Variable	Corporate Green Technological Innovation	*DGTI*
Independent Variable	Dynamic Capabilities	*DC*
	Independent Innovation	*IDA*
Mediating Variable	Cooperative R&D	*IDT*
	Technology Transaction	*CRDP*
Moderating Variable	Environmental Turbulence	*EU*
Control Variable	Company Size	*Size*
	Company Age	*Age*
	Company Growth	*Growth*
	R&D Investment	*R&D*
	Debt-to-Asset Ratio	*Asset*
	Equity Concentration	*Concen*

3.3. Model construction

To explore the impact of corporate dynamic capabilities on green technological innovation, referring to the study by Wu Yongxia and Wang Hongyu (2023)[83], the following model is constructed:

$$DGTI_{i,t} = \beta_0 + \beta_1 DC_{i,t} + \sum \beta_k Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t}$$

In the above equation: DGTIi,t represents the level of green technological innovation of company i in period t; DCi,t represents the dynamic capabilities of company i in period t; Controlsi,t is the set of control variables; i represents the sample companies, t represents the year; Year, Industry respectively represent the fixed effects of the year and individual fixed effects; εi,t is the random disturbance term.

4. Empirical Results Analysis

4.1. Descriptive statistics

The descriptive statistics in **Table 3** provide a comprehensive quantitative overview of corporate green technological innovation and related variables. This table involves multiple variables including corporate green technological innovation, dynamic capabilities, independent innovation, cooperative R&D, technology transactions, environmental turbulence, company size, company age, company growth, R&D investment, capital debt ratio, and equity concentration.

Table 3. Descriptive statistics of variables.

Name	Sample Size	Minimum Value	Maximum Value	Average Value	Standard Deviation	Median	VIF
DGTI	14257	0.000	6.848	0.568	0.975	0.000	
DC	12398	-0.469	0.818	0.202	0.210	0.218	1.191
IDA	14471	0.000	135.000	0.929	6.943	0.000	1.315
IDT	13986	0.000	3083.000	9.103	72.644	1.000	1.052
CRDP	13986	0.000	3365.000	4.711	68.640	0.000	1.323
EU	14014	0.013	15.569	1.179	0.984	0.950	1.233
Size	14106	16.704	31.191	22.306	1.460	22.053	1.135
Age	14471	0.000	61.000	15.357	5.779	15.000	1.394
Growth	14102	-0.992	13.958	0.174	0.412	0.124	1.202
R&D	14469	0.000	909.301	0.106	7.559	0.035	1.196
Asset	14105	-1.000	288.000	0.109	2.455	0.000	1.028
Concen	14282	0.000	1.000	0.759	0.428	1.000	1.191

Table 3 presents the descriptive statistics for the variables, offering insights into their distribution within the sample. Each variable includes information on sample size, minimum and maximum values, mean, standard deviation, median, and variance inflation factor (VIF).

The variable "DGTI" has a sample size of 14,257, with an average of 0.568 and a wide range from 0.000 to 6.848, indicating notable variability. "Dynamic Capabilities" (DC) has a sample size of 12,398, a mean of 0.202, and a standard deviation of 0.210, with a median of 0.218, reflecting a relatively concentrated distribution around the mean. The VIF for DC is 1.191, indicating minimal multicollinearity.The variables "IDA" (independent development activities) and "IDT" (independent technological investments) exhibit broad ranges, particularly "IDT," which spans from 0 to 3,083, accompanied by a high standard deviation of 72.644, indicating significant variation. Both have low median values, suggesting that many firms report lower levels of investment. Their VIFs, 1.315 and 1.052, suggest low multicollinearity."CRDP" (corporate research and development performance) also shows high variability, with a standard deviation of 68.640 and a median of 0.000, indicating that many firms have low performance, despite a few outliers. The VIF for "CRDP" is 1.323, confirming no multicollinearity concerns.

The variables "EU" (environmental uncertainty), "Size," and "Age" have average values of 1.179, 22.306, and 15.357, respectively. "Size" exhibits a consistent distribution across firms, while "Age" ranges up to 61 years, reflecting a mix of younger and more mature firms. Their VIFs are all below 1.4, confirming low multicollinearity."Growth" has a mean of 0.174 and a median of 0.124, with a wide range (-0.992 to 13.958), indicating that while some firms are expanding rapidly, others are contracting. "R&D" shows an average of 0.106 and a high standard deviation of 7.559, suggesting most firms invest minimally in R&D, though some invest significantly more. "Asset" and "Concentration" (Concen) also exhibit variability, with "Concen" having a median of 1.000 and a VIF of 1.191, indicating no significant multicollinearity.Overall, the variables display considerable diversity in their distributions, reflecting the heterogeneity of firms in the sample, with VIF values indicating that multicollinearity is not an issue in this dataset.

4.2. Baseline regression

The baseline regression results in **Table 4** aim to explore the impact of dynamic capabilities, company size, equity concentration, company growth, debt-to-asset ratio, and company age on corporate green technological innovation. This analytical method follows the approach of Wang Xu et al. (2022) to test the effect of each variable on corporate green technological innovation[84].

Table 4. Baseline regression.

	(1)	(2)	(3)	(4)	(5)
DC	0.453** (10.714)	0.562** (13.989)	0.564** (14.006)	0.619** (15.057)	0.619** (15.057)
Size		0.249** (38.039)	0.249** (38.024)	0.257** (38.629)	0.257** (38.629)
Age		0.058** (2.969)	0.058** (2.932)	0.042* (2.128)	-0.010** (-6.489)
Growth			0.021 (0.930)	0.021 (0.950)	0.021 (0.950)
R&D			-0.007 (-0.312)	-0.019 (-0.819)	-0.001 (-0.523)
Asset				-0.010** (-6.489)	-0.019 (-0.819)
Concen				-0.001 (-0.523)	0.042* (2.128)
Constant	0.504** (40.790)	-5.106** (-34.508)	-5.108** (-34.505)	-5.116** (-34.619)	-5.116** (-34.619)
Year	NO	NO	NO	NO	YES
Industry	NO	NO	NO	NO	YES
Sample Size	12109	12109	12109	12109	12109
R 2	0.009	0.115	0.115	0.119	0.119
△R 2	0.009	0.115	0.115	0.118	0.023

Dependent Variable: Corporate Green Technological Innovation

** p<0.05 ** p<0.01 (t values in parentheses)*

The effect of enterprise age (Age) is more complex. In the early models (2) and (3), it shows a significant positive impact, indicating that a longer enterprise history may contribute to the accumulation of innovation and resource integration. However, as more variables are introduced, particularly in models (4) and (5), the effect of enterprise age turns negative and significant, implying that older enterprises may face challenges in adapting to new technologies and achieving green innovation. Growth rate (Growth) does not show a significant effect in any of the models, suggesting that the speed of a company's growth has limited direct influence on green technological innovation. Similarly, R&D expenditure (R&D) does not exhibit significant effects across the models, indicating that R&D spending may not have a direct impact on green technological innovation and might require other mediating variables to be effective.

Asset (Asset) shows a significant negative impact in model (4), implying that asset liabilities might hinder corporate green technological innovation. Market concentration (Concentration) in model (5) displays a significant positive effect, suggesting that in industries with higher market concentration, companies may be more motivated or capable of promoting green technological innovation.

The explanatory power of the regression models increases gradually, with R^2 rising from 0.009 in model (1) to 0.119 in model (5), indicating that the introduction of additional control variables improves the model's explanatory ability. The significant increase in incremental explanatory power after including year and industry control variables demonstrates the importance of industry and temporal factors in corporate green technological innovation.Dynamic capabilities facilitate corporate green technological innovation. In all regression models, dynamic capabilities consistently show a significant positive effect on green technological innovation, with the coefficient increasing as more control variables are introduced, further supporting the hypothesis.The results verify H_1.

4.3. The mediating effect of R&D models on dynamic capabilities and corporate green technological innovation

This study employed hierarchical regression within a stepwise regression framework to examine the mediating effect. Specifically, by gradually introducing the mediating variables (namely, collaborative R&D, technology transactions, and independent R&D) into the regression model and observing changes in the coefficient of the main independent variable, dynamic capabilities, the presence of a mediating effect can be determined. This approach allows for a clear assessment of the mediating variables' roles in the relationship between the main independent and dependent variables, facilitating an understanding of how dynamic capabilities influence green technological innovation through specific R&D modes (such as collaborative R&D, technology transactions, and independent R&D). Stepwise control of these variables also reduces interference from other factors, thereby enhancing the clarity and reliability of the results.

Table 5 constructs a regression model that includes control variables such as company size, company age, company growth, R&D investment, capital debt ratio, and equity concentration, with corporate green technological innovation as the dependent variable and dynamic capabilities as the main explanatory variable, while considering R&D models as mediating variables.

Table 5 Mediating effect regression of different R&D models on dynamic capabilities and corporate green technological innovation.

	DGTI	*IDA*	*DGTI*	*DGTI*	*IDT*	*DGTI*	*DGTI*	*CRDP*	*DGTI*
DC	0.619** (15.057)	0.778** (-3.222)	0.635** (15.559)	0.618** (1.893)	0.619** (1.943)	0.620* (2.085)	-0.365* (-2.101)	0.316** (1.703)	0.376* (2.042)
IDA			0.021** (13.514)						
IDT						0.045** (11.273)			
CRDP									0.052** (15.621)
Size	0.257** (38.629)	1.178** (30.163)	0.232** (33.959)	0.095 (1.136)	0.091 (1.065)	0.032 (0.379)	-0.327 (-1.393)	-0.318 (-1.346)	-0.397 (-1.667)
Age	-0.010** (-6.489)	-0.058** (-6.157)	-0.009** (-5.772)	-0.115 (-1.222)	-0.121 (-1.284)	-0.104 (-1.112)	0.834** (4.579)	0.804** (4.316)	1.011** (5.370)
Growth	0.021 (0.950)	-0.284* (-2.140)	0.027 (1.220)	-0.597** (-8.356)	-0.601** (-8.321)	0.024 (-7.810)	-0.958** (-4.597)	-0.916** (-4.271)	-0.869** (-4.064)
R&D	-0.001 (-0.523)	0.001 (0.166)	-0.001 (-0.547)	0.263** (2.842)	0.267** (2.856)	0.311** (3.335)	0.110 (0.893)	0.111 (0.890)	0.198 (1.588)
Asset	-0.019 (-0.819)	-0.086 (-0.617)	-0.018 (-0.749)	0.523** (3.843)	0.513** (3.745)	0.482** (3.552)	-0.106 (-0.742)	-0.094 (-0.647)	-0.106 (-0.740)
Concen	0.042* (2.128)	0.438** (3.756)	0.033 (1.681)	0.094* (2.147)	0.091* (2.060)	0.078 (1.792)	-0.119 (-0.857)	-0.101 (-0.728)	-0.183 (-1.315)
Year	-5.116** (-34.619)	-24.688** (-28.401)	-4.605** (-30.392)	2.361** (3.342)	2.521** (3.447)	1.526* (2.034)	0.355 (1.902)	0.376* (1.999)	0.232 (1.237)
Industry	12109	12109	12109	12109	12109	12109	12109	12109	12109
Adjusted R^2	0.152	0.085	0.196	0.152	0.038	0.175	0.196	0.072	0.057

* $p<0.05$ ** $p<0.01$ (t values in parentheses)

Based on the data provided in **Table 5**, this study analyzes the mediating roles played by collaborative R&D, technology transactions, and independent R&D between dynamic capabilities and corporate green technological innovation. Specifically, this study verifies three hypotheses: H3a on the mediating role of collaborative R&D, H3b on the mediating role of technology transactions, and H3c on the mediating role of independent R&D.

The analysis results show that the coefficient of cooperative R&D (IDT) is significantly positive (0.045, $p<0.01$), indicating that cooperative R&D has a significant positive impact on corporate green technological innovation. Moreover, when considering cooperative R&D, the positive impact of dynamic capabilities (DC) on corporate green technological innovation is maintained (coefficient range from 0.618 to 0.619, $p<0.05$), thus validating the H3a hypothesis. Regarding the H3b hypothesis, the coefficient of technology trading (CRDP) is also significantly positive (0.052, $p<0.01$), indicating that technology trading plays a key role in promoting corporate green technological innovation. Although the impact of dynamic capabilities in the model considering technology trading shows some inconsistency, the mediating role of technology trading is still partially supported. Finally, the coefficient of independent R&D (IDA) is 0.021 ($p<0.01$), emphasizing the importance of independent R&D in enhancing the capability of corporate green technological innovation. At the same time, dynamic capabilities have a significant positive impact on corporate green technological innovation in the regression model including the independent R&D variable (coefficient is 0.635, $p<0.01$), confirming the H3c hypothesis.

The results of this study fully support the hypothesis that cooperative R&D, technology transactions, and independent R&D play a key role as mediating variables between dynamic capabilities and corporate green technological innovation. These findings emphasize the importance of fully utilizing and strengthening these R&D models in the pursuit of green technological innovation.

4.4. The moderating role of environmental turbulence

Table 6 presents the analysis of the moderating effects of dynamic capabilities and environmental turbulence on corporate green technological innovation. Model (3) includes an interaction term (dynamic capabilities*environmental turbulence) to test whether environmental turbulence as a moderating variable changes the relationship between dynamic capabilities and corporate green technological innovation. These three models include conventional control variables such as company size, company age, company growth, R&D investment, debt-to-equity ratio, and equity concentration, as well as the main explanatory variable of dynamic capabilities.

Table 6. The moderating effect of environmental turbulence.

	Model (1)	Model (2)	Model (3)
Size	0.272**	0.272**	0.272**
	(40.361)	(40.258)	(40.270)
Age	-0.008**	-0.008**	-0.009**
	(-5.241)	(-5.244)	(-5.334)
Growth	-0.011	-0.004	-0.016
	(-0.474)	(-0.181)	(-0.641)
R&D	2.040**	2.044**	2.045**
	(12.134)	(12.150)	(12.154)
Asset	-0.027	-0.025	-0.023
	(-1.047)	(-0.971)	(-0.900)
Concen	0.054**	0.054**	0.054**
	(2.730)	(2.721)	(2.756)
DC	0.470**	0.469**	0.468**
	(10.979)	(10.936)	(10.923)

	Model (1)	Model (2)	Model (3)
EU		-0.007 (-0.694)	-0.009 (-0.898)
*DC*EU*			-0.088* (-2.096)
Constant	-5.467** (-36.076)	-5.462** (-36.010)	-5.460** (-36.003)
Sample Size	12064	12064	12064
R 2	0.129	0.129	0.129
F Value	*F (7,12056)=255.163,p=0.000*	*F (8,12055)=223.318,p=0.000*	*F (9,12054)=199.050,p=0.000*
△R 2	0.129	0.000	0.000

Dependent Variable: Corporate Green Technological Innovation

** p<0.05 ** p<0.01 (t values in parentheses)*

Table 6. (*Continued*).

Table 6 shows the analysis of the moderating effects of dynamic capabilities and environmental turbulence on corporate green technological innovation. Through the interaction term (Dynamic Capabilities*Environmental Turbulence), it tests whether environmental turbulence, as a moderating variable, changes the relationship between dynamic capabilities and corporate green technological innovation. These three models include conventional control variables such as company size, company age, company growth, R&D investment, debt-to-equity ratio, and equity concentration, as well as the main explanatory variable, dynamic capabilities.

From the comparison between model (1) and model (2), it can be observed that after introducing environmental turbulence as a separate variable, the coefficients and significance levels of the model remain essentially unchanged, indicating that environmental turbulence itself does not significantly alter the overall results of the model. However, when considering the interaction term in model (3), that is, the interaction between dynamic capability and environmental turbulence, it is found that the coefficient of the interaction term is -0.088, and it is significant at the 5% level, indicating that environmental turbulence indeed moderates the impact of dynamic capability A on corporate green technological innovation. Specifically, this negative coefficient suggests that under higher conditions of environmental turbulence, the positive impact of dynamic capability A on corporate green technological innovation may be inhibited.

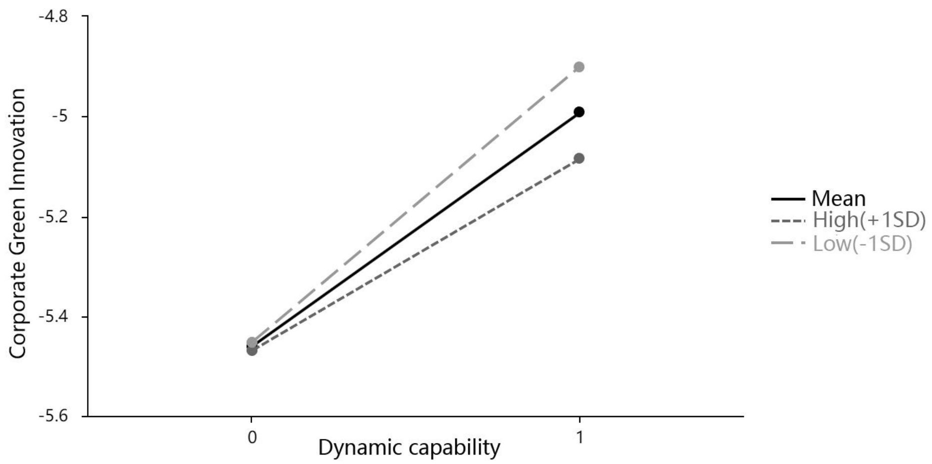

Figure 2. Schematic diagram of the moderating effect of environmental turbulence at different levels.

Figure 2 demonstrates that environmental turbulence exerts a negative moderating effect on the impact of dynamic capabilities on corporate green technological innovation. Specifically, in more turbulent environments, the ability of dynamic capabilities to foster green innovation may be reduced. Additionally, the overall model structure exhibits strong stability and significance, providing robust evidence for understanding how dynamic capabilities influence green innovation under varying levels of environmental turbulence, thereby also validating Hypothesis H_2.

4.5. Robustness test

To avoid differences in results due to different regression model estimation methods, this section conducts a robustness test by changing the econometric regression approach. Referencing[85] which utilizes the CEO's background situation (CB) and its alternative indicator dynamic capability A to analyze the impact on corporate green technological innovation. By using different measurement indicators (such as dynamic capabilities) to verify this finding, the robustness of the research results is enhanced. After changing the explanatory variables, the regression coefficient value of dynamic capabilities remains positive and passes the 1% significance test, meaning that dynamic capabilities still positively affect corporate green technological innovation, further indicating the robustness of this study.

Table 7. Robustness test

Item	POOL Model	RE Model	POOL Model	RE Model
Intercept	-4.526** (-37.446)	-3.816** (-20.787)	-5.116** (-34.619)	-3.889** (-18.081)
CB	1.608** (10.459)	0.922** (6.298)		
DC			0.619** (15.057)	0.338** (9.593)
Size	0.225** (40.572)	0.184** (21.042)	0.257** (38.629)	0.197** (19.351)
Age	-0.005** (-3.621)	0.008** (4.297)	-0.010** (-6.489)	-0.003 (-1.406)
Growth	-0.012 (-0.612)	-0.027 (-1.826)	0.021 (0.950)	0.004 (0.251)
R&D	-0.001 (-0.541)	-0.000 (-0.438)	-0.001 (-0.523)	-0.000 (-0.488)
Asset	-0.011 (-0.492)	-0.037* (-2.433)	-0.019 (-0.819)	-0.045** (-2.842)
Concen	0.021 (1.133)	0.028 (1.555)	0.042* (2.128)	0.050** (2.617)
R^2	0.130	0.118	0.119	0.107
Year	YES	YES	YES	YES
Industry	YES	YES	YES	YES
Sample Size	14026	14026	12109	12109

Dependent Variable: Corporate Green Technological Innovation

** p<0.05 ** p<0.01 (t values in parentheses)*

Following the robustness analysis, **Figure 3** presents the final model of this study, clarifying the relational pathways among dynamic capabilities, R&D modes, and corporate green technological innovation.

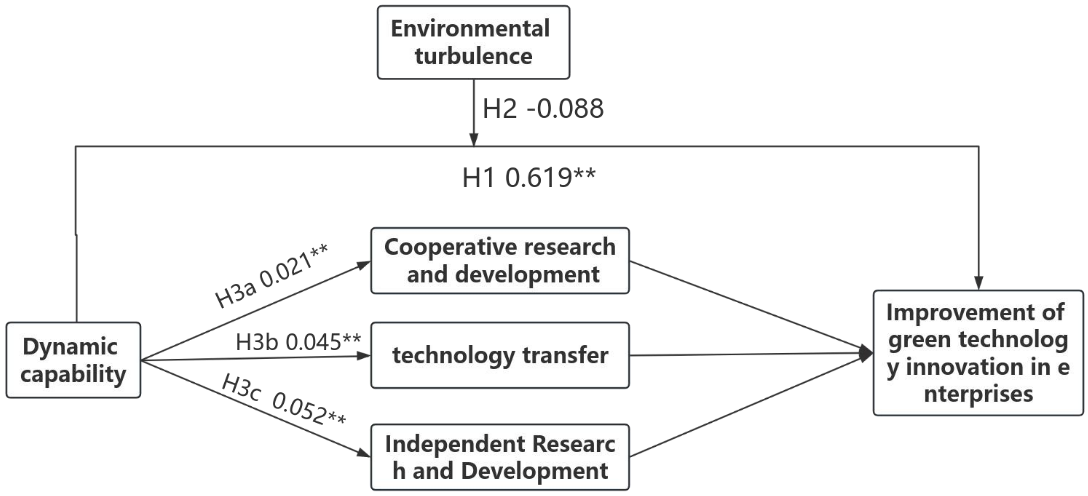

Figure 3. Relationship diagram of dynamic capabilities, R&D models, and corporate green technological innovation.

4.6. Further test

By analyzing groups of companies with different levels of dynamic capabilities (high, medium, low), **Table 8** provides an in-depth analysis of the support for the three hypotheses (H3a, H3b, H3c).

Table 8. Heterogeneity analysis

Item	High Dynamic Capability Sample			Medium Dynamic Capability Sample			Low Dynamic Capability Sample		
Intercept	-2.810** (-13.683)	-4.522** (-21.531)	-0.564** (-7.789)	-2.513** (-11.015)	-5.037** (-19.927)	1.011** (5.370)	-3.559** (-20.193)	-4.180** (-22.680)	0.594** (2.808)
IDA	0.011** (27.917)		0.314** (3.368)	0.003** (37.875)			0.009** (22.426)		
IDT		0.005 (6.778)			0.010** (3.332)			0.006** (4.446)	
CRDP			0.007* (1.777)			0.006* (0.740)			0.034** (4.579)
Size	0.155** (16.839)	0.236** (25.068)	0.019* (2.027)	0.132** (13.133)	0.250** (22.461)	-0.183 (-1.315)	0.180** (22.142)	0.207** (24.335)	-0.958** (-4.597)
Age	-0.006* (-2.482)	-0.007** (-2.846)	0.159 (1.028)	-0.004 (-1.931)	-0.004 (-1.475)	-0.376* (-2.042)	-0.005** (-2.632)	-0.004 (-1.650)	0.110 (0.893)
Growth	-0.006 (-0.156)	-0.025 (-0.619)	0.631** (2.899)	-0.018 (-0.629)	-0.015 (-0.461)	0.048 (0.283)	-0.050 (-1.649)	-0.045 (-1.409)	-0.106 (-0.742)
R&D	-0.000 (-0.446)	-0.000 (-0.351)	0.224 (1.181)	1.266** (6.024)	2.047** (8.594)	-0.100 (-0.668)	2.696** (9.287)	3.125** (10.259)	-0.119 (-0.857)
Asset	0.044 (0.914)	0.043 (0.831)	-0.441 (-1.818)	-0.043 (-1.468)	-0.063 (-1.912)	-0.241 (-1.872)	0.008 (0.261)	0.017 (0.538)	-0.365* (-2.101)
Concen	0.030 (0.918)	0.029 (0.836)	1.022** (5.418)	0.048 (1.728)	0.023 (0.723)	1.099** (4.850)	-0.039 (-0.570)	-0.016 (-0.225)	0.233 (1.432)
Year	YES	YES	YES	YES	YES	YES	YES	YES	YES
Industry	YES	YES	YES	YES	YES	YES	YES	YES	YES
R 2	0.244	0.135	0.135	0.312	0.110	0.158	0.220	0.138	0.452
Sample Size	5057	5057	5057	4834	4834	4834	4537	4537	4537

** p<0.05 ** p<0.01 (t values in parentheses)*

Through an in-depth analysis of groups of companies with different levels of dynamic capabilities (high, medium, low), this study provides evidence in Table 10's heterogeneity analysis on the support for hypotheses H4a, H4b, H4c. These hypotheses explore the differences in the impact of dynamic capability levels on companies' choices of different R&D paths (independent R&D, cooperative R&D, technology trading) to enhance green technological innovation capabilities. In the high dynamic capability sample, the coefficient for independent R&D (IDA) is significantly positive (0.011, $p<0.01$), indicating that companies with high dynamic capabilities significantly enhance their green technological innovation through independent R&D, validating the H4a hypothesis. This emphasizes that companies with high dynamic capabilities promote green technological innovation more effectively by utilizing internal resources and capabilities for independent R&D. For the medium dynamic capability sample, the positive coefficient for cooperative R&D (IDT) (0.010, $p<0.01$) indicates that these companies significantly enhance their green technological innovation through the cooperative R&D path, thereby supporting the H4b hypothesis. This result highlights the effectiveness of the strategy for companies with medium dynamic capabilities to enhance their green technological innovation through resource and knowledge sharing with partners.

In the sample of firms with low dynamic capabilities, the coefficient for technology transactions (CRDP) is significantly positive (0.034, $p<0.01$), indicating that these firms significantly enhanced their green technological innovation capabilities through technology transactions, thereby validating the H4c hypothesis. This finding suggests that firms with lower dynamic capabilities tend to promote their green technological innovation by introducing external mature technologies to compensate for the lack of internal R&D capabilities. Integrating these analytical results, it can be concluded that firms with different levels of dynamic capabilities choose the most appropriate R&D pathway for enhancing green technological innovation according to their capability levels. Firms with different dynamic capabilities choosing different R&D models have varying effects on enhancing green technological innovation, with firms having high dynamic capabilities preferring independent R&D, those with medium dynamic capabilities opting for cooperative R&D, and those with low dynamic capabilities choosing technology transactions. This discovery provides important insights into how firms can formulate green technological innovation strategies based on their level of dynamic capabilities.

5. Research conclusions and policy recommendations

5.1. Research conclusions

This study focuses on the key drivers and mechanisms of green technological innovation among Chinese publicly listed companies, examining in-depth the core role of dynamic capabilities. Findings demonstrate a significant positive effect of dynamic capabilities on corporate green innovation. Through constructing and testing various models, we validated the robustness of this relationship, highlighting the unique value of dynamic capabilities in fostering green innovation. Specifically, companies with strong dynamic capabilities are more agile in responding to external changes, effectively integrating internal resources and reallocating external resources to secure a competitive advantage in green technology innovation. Further analysis reveals the heterogeneous impact of dynamic capabilities, as varying levels directly influence strategic choices and implementation modes within green innovation pathways.

The study also reveals that companies with high dynamic capabilities favor independent innovation paths, leveraging their strengths in resource integration and technological reconfiguration to achieve breakthroughs in green technology. In contrast, companies with moderate to low dynamic capabilities rely on collaborative R&D or technology transactions to enhance their innovation capacity. This finding underscores the multi-layered effects of dynamic capabilities and uncovers mechanisms through which companies pursue differentiated innovation pathways under varying dynamic capabilities. Such empirical evidence provides valuable insights into the heterogeneity of green technological innovation. The study thus offers guidance for companies to select appropriate green innovation pathways according to their dynamic capability levels, laying a theoretical foundation for developing adaptive, environmentally resilient green innovation strategies. Results confirm that dynamic capabilities exert a substantial positive influence on green innovation. This implies that companies with strong dynamic capabilities can more effectively integrate and reconfigure resources, respond to rapidly changing external conditions, and thereby facilitate green technology innovation and application. The analysis also reveals that different R&D models serve as mediators in the relationship between dynamic capabilities and green technological innovation.

Overall, the findings contribute a fresh perspective on the drivers of green technology innovation and provide empirical evidence for companies to develop suitable green innovation strategies under varying environmental conditions. By applying empirical analysis, the study reveals the multi-level impact mechanism of dynamic capabilities in green innovation, particularly how different levels of dynamic capabilities shape corporate choices of innovation pathways in response to environmental change. This research not only reinforces the positive impact of dynamic capabilities on green innovation but also highlights the differentiated effects that dynamic capabilities exert under environmental turbulence, providing scientific support for companies aiming to enhance innovation efficiency in the face of external changes. Additionally, this study fills a research gap in green technology innovation strategy for firms with moderate or low dynamic capabilities. Whereas existing studies predominantly focus on companies with high dynamic capabilities that leverage resource integration and reconfiguration to promote innovation, this study identifies that firms with lower dynamic capabilities can also achieve green innovation through collaborative R&D and technology transactions.

Future research may further explore innovation pathway choices for these companies, analyzing how moderate to low dynamic capabilities advance green innovation through diverse collaborative and resource acquisition mechanisms. This approach not only contributes to a comprehensive theoretical framework for green technology innovation but also offers more universally applicable guidance for government and corporate policy-making. Particularly, in the pursuit of sustainable development goals, providing tailored innovation pathway recommendations for companies across different industries, resource capacities, and environmental pressures will further enhance the practical guidance for green innovation, advancing sustainable development objectives in a volatile market and policy landscape.

5.2. Policy recommendations

In the context of economic globalization, companies must not only face competition and changes in the domestic market but also pay attention to international market dynamics. Therefore, companies should enhance their insight into global market trends, seize opportunities for international cooperation, especially in the field of green technology, and actively participate in international R&D cooperation projects to attract foreign investment and technology introduction. With the Chinese government's increasing emphasis on the construction of ecological civilization and green development, companies should actively respond to national policy directions and increase their investment in green technological innovation. Meanwhile, they should utilize various supports provided by the government, such as financial subsidies, tax reductions, etc., to accelerate the R&D and application of green technology. Therefore, the following policy recommendations for Chinese listed companies in the field of green technological innovation are offered for reference:

Strengthening the Cultivation of Dynamic Capabilities: Given the significant positive impact of dynamic capabilities on corporate green technological innovation, companies should value and enhance the cultivation of internal dynamic capabilities. Specifically, companies should increase investment in employee skill training and knowledge updating, encourage cross-departmental collaboration, promote information sharing, and optimize decision-making processes to quickly respond to market changes.

Promoting the Coordinated Development of Independent R&D and R&D Models: For companies with high levels of dynamic capabilities, they should continue to strengthen their independent R&D capabilities, focusing on the development and innovation of original technologies. For companies with moderate dynamic capabilities, they should focus on developing R&D model mechanisms, through cooperation with other companies, universities, or research institutions, sharing resources and knowledge to enhance green technological innovation capabilities.

Pay attention to the impact of environmental turbulence on innovation strategies: Enterprises should closely monitor changes in the external environment, especially in turbulent conditions, and should adjust their innovation strategies flexibly. For example, in times of high market volatility, companies may need to rely more on rapid market response and flexible strategy adjustments to reduce innovation risks.

Enhance the efficiency of technology transactions and applications: For companies with lower dynamic capabilities, it is crucial to actively explore ways to enhance green technology through technology transactions. This includes collaborating with universities and research institutions, introducing advanced technologies from home and abroad, and simultaneously strengthening the capabilities to digest, absorb, and re-innovate transferred technologies.

Government Policy Support and Market Guidance: Governments should encourage corporate green technological innovation through policies such as tax incentives, financial support, and intellectual property protection. At the same time, market mechanisms should guide companies to focus on and invest in green technology, such as establishing green technology markets and promoting market acceptance of green products.

Establishing an Adaptive Organizational Structure: Companies should build flexible and adaptive organizational structures to cope with rapidly changing external environments. This includes promoting flat management, reducing management levels, accelerating information flow, and improving decision-making efficiency.

Conflict of interest

The authors declare no conflict of interest.

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