

Article

The Impact of Digital and Real Technological Integration on Corporate Green Collaborative Innovation

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Highlights

What are the main findings?

- We enrich the literature on the economic consequences of digital and real technological integration, further extending the perspective on the innovative effects of such integration.
- From the perspective of technological integration, we complement existing research on the antecedents of corporate green collaborative innovation.

What are the implications of the main findings?

- We reveal the underlying mechanisms and boundary conditions through which digital and real technological integration influences corporate green collaborative innovation.
- We provide theoretical basis and empirical evidence to help enterprises and policy-makers further advance green collaborative innovation through the empowerment of technological integration.

Abstract

Accelerating green collaborative innovation is crucial to achieving environmental sustainability. Using panel data from Chinese A-share listed firms, this study theoretically and empirically investigates the causal association between digital and real technological integration and corporate green collaborative innovation. We reveal that digital and real technological integration significantly promotes corporate green collaborative innovation. Mechanism analysis indicates that digital and real technological integration promotes corporate green collaborative innovation by mitigating asset specificity, reducing green agency costs and broadening green knowledge breadth. Furthermore, heterogeneity analysis shows that this positive effect of digital and real technological integration on corporate green collaborative innovation is more pronounced among firms with higher internal control quality, operating in high-tech industries, and located in eastern regions. This study not only deepens our understanding of the economic consequences of digital and real technological integration, but also provides crucial insights and evidence for exploring the antecedents of corporate green collaborative innovation.



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Keywords: digital and real technological integration; corporate green collaborative innovation; asset specificity; green agency costs; green knowledge breadth

1. Introduction

As the low-carbon transition, supported by a global consensus, continues to advance in depth, green innovation has evolved into a key pathway to sustainable development

within the framework of environmental issues [1]. Enterprises are at the forefront of green innovation efforts. Yet, shorter technology cycles, a complex innovation environment, and increasingly personalized green demands are challenges that enterprises must inevitably face and cannot afford to ignore [2]. Particularly in the Chinese market, the incompleteness and unevenness of institutional development have prevented enterprises from fully relying on mature institutions, resulting in a lack of timely and stable guarantees for accessing external resources. It is challenging for individual enterprises to possess all the heterogeneous resources required for green innovation [3]. Issues such as bearing the risks and reaping the positive externalities of innovation activities on their own lead to a lack of motivation and willingness to engage in green innovation.

Compared with analyses from a purely technical perspective, the exploration of green innovation models from an organizational perspective is not limited to examining only independent, autonomous green innovation [4]. Indeed, unlike green innovation within an organization, which involves the self-organization and self-adaptation of innovative elements, green collaborative innovation emphasizes the collaboration and solidarity of multiple organizational actors, ultimately establishing a symbiotic mechanism characterized by complementary strengths, shared benefits and shared risk-bearing [5]. As the basic units of innovation, enterprises occupy a central position among the many actors engaged in green collaborative innovation [6]. In essence, the effective promotion and implementation of corporate green collaborative innovation largely depend on the complementary resources and coordinated actions of multiple stakeholders. It is both crucial and urgent to break down and overcome the core obstacles in this process, such as information barriers, response delays, and knowledge dependencies.

Notably, technological integration is accelerating the transformation of corporate organizational models [7]. With the explosive growth of the digital economy, digital technologies are continuously empowering, integrating into, and reshaping real technologies [8]. By definition, the core characteristic of digital and real technological integration is the direct embedding of digital technologies into traditional technological systems and processes, thereby achieving digital transformation and modernization of traditional technologies. Theoretically, digital and real technological integration plays a central supporting role in corporate green collaborative innovation. The extreme pervasiveness and extensibility of digital technology break through traditional paradigms for connecting and expanding innovation factors [9], largely helping to optimize and improve the efficiency of multi-factor resource allocation [10]. Digital and real technological integration, through the empowerment derived from the circulation of data elements and the deep penetration of digital technologies into various scenarios, breaks down the rigid constraints of temporal and spatial boundaries and the homogenizing barriers created by resource silos in traditional innovation organizational processes. It reconfigures the cross-regional and cross-organizational pathways for information exchange, governance, and knowledge dissemination between enterprises and external innovation partners, thereby providing strong support for minimizing friction in green cooperation and revitalizing the dynamism of green collaborative innovation.

Given the fundamental trends of the booming digital economy, most previous studies have implicitly demonstrated that the penetration or empowerment of the digital economy, which enterprises collectively face or experience, is roughly equivalent to quantitative or level-based categories on an overall scale [11,12]. However, discussions centered around this topic generally overlook the critical perspective of digital and real technological integration, or largely assume that enterprises are relatively homogeneous in their ability to undergo dynamic evolution through complementary, symbiotic, and continuous interactions between technologies, which may result in the exclusion of digital and real

technological integration from the analytical framework. At the same time, it also emerges that technological integration predominantly concentrates on the convergence and coupling of technical knowledge or elements from different technological fields [13]. As digital technology continues to accelerate the expansion of technological boundaries, digital and real technological integration, unlike breakthroughs in individual technologies, is decisive in fostering collaborative innovation among multiple actors. However, current research on green collaborative innovation has not yet separated and distinguished digital and real technological integration from the broader framework of the digital economy or digitalization, nor has it identified the impact of this integration on corporate green collaborative innovation from this perspective.

In light of this, we seek to explore the impact of digital and real technological integration on corporate green collaborative innovation. To identify the underlying mechanisms, we integrate perspectives on transaction costs, governance, and knowledge resources to construct a framework for analyzing mechanisms that encompasses asset specificity, green agency costs, and the breadth of green knowledge. Such mechanisms explain and clarify the underlying logic of how digital and real technological integration promotes corporate green collaborative innovation from the perspectives of how such integration alleviates investment concerns, reduces moral hazard, and provides knowledge resources. Firstly, the project activities related to green collaborative innovation require a high degree of asset specificity. Risks of misallocation, sunk costs, as well as profit appropriation and dependency may weaken corporate willingness and ability to engage in green collaborative innovation [14]. Secondly, given the insufficient green investments and free-riding behavior in multi-party collaborations, these divergences in green objectives inevitably give rise to agency costs [15]. The accumulation of these green agency costs hinders the implementation and realization of green collaborative innovation. Finally, green collaborative innovation requires the integration of heterogeneous green knowledge across organizational boundaries and disciplines [16,17]. The broader the scope of green knowledge, the greater the potential for innovative outcomes resulting from its combination. Our research framework is shown in Figure 1.

The contributions of this study are threefold.

Firstly, we broaden the scope of research on collaborative innovation theory from the perspective of technological integration. Existing research has primarily focused on establishing theoretical frameworks at the macro level to examine the impact of the integration of the digital economy and the real economy on innovation [18], as well as on the innovation effects of technological integration in a broad sense [19–21]. Rather, there is still a relative lack of empirical evidence integrating the relationship between digital and real technological integration and corporate green collaborative innovation. From the unique perspective of digital and real technological integration, we provide theoretical support for green collaborative innovation at the micro-enterprise level.

Secondly, we reveal the underlying mechanisms by which digital and real technological integration drives corporate green collaborative innovation within the research paradigm of collaborative innovation. From the perspectives of transaction costs, contractual governance, and knowledge resources, we elucidate how the underlying mechanisms of asset specificity, green agency costs, and green knowledge breadth serve as key components in how digital and real technological integration supports and promotes corporate green collaborative innovation. This not only deepens our understanding of the underlying mechanisms by which digital and real technological integration empowers green collaborative innovation, but also further enriches and expands the academic recognition of the insight that technological integration is a source of innovation.

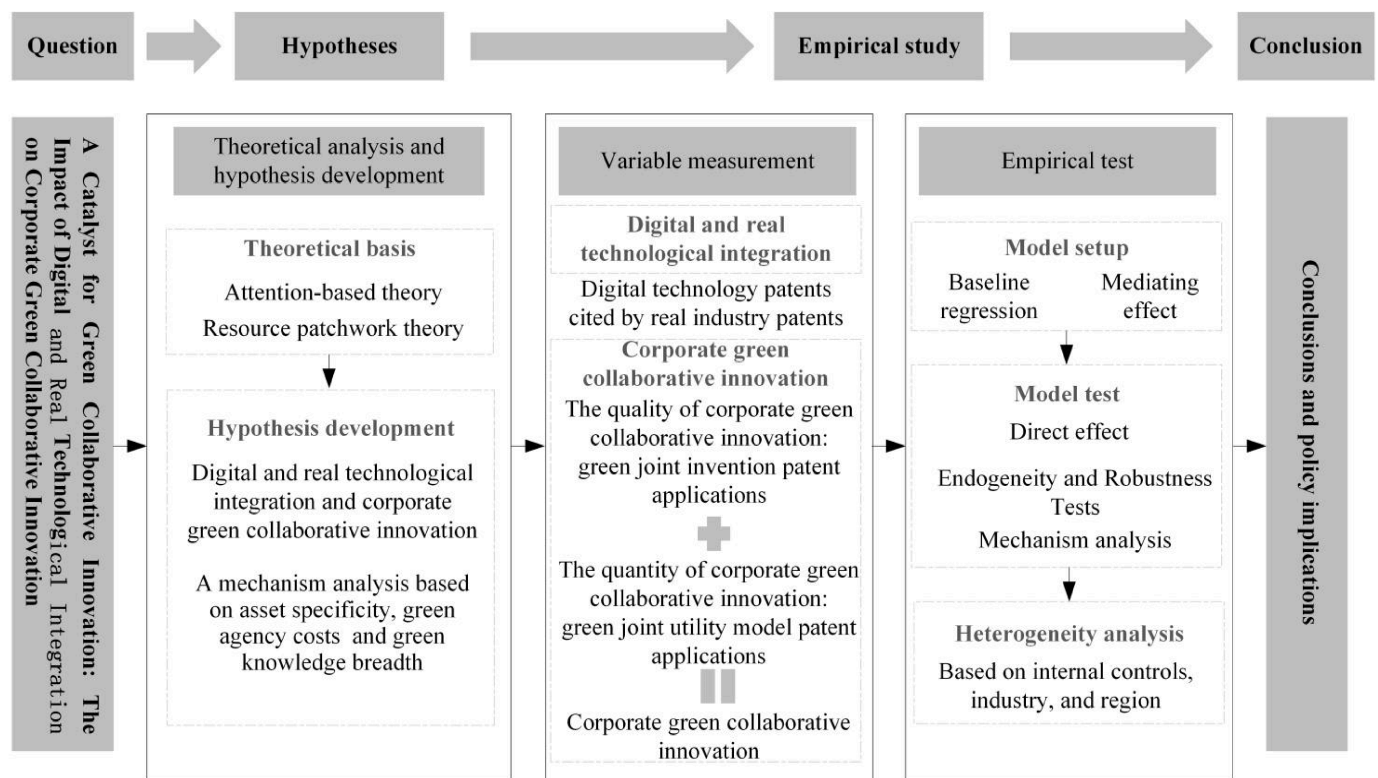


Figure 1. Research framework.

Finally, we examine the collaborative innovation effects of digital and real technological integration, providing practical guidance for further advancing green collaborative innovation in emerging markets where the supply of external innovation resources is volatile. We also provide empirical evidence to support targeted measures by corporate management and policymakers in the context of green collaborative innovation.

The remainder of this paper is organized as follows. Sections 2 and 3 include the literature review and hypothesis development. Sections 4 and 5 present the methods and empirical analysis, respectively. The conclusions and policy implications are in Section 6.

2. Literature Review

Technology integration typically occurs among industries that share a similar technological foundation and common technological platforms [22]. This integration process contributes to the emergence of a new field [23], creates new products and applications, and enhances innovation capabilities and performance [24]. Specifically regarding digital technology, with the emergence of digital tools, data analytics, and other emerging digital technologies, the network of technological integration has become increasingly rich and powerful [25]. Due to the inherent modular nature of digital technology, its accompanying spillover effects and inclusive nature encourage it to complement and interact with the specialized characteristics of real economy or physical industrial technologies. The cross-industry diffusion and deep integration of digital technologies help break the path dependence inherent in real economy or physical industrial technologies. Concurrently, real economy or physical industrial technologies play a crucial role in providing contextual support and value anchors for digital technologies. The digital and real technological integration reflects and highlights a systematic restructuring of corporate internal production factors based on the supply of external digital technologies [26].

Corporate green collaborative innovation refers to innovation activities that transcend organizational boundaries, in which enterprises and their partners jointly create and share

value by establishing networks and exchanging green innovation resources [27]. Green collaborative innovation serves as an important complement to corporate autonomous and independent innovation. Previous studies have recognized and confirmed the fundamental and essential nature of collaboration in the green innovation process, demonstrating the key role that collaborative green innovation plays in enabling organizations to jointly advance sustainability and environmental friendliness [28]. Furthermore, compared to collaborative innovation in the general sense, green collaborative innovation faces greater challenges in establishing sustainable long-term coordination mechanisms due to the intellectual complexity of green innovation, as well as the risks and long-term nature of the innovation process [29].

Collectively, most existing studies have demonstrated that digital and real technological integration drives innovation [30,31]. However, the partial lack of research on the relationship between digital and real technological integration and corporate green collaborative innovation has led to a theoretical understanding and recognition gap regarding the distinctive functions of such technological integration in the dual contexts of green innovation and collaborative innovation. A series of works on the drivers of corporate green collaborative innovation have been conducted in a relatively fragmented manner, focusing on green bonds or ESG within the frameworks of institutional theory or signaling theory [32,33], and have not yet extended to the field of digital and real technological integration. Current interpretations of innovation from the perspective of technological integration offer relatively limited insights into the diverse connections, coordination mechanisms, and joint outputs resulting from collaboration among different actors in green innovation.

3. Hypothesis Development

3.1. *Digital and Real Technological Integration and Corporate Green Collaborative Innovation*

Similar to incremental evolutionary models that highlight long-term, cumulative efforts and emphasize a step-by-step approach to breaking free from the constraints of established conventions [34], the transformation of organizational models for innovation similarly exhibits a cumulative nature rather than a radical, discontinuous one. The multi-stakeholder interactions and complementarities involved in collaborative innovation undergo a sequential process comprising initial negotiation, mid-stage collaboration, and, in the later stages, the stable introduction of external information and the diffusion of knowledge [35]. The process of corporate green collaborative innovation involves gradually expanding the scope of search and matching for innovation resources and partners, as the diverse resources and knowledge that align with their innovation needs are typically distributed across varying innovation systems [4]. Digital and real technological integration gradually breaks down explicit physical barriers and implicit collaboration thresholds to green innovation, progressively expanding the collaborative networks, composed of diverse actors, that are originally rooted in specific geographic spaces. It also progressively resolves the issue of technological path lock-in faced by enterprises that rely excessively on local networks.

Unlike independent and isolated innovation initiatives, corporate green collaborative innovation, characterized by integrated processes and shared objectives, generally involves colleagues working together to address substantial differences among heterogeneous partners in terms of scale, organizational structure, R&D learning curves and operational rhythms. The practical challenges and difficulties arising from the severe information asymmetry inherent in this process, delays in matching supply and demand, unclear rights and responsibilities for specific tasks, and misallocation of resources, inevitably hinder the achievement of the goals of green collaborative innovation [36]. Overall, digital and real

technological integration establishes networked interactions between production equipment and information systems at the operational level [37], fostering and strengthening collaboration between enterprises and their partners, restructuring existing innovation process frameworks, and enhancing corporate ability to identify, integrate, and disseminate internal and external information, resources, and knowledge. Concurrently, digital and real technological integration helps enterprises at the organizational level break free from path dependence in past approaches to green innovation [38], providing managers with in-depth insights and decision-making support. Overcoming the tendency to rely on dominant concepts gives enterprises an advantage in discovering new combinations of innovations and application scenarios and in breaking free from R&D activities confined to existing innovation trajectories.

Firstly, the fluidity and pervasiveness of digital and real technological integration overcome the spatial constraints imposed by traditional geographical distances on cross-regional corporate collaborative innovation, thereby strengthening the alignment between supply and demand [39]. More specifically, corporate green collaborative innovation is often subject to strong geographical constraints. The digital and real technological integration largely breaks down localized limitations such as the geographical and industry-specific scope of search, and by extending and reshaping more stable network associations, it strengthens the bonds between innovation actors. Simultaneously, the digital and real technological integration broadens the scope of innovation collaboration, enabling close coordination across all stages, real-time monitoring of changes among partners, and deeper relationship building. To a certain extent, expanding the search for complementary entities further elevates the efficiency of matching supply and demand.

Secondly, the phenomenon of information silos, caused by inconsistent standards, incompatible interfaces, and a lack of data sharing, is particularly pronounced, severely hindering information connectivity and undermining the effectiveness of collaboration. The digital and real technological integration shares the common traits of technological integration [40], namely, reducing information friction among different innovation actors and avoiding noise interference regarding the allocation of rights and responsibilities caused by information fragmentation and market fragmentation. In particular, the digital and real technological integration expands information processing bandwidth, streamlines decision-making processes and shortens the time lag between perception and action. Enhanced perception of partners helps uncover more information about innovation actors [41], while joint decision-making processes strengthen and facilitate the exchange of private information. This further ensures that all parties establish equal transactional relationships during the innovation process, ultimately laying a solid foundation for defining the rights and responsibilities between enterprises and their partners.

Finally, digital technologies, with their wide coverage, high penetration, and low replication costs, yield comparative advantages in improving resource coordination [19]. The digital and real technological integration breaks through the limitations of static planning, enabling dynamic allocation based on business needs and the use of flexible mechanisms to optimize resource allocation efficiency. Such improvements fundamentally enhance openness within organizations and interoperability between them [42], while reducing the practical barriers to the external application of algorithms between enterprises and their partners that arise from the complexity of underlying technologies. The digital and real technological integration also transforms dispersed and disorganized resources into a centralized, unified resource pool, which could largely eliminate excessive or inefficient resource allocation and ultimately avoid the resource misallocation caused by traditional fragmented data and delayed responses.

Taken together, we propose Hypothesis 1.

H1. *Digital and real technological integration promotes corporate green collaborative innovation.*

3.2. Mechanism Analysis

The analytical framework for mechanism analysis conducts an in-depth analysis based on the logic of transaction costs, governance and knowledge resources. Firstly, asset specificity focuses on examining how the digital and real technological integration in the early stages of collaboration reduces barriers to green investment and enhances corporate willingness and ability to jointly pursue green innovation. Secondly, the cost of green agency concentrates on examining how digital and real technological integration in the collaboration process can reasonably and effectively curb opportunistic behaviors such as shirking responsibility, fraud, and free-riding. Finally, the breadth of green knowledge focuses on examining how digital and real technological integration enhances interdisciplinary knowledge and knowledge supply, thereby enabling corporate collaborative green innovation.

3.2.1. Digital and Real Technological Integration, Asset Specificity and Corporate Green Collaborative Innovation

Transaction cost theory posits that asset specificity refers to an enterprise's investment in specialized assets that are suitable only for specific transaction counterparts [43]. Excessive asset specificity increases the rigidity of transaction costs and the difficulty of adjustment, raises sunk costs, and creates barriers to exiting specialized assets [44]. Apparently, green collaborative innovation involves a large number of customized, specialized assets and tends to involve multi-stage investments and assets that are difficult to repurpose [45]. Due to risk-averse considerations, enterprises tend to scale back their investments in green collaborative innovation.

The digital and real technological integration establishes a universal digital foundation across organizations, which can be integrated and applied to multiple key aspects of business operations [46]. Such integration not only drives efficiency improvements in individual processes but also promotes incremental digital upgrades and transformations across organizations through the cross-process flow of data. These initiatives and arrangements free us from historical tasks that are process-driven, repetitive, and formulaic, and unlock those close and highly interdependent transactional relationships [47]. Standardized evidence preservation, interoperability, and circulation inherently enhance the agility of operations and the flexibility of assets [48]. Following this logic, digital and real technological integration increases asset flexibility and mitigates the sunk costs and multilateral lock-in associated with failed or interrupted transactions.

Furthermore, as the exclusivity of assets diminishes, enterprises anticipate that the assets they invest in will retain market value even after a partnership ends, making them more willing to actively participate in building green innovation consortia. At the same time, since enterprises do not have to bear significant losses from asset disposal; this enables them to better manage, coordinate and flexibly adjust their green investments on their own [49], ultimately promoting corporate green collaborative innovation.

Taken together, we propose Hypothesis 2.

H2. *Digital and real technological integration mitigates asset specificity, thereby promoting corporate green collaborative innovation.*

3.2.2. Digital and Real Technological Integration, Green Agency Costs and Corporate Green Collaborative Innovation

The agency theory posits that differences between principals and agents in terms of objectives, risk preferences, and access to information give rise to agency costs, which

result in losses in terms of contractual effectiveness and efficiency [50]. In the context of green collaborative innovation, the interplay of nested principal-agent relationships among multiple stakeholders leads to the concealment and obfuscation of private information. Concerns about free-riding and opportunistic behavior often make enterprises reluctant to share green technologies and R&D costs, making it difficult to implement collaborative green innovation [51].

Similar to technological integration, digital and real technological integration permeates the ways in which innovative elements are connected, while automation and standardized operations enhance transparency across levels and organizations, forming strong links [52]. Under such circumstances, the reduction in redundant layers gives way to a decentralized and flat decision-making structure. Trustworthy and reliable execution arrangements and structures minimize coordination failures caused by deviations from objectives. At the same time, digital rights confirmation clearly defines the property rights of all parties involved and prevents agents from deviating from the principal's objectives for personal gain. Establishing smooth communication channels and feedback mechanisms helps overcome common issues such as a lack of mutual trust and efficient collaboration [53], thereby collectively reducing the costs of green agency.

Furthermore, reduced green agency costs ensure the stable operation of green collaborative innovation projects through compliance governance. This not only helps strengthen contract enforcement but also reduces implicit implementation obstacles. The establishment of a long-term cooperative framework between enterprises and their partners addresses the issue of speculation in multi-stakeholder green collaboration and reduces the overall loss of innovation benefits within the collaborative alliance.

Taken together, we propose Hypothesis 3.

H3. *Digital and real technological integration reduces green agency costs, thereby promoting corporate green collaborative innovation.*

3.2.3. Digital and Real Technological Integration, Green Knowledge Breadth and Corporate Green Collaborative Innovation

The breadth of green knowledge represents the scope of diverse green knowledge possessed by an enterprise. Independent enterprises with narrow boundaries of green knowledge inevitably face the dilemma that their in-house green knowledge is insufficient to support green collaborative innovation [54]. Traditional offline knowledge exchange also suffers from pain points such as slow information transmission, low standardization of knowledge, high costs of knowledge transfer and the risk of core green technology leaks, all of which inherently limit the cross-boundary flow of green knowledge.

Digital technologies generally reduce the marginal cost of replicating and disseminating knowledge to near zero [55], creating the conditions for cross-domain search and reorganization of green knowledge. Along these lines, these efforts link dispersed fragments of knowledge across organizations, and knowledge that can be encoded, thanks to digital technologies, can be expressed, shared and circulated in a timely manner among different organizations [56]. Concurrently, digital and real technological integration accelerates the consolidation of green knowledge and the process of trial-and-error iteration [57], creating a more inclusive network for the dissemination of green knowledge. Enhanced corporate capabilities in understanding, screening, and integrating external green knowledge enable the discovery of potential knowledge structures [58], accelerate the sharing of tacit green knowledge, and promote the expansion and broadening of green knowledge across disciplines.

Furthermore, broadening and expanding the scope of green knowledge effectively prevents enterprises from becoming trapped in their own closed, rigid knowledge-learning

systems [59], thereby avoiding and discouraging the cycle of falling into a learning trap. By identifying knowledge gaps between collaborating parties, complementary green knowledge can be precisely matched. This enhances the efficiency of knowledge reuse at a lower cost, shortens learning time and promotes corporate green collaborative innovation.

Taken together, we propose Hypothesis 4.

H4. *Digital and real technological integration broadens the breadth of green knowledge, thereby promoting corporate green collaborative innovation.*

Figure 2 illustrates the theoretical model.

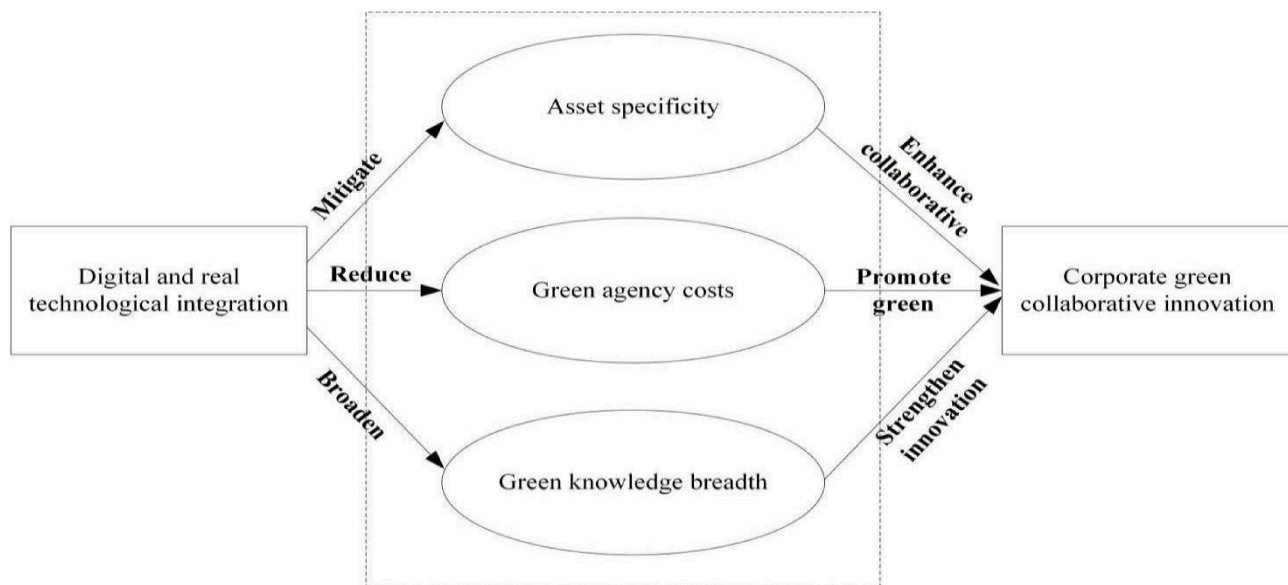


Figure 2. Theoretical model.

4. Methods

4.1. Sample Selection and Data Source

This study selects Chinese A-share listed firms from 2008 to 2023 as our research sample. We process the raw data as follows. Firstly, we exclude listed firms exhibiting severe key data gaps or containing outliers. Secondly, due to financial irregularities in firms subject to ST, *ST, or PT designations during the sample period, we also exclude such firms. Finally, given the distinct differences in the financial statement structures for listed firms in the financial and insurance industries, and considering the distinct requirements for financial data in the B-share capital market, we exclude the aforementioned firms.

Following this series of cleaning procedures, the final unbalanced panel data set comprises 17,428 firm-year observations. All continuous variables are winsorized at the 1% and 99% level. Patent data primarily originate from the China National Intellectual Property Administration's patent database, while other financial data are sourced from the CSMAR and Wind databases.

4.2. Variable Definitions and Measurement

4.2.1. Dependent Variable

The dependent variable is corporate green collaborative innovation (GCI). Generally, joint applications for green patents signify collaborative innovation between enterprises and external innovation entities. Drawing upon a similar study [60], we employ the total volume of green patents jointly applied for by listed firms and other entities, such as

enterprises, higher education institutions, and research organizations, to measure corporate green collaborative innovation.

4.2.2. Independent Variable

The independent variable is digital and real technological integration (DRTI). Corporate patent data is the most effective and direct carrier of technical information. It can comprehensively capture and map the technical fields in which companies operate, the characteristics of technical elements, and the basic status of technology flows. Similarly, technological integration across industries forms the foundation of industrial integration and the interconnections between technologies can also reflect industrial integration [61]. Citation information between patents serves as an objective and explicit record of the degree of technological interconnection [62], illustrating the overlap and integration of different technological fields and revealing new directions for technological integration [63]. Therefore, using the method of counting the number of times patents in the digital industry are cited by patents in the physical industry to measure digital and real technological integration not only represents a micro-level manifestation of this integration from the perspective of technology-driven industrial integration, but also reflects the integration of the digital and physical industry at the industrial level. We adopt this approach and, based on a similar study [64], identify the frequency with which digital technology patents are cited by physical industry patents, thereby measuring digital and real technological integration. The specific steps are as follows.

Firstly, based on the IPC classification main category number and utilizing the enterprise's patent database, we identify whether the patents and invention patents applied for belong to core digital economy industrial technologies. Secondly, based on the patent publication number, match the patent's citation information to identify whether the technology cited by that patent belongs to core digital economy industrial technologies. Thirdly, if an enterprise's patent application falls under a non-core digital economy industry technology IPC main category, yet one of its cited patents is classified as a core digital economy industry technology, this constitutes one instance of digital and real technological integration. If n patents are classified as core digital economy industry technologies, this represents n instances of digital and real technological integration. Finally, by extension, the frequency of digital and real technological integration at the enterprise-year level is derived based on the actual number of such integration instances occurring within the enterprise. The level of digital and real technology integration (DRTI) is then measured by taking the natural logarithm of the sum of these frequencies plus one. The greater the value of integration, the higher the degree of digital and real technological integration.

4.2.3. Control Variables

According to similar studies [65,66], we control for a range of characteristic variables that may influence corporate decisions regarding collaborative innovation. The control variables at the firm-level are firm size (Size), firm age (Age), financial leverage (Lev), financial performance (ROA), ownership structure (SOE), break-even situation (Loss), book-to-market ratio (BM) and R&D intensity (RD). The control variables at the corporate governance level are the proportion of independent directors (Independent), CEO duality (Dual) and shareholding concentration (Top).

The inclusion of firm size is based on the fact that large enterprises typically have more abundant R&D funding and a greater capacity to take risks, which are important foundations for collaborative innovation. The inclusion of firm age is based on the fact that the number of years since its establishment reflects its organizational inertia and accumulated knowledge. Mature enterprises tend to have broader networks of partners.

Financial and operational characteristics such as financial leverage, financial performance, break-even situation and book-to-market ratio are included because they are strongly correlated with financing constraints and internal cash flows, and serve as a financial safeguard and source of support for green collaborative innovation. The inclusion of ownership structure is due to the significant differences between state-owned and private enterprises in terms of their relationships with the government, preferential treatment under industrial policies, and business objectives. Their ability and willingness to engage in green collaborative innovation also differ. R&D intensity is included because it is directly linked to innovation activities. The corporate governance variables, such as the proportion of independent directors, CEO duality, and shareholding concentration, are included because green collaborative innovation constitutes a long-term strategic investment for enterprises, and the governance structure involving management, the board of directors, and major shareholders directly determines decision-making regarding green collaborative innovation. Table 1 presents the variable definitions.

Table 1. Variable definitions.

Variable Types	Variable Name	Variable Symbol	Explanation
Dependent Variable	Corporate green collaborative innovation	GCI	ln (the sum of green invention patents and green utility model patents jointly applied for by the listed firm and other entities during the current year + 1)
Independent Variable	Digital and real technological integration	DRTI	ln (the number of citations for digital industry technology patents + 1)
	Firm size	Size	ln (the number of total employees)
	Firm age	Age	ln (the number of years since the enterprise establishment + 1)
	Financial leverage	Lev	Total liabilities/Total assets
	Financial performance	ROA	Net profit/ Average total assets
	Ownership structure	SOE	State-controlled enterprises are 1, others are 0
Control Variables	Break-even situation	Loss	Dummy variable: 1 = the net profit is less than 0 and 0 = others
	Book-to-market ratio	BM	Book value/Total market capitalization
	R&D intensity	RD	The ratio of R&D expenditures to operating revenue
	Proportion of independent directors	Independent	Number of independent directors/Directors
	CEO duality	Dual	Dummy variable: 1 = the CEO and chairman are the same person and 0 = others
	Shareholding concentration	Top	Top 5 shareholders' shareholding/Total number of shares

4.3. Model Setup

To examine the impact of digital and real technological integration on corporate green collaborative innovation, we construct a fixed-effects model for unbalanced panel data, as detailed in Model (1).

$$GCI_{it} = \alpha_0 + \alpha_1 DRTI_{it} + \alpha_2 Controls_{it} + \theta_k + \mu_t + \varepsilon_{it} \quad (1)$$

In model (1), GCI_{it} represents the dependent variable, $DRTI_{it}$ represents the independent variable, and $Controls_{it}$ represents the set of control variables. We also control for fixed effects at the industry (θ_k) and year (μ_t) levels. i denotes the firm, k denotes the industry,

and t denotes the year. Additionally, $\varepsilon_{i,t}$ is the random disturbance term. We focus on the coefficient of α_1 , which represents whether H1 holds.

5. Empirical Analysis

5.1. Descriptive Statistics

Table 2 presents the relevant results of the descriptive statistics. The mean value for corporate green collaborative innovation (GCI) is 0.2120, with a median of 0, indicating that the overall level of corporate green collaborative innovation is relatively low. The mean value for digital and real technological integration (DRTI) is 0.2543, with minimum and maximum values of 0 and 6.2246, respectively, suggesting that most enterprises currently exhibit a low level of digital and real technological integration. The descriptive statistics for the other variables are all within reasonable ranges.

Table 2. Descriptive statistics results.

Variables	Obs	Mean	S.D	Median	Min	Max
GCI	17,428	0.2120	0.6375	0	0	6.9234
DRTI	17,428	0.2543	0.6038	0	0	6.2246
Size	17,428	7.7889	1.1812	7.6790	4.4308	10.9677
Age	17,428	2.8864	0.3484	2.9444	1.3863	3.5264
Lev	17,428	0.3962	0.1918	0.3898	0.0521	0.8943
ROA	17,428	0.0478	0.0621	0.0453	−0.2211	0.2162
SOE	17,428	0.2670	0.4424	0	0	1
Loss	17,428	0.0979	0.2972	0	0	1
BM	17,428	0.9055	0.9717	0.5994	0.0979	6.5038
RD	17,428	0.0556	5.2704	0.0419	0	0.1374
Independent	17,428	0.3765	0.0540	0.3636	0.1429	0.5714
Dual	17,428	0.3123	0.4634	0	0	1
Top	17,428	0.5344	0.1488	0.5328	0.1993	0.8872

5.2. Baseline Results

Table 3 reports the baseline regression results. We employ a stepwise approach to incorporate control variables and verify the main effects. Columns (1)–(3) show that the regression coefficient for DRTI is significantly positive at the 1% level, indicating that digital and real technological integration significantly promotes corporate green collaborative innovation, supporting H1.

Table 3. Baseline regression.

	(1) GCI	(2) GCI	(3) GCI
DRTI	0.2579 *** (0.0385)	0.2816 *** (0.0396)	0.2259 *** (0.0381)
Size			0.0856 *** (0.0130)
Age			0.0091 (0.0376)
Lev			0.0332 (0.0669)
ROA			0.2417 (0.1586)
SOE			0.0326 (0.0308)

Table 3. Cont.

	(1) GCI	(2) GCI	(3) GCI
Loss			−0.0387 * (0.0232)
BM			0.0410 ** (0.0202)
RD			0.0010 (0.0017)
Independent			0.1635 (0.1630)
Dual			0.0031 (0.0180)
Top			−0.0591 (0.0824)
Ind	NO	YES	YES
Year	NO	YES	YES
Constant	0.1464 *** (0.0092)	0.1404 *** (0.0089)	−0.6414 *** (0.1531)
Obs	17,428	17,428	17,428
A-R ²	0.0596	0.1150	0.1521

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. The numbers in parentheses are the standard errors corresponding to the firm-level cluster robust standard errors. The same applies to the tables below.

5.3. Endogeneity and Robustness Tests

5.3.1. IV

To address potential reverse causality or confounding effects from omitted variables that may distort causal identification, we employ the instrumental variables approach to mitigate endogeneity issues. We calculate the average level of digital and real technological integration among other enterprises of comparable scale each year, and cross-multiply this with the average number of fixed telephones per 10,000 people across cities in 1984 to construct the instrumental variable (DRTI-IV).

Firstly, advances in urban digital technology possess a momentum that builds on the past and paves the way for the future. The historical penetration rate of landline telephones reflects the endowment of regional information infrastructure; it forms the foundation for the development of digital technology and exhibits a path-dependence relationship with the diffusion and convergence of contemporary and current digital technologies, demonstrating a correlation. Secondly, the economic benefits of traditional telecommunications infrastructure gradually diminish as usage declines. Moreover, as the primary function of fixed-line telephones is to provide public telecommunications services, it is difficult for them to have a direct impact on the current innovation activities of specific enterprises, and there is no direct link between the two, thereby meeting the requirement of exclusivity [67]. Finally, the historical number of landline telephones is highly exogenous and is not influenced by current corporate innovation behaviour, confirming that the instrumental variable satisfies the exogeneity condition.

Furthermore, as the historical number of fixed-line telephones constitutes cross-sectional data, to meet the requirements of panel data analysis, we constructed an interaction term between the average number of fixed-line telephones per 10,000 people in 1984 and the annual mean of the real-value technical integration of other enterprises in the same industry, thereby endowing the instrumental variable with time-varying properties. Column (1) of Table 4 reports the results of the first-stage regression under the instrumental variables approach, where the regression coefficient for DRTI-IV is significantly positive.

Column (2) reports the results of the second-stage regression under the instrumental variables approach, where the coefficient for DRTI remains significantly positive, consistent with the baseline regression results.

Table 4. Endogeneity tests.

	IV (1) DRTI	(2) GCI	Heckman (3) GCI	PSM (4) GCI	Lag Period (5) GCI
DRTI		0.4972 *** (0.1208)	0.6427 *** (0.0402)	0.2588 *** (0.0411)	
DRTI-IV	0.0348 ** (0.0146)				
IMR			−0.0360 ** (0.0159)		
I.DRTI					0.2475 *** (0.0412)
Controls/Ind/Year	YES	YES	YES	YES	YES
Constant			−0.0389 ** (0.0166)	−0.7062 *** (0.1918)	−0.6948 *** (0.1769)
Obs	17,428	17,428	17,428	16,720	14,138
A-R ²			0.1523	0.1821	0.1610

Note: ***, ** indicate significance at the 1%, 5% levels, respectively.

Additionally, the results of the unidentifiability test (K-Park LM) and the weak instrument tests (C-Donald Wald F-statistic and K-Park Wald F-statistic) are 22.214, 1091.115, and 23.377, respectively. All these values exceed the critical value of 16.38 under the 10% error level specified by Stock and Yogo, strongly indicating that the instrumental variables do not suffer from unidentifiability or weakness.

5.3.2. Heckman

To mitigate the issue of sample selection bias, we employ Heckman's two-stage model. The Heckman two-stage method uses the presence or absence of digital and real technological integration as the dependent variable in the first stage, and introduces control variables, time and industry dummy variables into the model to enhance its explanatory power. Furthermore, we incorporate the level of digital and real technological integration among other firms in the same industry and year as an exclusionary constraint variable. Based on the estimation results from the first stage, we calculate the inverse Mills ratio (IMR) and substitute the IMR into the baseline regression model as a control variable for the second-stage regression, in order to correct for sample selection bias. Column (3) reports the test results. After incorporating the IMR into Model (1) and re-estimating, the IMR proves significant, confirming the presence of sample selection bias. Moreover, the coefficient for DRTI remains significantly positive, to some extent ruling out potential issues of sample selection bias.

5.3.3. Psm

We employ Propensity Score Matching (PSM) to mitigate potential self-selection bias in the sample. Specifically, we introduce a dummy variable for digital and real technological integration, using its median value by 'industry-year' as the threshold to divide the sample into two groups: 'high digital and real technological integration' and 'low digital and real technological integration', assigning values of 1 and 0 respectively. We then incorporate control variables as covariates to perform 1:1 nearest-neighbour matching.

Column (4) shows that the coefficient for DRTI remains significantly positive, supporting H1. Figure 3 shows that the standardized deviations of all variables have narrowed following matching, demonstrating the effectiveness of the matching procedure.

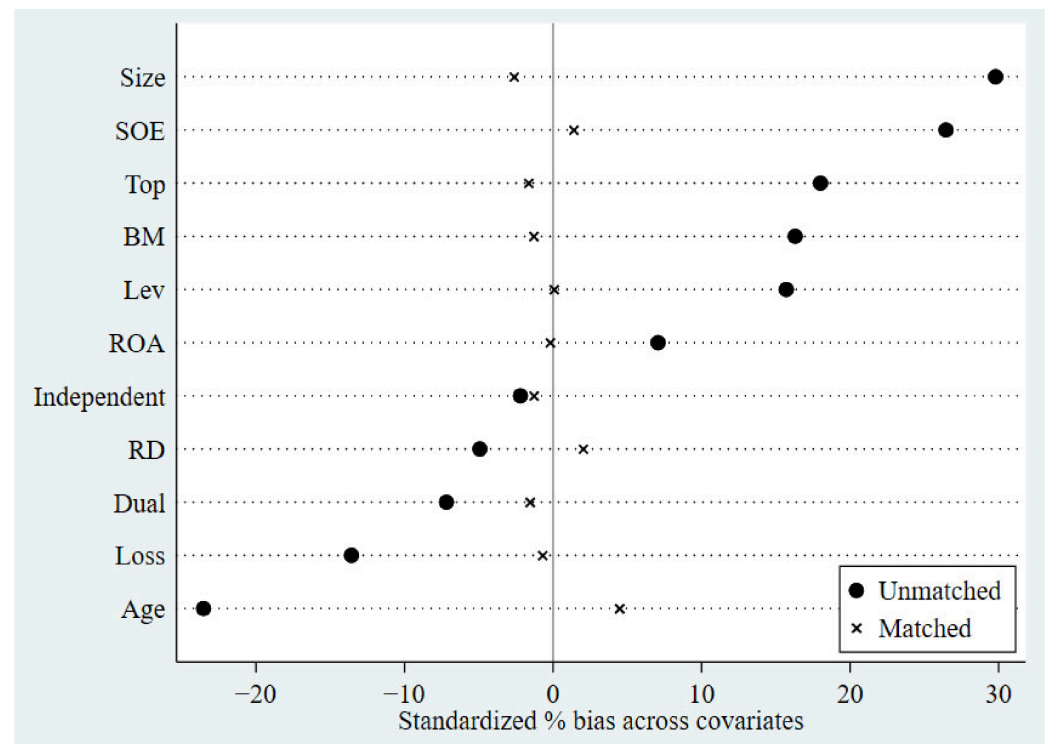


Figure 3. Standardization deviation of each variable.

5.3.4. Placebo Test

We conducted a placebo test using a randomly constructed index of digital and real technological integration. First, we construct a dummy variable for pseudo digital and real technological integration through random assignment. Second, we replace the digital and real technological integration variable with the pseudo digital and real technological integration dummy variable. Third, we repeat the aforementioned process 1000 times.

Figure 4 shows that the estimated coefficients exhibit a symmetrical distribution centred on zero. Their mean differs significantly from the coefficient value of 0.2259. Judging by the distribution of p -values, the p -values for most random sample regression coefficients are greater than 0.1, indicating that no significant correlation exists. The results of the placebo test confirm that the relationship between digital and real technological integration and corporate green collaborative innovation, as observed in the baseline results, is indeed valid, thereby largely ruling out the influence of the time variable and other random factors.

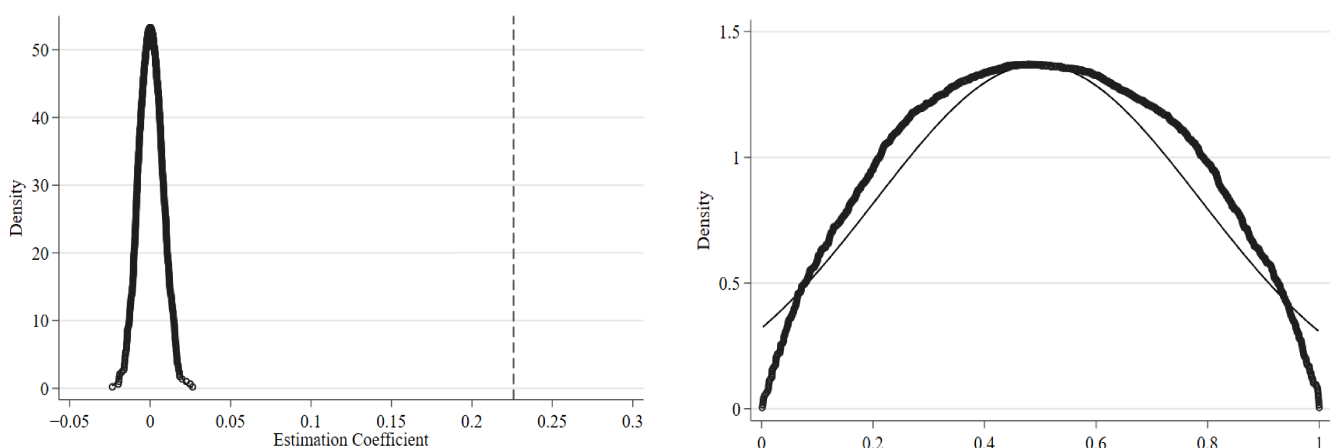


Figure 4. Results of the placebo test.

5.3.5. Lag Period

Given that the catalytic effects of digital and real technological integration may exhibit gradual and lagged characteristics, and that the realization of corporate green collaborative innovation also spans a temporal interval, we reintroduce a one-period lagged term for digital and real technological integration into model (1) for estimation. Column (5) shows that the first-order lagged term of digital and real technological integration (l.DRTI) remains significantly positive, thereby partially ruling out the possibility of reverse causality.

5.3.6. Robustness Tests

Firstly, drawing on existing research that utilizes patent classification code co-occurrence quantification to measure the degree of technological integration [68], we identify the co-occurrence frequency of patent applications at the ‘firm–year’ level where the main classification code belongs to the digital industry and at least one of the remaining classification codes belongs to the physical industry. We then re-measure the level of digital and real technological integration (DRTI_T) by taking the natural logarithm of this frequency plus one.

Secondly, further controlling for high-dimensional fixed effects often eliminates the influence of numerous confounding factors, such as heterogeneous regional environments and macro level time-varying factors [69]. Consequently, we introduce industry–year interaction fixed effects, city fixed effects, and city–year interaction fixed effects into Model (1).

Thirdly, given the occurrence of two major exogenous shocks during the study period, namely the 2015 stock market crash and the 2020 public health crisis, we exclude samples from 2015, 2020 and subsequent years.

Finally, given that control variables may be associated with digital and real technological integration, we reintroduce all control variables into model (1) after lagging them by one period.

Table 5 reports all the aforementioned tests, with the regression coefficient for DRTI remaining significantly positive, supporting H1.

Table 5. Robustness tests results.

	(1) Replace the Independent Variable GCI	(2) Control Industry–Year GCI	(3) Control City GCI	(4) Control City–Year GCI	(5) Remove Special Samples GCI	(6) Lagged Control Variables GCI
DRTI		0.2286 *** (0.0388)	0.2164 *** (0.0357)	0.2313 *** (0.0408)	0.2259 *** (0.0381)	0.2201 *** (0.0391)
DRTI_T	0.1227 *** (0.0308)					
Controls/Ind/Year	YES	YES	YES	YES	YES	YES
Ind–Year	NO	YES	NO	NO	NO	NO
City	NO	NO	YES	NO	NO	NO
City–Year	NO	NO	NO	YES	NO	NO
Constant	0.5754 *** (0.2037)	−0.6556 *** (0.1551)	−0.6454 *** (0.1601)	−0.6594 *** (0.1802)	−0.6150 *** (0.1381)	−0.7260 *** (0.1745)
Obs	17,422	17,428	17,428	17,428	9855	14,138
A-R ²	0.1113	0.1479	0.1829	0.1072	0.1957	0.1507

Note: *** indicate significance at the 1%.

5.4. Mechanism Tests

To further identify the mechanisms by which digital and real technological integration affects corporate green collaborative innovation, we draw on the approach of mediating effect testing [70] and use stepwise regression. The specific model is as follows.

$$Med_{it} = \beta_0 + \beta_1 DRTI_{it} + \beta_2 Controls_{it} + \theta_k + \mu_t + \varepsilon_{it} \quad (2)$$

$$GCI_{it} = \gamma_0 + \gamma_1 Med_{it} + \gamma_2 DRTI_{it} + \gamma_3 Controls_{it} + \theta_k + \mu_t + \varepsilon_{it} \quad (3)$$

In models (1) and (3), $GCI_{i,t}$ is the dependent variable, $DRTI_{i,t}$ is the independent variable, and $Controls$ is the set of control variables. In model (2), $Med_{i,t}$ denotes the dependent variables, namely asset specificity, green agency costs and green knowledge breadth. $DRTI_{i,t}$ serves as the independent variable, while $Controls_{i,t}$ represents the set of control variables. In accordance with model (1), we further control for fixed effects at the industry (θ_k) and year (μ_t) levels. i denotes the firm, k denotes the industry, and t denotes the year. Additionally, $\varepsilon_{i,t}$ is the random disturbance term. If α_1 , β_1 , γ_1 and γ_2 are significant, this indicates that H_2 , H_3 and H_4 hold.

Regarding asset specificity (AS), we employ the ratio (fixed assets + construction in progress + intangible assets + deferred expenses)/total assets to measure asset specificity [44]. Column (2) of Table 6 shows that the coefficient for DRTI is significantly negative, indicating that digital and real technological integration can mitigate asset specificity. Column (3) shows that the coefficient for AS is significantly negative, while the coefficient for DRTI is significantly positive, indicating that digital and real technological integration mitigates asset specificity and thereby promotes corporate green collaborative innovation. The reduction in asset specificity substantially diminishes the risk of assets becoming locked-in for purposes other than innovation strategy, dismantles information barriers arising from highly specialized assets, optimizes the efficiency of corporate resource allocation, enhances the adaptability and coordination of cross-organizational multi-source resource deployment, and fosters positive interaction and mutual reinforcement between enterprises and innovation entities during green collaborative innovation.

Table 6. Mediating effect tests: asset specificity.

	(1) GCI	(2) AS	(3) GCI
DRTI	0.2259 *** (0.0381)	−0.0027 *** (0.0010)	0.2255 *** (0.0380)
AS			−0.2029 ** (0.0809)
Controls/Ind/Year	YES	YES	YES
Constant	−0.6414 *** (0.1531)	0.0412 *** (0.0095)	−0.6207 *** (0.1511)
Obs	17,428	17,426	17,426
A-R ²	0.1521	0.1585	0.1541
Sobel test	0.003 ***		

Note: ***, ** indicate significance at the 1%, 5% levels, respectively.

Regarding green agency costs (GAC), based on the logic of agency costs [71,72], we measure green agency costs by dividing the total amount of expenses related to environmental management, such as landscaping and sanitation fees, from the administrative expenses subaccounts by operating revenue. These environmental and pollution control expenditures include a significant discretionary component, beyond the minimum compliance requirements, such as voluntary environmental investments and measures to address emissions exceeding standards. It is precisely this component that serves as the vehicle for agency problems. If management overspends to build an environmental reputation, or conversely, cuts back on necessary expenditures to boost short-term performance, such actions are reflected in abnormal fluctuations in this metric. Column (2) of Table 7 presents that the coefficient for DRTI is significantly negative, indicating that digital and real techno-

logical integration can reduce green agency costs. Column (3) shows that the coefficient for GAC is significantly negative, while the coefficient for DRTI is significantly positive, indicating that digital and real technological integration reduces green agency costs and thereby promotes corporate green collaborative innovation. The reduction in green agency costs alleviates agency conflicts, diminishes innovation friction both within the firm and between the firm and external innovation agents, and safeguards the firm's long-term capital investment. Ultimately, this facilitates the implementation and stable operation of corporate green collaborative innovation strategy.

Table 7. Mediating effect tests: green agency costs.

	(1) GCI	(2) GAC	(3) GCI
DRTI	0.2259 *** (0.0381)	−0.0473 ** (0.0198)	0.2226 *** (0.0378)
GAC			−0.0402 * (0.0233)
Controls/Ind/Year	YES	YES	YES
Constant	−0.6414 *** (0.1531)	0.8501 * (0.4701)	−0.6538 *** (0.1576)
Obs	17,428	17,167	17,167
A-R ²	0.1521	0.3001	0.1506
Sobel test	0.009 ***		

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Regarding green knowledge breadth (GKB), we draw upon the patent breadth method from a similar study to measure green knowledge breadth at the enterprise level [73]. Column (2) in Table 8 shows that the coefficient for DRTI is significantly positive, indicating that digital and real technological integration can broaden green knowledge. Column (3) shows that the coefficient for GKB is significantly positive, while the coefficient for DRTI is significantly positive, indicating that digital and real technological integration broadens green knowledge breadth and thereby promotes corporate green collaborative innovation. This expansion of green knowledge helps enterprises bridge potential gaps in their green knowledge base, enrich their experience reserves related to green innovation, and deepen their green knowledge. It provides a foundation for more efficient knowledge matching and interaction with collaborative partners, ultimately enhancing diverse knowledge combinations and enabling green collaborative innovation.

Table 8. Mediating effect tests: green knowledge breadth.

	(1) GCI	(2) GKB	(3) GCI
DRTI	0.2259 *** (0.0381)	0.1511 *** (0.0405)	0.2231 *** (0.0399)
GKB			0.0316 *** (0.0068)
Controls/Ind/Year	YES	YES	YES
Constant	−0.6414 *** (0.1531)	−3.7767 *** (0.3607)	−0.5702 (0.8229)
Obs	17,428	17,311	17,311
A-R ²	0.1521	0.6663	0.1574
Sobel test	0.012 **		

Note: ***, ** indicate significance at the 1%, 5% levels, respectively.

Additionally, Tables 6–8 show that the Z-statistics for the Sobel tests are all significant, confirming the presence of a mediating effect. The results using bootstrap methods (with 1000 bootstrap samples) in Table 9 show that the 95% confidence intervals for both the indirect and direct effects do not include 0, indicating that the mediating effect is significant and partial.

Table 9. Bootstrap tests.

		95% Confidence Interval	
		Lower Limit	Upper Limit
AS	Indirect Effect	0.0002	0.0017
	Direct Effect	0.1888	0.2611
GAC	Indirect Effect	0.0001	0.0006
	Direct Effect	0.1942	0.2667
GKB	Indirect Effect	0.0031	0.0063
	Direct Effect	0.1909	0.2674

5.5. Heterogeneity Analysis

5.5.1. Analysis of Heterogeneity Based on the Internal Control Quality

The quality of internal controls determines compliance with corporate regulations and procedures, evolving into the foundational safeguard for the orderly advancement and steady coordination of corporate innovation activities [74]. We calculate the internal control quality (DIB) by adding 1 to the internal control score from the “DIB China Listed Companies Internal Control Index” and taking its natural logarithm. A higher DIB indicates superior internal control quality. We group and regress based on the annual median of internal control quality within the industry. Columns (1) and (2) of Table 10 indicate that the promotion of corporate green collaborative innovation by digital and real technological integration is more pronounced in firms with high internal control quality. Fisher’s combined test reveals a statistically significant difference in the inter-group coefficient at the 10% level, supporting the findings of this heterogeneity analysis.

Table 10. Heterogeneity tests.

	(1) High Internal Control Quality	(2) Low Internal Control Quality	(3) High-Tech Enterprise	(4) Non-High-Tech Enterprises	(5) Eastern Enterprises	(6) Central and Western Enterprises
	GCI	GCI	GCI	GCI	GCI	GCI
DRTI	0.2395 *** (0.0501)	0.1843 *** (0.0474)	0.2434 *** (0.0485)	0.1875 ** (0.0511)	0.2389 *** (0.0482)	0.1902 *** (0.0510)
Controls/Ind/Year	YES	YES	YES	YES	YES	YES
Constant	−0.6971 *** (0.2089)	−0.5047*** (0.1932)	−0.6640 *** (0.1872)	−0.5974 ** (0.2583)	−0.7724 *** (0.2003)	−0.5072 ** (0.2337)
Obs	9670	7758	13,158	4270	9410	8018
A-R ²	0.1311	0.2190	0.1223	0.1242	0.1208	0.2432
p-value	0.088 *		0.012 **		0.003 ***	

Note: The *p*-value for the test of differences in coefficients between groups is obtained using Fisher’s combined test (1000 samples). ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

The underlying reason for this outcome may be that high-quality internal controls establish a proactive control environment. Rigorous institutional arrangements form process-oriented control activities, providing procedural safeguards for enterprises undertaking green collaborative innovation projects [75]. Simultaneously, high-quality internal controls closely ensure the timeliness of risk assessment and response, largely creating an environment that elevates mutual trust among innovation participants and mitigates moral

hazard. This, in turn, reduces disagreements and resistance during innovation project implementation. Consequently, the promotional effect of digital and real technological integration on corporate green collaborative innovation is more pronounced in enterprises with high internal control quality.

5.5.2. Analysis of Heterogeneity Based on the Industry in Which the Enterprise Operates

The heterogeneity of industry attributes characterizes differences in corporate investment tendencies and production operations, potentially influencing the level of digital and real technological integration. Therefore, based on differing industry attributes and in accordance with the document “National Key Supported High-Tech Fields,” we assign high-tech industry codes to classify sample enterprises into two categories: high-tech and non-high-tech enterprises. We employ separate regression analyses for each group to test for industry attribute heterogeneity. Columns (3) and (4) demonstrate that the promotion of corporate green collaborative innovation through digital and real technological integration is more pronounced in high-tech enterprises. Fisher’s combined test reveals a significant difference in the inter-group coefficients at the 5% level, supporting the findings of this heterogeneity analysis.

The underlying reason for this outcome may be that high-tech enterprises are knowledge-intensive and technology-intensive economic entities. Engaged in high-tech-related operations and management for extended periods, they possess the foundational capabilities for technological integration. Furthermore, such enterprises treat technology as their core competitive advantage, exhibiting stronger demands for technological renewal and iteration. Consequently, they are more inclined to proactively drive the integration of digital and real technologies within their organizations [76]. Conversely, non-high-tech enterprises may face higher costs in knowledge search and absorption, making it nearly impossible to uncover potential linkages between technological integration. Consequently, the promotional effect of digital and real technological integration on corporate green collaborative innovation is more pronounced among high-tech enterprises.

5.5.3. Analysis of Heterogeneity Based on the Region Where Enterprises Are Located

Regional heterogeneity manifests in differences across institutional policies, information infrastructure, and market efficiency, which may influence the process and outcomes of corporate green collaborative innovation. Based on the National Bureau of Statistics’ classification criteria for eastern, central, and western regions, and according to the actual operational provinces of listed firms, we divide the entire sample into two categories: enterprises located in eastern regions and those in central and western regions. We then employ separate regression analyses for each group to test for regional heterogeneity. Columns (5) and (6) reveal that the promotion of corporate green collaborative innovation through digital and real technological integration is more pronounced among eastern enterprises. Fisher’s combined test reveals a significant difference in the inter-group coefficients at the 1% level, supporting the findings of this heterogeneity analysis.

The underlying reason for this outcome may be that eastern regions boast more developed economies, featuring more mature market environments and institutional infrastructure. Superior resource allocation and a favorable resource environment provide the foundation for sustained communication and collaboration among innovation entities. Simultaneously, the more intense and comprehensive competition in eastern regions has, to some extent, compelled enterprises to advance the integration of digital and real technologies, thereby securing market position and competitive advantages. Consequently, the promotional effect of digital and real technological integration on corporate green collaborative innovation is more pronounced among enterprises in eastern regions.

6. Conclusions and Policy Implications

6.1. Conclusions

Using China's A-share listed firms as our research sample and based on firm-level microdata, we conduct an in-depth exploration of the impact and mechanism of digital and real technological integration on corporate green collaborative innovation. Our findings reveal that digital and real technological integration significantly promotes green collaborative innovation, and this conclusion remains valid after undergoing a series of endogeneity and robustness tests. Mechanism analysis indicates that digital and real technological integration facilitates green collaborative innovation by reducing green agency costs, suppressing asset specificity, and expanding the breadth of green knowledge. Heterogeneity analysis reveals that the positive impact of digital and real technological integration on corporate green collaborative innovation is more pronounced among firms with higher internal control quality, operating in high-tech industries, and located in eastern regions, compared to those with lower internal control quality, in non-high-tech industries, and in central and western regions.

6.2. Policy Implications

Firstly, the government should establish a top-level design framework to provide institutional guidance and policy safeguards. On the one hand, it should setup a special fund for the integration of digital and physical technologies, clearly defining key areas for support. By deploying differentiated policy tools, it can effectively stimulate enterprises' intrinsic motivation for technological convergence, fostering the formation of digital technology industry clusters with high technical barriers and significant value-added potential. It should encourage collaborative transformation among enterprises within these clusters. On the other hand, the government should advance the internationalization of technical standards to enhance global influence. By collaborating with industry associations, research institutions, and leading enterprises, it should assemble cross-sectoral and cross-regional expert teams to systematically develop foundational universal standards, key technical standards, and industrial application standards for the integration of digital and physical technologies.

Secondly, the government should strengthen capacity building and knowledge transfer between enterprises and external innovation entities. On the one hand, relevant departments should establish a pairing assistance mechanism to support digitally advanced enterprises in providing services such as smart manufacturing solution design, industrial software application training, and digital transformation planning consultation to lagging enterprises through technology transfer, management empowerment, and joint R&D. On the other hand, government departments should amplify the exemplary impact of model enterprises in areas like smart factory construction, industrial internet applications, and supply chain digital restructuring. This can be achieved through organizing on-site demonstrations, compiling transformation white papers, and establishing digital exhibition halls, thereby fostering a virtuous cycle of interaction.

Finally, enterprises themselves should accelerate digital transformation and technological architecture. On the one hand, existing core production management systems such as ERP and MES should undergo cloud-based and microservices-oriented upgrades to enhance their flexibility and openness, enabling rapid integration with cutting-edge technologies like AI and big data analytics. Simultaneously, breaking down departmental silos is essential, forming integrated teams comprising business units, IT departments, production operations, and data analysts to ensure technological solutions closely align with the practical demands of green collaborative innovation. On the other hand, enterprises can conduct a comprehensive digital maturity assessment by benchmarking against industry

leaders. They should develop a phased implementation plan, simultaneously advancing the construction of technical platforms and the development of organizational talent reserves. Enterprises must precisely identify entry points for integrating digital technologies with physical systems and the anticipated value. They should establish agile, fault-tolerant R&D and project management mechanisms that encourage rapid experimentation and continuous iteration.

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