



Firms' digital capabilities and green collaborative innovation: The role of green relationship learning

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ABSTRACT

With the growth of the digital economy and environmental concerns, an increasing number of manufacturing firms are leveraging digitalization to advance their green innovation and sustainable development. Although previous studies have examined the impact of digitalization on green innovation, few studies have investigated the effect of digital capabilities on green collaborative innovation. We theoretically classify four dimensions of firms' digital capabilities—digital infrastructure capability, digital perception capability, digital operation capability, and digital collaboration capability—and categorize green collaborative innovation into green product collaborative innovation and green process collaborative innovation. Based on the survey data of Chinese high-tech manufacturing firms, we found that (a) four dimensions of firms' digital capabilities have positive impacts on green product and green process collaborative innovation; (b) green relationship learning mediates the relationships among four dimensions of digital capabilities and two types of green collaborative innovation; and (c) green organizational identity positively moderates the relationships among digital infrastructure capability, digital perception capability, and digital collaboration capability and two types of green collaborative innovation; a collaborative innovation atmosphere positively moderates the relationship between green relationship learning and two types of green collaborative innovation. These findings contribute theoretically to the fields of digital capabilities and green collaborative innovation while providing new implications for managers to achieve sustainability in the digital transformation context.

Introduction

Given the urgent severity of environmental challenges and the inherent complexities of technological innovation, green collaborative innovation has emerged as a crucial strategy for organizations seeking to address environmental issues through collective action (Coughlan et al., 2023; Hong et al., 2019). This collaborative innovation is vital for combating climate change, minimizing resource consumption, and adhering to evolving regulatory standards (Melander, 2017; Zubeltzu-Jaka et al., 2018). Concurrently, digitalization has played a transformative role by offering advanced platforms and technologies that enhance collaboration and address externalities related to environmental and technological challenges (Annarelli et al., 2021; Xie et al., 2022a). Companies that effectively develop digital capabilities are therefore better positioned to enhance green innovation (Li et al., 2023a; Tian et al., 2022) and collaboration related to environmental challenges (Xie et al., 2022a). Consequently, understanding how digital capabilities can influence green collaborative innovation is crucial for advancing

sustainability.

The influence of digital capabilities on green collaborative innovation represents an important question in the literature on open innovation theory (Laursen & Salter, 2006; 2014) and environment management (Liu et al., 2024; Zhang & Meng, 2023). The literature has examined the positive effect of digital capabilities on green innovation (Jing et al., 2023; Zhang & Meng, 2023). Thus, studies have implicitly assumed that a firm's internal digital capabilities can influence its green innovation. This implicit assumption may hinder our understanding of enterprise digital capabilities by overlooking other participants in green innovation. For example, collaborations with external partners (e.g., customers) offer opportunities for new product designs and provide benefits for green product innovation (Melander, 2018b). Although some scholars have marginally relaxed the implicit assumption and argued that digital capabilities contribute to green supply chain innovation (Qiao et al., 2023; Sarkis et al., 2020) and green industry–university–research innovation (Zhang et al., 2020) and involve several external partners from a limited perspective, it is not clear

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whether digital capabilities affect green collaborative innovation on a general level. To address this question, we further relax the implicit assumption and propose our first research question (RQ1): Do digital capabilities positively affect green collaborative innovation?

Furthermore, although the literature reveals the indirect effects of green supply chain learning (Qiao et al., 2023) and green innovation intention (Tian et al., 2022) on the relationship between digital capabilities and green innovation, more in-depth research on the underlying mechanism of digital capabilities and green collaborative innovation is still required. According to organizational learning theory, green relationship learning is defined as a collective interorganizational learning encompassing green information sharing, green knowledge integration, and common understanding of green knowledge (Cui et al., 2020; Juo & Wang, 2022; Selnes & Sallis, 2003). Green relationship learning could therefore serve as a crucial link between digital capabilities and green collaborative innovation, considering its mediating role in the path of green innovation (Pham et al., 2023; Zhang & Zhu, 2019). Digital capabilities enable firms to extensively integrate their digital assets with external green resources and leverage digital platforms to create green collaborative innovation networks, thereby promoting green relationship learning (Annarelli et al., 2021; Juo & Wang, 2022). Green relationship learning also allows firms to gain the opportunity to share green information with their partners (Juo & Wang, 2022), acquire green knowledge and green ideas from various stakeholders (Zhang & Zhu, 2019), and develop a shared understanding of green significance among green innovators (Selnes & Sallis, 2003), thus enhancing green collaborative innovation. However, few studies have examined the internal mechanism behind the relationship between digital capabilities and green collaborative innovation from the green relationship learning perspective. This study therefore addresses this gap in the literature by investigating the second research question (RQ2): How do digital capabilities affect green collaborative innovation through green relationship learning?

Although recent studies have examined various contextual factors that could influence the benefits of digital capabilities, including internal and interorganizational contextual factors (Cenamor et al., 2019; Gong et al., 2023; Huang et al., 2022), minimal research has explored possible ramifications of the impact of digital capabilities on green collaborative innovation. We therefore introduced internal and interorganizational contextual factors to enrich the links among digital capabilities, green relationship learning, and green collaborative innovation. For internal organizational contextual factors, given that previous research has suggested that innovators with green organizational identity are deeply committed to sustainability (Chen, 2011; Song et al., 2019), we introduced green organizational identity to explore its moderating effect on the relationship between digital capabilities and green collaborative innovation. For interorganizational contextual factors, previous studies have suggested that a collaborative innovation atmosphere, which is an emotional setting that fosters trust, open communication, shared goals, and mutual respect among innovators, is crucial for green relationship learning in green collaborative innovation networks (Amabile et al., 1996; Meena et al., 2023; Sun et al., 2023). Consequently, we introduced the collaborative innovation atmosphere to investigate its moderating effect on the relationship between green relationship learning and green collaborative innovation. This study therefore addresses this gap in the previous literature by examining the third research question (RQ3): When do green organizational identity and a collaborative innovation atmosphere affect the relationship between digital capabilities and green collaborative innovation?

In this study, we sought to close the aforementioned research gaps. First, we divided digital capabilities into four dimensions—digital infrastructure capability, digital perception capability, digital operation capability, and digital collaboration capability. Then we distinguished between two types of green collaborative innovation—green product and green process collaborative innovation—and examined the influence of four dimensions of digital capabilities on two types of green

collaborative innovation. Thus, this study makes a broader contribution to open innovation theory and green innovation research by highlighting the role of digital capabilities in promoting green collaborative innovation. Second, this study investigates the mediating role of green relationship learning in the relationship between digital capabilities and green collaborative innovation. This contribution thereby broadens the scope of the research on the internal mechanism of the digital capabilities driving green collaborative innovation from the perspective of organizational learning and extends the application of organizational learning theory into green collaborative innovation research. Third, this study examines the moderating effects of green organizational identity and a collaborative innovation atmosphere on the relationships among digital capabilities, green relationship learning, and green collaborative innovation. Thus, we advance the green collaborative innovation literature by examining when internal and interorganizational contextual factors affect the determinants of green collaborative innovation.

Theory and hypotheses

Theoretical background and framework

Since the beginning of the fourth industrial revolution, termed Industry 4.0, digital technologies have offered various opportunities to address environmental issues and drive green innovation (Mubarak & Petraite, 2020). Firms' production and innovation processes have become more intelligent because of digital technologies (Chen et al., 2024), and by enabling real-time data sharing and connectivity, digital technologies facilitate partnerships among firms, governments, and other stakeholders, enabling the joint development of sustainable solutions (Jiao et al., 2021). As scholars delve into the integration of digital technologies, digital capabilities have clearly become essential for firms to provide innovative solutions, foster collaboration across sectors, and ultimately lead to sustainability (Albats et al., 2022; Quttainah & Ayadi, 2024). Digital capabilities are therefore becoming the ultimate catalyst for transformative change in green collaborative innovation.

This study develops a comprehensive theoretical framework to understand how firms leverage digital capabilities to enhance green collaborative innovation. Specifically, we present seven hypotheses regarding firms' green collaborative innovation. First, this study divides digital capabilities into four dimensions—digital infrastructure capability, digital perception capability, digital operation capability, and digital collaboration capability—and identifies two types of green collaborative innovation—green product and green process collaborative innovation. Specifically, this study proposes that digital infrastructure capability can drive two types of green collaborative innovation (H1), digital perception capability can drive two types of green collaborative innovation (H2), digital operation capability can drive two types of green collaborative innovation (H3), and digital collaboration capability can drive two types of green collaborative innovation (H4). Second, from an organizational learning perspective, green relationship learning may play a mediating role in the relationship between digital capabilities and green collaborative innovation (H5). Third, green organizational identity can be an internal organizational contextual factor that affects the relationship between digital capabilities and green collaborative innovation (H6). Collaborative innovation atmosphere can be an interorganizational contextual factor that affects the relationship between green relationship learning and green collaborative innovation (H7). Together, this framework offers an integrated perspective on how firms leverage digital capabilities to improve green collaborative innovation (Fig. 1).

Digital capabilities and green collaborative innovation

Digital capabilities refer to the comprehensive ability of a firm to apply digital technology to integrate digital assets and resources, innovate products and processes, and achieve sustained competitive

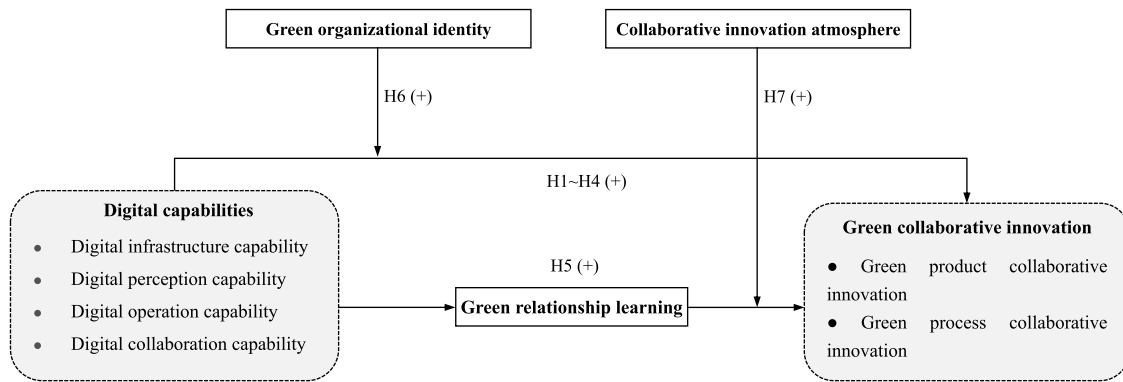


Fig. 1. Conceptual model.

advantages (Annarelli et al., 2021; Vial, 2019). Integrating the technological and dynamic capability perspectives, digital capabilities are categorized into four dimensions: digital infrastructure capability, digital perception capability, digital operation capability, and digital collaboration capability (Lenka et al., 2017; Warner & Waeger, 2019; Wheeler, 2002). Digital infrastructure capability involves the deployment of digital technologies, the digitization of internal resources, and basic data analysis skills, representing a fundamental digital competence (Lenka et al., 2017). Digital perception capability encompasses the use of digital tools and systems to collect, analyze, and derive insights from data for informed decision-making (Warner & Waeger, 2019). Digital operation capability highlights how firms utilize digital technology to digitize internal R&D, production, marketing, and services, reflecting a sophisticated ability to deliver advanced digital solutions (Warner & Waeger, 2019). Digital collaboration capability pertains to the flexible allocation and integration of internal and external resources through digital technology, thereby enabling effective collaboration across departments and with external partners (Warner & Waeger, 2019).

Green collaborative innovation encompasses the cocreation of innovations and value-sharing among firms and their partners through the establishment of a collaborative network and the exchange of green innovation resources, including technologies, equipment, and knowledge (Coughlan et al., 2023; Hong et al., 2019). According to innovation objectives, green collaborative innovation can be categorized into two types: green product collaborative innovation and green process collaborative innovation (Coughlan et al., 2023; Melander, 2018b). Green product collaborative innovation refers to the joint efforts of all partners to enhance the environmental friendliness of products, including addressing green innovation demands, investing in practices that reduce environmental impact throughout the product lifecycle, and improving material reuse and recycling efficiency (Melander, 2017; Xie et al., 2019a). Green process collaborative innovation emphasizes joint investments in clean production technologies and green processes, aiming to minimize environmental impact and energy consumption across each stage of the production value chain (Coughlan et al., 2023; Xie et al., 2022b). Next, we will elaborate on how the four dimensions of digital capabilities affect two types of green collaborative innovation.

Digital infrastructure capability and green collaborative innovation

Digital infrastructure capability assesses whether a firm has a digital infrastructure foundation and the capability to apply digital technology (Lenka et al., 2017). First, we propose that firms' digital infrastructure capability can promote green product collaborative innovation. Specifically, firms equipped with digital infrastructure capabilities can effectively showcase the carbon footprint of products through digital technology and enhance the transparency of green product information (Li et al., 2023b). Firms with digital infrastructure capabilities can support third parties in completing digital certifications for green products, ensure compliance with environmental standards, and

facilitate their integration into the green collaborative innovation network (Tian et al., 2024), thereby advancing green product collaborative innovation. Second, we propose that firms' digital infrastructure capability can promote green process collaborative innovation. Specifically, firms with digital infrastructure capability can optimize production processes and monitor production stages using technologies such as real-time logistics tracking for warehousing, packaging, transportation, loading, and unloading (Tian et al., 2022). This approach allows firms to oversee low-carbon operations for themselves and their partners, ensuring that all stages comply with low-carbon standards, thereby advancing green process collaborative innovation. Therefore, we propose:

H1: Firms' digital infrastructure capability positively impacts green collaborative innovation (H1a: green product collaborative innovation; H1b: green process collaborative innovation).

Digital perception capability and green collaborative innovation

Digital perception capability evaluates how firms leverage digital technology to detect current and emerging market demands, analyze the competitive landscape, and discern digital trends (Warner & Waeger, 2019). First, we propose that firms' digital perception capability can promote green product collaborative innovation. Specifically, firms with digital perception capability can expand information sources through digital technology, gather data on potential market demand for green products, and align market feedback with partners to refine green innovation (Demirel & Kesidou, 2019). Consequently, firms and their partners collaboratively enhance green product design to align with future trends while mitigating the risk of losing the green competitive advantage because of knowledge rigidity (Melander, 2018a), thereby advancing green product collaborative innovation. Second, we propose that firms' digital perception capability can promote green process collaborative innovation. Digital perception capability enhances a firm's capacity to conduct cross-sector searches, thereby facilitating the optimal allocation of limited green innovation resources, improving production and operational processes within the supply chain, and increasing the efficiency of green process collaborative innovation (Wong et al., 2020). Further, firms can leverage digital perception capability to enhance their ability to learn and assimilate green knowledge, facilitate the replacement of outdated processes, and implement new technologies for themselves and their partners, thereby advancing green process collaborative innovation (Tian et al., 2022; Xie et al., 2022b). Therefore, we propose:

H2: Firms' digital perception capability positively impacts green collaborative innovation (H2a: green product collaborative innovation, H2b: green process collaborative innovation).

Digital operation capability and green collaborative innovation

Digital operation capability refers to the flexible management skill that drives business development, delivers digital solutions, and

innovates business models through digital technologies (Warner & Waeger, 2019). First, we propose that firms' digital operation capability can promote green product collaborative innovation. Firms with digital operation capability can leverage digital channels, such as e-commerce platforms and social networks, to engage promptly with external stakeholders (Rong et al., 2022). This facilitates accurate targeting and delivery of green products to customers and enables the integration of external green ideas into product development to address diverse market demands, thereby enhancing green product collaborative innovation (Makkonen & Komulainen, 2018). Second, we propose that firms' digital operation capability can promote green process collaborative innovation. For example, firms can employ digital twin technology to simulate transportation processes, enhancing the environmental efficiency of logistics (Defraeye et al., 2019). Firms with digital operation capability can therefore offer digital solutions for manufacturing processes by extensively monitoring and optimizing material and energy flows, thus fostering green process collaborative innovation. Therefore, we propose:

H3: Firms' digital operation capability positively impacts green collaborative innovation (H3a: green product collaborative innovation, H3b: green process collaborative innovation).

Digital collaboration capability and green collaborative innovation

Digital collaboration capability focuses on the flexible configuration and digital governance skills of enterprises to achieve data collaboration, resource collaboration, and business process collaboration through digital technologies (Warner & Waeger, 2019). First, we propose that firms' digital collaboration capability can promote green product collaborative innovation. Specifically, firms with digital collaboration capability can utilize digital technology to enhance data connectivity and optimize data flow across their networks, facilitating the sharing of green product information among partners and mitigating one-dimensional views of green product innovation (Albats et al., 2022). Firms and their partners therefore develop a shared understanding of green product innovation, thereby enhancing the efficiency and quality of green product collaborative innovation (Fang et al., 2022; Quttainah & Ayadi, 2024). Second, we propose that firms' digital collaboration capability can promote green process collaborative innovation. Digital collaboration capability fosters seamless communication, coordination, and data sharing among firms and their partners, thereby enabling the more effective integration of green practices into processes (Ghobakhloo et al., 2021). Firms can also leverage digital collaboration capability to acquire green process information and technology, effectively integrate external green resources across various partners, and consequently enhance green process collaborative innovation (Lin & Maruping, 2022). Therefore, we propose:

H4: Firms' digital collaboration capability positively impacts green collaborative innovation (H4a: green product collaborative innovation; H4b: green process collaborative innovation).

Mediating effect of green relationship learning

Green relationship learning refers to collective interorganizational learning that encompasses green information sharing, a shared understanding of green concepts, and the integration of green knowledge among firms and their partners (Juo & Wang, 2022; Selnes & Sallis, 2003). Considering that partners within the green collaborative innovation network are digitally connected, the integration of internal and external knowledge enhances green relationship learning and encourages partners to participate in green collaborative innovation (Albats et al., 2022). Green relationship learning therefore plays a mediating role in the relationship between digital capabilities and green collaborative innovation.

First, we propose that green relationship learning mediates the relationship between digital infrastructure capability and green collaborative innovation. Digital infrastructure capability helps firms establish a green relationship network and facilitates green relationship learning.

Digital infrastructure capability enables firms to bridge geographical and intangible (e.g., cognitive and social) distances and build a green relationship network among partners through digital tools (Abbasiharofteh et al., 2024; Rimjhim et al., 2020), in turn encouraging partners within the network to engage in cross-border green relationship learning. Green relationship learning also encourages firms to use digital infrastructure capabilities to acquire more market information for green products, attracting more collaborative partners (Melander, 2018b), thus promoting green product collaborative innovation. Green relationship learning also aids firms and partners in understanding new green technologies and processes, facilitating the application of digital infrastructure in green process innovation and enhancing green process collaborative innovation (Yang & Sun, 2023). Overall, firms with digital infrastructure capability can build a green relationship network through digital technology and realize the sharing of green information and technology, thus achieving green collaborative innovation through green relationship learning. Therefore, we propose:

H5a: Green relationship learning mediates the relationship between digital infrastructure capability and green collaborative innovation (H5a₁: green product collaborative innovation; H5a₂: green process collaborative innovation).

Second, we propose that green relationship learning mediates the relationship between digital perception capability and green collaborative innovation. Digital perception capability enables firms to acquire external knowledge and information from partners, thereby enhancing green relationship learning. Digital perception capability enhances information transmission and communication efficiency with collaborative partners and facilitates effective interorganizational communication, advancing green relationship learning (Quttainah & Ayadi, 2024; Warner & Waeger, 2019). Green relationship learning also deepens innovators' understanding of green innovation, thereby enhancing green collaborative innovation among firms and their partners. Specifically, green relationship learning fosters a shared understanding of market demand for green products among innovative partners, optimizes the distribution of benefits for green product collaborative innovation, and thus promotes such innovation (Juo & Wang, 2022; Melander, 2017). Green relationship learning also enhances innovators' comprehension of green technologies and processes, improving the prediction of disruptive green technologies and reducing uncertainty in green process innovation for firms and their partners, in turn, fostering green process collaborative innovation (Benzidia et al., 2021). Overall, firms with digital perception capability can enhance the efficiency of green knowledge sharing, deepen green cognition, and foster green collaborative innovation through green relationship learning. Therefore, we propose:

H5b: Green relationship learning mediates the relationship between digital perception capability and green collaborative innovation (H5b₁: green product collaborative innovation; H5b₂: green process collaborative innovation).

Third, we propose that green relationship learning mediates the relationship between digital operation capability and green collaborative innovation. Digital operation capability enhances green operations solutions, attracts more green partners, expands the knowledge base within the green relational network, and stimulates the willingness to learn among partners, thereby strengthening green relationship learning (Benzidia et al., 2021). In addition, green relationship learning optimizes the structure of technological resources within internal business operations and the green collaborative innovation network, thereby advancing green collaborative innovation. Green relationship learning encourages innovation actors to invest more in green-specific human resources that aid in the research and design of green products, attracting more partners for green product development and fostering green product collaborative innovation (Melander, 2018b; Yong et al., 2019). Green relationship learning therefore fosters positive communication among green innovation actors, accelerating resource transfer within the network and minimizing wasteful investments in green

technologies and process innovation costs, in turn, promoting green process collaborative innovation (Ghobakhloo et al., 2021; Juo & Wang, 2022). Overall, firms with digital operation capability can leverage digital technology to enhance green operations and attract more partners for green relationship learning, further promoting green collaborative innovation. Therefore, we propose:

H5c: Green relationship learning mediates the relationship between digital operation capability and green collaborative innovation (H5c₁: green product collaborative innovation; H5c₂: green process collaborative innovation).

Finally, we propose that green relationship learning mediates the relationship between digital collaboration capability and green collaborative innovation. Digital collaboration capability enhances firms' knowledge integration and facilitates the circulation of data and technologies within green collaborative networks, promoting green relationship learning (Kohtamäki & Partanen, 2016). Green relationship learning also encourages firms and their partners to collaboratively address environmental issues, fostering green collaborative innovation. For example, green relationship learning between suppliers and customers aids in tracking carbon emissions within supply chains and setting low-carbon standards, thereby enhancing green product collaborative innovation (Hong et al., 2019). Additionally, green relationship learning encourages firms to interact with their green partners during manufacturing processes and facilitates joint efforts to address unresolved green technology issues within the collaborative innovation network (Wu et al., 2022), advancing green process collaborative innovation. Overall, digital collaboration capability motivates firms and their partners to collaboratively address environmental issues during green product and process innovation, fostering green collaborative innovation through effective green relationship learning. Therefore, we propose:

H5d: Green relationship learning mediates the relationship between digital collaboration capability and green collaborative innovation (H5d₁: green product collaborative innovation; H5d₂: green process collaborative innovation).

Moderating effect of green organizational identity

Green organizational identity represents a shared understanding among members of the organization regarding its green identity, including achieving consensus on sustainable development and green innovation strategies, committing to the integration and development of green resources, and enhancing the organization's green competitive advantage (Chen, 2011; Song et al., 2019). First, we propose that green organizational identity moderates the relationships between digital infrastructure capability and green collaborative innovation. Green organizational identity can enhance the impact of digital infrastructure capability on green product collaborative innovation. Firms with a strong green organizational identity can leverage digital infrastructure capability to integrate diverse green technologies and resources, enhancing their adaptability in product innovation (Song et al., 2019). Furthermore, green organizational identity influences partners' behavioral norms and intensifies their focus on green products, driving firms and partners to utilize digital infrastructure for technology training and mutual environmental monitoring (Panda, 2023), further promoting the impact of digital infrastructure capability on green collaborative product innovation. Green organizational identity can also enhance the impact of digital infrastructure capability on green process collaborative innovation. Firms with a strong green organizational identity place greater emphasis on environmental performance data, such as carbon emissions and energy consumption, monitored via digital infrastructure (Panda, 2023; Tian et al., 2024). This emphasis enhances the capability of digital infrastructure to address environmental issues in production processes and attracts more partners involved in green production and operations, thereby reinforcing the positive impact of digital infrastructure on green process collaborative innovation (Ghobakhloo et al.,

2021). Therefore, we propose:

H6a: Green organizational identity positively moderates the relationship between digital infrastructure capability and green collaborative innovation (H6a₁: green product collaborative innovation; H6a₂: green process collaborative innovation).

Second, we propose that green organizational identity moderates the relationships between digital perception capability and green collaborative innovation. Green organizational identity can enhance the impact of digital perception capability on green product collaborative innovation. Specifically, firms with a strong green organizational identity are more likely to view green product innovation as an opportunity to enhance their competitiveness (Panda, 2023). Firms with a strong green organizational identity can therefore leverage digital perception capability to better understand market demand for green products through digital platforms and increase their efforts to seek partners for green product innovation (Melander, 2017; Xie et al., 2022a), enhancing the role of digital perception capability in promoting green product collaborative innovation. Green organizational identity can also enhance the impact of digital perception capability on green process collaborative innovation. Specifically, firms with high green organizational identity not only leverage digital perception capability to encourage their partners to actively learn new digital technology to change the traditional production process (Şengüllendi et al., 2023) but also enhance the environmental awareness of managers and pay more attention to green supply chain management (Wiredu et al., 2024). This scenario promotes the role of digital perception capability in driving green process collaborative innovation. Green organizational identity also helps firms to use digital perception to evaluate the balance of the costs and benefits of green process innovation and improve firms' green competitiveness, attracting more partners to participate in green process innovation (Panda, 2023). Green organizational identity therefore strengthens the promotion effect of digital perception capability on green process collaborative innovation. Therefore, we propose:

H6b: Green organizational identity positively moderates the relationship between digital perception capability and green collaborative innovation (H6b₁: green product collaborative innovation; H6b₂: green process collaborative innovation).

Third, we propose that green organizational identity plays a moderating role in the relationships between digital operation capability and green collaborative innovation. Green organizational identity can enhance the impact of digital operation capability on green product collaborative innovation. Specifically, firms with a strong green organizational identity can leverage their digital operation capability to shape their green brand image and increase the value creation in green products (Chen et al., 2021). This ability attracts more partners to engage in green product innovation, amplifying the role of digital operation capability in driving green product collaborative innovation. Further, firms with a strong green organizational identity can use their digital operation capability to highlight the potential value of green products through digital marketing and attract more partners to participate in green product innovation (Melander, 2017; Warner & Waeger, 2019). This effect strengthens the promotion effect of digital operation capability on green product collaborative innovation. Green organizational identity can also enhance the impact of digital operation capability on green process collaborative innovation. Specifically, green organizational identity ensures that firms prioritize green operations and effectively apply digital operation capability to develop green processes (Borah et al., 2023). In addition, green organizational identity, as a facet of corporate culture, enhances stakeholders' understanding of green process innovation (Chang & Chen, 2013). This improved understanding enables firms to leverage digital operation capability to increase partners' willingness to share digital solutions and green technologies (Song et al., 2019), further strengthening the impact of digital operation capability on green process collaborative innovation. Therefore, we propose Hypothesis 6c:

H6c: Green organizational identity positively moderates the

relationship between digital operation capability and green collaborative innovation (H6c₁: green product collaborative innovation; H6c₂: green process collaborative innovation).

Finally, we propose that green organizational identity moderates the relationships between digital collaboration capability and green collaborative innovation. Green organizational identity can enhance the impact of digital collaboration capability on green product collaborative innovation. Specifically, firms with a strong green organizational identity emphasize information sharing among green partners, thereby encouraging the use of digital collaboration capability to create information-sharing channels (Kulangara et al., 2016). This encouragement facilitates identifying gaps in the firm's green product knowledge base and encourages partners to pursue green cooperation (e.g., soliciting green product ideas from customers), thus amplifying the effectiveness of digital collaboration in advancing green product innovation (Melander, 2018a). Green organizational identity can enhance the impact of digital collaboration capability on green process collaborative innovation. Green organizational identity prioritizes environmental risk management and encourages firms to use digital collaborative capability to share technological risks with partners during green process innovation. Thus, green organizational identity helps firms and their partners focus on optimizing industrial processes with digital tools and enables a comprehensive analysis of the risks and benefits of green process collaborative innovation (Yang & Sun, 2023), thereby strengthening the role of digital collaboration capability in promoting green process collaborative innovation. Therefore, we propose:

H6d: Green organizational identity positively moderates the relationship between digital collaboration capability and green collaborative innovation (H6d₁: green product collaborative innovation; H6d₂: green process collaborative innovation).

Moderating effect of a collaborative innovation atmosphere

The collaborative innovation atmosphere refers to an environment or setting that fosters and supports the development of new ideas and solutions through collective effort (Meena et al., 2023; Sun et al., 2023). In such an environment, innovators respect one another's cultures, implement clear contractual and relational norms, and promote innovation and open communication (Sun et al., 2023). This atmosphere can influence network members' attitudes toward relationship learning and their willingness to engage in green collaborative innovation.

First, a collaborative innovation atmosphere can enhance the impact of green relationship learning on green product collaborative innovation. In a good collaborative innovation atmosphere, firms and their partners have a better understanding of green practices throughout the product lifecycle (Zeng et al., 2022). This atmosphere not only stimulates network members' willingness to engage in green relationship learning but also enhances the quality of green product information sharing, thereby strengthening the connection between green relationship learning and green product collaborative innovation. Second, collaborative innovation atmosphere can enhance the impact of green relationship learning on green process collaborative innovation. A collaborative innovation atmosphere can help firms and their partners build a green collaborative innovation network in green relationship learning and promote the absorption of heterogeneous and nonredundant green technologies within the collaborative network (Ghobakhloo et al., 2021; Sun et al., 2023). In addition, in a good collaborative innovation atmosphere, firms engage in more transparent communication with their partners, within which green relationship learning accelerates the evaluation of green process gaps and encourages all parties to optimize green processes (Wu et al., 2022), strengthening the positive effect of green relationship learning on green product collaborative innovation.

Overall, a collaborative innovation atmosphere accelerates the formation of green relationship learning and green collaborative

innovation networks among firms and their partners. Firms with a high level of collaborative innovation atmosphere can therefore better leverage green relationship learning to enhance their green collaborative innovation. Thus, we propose:

H7: A collaborative innovation atmosphere positively moderates the relationship between green relationship learning and green collaborative innovation (H7a: green product collaborative innovation; H7b: green process collaborative innovation).

Methods

Data and sample

This study collected survey data from Chinese high-tech manufacturing firms because high-tech manufacturing firms exhibit strong capabilities and intentions for digital transformation through digital technologies. High-tech manufacturing in this study includes six sectors according to the Classification of High-tech Industries (Manufacturing) (2017).^a We collected data in three steps. First, given that the respondents are required to have a certain understanding of digital technologies such as big data, we selected respondents with project experience, primarily managers and R&D staff, as our research subjects. Second, we developed an online questionnaire and randomly distributed a total of 632 questionnaires to experienced project leaders in high-tech manufacturing firms through industry associations and alumni networks. We received 307 valid samples, with an effective response rate of 48.58 %.

The characteristics of the sample are presented in Table 1. In terms of firm size, 74.2 % of firms had 20–1000 employees. Regarding firm sales, 65.8 % of the firms had averaged annual sales of between CNY 3 million and CNY 40 million over the previous three years. In terms of firm age,

Table 1
Sample characteristics.

Classification	Items	Number	Percentage (%)
◆ Firm size	• <20	38	12.4 %
	• 20–300	94	30.6 %
	• 300–1000	134	43.6 %
	• >1000	41	13.4 %
◆ Firm sales	• <3	25	8.1 %
	• 3–20	106	34.5 %
	• 20–40	96	31.3 %
	• >40	80	26.1 %
◆ Firm age	• <3	28	9.1 %
	• 3–5	83	27.0 %
	• 6–10	90	29.3 %
	• 11–15	64	20.8 %
	• >15	42	13.7 %
◆ Ownership	• SOEs	80	26.1 %
	• PEs	113	36.8 %
	• CREs	70	22.8 %
	• FIEs	44	14.3 %
◆ Industry	• Pharmaceutical manufacturing	57	18.6 %
	• Aviation, spacecraft and equipment manufacturing	45	14.7 %
	• Electronic and communication equipment manufacturing	51	16.6 %
	• Computer and office equipment manufacturing	62	20.2 %
	• Medical equipment and instrument manufacturing	47	15.3 %
	• Electronic chemicals manufacturing	38	12.4 %
	• Other manufacturing	7	2.3 %

^a https://www.stats.gov.cn/sj/tjbz/gjtjbz/202302/t20230213_1902772.html.

90.9 % of the firms had been established more than three years before the survey. Concerning ownership, 36.8 % of the firms were private enterprises (PEs), 26.1 % were state-owned enterprises (SOEs), 22.8 % were collectively run enterprises (CREs), and 14.3 % were foreign-invested enterprises (FIEs). Last, among the seven high-tech manufacturing industries, computer and office equipment manufacturing had the highest proportion, accounting for 20.2 %.

Measures

Dependent variable: green collaborative innovation

Green collaborative innovation in this study is divided into two dimensions: green product collaborative innovation (GPCI) and green process collaborative innovation (GRCI) (Coughlan et al., 2023; Melander, 2018b). Green product collaborative innovation examines how firms and their partners jointly innovate green products to enhance recycling efficiency and reduce the environmental impact throughout the entire product lifecycle (Melander, 2018a; Wong et al., 2020). Based on the research of Chang (2020), Sarfraz et al. (2018), green product collaborative innovation was therefore assessed using three items: (1) “Your company collaborates with partners to innovate for the needs of green product innovation,” (2) “Your company and partners select materials with the least environmental impact for product design and development,” and (3) “Your company and partners consider whether the product is easy to recycle, reuse, and decompose during the product design and development process.” Green process collaborative innovation examines how firms and their partners collectively work on clean production technologies and green processes to minimize the environmental impact during production and operational activities (Coughlan et al., 2023). Therefore, based on the research of Hong et al. (2019), Qiao et al. (2022), green process collaborative innovation was also assessed using three items: (1) “Your company exchanges environmental knowledge with partners to improve the current green technology,” (2) “Your company and partners actively adopt new energy-saving technologies and fewer polluting production processes,” and (3) “Your company and partners actively improve production and operation processes to reduce the impact on the environment.” All items were assessed by the respondents using a seven-point Likert scale (1 = “strongly disagree” to 7 = “strongly agree”).

Independent variable: digital capabilities

Digital capabilities are classified into four dimensions: digital infrastructure capability (DIC), digital perception capability (DPC), digital operation capability (DOC), and digital collaboration capability (Lenka et al., 2017; Warner & Waeger, 2019). Digital infrastructure capability examines whether a firm is equipped with digital technology infrastructure and data analysis capabilities (Lenka et al., 2017). Thus, based on the research of Lenka et al. (2017), we measured digital infrastructure capability from the perspective of hardware technology foundation, software technology foundation, and data analysis, including three items: (1) “Your company has good digital hardware facilities,” (2) “Your company can use digital technology to integrate different data (e. g., business, inventory, external public data),” and (3) “Your company can use digital technology to intelligently analyze the collected information.” Digital perception capability is the ability of firms to identify market information and perceive dynamic changes in the external environment through digital technology (Warner & Waeger, 2019). Thus, based on the research of Warner and Wäger (2019), we measured digital perception capability from the perspective of digital technology perception, industry opportunity perception, and market competition perception, including three items: (1) “Your company can recognize and identify data sources with commercial value and customer value,” (2) “Your company can get the latest development information on external processes, products, and services based on big data,” and (3) “Your company can detect changes in the market competition environment based on big data.” Digital operation capability examines the ability of

firms to optimize business processes and enhance business model innovation through the use of digital technology in marketing, service, and other business processes (Warner & Waeger, 2019). Thus, based on the research of Warner and Wäger (2019), we measured digital operation capability from the perspective of R&D, production, marketing, and service, including three items: (1) “Your company can provide digital marketing management strategy for the market analysis and customer experience,” (2) “Your company can use digital means to optimize business processes or resource allocation,” and (3) “Your company can carry out real-time dynamic analysis of services and resources for flexible adjustment.” Digital collaboration capability is the flexible ability of firms to integrate and coordinate internal data, business processes, and knowledge resources (Warner & Waeger, 2019). Thus, based on the research of Warner and Wäger (2019), we measured digital collaboration capability using the aspects of data information, business processes, and knowledge resources, comprising three items: (1) “Your company’s business systems have a unified information exchange interface or method,” (2) “Your company can coordinate and optimize the key process phases of the organization,” and (3) “Your company can aggregate internal and external digital resources.” All items were assessed by the respondents using a seven-point Likert scale (1 = “strongly disagree” to 7 = “strongly agree”).

Mediator variable: green relationship learning

Green relationship learning (GRL) focuses on establishing a green relationship network through which firms and partners can share green information, address environmental issues, and develop a common understanding of green concepts (Juo & Wang, 2022; Selnes & Sallis, 2003). Based on the measurement of Juo and Wang (2022), green relationship learning was assessed using three items: (1) “Your company exchanges green information related to products with partners,” (2) “Your company establishes joint teams to solve environmental protection problems in the relationship,” and (3) “Your company frequently communicates with partners to adjust your common understanding of trends in green technology related to your business.” All items were assessed by the respondents using a seven-point Likert scale (1 = “strongly disagree” to 7 = “strongly agree”).

Moderator variables

The research framework of this study includes two moderating variables. Green organizational identity (GOI) refers to a strong identification among organizational members with environmental responsibility (Chen, 2011). Based on the measurement of Song and Yu (2018), we assessed green organizational identity using three items: (1) “Your company’s managers and employees have a sense of pride in the company’s environmental goals and missions,” (2) “Your company’s managers and employees feel that the company has carved out a significant position with respect to environmental management and protection,” and (3) “Your company’s managers and employees identify strongly with the company’s actions with respect to environmental management and protection.” Collaborative innovation atmosphere (CIA) refers to the cultural environment in which innovators openly communicate, respect partners’ cultures, and adhere to clear contractual and relational norms (Sun et al., 2023). Based on the measurement of Sun et al. (2023), we assessed collaborative innovation atmosphere using four items: (1) “Your company and partners can communicate and cooperate openly and transparently,” (2) “Your company and partners can respect each other’s cultures,” (3) “Your company and partners cannot be induced by profit to violate the agreement,” and (4) “Your company and partners can understand the symbolic terminology of the cooperation domain.” All items were assessed by the respondents using a seven-point Likert scale (1 = “strongly disagree” to 7 = “strongly agree”).

Controls

Given that prior research has shown that particular firm-level factors can influence a firm's green collaborative innovation, we included 10 control variables in our model (Xie et al., 2019b). We measured firm size by the number of employees, using a categorical variable (from 1 = "< 20" to 5 = "> 1000") as a control because a firm is more likely to apply external knowledge to conduct green innovation as the firm size grows (Martínez-Ros & Kunapatarawong, 2019). Following Xie et al. (2022c), we measured firm sales by the average annual sales over the past three years (from 1 = "< 3" to 5 = "> 40"). Following Tariq et al. (2019), we assessed firm age by the number of years since the firm's establishment (from 1 = "< 3" to 5 = "> 15"). Ownership, which is closely related to firm innovation (Xie et al., 2019a), was measured using four categorical variables: SOEs, PEs, CREs, and FIEs. Type of industry consisted of seven possible choices: pharmaceutical manufacturing, aviation, spacecraft and equipment manufacturing, electronic and communication equipment manufacturing, computer and office equipment manufacturing, medical equipment and instrument manufacturing, electronic chemicals manufacturing, or other manufacturing industries.

Reliability and validity

We used a variety of tests to assess the reliability and validity of this study (Clark & Watson, 1995; Schermelleh-Engel et al., 2003), and the results of these tests are presented in Table 2. First, the Cronbach's alpha and composite reliability (CR) of each construct are well above the threshold of 0.70, implying good internal consistency. Second, we conducted confirmatory factor analysis (CFA) to assess the convergent and discriminant validity of the constructs. For convergent validity, the average variance extracted (AVE) value of each construct was greater than 0.7. The factor load of all items was also greater than 0.6, indicating good convergence validity. For discriminant validity, our analyses show that χ^2/df was 1.144 (less than 3); the root mean square error of approximation (RMSEA) and standardized root mean square residual (SRMR) were 0.022 and 0.023, respectively (both less than 0.05); and the goodness of fit index (GFI), comparative fit index (CFI), normed fit index (NFI), and Tucker–Lewis index (TLI) were 0.926, 0.994, 0.948, and 0.993, respectively (all greater than 0.9), demonstrating a good model fit.

Common method variance

Because self-reporting can lead to common method variance (CMV) (Spector, 2006), we decreased the concern regarding common method bias using two approaches. First, we conducted CFA to test the fit of the single-factor model using all scale items. Results show that the model fit ($\chi^2/df = 7.741 > 3$, RMSEA = 0.148 > 0.08, CFI = 0.675 < 0.9, GFI = 0.557 < 0.9, TLI = 0.649 < 0.9) was not as strong as the original model, suggesting the absence of significant CMV (Dulac et al., 2008). Second, we used the unmeasured latent method construct approach to test the fit of a new model that includes a new latent common method factor (Podsakoff et al., 2003). Comparing the main fit indices of the original model, the goodness of fit showed no significant improvement with the addition of the latent common method factor in the new model ($\Delta RMSEA = -0.004 < 0.05$, $\Delta SRMR = -0.003 < 0.005$, $\Delta CFI = 0.002 < 0.1$, $\Delta TLI = 0.002 < 0.1$), indicating that CMV was not a concern. Therefore, CMV does not pose significant problems in this study.

Results

Table 3 provides correlations among all the variables. The correlation matrix shows that digital infrastructure capability, digital perception capability, digital operation capability, digital collaboration capability, and green relationship learning have significant positive

Table 2

Construct measurement and confirmatory factor analysis.

Constructs	Loading
Digital infrastructure capability (Lenka et al., 2017; Warner & Wäger, 2019; Cronbach's α = 0.852; KMO = 0.728; CR = 0.853; AVE = 0.659)	
DIC1: Your company has good digital hardware facilities.	0.796
DIC2: Your company can use digital technology to integrate different data (business, inventory, external public data, etc.).	0.812
DIC3: Your company can use digital technology to intelligently analyze the collected information.	0.827
Digital perception capability (Lenka et al., 2017; Warner & Wäger, 2019; Cronbach's α = 0.906; KMO = 0.755; CR = 0.905; AVE = 0.762)	
DPC1: Your company can recognize and identify data sources with commercial value and customer value.	0.883
DPC2: Your company can get the latest development information on external processes, products, and services based on big data.	0.866
DPC3: Your company can detect changes in the market competition environment based on big data.	0.869
Digital operation capability (Lenka et al., 2017; Warner & Wäger, 2019; Cronbach's α = 0.877; KMO = 0.741; CR = 0.877; AVE = 0.704)	
DOC1: Your company can provide digital marketing management strategy for market analysis and customer experience.	0.838
DOC2: Your company can use digital means to optimize business processes or resource allocation.	0.867
DOC3: Your company can carry out real-time dynamic analysis of services and resources for flexible adjustment.	0.812
Digital collaboration capability (Lenka et al., 2017; Warner & Wäger, 2019; Cronbach's α = 0.889; KMO = 0.746; CR = 0.898; AVE = 0.728)	
DCC1: Your company's business systems have a unified information exchange interface or method.	0.840
DCC2: Your company can coordinate and optimize the key process phases of the organization.	0.869
DCC3: Your company can aggregate internal and external digital resources.	0.851
Green relationship learning (Juo & Wang, 2022; Cronbach's α = 0.907; KMO = 0.757; CR = 0.907; AVE = 0.764)	
GRL1: Your company exchanges green information related to products with partners.	0.865
GRL2: Your company establishes joint teams to solve environmental protection problems in the relationship.	0.875
GRL3: Your company frequently communicates with partners to adjust your common understanding of trends in green technology related to your business.	0.882
Green product collaborative innovation (Chang, 2020; Sarfraz et al., 2018; Cronbach's α = 0.921; KMO = 0.763; CR = 0.921; AVE = 0.796)	
GPCI1: Your company collaborates with partners to innovate for the needs of green product innovation.	0.903
GPCI2: Your company and partners select materials with the least environmental impact for product design and development.	0.880
GPCI3: Your company and partners consider whether the product is easy to recycle, reuse, and decompose during the product design and development process.	0.893
Green process collaborative innovation (Hong et al., 2019; Qiao et al., 2022; Cronbach's α = 0.922; KMO = 0.763; CR = 0.922; AVE = 0.796)	
GRCI1: Your company exchanges environmental knowledge with partners to improve the current green technology.	0.880
GRCI2: Your company and partners actively adopt new energy-saving technologies and fewer polluting production processes.	0.896
GRCI3: Your company and partners actively improve production and operation processes to reduce the impact on the environment.	0.903
Green organizational identity (Song & Yu, 2018; Cronbach's α = 0.892; KMO = 0.743; CR = 0.891; AVE = 0.734)	
GOI1: Your company's managers and employees have a sense of pride in the company's environmental goals and missions.	0.834
GOI2: Your company's managers and employees feel that the company has carved out a significant position with respect to environmental management and protection.	0.857
GOI3: Your company's managers and employees identify strongly with the company's actions with respect to environmental management and protection.	0.879
Collaborative innovation atmosphere (Sun et al., 2023; Cronbach's α = 0.922; KMO = 0.861; CR = 0.921; AVE = 0.746)	
CIA1: Your company and partners can communicate and cooperate openly and transparently.	0.857
CIA2: Your company and partners can respect one another's cultures.	0.856

(continued on next page)

Table 2 (continued)

Constructs	Loading
CIA3: Your company and partners cannot be induced by profit to violate the agreement.	0.871
CIA4: Your company and partners can understand the symbolic terminology of the cooperation domain.	0.871

$\chi^2/df = 1.144$; RMSEA = 0.022; SRMR = 0.023; GFI = 0.926; CFI = 0.994; NFI = 0.948; TLI = 0.993.

correlations with green product collaborative innovation and green process collaborative innovation, providing fundamental support for the discussion of further regression analysis of the relationship between variables.

We first tested the impact of digital capabilities on green collaborative innovation. As shown in Table 4, the largest variance inflation factor (VIF) value was less than 5, indicating that multicollinearity was not a concern in our study. The results of Models 2 and 7 demonstrate that digital infrastructure capability has positive effects on green product collaborative innovation ($\beta = 0.607$, $P < 0.001$) and green process

collaborative innovation ($\beta = 0.572$, $P < 0.001$), supporting H1a and H1b. The results of Models 3 and 8 demonstrate that digital perception capability has positive effects on green product collaborative innovation ($\beta = 0.647$, $P < 0.001$) and green process collaborative innovation ($\beta = 0.512$, $P < 0.001$), supporting H2a and H2b. The results of Models 4 and 9 demonstrate that digital operation capability has positive effects on green product collaborative innovation ($\beta = 0.515$, $P < 0.001$) and green process collaborative innovation ($\beta = 0.452$, $P < 0.001$), supporting H3a and H3b. The results of Models 5 and 10 demonstrate that digital collaboration capability has positive effects on green product collaborative innovation ($\beta = 0.579$, $P < 0.001$) and green process collaborative innovation ($\beta = 0.567$, $P < 0.001$), supporting H4a and H4b. Overall, H1–H4 were supported. These findings suggest that the four dimensions of digital capabilities have positive effects on green product and green process collaborative innovation. These results align with recent studies (Jiao et al., 2021; Mubarak & Petraite, 2020) that emphasized the role of digital tools in enhancing collaborative innovation. By integrating digital capabilities, firms can establish green collaborative innovation networks and enhance their collaborative efforts in developing

Table 3

Mean, standard deviations, and correlations.

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Firm size	1													
2. Firm sales	0.526**	1												
3. Firm age	0.355**	0.300**	1											
4. Ownership	−0.076	−0.055	−0.145*	1										
5. Industry	0.075	0.062	0.085	−0.014	1									
6. DIC	0.107	0.150**	0.071	0.082	−0.020	1								
7. DPC	0.112*	0.083	0.055	0.032	−0.012	0.726**	1							
8. DOC	0.065	0.100	0.037	0.068	0.030	0.791**	0.707**	1						
9. DCC	0.070	0.120*	0.059	0.068	−0.021	0.798**	0.682**	0.739**	1					
10. GPCI	0.106	0.071	0.024	0.068	0.013	0.606**	0.652**	0.520**	0.580**	1				
11. GRCI	0.081	−0.018	0.054	0.071	0.081	0.560**	0.514**	0.452**	0.558**	0.607**	1			
12. GRL	0.103	0.001	0.018	0.027	−0.047	0.576**	0.500**	0.527**	0.520**	0.526**	0.517**	1		
13. GOI	0.034	0.076	0.009	−0.020	−0.004	0.751**	0.638**	0.693**	0.706**	0.613**	0.574**	0.605**	1	
14. CIA	0.038	−0.003	0.016	−0.001	0.053	0.419**	0.405**	0.386**	0.419**	0.401**	0.455**	0.438**	0.460**	1
Mean	2.580	2.750	3.030	2.250	3.450	5.519	5.104	5.270	5.267	4.987	5.143	5.178	5.313	5.336
S.D.	0.872	0.934	1.181	1.000	1.728	1.140	1.587	1.355	1.426	1.612	1.558	1.513	1.413	1.389

Note. $N = 307$; Significance level: * $p < 0.05$; ** $p < 0.01$ (two-tailed).

Table 4

Regression results: impact of digital capabilities on green collaborative innovation.

Variables	Green collaborative innovation									
	Green product collaborative innovation					Green process collaborative innovation				
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10
Firm size	0.102 (0.069)	0.079 (0.055)	0.042 (0.053)	0.093 (0.060)	0.099† (0.057)	0.114 (0.069)	0.092 (0.057)	0.066 (0.059)	0.106† (0.062)	0.111† (0.057)
Firm sales	0.024 (0.068)	−0.053 (0.055)	0.003 (0.052)	−0.023 (0.058)	−0.041 (0.056)	−0.092 (0.068)	−0.164** (0.056)	−0.108† (0.058)	−0.133* (0.060)	−0.156** (0.056)
Firm age	−0.009 (0.062)	−0.031 (0.050)	−0.022 (0.048)	−0.015 (0.054)	−0.031 (0.051)	0.047 (0.062)	0.026 (0.051)	0.036 (0.053)	0.041 (0.055)	0.025 (0.051)
Ownership	0.075 (0.058)	0.017 (0.046)	0.047 (0.044)	0.036 (0.050)	0.030 (0.047)	0.082 (0.058)	0.027 (0.048)	0.060 (0.049)	0.048 (0.051)	0.037 (0.048)
Industry	0.006 (0.057)	0.026 (0.046)	0.021 (0.044)	−0.006 (0.049)	0.023 (0.047)	0.076 (0.057)	0.094 (0.047)	0.087† (0.049)	0.065 (0.051)	0.093† (0.047)
DIC		0.607*** (0.047)					0.572*** (0.049)			
DPC			0.647*** (0.044)					0.512*** (0.049)		
DOC				0.515*** (0.050)					0.452*** (0.051)	
DCC					0.579*** (0.047)					0.567*** (0.047)
R^2	0.017	0.373	0.429	0.278	0.345	0.025	0.342	0.284	0.226	0.340
Adjusted R^2	0.001	0.361	0.418	0.263	0.332	0.009	0.329	0.269	0.211	0.327
F-value	1.070	29.750***	37.624***	19.235***	26.341***	1.572	25.974***	19.810***	14.615***	25.776***
Largest VIF	1.471	1.472	1.479	1.471	1.471	1.471	1.472	1.479	1.471	1.471

Note. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; † $p < 0.1$. All regression coefficients shown are standardized. Standard errors in parentheses. $N = 307$.

environmentally friendly products and processes.

Table 5 reports the mediating effect of green relationship learning in the relationship between digital capabilities and green collaborative innovation. Following Baron and Kenny (1986), we adopted the three-step method to evaluate mediating effects. For H5a, the independent variable (digital infrastructure capability) was positively related to the mediator (green relationship learning) (Model 1: $\beta = 0.587$, $P < 0.001$). Additionally, after controlling for digital infrastructure capability, green relationship learning was positively related to green product collaborative innovation (Model 5: $\beta = 0.262$, $P < 0.001$) and green process collaborative innovation (Model 9: $\beta = 0.279$, $P < 0.001$). The effect of digital infrastructure capability on green product collaborative innovation (Model 2 of Table 4: $\beta = 0.607$, $P < 0.001$; Model 5 of Table 5: $\beta = 0.453$, $P < 0.001$) and green process collaborative innovation (Model 7 of Table 4: $\beta = 0.572$, $P < 0.001$; Model 9 of Table 5: $\beta = 0.408$, $P < 0.001$) became weaker, thus supporting H5a₁ and H5a₂. Similarly, we replaced the independent variable with the remaining three dimensions of digital capabilities and sequentially employed a three-step method to test the mediating effect of green relationship learning between these dimensions and green collaborative innovation. The results supported H5b–H5d. Moreover, given that the bootstrapping method can provide more accurate confidence intervals and handle complex models better than the three-step method, we further employed the bootstrapping approach to test the mediating effect (Hayes & Preacher, 2010). Specifically, we conducted bootstrap analysis with 5000 replications and a 95 % confidence interval (CI) to further test H5. As displayed in Table 6, the mediating effects on the relationships between digital infrastructure capability and green product collaborative innovation and green process collaborative innovation are 0.153 (CI = [0.077, 0.235]) and 0.167 (CI = [0.086, 0.251]), respectively. The CIs of the above results do not include 0, thus further supporting H5a. Similarly, the remaining results support H5b–H5d. These findings suggest that green relationship learning positively mediates the relationships between digital capabilities and green collaborative innovation. Unlike the work of Tian et al. (2022), which revealed the mediating role of green innovation intention in the digital capability–green innovation link, we shifted the focus to the interorganizational perspective, demonstrating how firms can leverage digital capabilities driving green collaborative innovation through green relationship learning.

Tables 7 and 8 report the moderating effect of green organizational identity on the relationship between digital capabilities and green collaborative innovation. The results of Model 3 in Tables 7 and 8 demonstrate that the interaction term *Digital Infrastructure Capability* $\times$ *Green Organizational Identity* has a significant and positive effect on green product collaborative innovation ($\beta = 0.184$, $P < 0.001$) and green process collaborative innovation ($\beta = 0.093$, $P < 0.05$), supporting H6a. Second, the results of Model 6 in Tables 7 and 8 demonstrate that the interaction term *Digital Perception Capability* $\times$ *Green Organizational Identity* has a significant and positive effect on green product collaborative innovation ($\beta = 0.157$, $P < 0.001$) and green process collaborative innovation ($\beta = 0.131$, $P < 0.01$), supporting H6b. Third, the results of Model 9 in Tables 7 and 8 demonstrate that the interaction term *Digital Operational Capability* $\times$ *Green Organizational Identity* has an insignificant and positive effect on green product collaborative innovation ($\beta = 0.052$, $P > 0.1$) and green process collaborative innovation ($\beta = 0.052$, $P > 0.1$). Therefore, H6c is not supported. The reason for these findings is that high-level green organizational identity may lead firms and partners to pay too much attention to environmental protection objectives and ignore the improvement of digital operation capability. Such an attention shift may weaken the efficiency improvement and cost reduction brought by digital operation capability to the process of green collaborative innovation. Finally, the results of Model 12 in Tables 7 and 8 demonstrate that the interaction term *Digital Collaboration Capability* $\times$ *Green Organizational Identity* has a significant and positive effect on green product collaborative innovation ($\beta = 0.107$, $P < 0.05$) and green process collaborative innovation ($\beta = 0.100$, $P < 0.05$), supporting H6d.

Additionally, as shown in Fig. 2, green organizational identity enhances the positive effect of three dimensions of digital capabilities (digital infrastructure capability, digital perception capability, and digital collaboration capability) on green product and green process collaborative innovation. This finding contrasts with the literature, which has often treated green organizational identity as separate constructs without examining the interactive effects of green organizational identity on digital capabilities (Song et al., 2019). By highlighting the role of green organizational identity in enhancing the effectiveness of digital capabilities on green collaborative innovation, our study underscores the importance of integrating identity and capability in driving green collaborative innovation, suggesting that firms with a strong green organizational identity are better positioned to leverage digital capabilities for collaborative efforts in sustainability.

Table 9 shows the moderating effect of a collaborative innovation atmosphere on the relationship between green relationship learning and green collaborative innovation. The results of Models 3 and 6 demonstrate that the interaction term *Green Relationship Learning* $\times$ *Collaborative Innovation Atmosphere* has a significant and positive effect on green product collaborative ($\beta = 0.165$, $P < 0.001$) and green process collaborative innovation ($\beta = 0.172$, $P < 0.001$), supporting H7a and H7b. Additionally, as shown in Fig. 3, a collaborative innovation atmosphere enhances the positive effect of green relationship learning on green product and green process collaborative innovation. Different from the literature, which focuses on the mediating role of a collaborative innovation atmosphere in the relationship between innovation platforms' relational governance and green innovation (Sun et al., 2023), our findings highlight the importance of a collaborative innovation atmosphere as a critical moderator and suggest that fostering a collaborative innovation atmosphere can enhance knowledge sharing and mutual learning among partners, leading to more effective green collaborative innovation.

Discussion

In recent years, management scholars have given digital capabilities greater attention because of the important role they play in open innovation and green innovation (Jiao et al., 2021; Yang & Sun, 2023). In this research, we suggest that digital capability is a key capability that firms can leverage to jointly achieve sustainable development with their partners (Albats et al., 2022; Quttainah & Ayadi, 2024). However, the literature has often focused on the effects of specific digital technologies while overlooking the digital capabilities of firms (Benzidia et al., 2021; Xie et al., 2022a). To address these gaps, we conceptualized digital capability as the capability of firms to apply digital technologies and categorize it into four dimensions to examine their impact on green collaborative innovation. Furthermore, we complement previous studies (e.g., Hong et al., 2019; Melander, 2017) by providing a more fine-grained analysis of green collaborative innovation from the perspective of green product and green process collaborative innovation and identifying the drivers of green collaborative innovation through the lens of digital capabilities. This study also explores the underlying mechanisms linking digital capabilities to green collaborative innovation, particularly through green relationship learning. Furthermore, the study identifies boundary conditions in the relationship between digital capabilities, green relationship learning, and green collaborative innovation, by considering contextual factors such as green organizational identity and the collaborative innovation atmosphere. Consequently, this research provides an integrated framework for understanding how digital capabilities enhance green collaborative innovation. The research findings contribute theoretically to the fields of digital capabilities and green collaborative innovation, providing new insights for managers striving to achieve sustainability in the context of digital transformation.

Table 5
Regression results: mediating role of green relationship learning.

Variables	Green relationship learning				Green collaborative innovation							
					Green product collaborative innovation				Green process collaborative innovation			
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
Firm size	0.126* (0.056)	0.102† (0.060)	0.39* (0.059)	0.145* (0.058)	0.046 (0.054)	0.015 (0.051)	0.045 (0.057)	0.055 (0.054)	0.057 (0.055)	0.031 (0.056)	0.053 (0.058)	0.067 (0.054)
Firm sales	−0.144* (0.056)	−0.086 (0.059)	−0.118* (0.059)	−0.129* (0.058)	−0.015 (0.053)	0.026 (0.050)	0.018 (0.055)	−0.002 (0.053)	−0.124* (0.054)	−0.079 (0.055)	−0.088 (0.057)	−0.117* (0.054)
Firm age	−0.025 (0.051)	−0.014 (0.054)	−0.010 (0.053)	−0.024 (0.053)	−0.024 (0.048)	−0.019 (0.045)	−0.011 (0.050)	−0.023 (0.048)	0.033 (0.049)	0.041 (0.050)	0.045 (0.052)	0.032 (0.049)
Ownership	−0.024 (0.047)	0.011 (0.050)	−0.008 (0.049)	−0.009 (0.049)	0.023 (0.045)	0.044 (0.042)	0.039 (0.047)	0.032 (0.045)	0.034 (0.046)	0.056 (0.046)	0.051 (0.048)	0.040 (0.045)
Industry	−0.034 (0.047)	−0.042 (0.054)	−0.065 (0.049)	−0.037 (0.049)	0.035 (0.044)	0.032 (0.042)	0.017 (0.047)	0.035 (0.045)	0.104* (0.045)	0.102* (0.046)	0.090 (0.048)	0.104* (0.045)
DIC	0.587*** (0.047)				0.453*** (0.055)				0.408*** (0.056)			
DPC		0.495*** (0.050)				0.514*** (0.048)				0.341*** (0.053)		
DOC			0.533*** (0.049)				0.329*** (0.055)				0.248*** (0.056)	
DCC				0.527*** (0.049)				0.419*** (0.053)				0.409*** (0.053)
GRL					0.262*** (0.055)	0.268*** (0.048)	0.348*** (0.055)	0.304*** (0.053)	0.279*** (0.056)	0.346*** (0.053)	0.383*** (0.057)	0.301*** (0.053)
R ²	0.351	0.260	0.298	0.290	0.418	0.483	0.363	0.411	0.392	0.372	0.329	0.404
Adjusted R ²	0.338	0.245	0.284	0.275	0.404	0.470	0.348	0.397	0.378	0.358	0.313	0.390
F-value	27.048***	17.573***	21.196***	20.384***	30.621***	39.835***	24.314***	29.757***	27.594***	25.324***	20.954***	28.993***
Largest VIF	1.472	1.479	1.471	1.471	1.566	1.493	1.498	1.500	1.566	1.493	1.498	1.500

Note. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; † $p < 0.1$. All regression coefficients shown are standardized. Standard errors in parentheses. $N = 307$.

Table 6

Bootstrap results: mediating role of green relationship learning.

Dependent variable	Path	Total effect Effect	t-value	Direct effect Effect	t-value	Indirect effect Effect	Boot LLCI	Boot ULCI
Green product collaborative innovation (GPCI)	DIC→GPCI	0.606	13.303	0.453	8.446	0.153	0.077	0.235
	DPC→GPCI	0.652	15.015	0.519	10.844	0.133	0.072	0.206
	DOC→GPCI	0.520	10.633	0.336	6.218	0.184	0.113	0.268
	DCC→GPCI	0.580	12.447	0.421	8.128	0.160	0.096	0.236
Green process collaborative innovation (GRCI)	DIC→GRCI	0.560	11.798	0.392	7.047	0.167	0.086	0.251
	DPC→GRCI	0.514	10.453	0.340	6.394	0.173	0.104	0.254
	DOC→GRCI	0.452	8.851	0.249	4.444	0.203	0.131	0.282
	DCC→GRCI	0.558	11.755	0.397	7.524	0.161	0.095	0.236

Note. 5000 Bootstrap samples.

Theoretical implications

This study contributes to the literature in three ways. First, it adds to the emerging body of research on open innovation and green innovation within the context of digital transformation by considering the effectiveness of digital capabilities in improving green collaborative innovation. Studies have focused on the influence of digital capabilities on green innovation (Jing et al., 2023; Tian et al., 2022), but they paid little attention to collaborations with external partners on green innovation. Advancing the existing literature, our results suggest a novel consequence of enterprises' digital capabilities in promoting green collaborative innovation, responding to recent calls for finding consequences of digital capabilities to further develop the capability-based conceptual model in a digital context (Annarelli et al., 2021). Further, no consensus has been reached in the existing literature regarding the dimensional classification of digital capabilities (Annarelli et al., 2021; Warner & Waeger, 2019). Our research synthesizes previous studies (Lenka et al., 2017; Warner & Waeger, 2019) to propose a more comprehensive classification and divides digital capabilities into four dimensions—digital infrastructure capability, digital perception capability, digital operation capability, and digital collaboration capability, offering a broader perspective for future research on the dimensional classification of digital capabilities. Previous research has also indicated the positive impact of digital trust on open innovation (Mubarak & Petraite, 2020); we extend this perspective by identifying digital capabilities as a key driver of green collaborative innovation and suggesting that four dimensions of digital capabilities enhance both green product and green process collaborative innovation. Therefore, we extend open innovation theory by providing a new perspective—the dynamic capability perspective—to shed light on which capability (i.e., digital capability) enterprises should develop when collaborating with external green innovators.

Second, our study advances the organizational learning literature by uncovering the mechanism of green relationship learning through which digital capabilities affect green collaborative innovation. Although most studies have examined the direct effect of digital capabilities on green innovation (Qiao et al., 2023; Tian et al., 2022), few have investigated the internal mechanisms linking digital capabilities with green collaborative innovation. To date, only one study has explored the underlying mechanisms of digital capability advantages and green supply chain innovation from an interorganizational learning perspective (Qiao et al., 2023). Building on this perspective, our findings support the mediating role of green relationship learning in the link between digital capabilities and green collaborative innovation. Furthermore, according to organizational learning theory, green relationship learning can be viewed as collective interorganizational learning among green innovators, benefiting a firm's green innovation (Cui et al., 2020; Juo & Wang, 2022; Selnes & Sallis, 2003). In contrast to the work of Tian et al. (2022), which suggested the mediating role of green innovation intention in the relationship between digital capability and green process innovation from a planned behavior perspective, we highlight the mediating role of green relationship learning in the relationship between

digital capabilities and green collaborative innovation from an interorganizational learning perspective. By demonstrating the benefits of green relationship learning, our study supplements the existing research on the role of green knowledge integration in green collaborative innovation (Fu & Li, 2022) and extends the application of organizational learning theory to research on the link between digital capabilities and green collaborative innovation.

Third, our study integrates the internal and interorganizational contextual factors in the digital capabilities–green relationship learning–green collaborative innovation link to provide a more complete picture of how firms leverage digital capabilities to develop green collaborative innovation. Regarding internal organizational contextual factors, previous studies have primarily discussed the influence of contextual factors such as cross-functional cooperation (Xu et al., 2022), green leadership (Idrees et al., 2023), and innovation capability (Melander, 2017) in the process of green collaborative innovation. Although some studies acknowledge the positive impact of green organizational identity on green innovation (Song et al., 2019), few have examined its contingent role in the process of green collaborative innovation. Our study fills this gap by empirically investigating the moderating role of green organizational identity in the relationship between digital capabilities and green collaborative innovation. Regarding interorganizational contextual factors, the existing literature has primarily emphasized the negative aspects of relationship atmosphere elements in collaboration and innovation (Meena et al., 2023) while neglecting the positive aspect of a collaborative innovation atmosphere. This study challenges this perspective by suggesting that the effect of green relationship learning on green collaborative innovation is stronger when a high level of collaborative innovation atmosphere exists among innovators. We therefore advanced the research on relationship atmosphere by recognizing the positive moderating role of a collaborative innovation atmosphere in which firms' green relationship learning fosters green collaborative innovation.

Managerial implications

This study provides important practical implications for managers. First, given the role of digital capabilities in facilitating green relationship learning and green collaborative innovation, firms should proactively implement digital strategies, thereby achieving sustainable competitive advantages. For example, firms might wish to build up digital platforms to interact with partners (Xie et al., 2022a), enabling innovators to share green product ideas and new production processes. Our findings also provide important implications for firms in developing and developed countries. In developing countries where the level of digitalization among enterprises is still at an early stage, manufacturing firms should prioritize developing digital infrastructure capability to enhance green collaborative innovation. For example, developing basic digital skills and IT infrastructure is essential for these firms to collaborate with partners, share knowledge, and implement sustainable practices more efficiently (Lenka et al., 2017; Tian et al., 2022). In developed countries, because it is crucial to promote digital applications

Table 7
Regression results: moderating role of green organizational identity (DV: Green product collaborative innovation).

Variables	Green product collaborative innovation											
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
Firm size	0.079 (0.055)	0.092† (0.053)	0.092† (0.051)	0.145* (0.058)	0.046 (0.054)	0.015 (0.051)	0.045 (0.057)	0.055 (0.054)	0.057 (0.055)	0.031 (0.056)	0.053 (0.058)	0.067 (0.054)
Firm sales	−0.053 (0.055)	−0.048 (0.052)	−0.053 (0.051)	−0.129* (0.058)	−0.015 (0.053)	0.026 (0.050)	0.018 (0.055)	−0.002 (0.053)	−0.124* (0.054)	−0.079 (0.055)	−0.088 (0.057)	−0.117* (0.054)
Firm age	−0.031 (0.050)	−0.014 (0.048)	−0.015 (0.046)	−0.024 (0.053)	−0.024 (0.048)	−0.019 (0.045)	−0.011 (0.050)	−0.023 (0.048)	0.033 (0.049)	0.041 (0.050)	0.045 (0.052)	0.032 (0.049)
Ownership	0.017 (0.046)	0.052 (0.045)	0.039 (0.044)	−0.009 (0.049)	0.023 (0.045)	0.044 (0.042)	0.039 (0.047)	0.032 (0.045)	0.034 (0.046)	0.056 (0.046)	0.051 (0.048)	0.040 (0.045)
Industry	0.026 (0.046)	0.019 (0.044)	0.025 (0.043)	−0.037 (0.049)	0.035 (0.044)	0.032 (0.042)	0.017 (0.047)	0.035 (0.045)	0.104* (0.045)	0.102* (0.046)	0.090 (0.048)	0.104* (0.045)
DIC	0.607*** (0.047)	0.318*** (0.068)	0.524*** (0.082)									
DPC				0.647*** (0.044)	0.427*** (0.054)	0.433*** (0.053)						
DOC							0.515*** (0.050)	0.166*** (0.063)	0.194** (0.067)			
DCC										0.579*** (0.047)	0.283*** (0.063)	0.348** (0.068)
GOI		0.376*** (0.067)	0.347*** (0.065)		0.341*** (0.051)	0.419*** (0.057)		0.499*** (0.062)	0.511*** (0.063)		0.415*** (0.062)	0.430*** (0.062)
DIC * GOI			0.184*** (0.043)									
DPC * GOI						0.157*** (0.044)						
DOC * GOI									0.052 (0.045)			
DCC * GOI												0.107* (0.044)
R ²	0.373	0.433	0.465	0.429	0.498	0.518	0.278	0.406	0.408	0.345	0.430	0.442
Adjusted R ²	0.361	0.420	0.451	0.418	0.486	0.505	0.263	0.392	0.392	0.332	0.417	0.427
F-value	29.750***	32.631***	32.418***	37.624***	42.298***	40.031***	19.235***	29.136***	25.688***	26.341***	32.274***	29.448***
Largest VIF	1.472	2.426	3.751	1.479	1.723	2.005	1.471	1.967	2.266	1.471	2.051	2.435

Note. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; † $p < 0.1$. All regression coefficients shown are standardized. Standard errors in parentheses. $N = 307$.

Table 8
Regression results: moderating role of green organizational identity (DV: Green process collaborative innovation).

Variables	Green process collaborative innovation											
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
Firm size	0.079 (0.055)	0.092† (0.053)	0.092† (0.051)	0.145* (0.058)	0.046 (0.054)	0.015 (0.051)	0.045 (0.057)	0.055 (0.054)	0.057 (0.055)	0.031 (0.056)	0.053 (0.058)	0.067 (0.054)
Firm sales	−0.053 (0.055)	−0.048 (0.052)	−0.053 (0.051)	−0.129* (0.058)	−0.015 (0.053)	0.026 (0.050)	0.018 (0.055)	−0.002 (0.053)	−0.124* (0.054)	−0.079 (0.055)	−0.088 (0.057)	−0.117* (0.054)
Firm age	−0.031 (0.050)	−0.014 (0.048)	−0.015 (0.046)	−0.024 (0.053)	−0.024 (0.048)	−0.019 (0.045)	−0.011 (0.050)	−0.023 (0.048)	0.033 (0.049)	0.041 (0.050)	0.045 (0.052)	0.032 (0.049)
Ownership	0.017 (0.046)	0.052 (0.045)	0.039 (0.044)	−0.009 (0.049)	0.023 (0.045)	0.044 (0.042)	0.039 (0.047)	0.032 (0.045)	0.034 (0.046)	0.056 (0.046)	0.051 (0.048)	0.040 (0.045)
Industry	0.026 (0.046)	0.019 (0.044)	0.025 (0.043)	−0.037 (0.049)	0.035 (0.044)	0.032 (0.042)	0.017 (0.047)	0.035 (0.045)	0.104* (0.045)	0.102* (0.046)	0.090 (0.048)	0.104* (0.045)
DIC	0.572*** (0.049)	0.293*** (0.070)	0.397*** (0.086)									
DPC				0.512*** (0.049)	0.233*** (0.059)	0.238*** (0.059)						
DOC							0.452*** (0.051)	0.087 (0.065)	0.115† (0.069)			
DCC										0.567*** (0.047)	0.304*** (0.064)	0.365*** (0.069)
GOI		0.364*** (0.056)	0.349*** (0.069)		0.434*** (0.059)	0.499*** (0.063)		0.523*** (0.064)	0.535*** (0.065)		0.369*** (0.063)	0.384*** (0.063)
DIC * GOI			0.093* (0.046)									
DPC * GOI						0.131** (0.049)						
DOC * GOI									0.052 (0.046)			
DCC * GOI												0.100* (0.045)
R ²	0.342	0.398	0.406	0.284	0.394	0.408	0.226	0.367	0.269	0.340	0.408	0.417
Adjusted R ²	0.329	0.384	0.390	0.269	0.380	0.393	0.211	0.352	0.352	0.327	0.394	0.402
F-value	25.974***	28.245***	25.489***	19.810***	27.795***	25.720***	14.615***	24.712***	21.802***	25.776***	29.400***	26.698***
Largest VIF	1.472	2.426	3.751	1.479	1.723	2.005	1.471	1.967	2.266	1.471	2.051	2.435

Note. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; † $p < 0.1$. All regression coefficients shown are standardized. Standard errors in parentheses. $N = 307$.

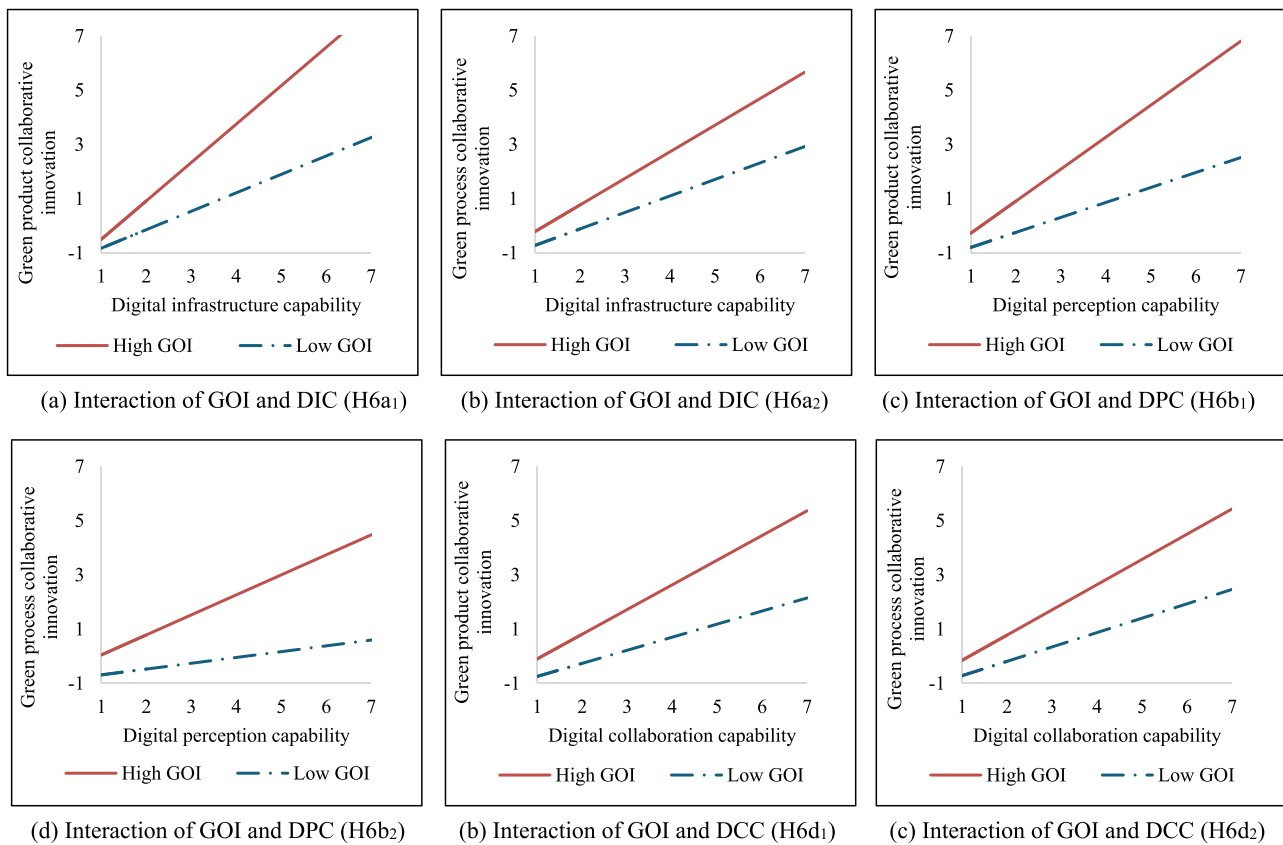


Fig. 2. Moderating effect of green organizational identity (H6).

Table 9

Regression results: moderating role of collaborative innovation atmosphere.

Variables	Green collaborative innovation					
	Green product collaborative innovation			Green process collaborative innovation		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Firm size	0.025 (0.060)	0.028 (0.058)	0.030 (0.057)	0.038 (0.060)	0.042 (0.057)	0.044 (0.056)
Firm sales	0.060 (0.058)	0.061 (0.057)	0.063 (0.055)	-0.056 (0.058)	-0.055 (0.056)	-0.053 (0.054)
Firm age	-0.007 (0.053)	-0.008 (0.052)	-0.017 (0.051)	0.049 (0.053)	0.047 (0.051)	0.037 (0.050)
Ownership	0.058 (0.049)	0.061 (0.048)	0.051 (0.047)	0.065 (0.049)	0.069 (0.047)	0.059 (0.046)
Industry	0.034 (0.049)	0.018 (0.048)	0.029 (0.047)	0.103 (0.049)	0.082 (0.047)	0.094 (0.046)
GRL	0.524*** (0.049)	0.430*** (0.054)	0.475*** (0.053)	0.515*** (0.049)	0.393*** (0.053)	0.440*** (0.052)
CIA		0.211*** (0.053)	0.241*** (0.052)		0.276*** (0.052)	0.308*** (0.051)
GRL * CIA			0.165*** (0.042)			0.172*** (0.041)
R ²	0.286	0.322	0.356	0.286	0.347	0.384
Adjusted R ²	0.272	0.306	0.339	0.272	0.332	0.367
F-value	20.073***	20.303***	20.589***	20.018***	22.713***	23.204***
Largest VIF	1.493	1.493	1.493	1.493	1.493	1.493

Note. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; $^{\dagger}p < 0.1$. All regression coefficients shown are standardized. Standard errors in parentheses. $N = 307$.

across various sectors of society and achieve the overall advancement of the digital economy in these countries, manufacturing firms should focus on developing more advanced digital capabilities, such as digital operation capabilities and digital collaboration capabilities, which will enable them to break down organizational boundaries and encourage cooperation among industries and supply chains (Benzidia et al., 2021; Quttainah & Ayadi, 2024).

Second, green relationship learning is a crucial mechanism for enhancing green collaborative innovation during digital transformation. Managers should recognize that green relationship learning is essential for acquiring external green knowledge and technologies. In addition, emphasizing the circulation of heterogeneous and nonredundant resources and technologies will further enhance relationship learning (Cheung et al., 2010). Therefore, it is imperative to strengthen the

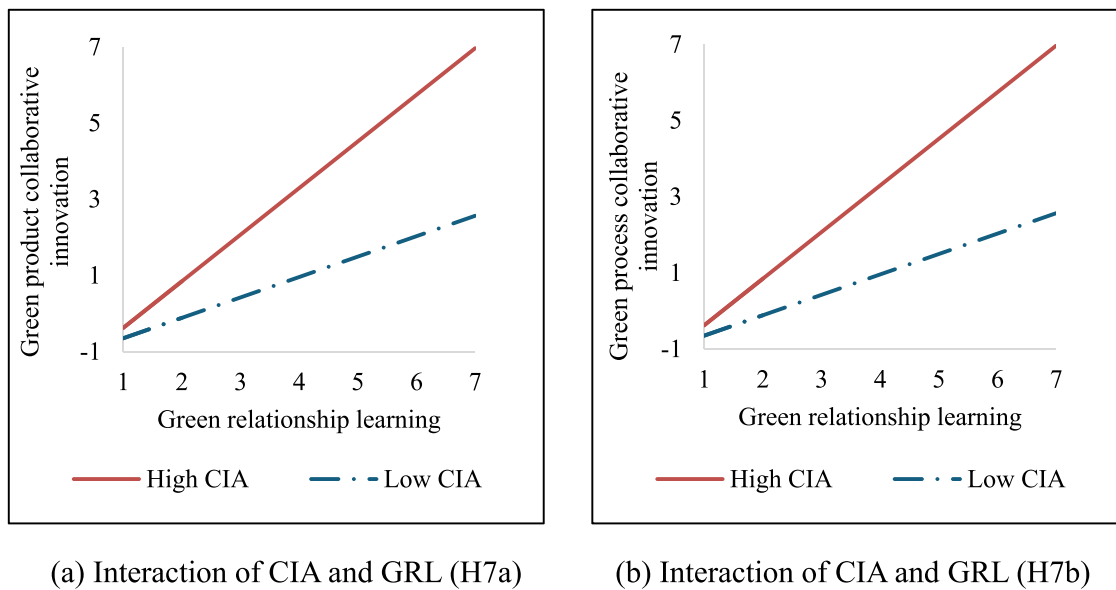


Fig. 3. Moderating effect of collaborative innovation atmosphere (H7).

development and maintenance of green relationship networks and ensure the accuracy and reliability of the information shared within these networks.

Third, our results indicate that firms with a strong green organizational identity and collaborative innovation atmosphere are better positioned to leverage digital capabilities and green relationship learning for advancing green collaborative innovation. According to Song et al. (2019), green organizational identity is a critical pathway for companies to fulfill corporate social responsibility and achieve successful green innovation. To cultivate a strong green organizational identity, firms should embed environmental values into their core mission and culture, actively engage external stakeholders in sustainability efforts, and align their collaborations with green goals. Fostering external partnerships and continuously innovating green practices can therefore reinforce the firm's commitment to environmental responsibility and drive successful green collaborative innovation. Managers should also jointly establish green visions with partners when planning green collaborative innovation strategies. By doing so, each partner can clarify their responsibilities and roles, thereby fostering a positive collaborative innovation atmosphere under shared green goals, which will facilitate more effective green collaborative innovation.

Limitations and future research

This study has several limitations that should be addressed in future research on this topic. First, we focus on interorganizational learning within strong relational contexts (i.e., green relationship learning) and use it as a mediator for the effect of digital capabilities on green collaborative innovation. However, we do not explore interorganizational learning in weaker relational contexts (Abbasiharofteh et al., 2024). Second, the results are based on data collected from China's high-tech manufacturing industry, potentially limiting the generalizability of the findings to other contexts. Third, survey data may also be subjective and susceptible to reverse causality. Only a longitudinal study can completely reveal digital capabilities and green collaborative innovation levels.

Future research could address these limitations in the following ways. First, to address the limitations of mediators, future research should examine how digital capabilities facilitate green collaborative innovation through weaker relational networks, thereby elucidating the mechanisms through which digital capabilities influence green collaborative innovation. Second, to address the limitations of the research

context, future research could expand this work to other settings (e.g., different transition economies, developed countries, or industry sectors), potentially revealing varying effects of digital capabilities on green collaborative innovation. Third, to address the limitations of survey data, future research could adopt a longitudinal study design and use multisource data (i.e., primary and secondary data) to offer a more comprehensive understanding of the relationship between digital capabilities and green collaborative innovation.

Conclusion

This study examines how firms leverage digital capabilities to improve green collaborative innovation. Based on the survey data from 307 Chinese high-tech manufacturing firms, we summarized the following insights derived from our findings: (a) four dimensions of firms' digital capabilities have a positive impact on green product and green process collaborative innovation; (b) green relationship learning mediates the relationship between digital capabilities and green collaborative innovation, indicating firms can leverage digital capabilities to improve green collaborative innovation through green relationship learning; and (c) green organizational identity positively moderates the relationships among three dimensions of digital capabilities (digital infrastructure capability, digital perception capability, and digital collaboration capability) and two types of green collaborative innovation, indicating that a high level of green organizational identity enhances the effectiveness of specific digital capabilities in driving green collaborative innovation. Moreover, a collaborative innovation atmosphere positively moderates the relationship between green relationship learning and green collaborative innovation, indicating firms can enhance the effectiveness of green relationship learning by creating a collaborative innovation atmosphere. Overall, the study emphasizes the critical role of digital capabilities in promoting green collaborative innovation and advocates for greater adoption of digital capabilities to advance sustainability.

CRediT authorship contribution statement

Xuemei Xie: Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization. **Mengge Wang:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

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