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The non-linear effect of digital business strategies on green innovation in manufacturing: A moderated mediation analysis

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ABSTRACT

The role of digital business strategies in fostering green innovation represents a critical knowledge gap in the literature. Drawing on the dynamic capability framework, we investigate the impact of digital business strategies on green innovation and analyze data from 175 Chinese manufacturing firms using hierarchical regression and fuzzy-set qualitative comparative analysis (fsQCA). The results demonstrate that digital business strategies exhibit an inverted U-shaped relationship with green innovation and green dynamic capabilities; the latter partially mediates the inverted U-shaped relationship between digital business strategies and green innovation. Institutional pressures positively moderate these two inverted U-shaped relationships and the linear link between green dynamic capabilities and green innovation. The fsQCA results corroborate the regression findings and advance the configurational literature on green innovation, identifying two distinct configurational paths to high green innovation. These findings elucidate the intricate mechanisms underlying the influence of digital business strategies on green innovation and offer a roadmap for manufacturing firms to effectively leverage these strategies.

Introduction

A digital business strategy is a firm-level plan to generate differentiated values by embedding digital technologies and using digital resources in the firm's solutions, operations, and business activities to achieve competitive advantages (Zheng, 2024). The literature shows that digital business strategies influence various organizational outcomes, such as value co-creation and innovation performance (Qiao & Liu, 2024; Zheng, 2024). Moreover, digital business strategies that fuse digital technologies with business strategies to enhance operational efficiency and customer engagement (Bharadwaj et al., 2013) can potentially transform traditional business models and drive sustainable innovation. As firms increasingly recognize the importance of environmental sustainability, green innovation has gained significant attention from both practitioners and scholars (Qin et al., 2025). Green innovation is the development of products, processes, or services that contribute to environmental sustainability (Qin et al., 2025). It is particularly relevant for the manufacturing sector—a critical frontier for advancing green innovation. The 20th National Congress of the Communist Party of China identified green development and digital intelligence as two of three core directions for the future growth of the manufacturing sector. In 2024, the Ministry of Industry and Information Technology, in collaboration with six other departments, released guidelines emphasizing the need to accelerate green development in the manufacturing sector. These guidelines emphasize the deep integration of digitalization and green practices in manufacturing processes. In this context, the integration of digital business strategies with sustainable practices has emerged as a critical issue for manufacturing firms aiming to navigate the complexities of the contemporary business environment. Existing literature has examined the impact of digital business strategies on efficiency (Eniola et al., 2022), service innovation (Yin et al., 2025), innovation performance (Zheng, 2024), and value creation (Chi et al., 2022; Qiao & Liu, 2024). By contrast, the interplay between digital business strategies and green innovation remains underexplored, compelling a deeper analysis of the mechanisms underlying this relationship.

Exploring the relationship between digital business strategies and green innovation in manufacturing firms, as well as clarifying their associated mechanistic pathways and boundary conditions, has theoretical and practical significance. First, it responds to the urgent need to encourage sustainable development in the manufacturing sector. As a core pillar of the global economy, this sector is a major source of

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resource consumption and carbon emissions as well as a key area for achieving carbon neutrality and sustainable development (Dou et al., 2024). With increasingly stringent environmental regulations and escalating green demand from consumers, manufacturing firms must overcome development bottlenecks through green innovation (Wang et al., 2024a). Digital business strategies integrate technologies, such as the Internet of Things (IoT) and Big Data, to optimize production processes and reduce environmental costs (Meyer et al., 2023; Mithas et al., 2013). Thus, digital strategies have potential to emerge as an engine for green innovation. Investigating the relationship between these two constructs directly addresses the practical demand for win–win outcomes between environmental protection and economic performance in the manufacturing sector (Dou et al., 2024). The analysis provides theoretical support for firms to navigate the dilemmas of sustainable development. Second, this study provides practical value for guiding manufacturing firms in leveraging digitalization to drive green innovation. Against the backdrop of deep integration of the digital and green economies, manufacturing firms struggle to achieve green transformation through digitalization (Wang et al., 2024a; Yu et al., 2025). Some firms have invested substantial resources in digitalization efforts but failed to effectively convert them into substantive green innovation (Zhang & Shi, 2024). Investigating the mechanistic pathways and boundary conditions between digital business strategies and green innovation could provide actionable insights for firms. These recommendations help firms formulate strategies that balance digitalization and green development, reduce the waste of digital resources, and strengthen competitiveness in sustainable development. Third, this study helps address the theoretical gap in research at the intersection of digital business strategies and green innovation. Digital business strategies are not simple applications of digital technologies but involve systematic changes encompassing transformation of organizational structure, development of information technology infrastructure, cross-functional resource integration, and value creation (Nadeem et al., 2018; Qiao & Liu, 2024). Although dozens of studies have examined the impact of digital business strategies on organizational behaviors and performance (Chi et al., 2022; Qiao & Liu, 2024; Zheng, 2024), scholars have not yet clearly elucidated how these strategies influence firms' green innovation outcomes. Therefore, investigating this relationship addresses the theoretical gap in the literature and refines the antecedents to green innovation.

To provide a theoretical framework for this investigation, this study uses the dynamic capability theory, which emphasizes the importance of firms' ability to adapt, integrate, build, and reconfigure internal and external resources to address rapid changes in the business environment (Teece et al., 1997). This theory is relevant for our study as it emphasizes the importance of developing organizational capabilities to innovate and maintain competitiveness in the digital age (Orero-Blat et al., 2025). The dynamic capabilities theory provides a robust lens to examine how firms can leverage digital business strategies to enhance their green innovation efforts.

A key aspect of this relationship is the role of green dynamic capabilities, defined as the organizational ability to sense and seize green opportunities and reconfigure internal and external green resources to address environmental challenges (Appiah, 2024; Mensah et al., 2025). These competencies are essential for firms to develop and implement green innovations effectively (Appiah, 2024; Khan et al., 2025). By understanding how digital business strategies contribute to the development of green dynamic capabilities, we can gain critical insights into their mediating role in fostering green innovation.

Moreover, institutional pressures, a core feature of the external environment, are essential in shaping the dynamics between digital business strategies and green innovation (Akhtar et al., 2024). Institutional pressures, which arise from regulatory requirements, societal expectations, and competitive dynamics, can affect organizational behavior and strategic decision-making (DiMaggio & Powell, 1983). Prior research has examined the impact of institutional pressures on corporate green innovation (Huang & Huang, 2024); however, their moderating role in the relationship between digital business strategies and green innovation, including interactions with green dynamic capabilities, remains unexplored. This research gap highlights the need to examine institutional pressures as contextual factors that can either enhance or inhibit the effectiveness of digital business strategies in promoting green innovation.

This study aims to address the following research questions. How do digital business strategies affect green innovation? What is the role of green dynamic capabilities in mediating this relationship? How do institutional pressures moderate these relationships? By examining these questions, this study aims to provide a comprehensive overview of how digital business strategies can be leveraged to drive firms' green innovation, particularly that of manufacturing firms.

This study contributes to the literature in four ways. First, this study enriches the literature on digital business strategies in the sustainability context by revealing an inverted U-shaped relationship between digital business strategies and green innovation. Unlike the linear impact of digital business strategies on innovation performance (Zheng, 2024), initial investments in digital business strategies enhance green innovation to a certain threshold, beyond which additional investments may be counterproductive. This extends the digitalization paradox to the sustainability domain by providing empirical evidence (Gao et al., 2025; Qi et al., 2025). Second, this study applies dynamic capabilities to sustainability contexts in the digital era by identifying a novel antecedent of green dynamic capabilities. Prior studies have contributed theoretically by revealing antecedents, such as green human resource management (Wang et al., 2025), green intellectual capital (Mensah et al., 2025), corporate environmental social responsibility (Saleem & Bashir, 2024), and proactive boundary-spanning search (Appiah, 2024). Likewise, this research identifies digital business strategy as an additional antecedent. However, the influence of digital business strategies on green dynamic capabilities shows an inverted U-shape rather than a linear pattern. Third, the identification of institutional pressures as a positive moderator of the relationships under study enables a comprehensive understanding of the contextual factors that influence digital business strategies to foster green innovation. Prior studies have emphasized the need for examining the varying impact of digitalization on corporate innovation across institutional environments (Zhang et al., 2023). Existing literature has primarily focused only on the separate impact of institutional pressures and digital business strategies on green innovation (Singh & Joshi, 2024). Our study addresses this gap by revealing the interaction effects of these two factors on both green dynamic capabilities and green innovation. Finally, this study reveals two novel configurational paths to high green innovation, thereby contributing to the configurational research on green innovation. Existing literature has identified three configurational patterns leading to high radical green innovation based on resource orchestration theory (Cui et al., 2025), four configurational paths to high green innovation in construction enterprises (Li et al., 2023b), five configurational paths to green innovation in high-tech enterprises, and two configurations for non-high-tech enterprises (Liu & Wang, 2025). The present study identifies two novel configurational paths to high green innovation in the manufacturing sector, thus enriching the repertoire of configurations toward green innovation in the literature.

Theoretical background and hypothesis development

Digital business strategy and green innovation

Green innovation refers to organizational activities that reduce environmental pollution, decreasing energy consumption and improving environmental performance through innovative products and processes (Vo-Thai & Tran, 2025). In the related literature, green innovation is also known as ecological innovation, reflecting the environmentally or ecologically friendly nature of such innovative actions.

Broadly, green innovation encompasses green product innovation and green process innovation (Vo-Thai & Tran, 2025). The former entails the use of environmentally friendly raw materials and auxiliary materials, and product recyclability. The latter involves the application of green manufacturing technologies, improvement in energy efficiency, and optimization of processes to reduce natural resource consumption. Recent studies have showed that the integration of digital technology is a critical enabler of environmental innovation, optimizing energy consumption patterns and reducing carbon emissions (Quttainah & Ayadi, 2024). Thus, it helps mitigate environmental pollution and enhance environmental performance (Du & Zhang, 2025). Two perspectives can explain the relationship between digital business strategies and the green innovation practices of manufacturing firms.

A moderate digital business strategy can promote green innovation. First, digital business strategies boost the efficient management of green information and knowledge through their lifecycle—from acquisition to application (Falcó et al., 2025). Digital technologies are foundational drivers that enable manufacturing firms to rapidly scan external sustainability environments and proactively acquire the latest green knowledge and information essential for green innovation (Asbeetah et al., 2025). In turn, this ensures the proactiveness of green information and knowledge (Patwary et al., 2024). Digital business strategies facilitate the cross-departmental flow and sharing of knowledge and information within firms (Falcó et al., 2025), creating favorable conditions for absorbing, integrating, and using the green knowledge and information required for green innovation (Guo, 2023). Hence, digital business strategies not only ensure the proactiveness and transparency of green information and knowledge but also enable their efficient integration and application.

Second, digital business strategies promote green innovation through efficient allocation and utilization of green resources. Digital business strategies optimize the allocation efficiency of multiple resources, including technological, human, capital, and equipment (Chi et al., 2022; Liu & Rong, 2025; Zhao et al., 2025). Efficient resource allocation reduces input costs and provides stable resource support for corporate green innovation, thereby improving output efficiency. Specifically, the application of digital platforms and cross-departmental data interfaces can break down resource barriers, lower the costs of green resource integration (Chi et al., 2022), and enhance the efficient integration and utilization of green resources. Meanwhile, digital tools such as cloud-sharing systems can accelerate the flow of green intellectual capital within organizations, optimize intellectual capital, and improve firms' green innovation capabilities (Liang and Sun, 2024). Thus, a moderate digital business strategy can develop green innovation by optimizing resource deployment and utilization.

Third, digital business strategies enhance green innovation capabilities by improving internal and external collaboration. The in-depth integration of digital technologies with business strategies enables digital technologies to permeate various business processes of firms, including production, marketing, human resources, technological research and development (R&D), administrative management, and strategic planning (Appiah-Kubi et al., 2025). For instance, sensors and information analysis technologies deployed in production, R&D, and business operations can identify deficiencies in green innovation and enable rapid corrections in a timely manner (Tao et al., 2025). Through digital communication technologies and digital collaborative innovation platforms, firms' internal departments can achieve seamless connectivity and coordinated operations (Ren et al., 2024), enabling real-time collaboration and joint decision-making across teams, departments, and regions in green innovation goals (Wei & Sun, 2021). This reduces the circulation and coordination time in the innovation process and improves the efficiency of innovation activities. Furthermore, high-quality green innovation requires efficient collaboration with external partners. Industry–academia–research collaboration is a key enabler of green innovation by partnering with external stakeholders (Gao et al., 2023). In this collaborative model, enterprises, academia, and research institutions can communicate and collaborate through digital innovation platforms and information and communication technologies to accomplish green innovation tasks. Consequently, by implementing digital business strategies, firms can accelerate digital transformation, develop digital capabilities, and effectively drive green collaborative innovation (Xie & Wang, 2025).

By contrast, excessive implementation of digital business strategies could have a detrimental impact on green innovation. First, it could do so through trigger information overload. Widespread application of digital technologies in business operations generates massive volumes of data (Wang et al., 2024b), but the effective data streams that enable green innovation are limited. Overly aggressive digital business strategies lead to exponential growth in data information, further exacerbating the problem of information bubbles (Irfan et al., 2022). Given the significant differences in information sources, types, and attributes, managers must adopt diverse information-processing methods and requirements (Jiang et al., 2025), which increases the complexity of information processing. When such massive and diverse information exceeds a specific threshold, firms encounter more information than they can effectively manage and process, resulting in information overload, which directly impairs firms' ability to extract valuable insights for green innovation from vast amounts of data in a timely manner (Wang et al., 2024b). More importantly, an overabundance of information diverts decision-makers' attention. According to the attention-based view, decision-makers' attention is a limited cognitive resource (Ocasio, 1997). When firms fail to focus attention on the core issues of green innovation, activities related to green innovation are not implemented (Wu et al., 2025), ultimately adversely affecting green innovation outcomes.

Second, excessive investment in digital business strategies triggers imbalanced resource deployment within firms. Grounded in the resource-based view, successful green innovation requires substantial green resources (Huan & Chen, 2023). However, the implementation of digital business strategies requires significant initial investments in digital infrastructure and continuous maintenance costs (Mithas et al., 2013). Under finite resource constraints, overinvestment in digitalization inevitably induces a crowding-out effect that diverts resources away from critical green innovation domains, such as green human resource management and eco-technology R&D (Han et al., 2024; Wang et al., 2024b). This misallocation engenders a striking paradox: Excessive digitalization generates idle and underutilized digital resources (Dou & Gao, 2022), whereas insufficient resource inputs constrain green innovation (Gao et al., 2022). Fundamentally, overexpansion of digital business strategies distorts resource flow. The resources required for engaging green suppliers and developing environmental technologies are diverted to digitalization initiatives. This "digitalization trap" impedes green innovation progress. Thus, excessive implementation of digital business strategies could undermine green innovation outcomes.

Third, the primary focus of firms engaged in implementing digital business strategies tends to center on business models, customer engagement, operational efficiency, and financial performance (Park & Mithas, 2020; Yin et al., 2025). Thus, an excessive digital business strategy implies that a firm focuses overly on improving efficiency and financial performance, while neglecting sustainability, environmental impact, and green innovation. In such cases, the focus of firms' innovation activities shifts toward innovation efficiency and effectiveness rather than the greening of innovation or green innovation itself. Furthermore, an excessive digital business strategy can cause over-reliance on digital technologies, overlooking the advantages of human capital in driving green innovation (Zheng et al., 2024). Employee creativity and engagement are key drivers of green innovation (Aslam et al., 2024; Tian et al., 2023). From the attention-based view, firms prioritize addressing the issues they focus on most intensely (Ocasio, 1997). Drawing on this perspective, excessive digital business strategies drive firms to focus overly on enhancing efficiency and improving financial performance through the integration of digital

technologies, thereby marginalizing green innovation and the positive role of human capital in advancing it. Consequently, excessive digital business strategies can impede green innovation.

As argued above, the relationship between digital business strategies and green innovation in manufacturing firms does not follow a linear trajectory but an inverted U-shaped pattern—initially positive before turning negative. Moderate implementation of digital business strategies is conducive to advancing green innovation, whereas disproportionate adoption could yield counterproductive outcomes. Based on this discussion, the following hypothesis is proposed:

H1. An inverted U-shaped relationship exists between digital business strategies and green innovation of manufacturing firms.

Digital business strategy and green dynamic capability

The core tenet of dynamic capability theory asserts that firms secure competitive advantages by building, integrating, and reconfiguring internal and external resources to navigate environmental shifts (Teece et al., 1997). Recent studies have extended this theory to sustainability domains, with significant advances in conceptual nomenclature, connotative refinement, dimensional taxonomy, antecedent identification, and outcome exploration. This theoretical evolution manifests as three primary dimensions.

First, dynamic capabilities in the sustainability domain have been conceptualized as specific terms. With the introduction of specific dynamic capabilities in the sustainability field, scholars have proposed concepts such as sustainable dynamic capability, green dynamic capability, and environmental dynamic capability. Specifically, sustainable dynamic capability refers to a set of dynamic capabilities centered on sustainability (Bari et al., 2024). It possesses sufficient dynamism to be updated, revised, and adjusted in response to the requirements of a constantly changing business environment. It has five dimensions: organizational learning, relationship building, shared vision, cross-functional integration, and technology sensing and response (Alenazi & Alanazi, 2023). Green dynamic capability refers to the ability of firms to achieve sustainable development by adapting to changes and requirements in the external environment through sensing and seizing green opportunities and reconfiguration of internal and external green resources (Appiah, 2024; Mensah et al., 2025). Its dimensional structure comprises sensing, seizing, and reconfiguration (Appiah, 2024). Environmental dynamic capability encompasses practices through which organizations develop, combine, expand, and restructure their resources and expertise to create sustainable values in constantly evolving environmental conditions (Trujillo-Gallego et al., 2025). It has two dimensions: high-order environmental dynamic capabilities (e.g., eco-design, internal environmental management) and low-order environmental dynamic capabilities (e.g., green manufacturing, green logistics; Trujillo-Gallego et al., 2025). We adopt the concept of green dynamic capability, given its close alignment with our research context, namely, green innovation.

Second, a dual-goal orientation anchors dynamic capabilities in sustainability. Extending dynamic capabilities to sustainability requires transcending conventional competitive advantage paradigms. This reorientation prioritizes green value creation that strategically balances economic efficiency and environmental benefits (Mensah et al., 2025). Consequently, green dynamic capabilities are relevant for investigating environmental performance, sustainability outcomes, and green innovation (Borah et al., 2025; Wang et al., 2025).

Third, several distinct antecedents characterize dynamic capabilities in sustainability. Those of green dynamic capabilities include green human resource management (Wang et al., 2025), green intellectual capital (Mensah et al., 2025), environmental corporate social responsibility (Saleem & Bashir, 2024), and proactive boundary-spanning search (Appiah, 2024), all of which enable green dynamic capabilities. These factors differ slightly from the antecedents of traditional dynamic capabilities, which underlies the significance of exploring the antecedents of green dynamic capabilities. This study, therefore, identifies digital business strategies as a new antecedent and examines in depth the intricate relationship between digital business strategies and green dynamic capabilities as follows.

Grounded in dynamic capability theory, green dynamic capabilities are conceptualized as sensing, seizing, and reconfiguring. Moderate digital business strategies can enhance manufacturing firms' green dynamic capabilities.

First, moderate digital business strategies are beneficial for enhancing firms' ability to sense and seize green opportunities, thereby improving the firms' green dynamic capabilities. The implementation of digital business strategies drives the widespread application of modern digital technologies within firms. By leveraging industry green data-sharing platforms and using Big Data analytics with data processing systems, firms can collect dispersed green information, such as green trends in markets and technologies, environmental policy changes, supply chain carbon footprints, consumer behaviors, and competitive dynamics (Tao et al., 2025), which could enhance the efficiency of acquiring external green intelligence (Patwary et al., 2024). Moreover, digital business strategies foster deeper interactions with customers and stakeholders through digital platforms and instant communication tools. This direct engagement enables firms to obtain firsthand data on environmental needs and preferences, ensuring information timeliness and accuracy (Patwary et al., 2024; Tao et al., 2025). Furthermore, digital business strategies emphasize the integration of digital technologies with business contexts, which enhances firms' data processing capabilities, generating data-driven decision-making insights (Yin et al., 2025). This not only ensures timely access to green technology and market development information but also deepens the identification of green innovation opportunities, aiding firms in swiftly pinpointing green trends and innovation directions. It encourages firms to mobilize and utilize resources to seize green opportunities. Thus, moderate digital business strategies effectively empower green dynamic capabilities in terms of sensing and seizing capabilities.

Second, moderate digital business strategies enhance green dynamic capabilities by integrating and reconfiguring green resources. The embedded use of mobile computing, cloud storage, social media, IoT, and artificial intelligence technologies fundamentally transform organizational operations, processes, and business models (Guenzi & Habel, 2020). This digital integration streamlines operational procedures, increases organizational flexibility, and improves green resource planning and utilization (Tao et al., 2025), thereby strengthening the capability to utilize and reconfigure green resources. Specifically, fusing digital technologies with departmental business operations enables rapid cross-unit information flow and sharing (Wu et al., 2023a), allowing enterprises to efficiently identify and acquire the required green resources. This fusion further reduces information asymmetry and corrects green resource misallocations (Li et al., 2023c), facilitating timely redistribution of surplus resources across departments. Accordingly, organizations achieve optimal green resource deployment through continuous reconfiguration (Li et al., 2023c; Liu et al., 2023), improving utilization efficiency. Implementation of digital business strategies enables firms to identify and acquire complementary green resources internally and externally through digital platforms and IoT ecosystems (Pan & Yang, 2024), thus enhancing green resource coordination and integration capabilities (Liu & Rong, 2025; Zhao et al., 2025). Additionally, digital collaboration networks enable strategic green resource restructuring through knowledge spillover effects (Shi et al., 2023), further advancing reconfiguration capacities. Thus, moderate digital business strategies strengthen firms' green dynamic capabilities.

However, excessive implementation of digital business strategies impedes the development of green dynamic capabilities and has a negative impact. First, excessive digital business strategies may generate information overload. Although moderate digital business strategies enhance firms' informatization and digitalization, overemphasis risks

triggering information overload (Arnold et al., 2023; Jiang et al., 2025). Specifically, excessive investment in a digital business strategy can induce information overload. This not only consumes cognitive resources but also diverts managerial attention, eventually undermining both green sensing and seizing capabilities. This overload manifests as three detrimental consequences. First, it erodes the ability to identify core signals. The vast volume of non-critical information generated through an excessive digital business strategy—including redundant user behavior data and technical parameter details—diminishes managers' cognitive resources. This impairs managers' ability to discern the meaning and value of information, fostering uncertainty about its significance (Matthes et al., 2024). Such uncertainty reduces self-efficacy, undermines managers' accuracy in judging critical environmental factors (Matthes et al., 2024), and compels them to overlook essential green signals, such as key policy clauses or the essence of consumers' environmental preferences. Another ramification is compromised information-processing quality. When information is complex, dynamic, or conflicting, overload fragments managerial attention, weakens information-processing capacity, and degrades the quality of information integration and utilization (Li et al., 2023a). This dynamic directly diminishes the efficiency of identifying green opportunities. Most critically, it may cause decision quality to deteriorate and lead to superficial insights. Information overload fosters a shallow understanding of green information, triggering delayed judgments, suboptimal decisions, or even errors (Jiang et al., 2025). Eventually, this undermines the overall effectiveness of sensing and seizing green opportunities. Consequently, firms' green dynamic capabilities are adversely affected.

Second, digital business strategies do not simply introduce information systems or digital technologies but also require firms to have corresponding conditions. Digital business strategies demand coordination and synergies between organizational culture, market positioning, and business models (Qiao & Liu, 2024). As digital business strategies deepen, the challenges of coordination and synergies increase, resulting in intensifying inconsistency among them and declining efficiency in mobilizing and integrating resources to adapt to environmental changes (Martínez-Caro et al., 2020). This weakens manufacturing firms' capability to use green opportunities.

Third, digital business strategies emphasize the alignment of digital technologies with business strategies. Initially, this alignment can minimize organizational inertia and enhance organizational flexibility (Zheng et al., 2025). However, when digital technologies align strongly with business strategies, firms tend to rely much on digital technologies and massive data to drive organizational routines and business operations (Gerow et al., 2014; Liang et al., 2017). Over time, such reliance induces new organizational inertia, diminishes organizational agility (Liang et al., 2017), and impairs firms' efficiency in responding to green opportunities (Li et al., 2024), eventually hampering the renewal and upgrading of green dynamic capabilities.

In summary, a moderate level of digital business strategies can enhance green dynamic capabilities, but excessive digital business strategies that do not align with the stage and context of firms' development may impede the development of green dynamic capabilities. In other words, the impact of digital business strategies on green dynamic capabilities is not linear but follows an inverted U-shaped pattern, demonstrating an initial rise followed by a decline. Based on the above analysis, the following hypothesis is proposed:

H2. An inverted U-shaped relationship exists between digital business strategies and green dynamic capabilities of manufacturing firms.

Green dynamic capability and green innovation

Green dynamic capabilities are critical assets for firms seeking to navigate the ever-evolving external environment and achieve sustainable development (Ullah et al., 2025). These competencies encompass the abilities to identify and capitalize on green opportunities and reorganize resources for environmentally friendly innovations (Sarwar et al., 2023). First, sensing capability is a pivotal component of green dynamic capabilities, enabling firms to detect opportunities swiftly and precisely for green innovation (Haug et al., 2025). The success of green innovation correlates with a deeper understanding of customers' green demand, green consumption trends, and the landscape of green development policies and regulations (Ullah et al., 2024). Firms must have expertise to acquire updates on green market dynamics, policy shifts, and industry transformations prior to conducting precise analyses and judgments to remain at the cutting edge of green innovation. Such a sensing capability, a cornerstone of green dynamic capabilities, facilitates this process. It denotes firms' profound understanding of insights into the external environment (Singh et al., 2022), indicating the firms' capacity to track and collect green knowledge and information from the external environment, and identify potential opportunities for green development. This capability empowers firms to develop keen sensitivity to the nuances of green market demand, green technologies, and green policy regulations as well as their fluctuating trends (Haug et al., 2025). Hence, green dynamic capabilities align firms' green innovation efforts with policy directives, the mandates of environmental regulatory bodies, and customer needs, thereby achieving superior green innovation outcomes. Second, seizing and reconfiguring capabilities, as critical components of dynamic capabilities, are essential for firms to effectively convert green opportunities into green innovation (Abbas, 2024; Haug et al., 2025). The development of green products and optimization of green processes requires specific organizational resources, knowledge, and technological expertise (Shehzad et al., 2024). Firms with green dynamic capabilities can dynamically evaluate existing green resources and mobilize them to seize green opportunities and reconfigure their resources to support the implementation of green innovation (Appiah, 2024). In this context, green dynamic capabilities enhance the efficiency of transforming green opportunities into green innovation practices. Based on these considerations, the following hypothesis is proposed:

H3. Green dynamic capabilities positively influence the green innovation of manufacturing firms.

Mediating effect of green dynamic capability

Dynamic capabilities can explain the internal mechanisms through which organizational strategies enable firms to gain sustainable competitive advantages (Cheng & Miao, 2025). A digital business strategy is recognized as a firm-level strategy (Zheng, 2024), and green innovation is a critical source of sustainable competitive advantage (Van et al., 2025). Therefore, drawing from dynamic capabilities, green dynamic capabilities can be considered as internal mechanisms to explain how firms' digital business strategies influence green innovation (Zheng, 2024). As posited in H1, digital business strategies stimulate green innovation in manufacturing firms. However, the relationship is not linear; it has an inverted U-shape. This implies that a moderate level of digital business strategies is most conducive to green innovation. Additionally, the implementation of digital business strategies is posited to promote green dynamic capabilities. However, this relationship also has an inverted U-shape, because excessive digital business strategies could lead to serious organizational inertia and information overload, thereby weakening green dynamic capabilities. As green dynamic capabilities have a positive linear relationship with green innovation, weakening of green dynamic capabilities could cause green innovation to decline. Therefore, a moderate level of digital business strategies enhances green dynamic capabilities, subsequently improving green innovation. Conversely, excessive emphasis on a digital business strategy weakens green dynamic capabilities and reduces green innovation. In other words, the inverted U-shaped impact of digital business strategies on green innovation can be achieved through the mediation of green dynamic capabilities. Based on this premise, the following hypothesis is proposed:

H4. Green dynamic capabilities play a mediating role in the relationship between digital business strategies and green innovation.

Moderating effect of institutional pressures

Institutional pressures are external forces that shape organizational structures and behaviors, consistent with the expectations of various stakeholders. They are commonly categorized into three dimensions: regulatory, normative, and cognitive (Jiang et al., 2024). Regulatory pressures are attributable to governments' environmental guidelines, regulations, and policies (Liao, 2018). Customers' demand for environmentally friendly products, suppliers' environmental awareness, and social media attention on environmental protection drive normative pressures (Liao, 2018). Cognitive pressures emerge from the successful environmental practices of competitors (Liao, 2018). This pressure is a key determinant of how companies tackle environmental challenges and is intricately linked to their green innovation and environmental initiatives (Singh & Joshi, 2024). We posit that institutional pressures have a triple moderating effect on the relationship between digital business strategies and green innovation.

Institutional pressures are hypothesized to amplify the inverted U-shaped relationship between digital business strategies and green innovation. First, institutional pressures strengthen the positive impact of a moderate digital business strategy on green innovation. As posited by institutional theory, institutional pressures originate from the institutional environment and function as key factors influencing firms' decision-making abilities and behaviors (Scott, 2008). However, the degree to which institutional pressures shape corporate behaviors depends on institutional strength (Martín-Tapia & Llamas-Sánchez, 2025). Although a moderate digital business strategy facilitates knowledge management and information sharing for green innovation (Xue et al., 2025; Zheng, 2024), firms typically lack strong motivation and urgency to engage in green innovation in the absence of relevant institutional pressures or when such pressures are low (Xue & Wang, 2025). Consequently, green innovation might not be prioritized during the implementation of digital business strategies. Conversely, under high institutional pressures, firms are compelled to implement substantial green initiatives, driving them to effectively leverage digital business strategies for green innovation purposes. This dynamic amplifies the benefits of digital business strategies in advancing green innovation. Thus, although a moderate digital business strategy can boost green innovation under low institutional pressures, its positive effect is magnified under high institutional pressures.

Second, institutional pressures exacerbate the detrimental effects of an overly aggressive digital business strategy on green innovation. Excessive focus on digital business strategies induces information overload, which in turn constrains firms' green innovation efforts (Wang et al., 2024b). In environments with high institutional pressures, this adverse effect is further amplified. As institutional pressures intensify, firms are compelled to prioritize and actively manage environmental information from external stakeholders. However, in contexts in which information overload is evident, heightened focus on green-related information and knowledge fails to improve information-processing efficiency, instead exacerbating inefficiencies (Li, 2017). This intensifies the negative impact of excessive digital business strategies on green innovation. Under resource constraints, over-investment in digital business strategies restricts firms' resource allocation to green innovation (Yu et al., 2021). In such contexts, intensified institutional pressures exacerbate this resource crowding-out effect. According to institutional theory, external institutional pressures—mandatory environmental regulations—strongly influence firms' decision-making ability and behavior regarding resource allocation and utilization (Guo et al., 2024). As external institutional pressures increase, firms are incentivized to prioritize compliance and legitimacy, directing their resources toward digital compliance systems (e.g., carbon emission monitoring platforms) to reduce pollution and emissions (Liu & Xu, 2024). This crowds out investments in green innovation (Liu & Xu, 2024), exacerbating the negative impact of excessive digital business strategies on green innovation. In summary, institutional pressures strengthen the positive effect of moderate digital business strategies on green innovation while exacerbating the negative impact of excessive digital business strategies on green innovation. Thus, the following hypothesis is proposed:

H5a. Institutional pressures have a positive moderating effect on the inverted U-shaped relationship between digital business strategies and green innovation.

Institutional pressures positively moderate the inverted U-shaped relationship between digital business strategies and green dynamic capabilities. First, institutional pressures facilitate the shaping of green dynamic capabilities through moderate digital business strategies. Digital business strategies provide the technological, organizational, and procedural foundations for dynamic capabilities, driving their evolution (Qiao & Liu, 2024) and helping develop green dynamic capabilities. However, the effectiveness of such strategies in enhancing these capabilities depends on institutional pressures from various stakeholders. According to institutional theory, high institutional pressures, specifically, coercive regulatory pressures, prompt firms to prioritize the acquisition and processing of green dynamic information (e.g., green regulations and market demand; Chen et al., 2025). This renders the advantages of digital business strategies—in terms of green sensing capabilities and green seizing capabilities—particularly beneficial, thereby making digital business strategies more conducive to the development of green dynamic capabilities. Furthermore, institutional theory suggests that under high environmental institutional pressures, firms actively allocate and use resources in response to such pressures (Guo et al., 2024). Digital business strategies have distinct advantages in resource planning and utilization (Tao et al., 2025), enabling firms to effectively leverage these strategies under high institutional pressures to enhance their ability to integrate and utilize green resources. Thus, institutional pressures strengthen the positive impact of digital business strategies on green dynamic capabilities.

Second, institutional pressures exacerbate the detrimental effects of excessive digital business strategies on green dynamic capabilities. Over-emphasis on digitalization compels firms to rely on digital technologies and existing digital technology-driven operational models, hindering the integration of information systems with external stakeholders (Yang et al., 2025) and impeding the development of green dynamic capabilities. In particular, when institutional pressures intensify, firms are obliged to adjust or reshape their green dynamic capabilities through digital business strategies to adapt to institutional environments (Lee et al., 2024). Such adjustments or reshaping pose huge challenges to a rigid operational model overly reliant on digital technologies, undermining the efficiency of green resource integration and reconfiguration and resulting in diminishing green dynamic capabilities. Additionally, over-emphasis on digital strategies may lead to information overload (Zhang et al., 2024). This further intensifies the information-processing burden when coupled with the need to manage an increasing volume of green-related information under high institutional pressures. This could lead to inefficiencies in sensing and seizing green opportunities, resulting in an overall decline in green dynamic capabilities. Therefore, under increased institutional pressures, the negative impact of excessive digital business strategies on the development of green dynamic capabilities seems pronounced. Based on the above discussion, the following hypothesis is proposed:

H5b. Institutional pressures have a positive moderating effect on the inverted U-shaped relationship between digital business strategies and green dynamic capabilities.

Institutional pressures have a positive moderating effect on the relationship between green dynamic capabilities and green innovation. Grounded in dynamic capability theory, green dynamic capabilities

form the foundation for firms to respond to external green development environments (Saleem & Bashir, 2024), while rooted in institutional theory. Institutional pressures are external environmental stimuli that firms are compelled to address (Mishra et al., 2025). First, regulatory pressures derive from the rules, regulations, standards, and policies formulated by governments (Shi & Mai, 2025). Within the sustainability domain, grounded in institutional theory, these pressures function as coercive forces that mandate the fundamental environmental requirements firms must satisfy while offering incentives to guide them toward adopting sustainability practices (Lee et al., 2024). Consequently, when firms encounter stringent regulatory pressures, those endowed with robust green dynamic capabilities respond more swiftly to the regulatory environment by mobilizing, integrating, and reconfiguring green resources for green initiatives (Huan & Chen, 2023). This agility drives them to strategically leverage green resources for green innovation. Thus, regulatory pressures enhance the contribution of green dynamic capabilities to green innovation. Second, normative pressures encompass customers' expectations and suppliers' aspirations for green innovation (Liao, 2018). Specifically, pressures emanating from customers are pronounced. Existing research has indicated that customers represent a critical source of pressure driving firms to adopt green practices (Li et al., 2023d). From the perspective of institutional theory, firms tend to respond proactively to such pressures to gain normative legitimacy (Mishra et al., 2025). As these pressures intensify, firms with strong green dynamic capabilities become more attuned to such expectations and demand, and swiftly mobilize and allocate green resources to meet them. Thus, normative pressures strengthen the role of green dynamic capabilities in facilitating green innovation. Third, cognitive pressures emerge when competitors make substantial strides in green development and achieve remarkable green innovation (Liao, 2018). Firms with robust green dynamic capabilities are quick to recognize such pressures. To keep abreast of competitors' successful green performance and acquire cognitive legitimacy (Layaoen et al., 2024), these firms actively integrate and leverage green resources, increasing their application in innovation processes and enhancing their green innovation efforts. Thus, cognitive pressures amplify the positive influence of green dynamic capabilities on green innovation. Based on the above discussion, the following hypothesis is proposed:

H5c. Institutional pressures exert a positive moderating effect on the relationship between green dynamic capabilities and green innovation.

The proposed research model is presented in Fig. 1.

Research method

Sample and data

The study sample comprises Chinese manufacturing firms, an ideal research context given their strong alignment with the research theme. First, manufacturing ranks among the sectors receiving highest attention in digital transformation, offering a robust setting for exploring digital business strategies in this study (Wang & Su, 2021). To accelerate the digitalization and digital transformation of manufacturing firms, the Chinese government has introduced a series of supportive policies and action plans, such as the Implementation Guidelines for the Digital Transformation of Manufacturing Enterprises. Additionally, targeted policies have been issued for specific sub-sectors, including the Implementation Plan for the Digital Transformation of the Electronic Information Manufacturing Sector for electronic manufacturing and the Implementation Plan for the Digital and Intelligent Transformation of the Pharmaceutical Industry (2025–2030) for pharmaceutical manufacturing. Guided by these policy initiatives, manufacturing firms have actively explored digital business strategies (Wang & Su, 2021), creating a favorable foundation for sampling and conducting quantitative analysis in this study. Second, the manufacturing sector encompasses both green product innovation and green process innovation, which aligns closely with how green innovation is conceptualized in this research. As a sector in which green innovation is concentrated and highly concerned, manufacturing exhibits clear manifestations of both green product innovation and green process innovation (Xie & Wang, 2025), the two core components of green innovation examined in this study. This strong congruence justifies the use of Chinese manufacturing firms as the research sample. Third, the environmental institutional pressures faced by the manufacturing sector display significant variability. The sector includes both high-pollution and low-pollution firms, each subject to distinctly different environmental institutional pressures (Ning et al., 2022). This variability creates an excellent research context for capturing variance in institutional pressure variables, which is critical for the analysis in this study.

We adopted a survey questionnaire—a research methodology consistent with the established practices in prior literature—to collect the study data (Zheng, 2024). To ensure the validity and quality of the survey, we implemented two critical measures. First, we developed an implicit screening question at the beginning of the questionnaire. Acknowledging that respondents' positions and tenures within their current organizations could affect data accuracy (Zheng, 2024), we delineated specific job titles and tenure requirements for qualified

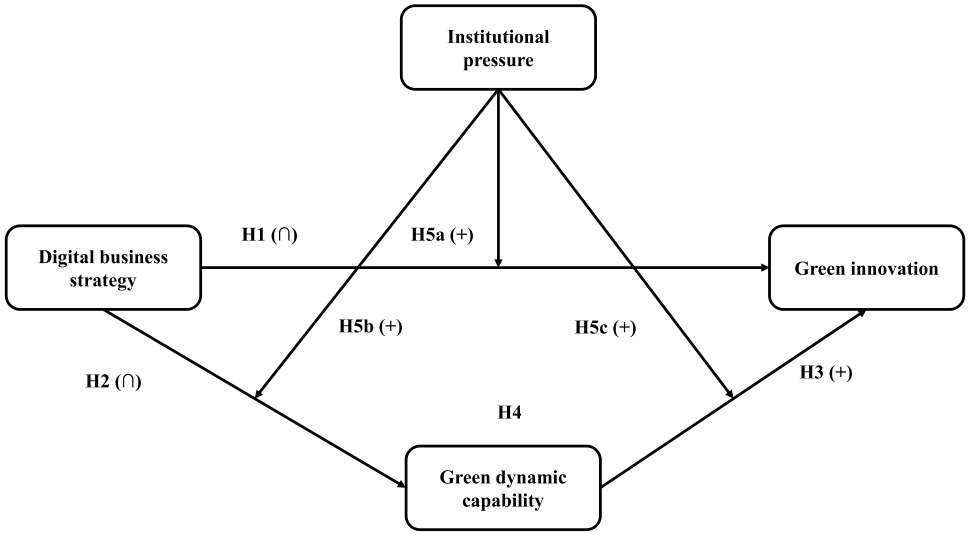

Fig. 1. Research model and hypotheses.

respondents in the questionnaire instructions. Nevertheless, the potential for respondents who did not meet these criteria remained. To address this issue, we included explicit questions concerning respondents' job titles and tenures, enabling us to exclude data from individuals who did not fulfill the specified requirements after the collection of questionnaires. Second, we conducted a pre-test designed to revise and enhance the questionnaire (Mengistu et al., 2025). The primary aim of the pre-test was to identify and rectify potential ambiguities, errors, or omissions. After two rounds of pre-tests, which involved a total of 32 respondents and the corresponding revisions, we employed the refined questionnaire for the formal survey.

Consistent with conventional practice in related scholarship, we defined the research population as chief information officers, chief product officers, chief technology officers, or chief innovation officers employed by manufacturing enterprises operating in mainland China (Zheng, 2024). Attributable to their positional roles, these managers have in-depth understanding and decision-making involvement in their enterprises' digital strategies, operational management, and innovation activities (Mithas et al., 2013; Zheng, 2024). Qualified respondents must satisfy three specific criteria. First, they must work in the eligible manufacturing firms mentioned above. Second, they must hold leadership positions that afford familiarity with the company's information technology, product production, technological R&D, or innovation management. Third, they must have held their current positions for at least one year to ensure sufficient understanding of their enterprises' practices.

The questionnaires were disseminated through both online and offline channels. This approach included leveraging the personal networks of current Master of Business Administration students, engaging with qualified companies via the alumni network, and conducting on-site surveys during social service initiatives and corporate training events. Applying these methods, we distributed over 560 questionnaires and received 183 responses, resulting in a response rate of 32.68%. We obtained 175 valid responses after excluding incomplete questionnaires, responses that did not comply with the stipulated requirements, and responses from individuals who did not meet the job title and tenure criteria. In terms of firm age, 6.86% of firms had operated for fewer than 6 years, 21.14% for 6–10 years, 17.14% for 11–15 years, 15.43% for 16–20 years, 25.71% for 21–25 years, 12% for 26–30 years, and 1.71% for 31 or more years. Regarding firm size (measured by number of employees), 10.29% of firms had fewer than 100 employees, 19.43% had 100–299 employees, 25.71% had 300–499 employees, 23.43% had 500–999 employees, 13.71% had 1000–1999 employees, 2.29% had 2000–2999 employees, and 5.41% had 3000 or more employees. In terms of R&D input (in 10,000 Yuan), 14.29% of firms invested less than 51, 16.57% invested 51–100, 33.71% invested 101–500, 20.57% invested 501–1000, 8% invested 1001–5000, 5.14% invested 5001–10,000, and 1.71% invested more than 10,000. Table 1 presents the sample structure.

Table 1
Descriptive statistics of the sample.

Items	Options	Frequency	Percentage
Firm age (years)	≤ 5	12	6.86%
	6–10	37	21.14%
	11–15	30	17.14%
	16–20	27	15.43%
	21–25	45	25.71%
	26–30	21	12.00%
	≥ 31	3	1.71%
Firm size (employees)	≤ 99	18	10.29%
	100–299	34	19.43%
	300–499	45	25.71%
	500–999	41	23.43%
	1000–1999	24	13.71%
	2000–2999	4	2.29%
	≥ 3000	9	5.14%
R & D input (10,000 Yuan)	≤ 50	25	14.29%
	51–100	29	16.57%
	101–500	59	33.71%
	501–1000	36	20.57%
	1001–5000	14	8.00%
	5001–10,000	9	5.14%
	> 10,000	3	1.71%

Common method bias

To mitigate the potential adverse effects of common method bias, we adopted three measures, consistent with the recommendations of Podsakoff et al. (2003). First, all measurement items were derived from well-established scales in the existing literature, thereby minimizing the inclusion of irrelevant or missing measurements. Second, the survey was conducted anonymously (Yin et al., 2025) and respondents were explicitly informed that there were no right or wrong answers, as the survey aimed to encourage honest and unbiased responses. Finally, to reduce the likelihood of respondents associating the related constructs, we placed measurements of digital business strategies, green dynamic capabilities, and green innovation in different locations of the questionnaire rather than adjacent areas.

To assess common method bias, we employed four distinct approaches. First, we conducted Harman's single-factor test. The results indicate that the first factor in the unrotated solution accounts for only 20.344% of the variance, which is below the commonly accepted threshold (Baumgartner & Weijters, 2012).

Second, we introduced a common method variance factor into factor analysis. We compared the fit of a multi-factor model with that of a model incorporating the common method variance factor (Dotty & Glick, 1998). The results demonstrate that fit indexes for the multi-factor model ($\chi^2 = 457.810$, degrees of freedom [df] = 368, root mean square error of approximation [RMSEA] = 0.037, incremental fit index [IFI] = 0.983, Tucker–Lewis index [TLI] = 0.981, comparative fit index [CFI] = 0.982) change marginally after the addition of the common method factor ($\chi^2 = 425.070$, $df = 339$, RMSEA = 0.038, IFI = 0.983, TLI = 0.980, CFI = 0.983). $\Delta\chi^2 = 32.740$ is less than the critical value of $\chi^2 = 42.557$ ($p < 0.05$). The results suggest that the introduction of the common method factor does not significantly improve model fit.

Third, we conducted a confirmatory factor analysis (CFA) involving the four focal variables. The current sample size is consistent with the basic requirements for conducting this analytical technique. Our justification is based on two widely cited academic standards: (1) This study's sample size meets the criteria recommended by Kline (2023). Multiple empirical guidelines for CFA sample size exist in academic circles. The most frequently cited standard for absolute sample size is a minimum of 100 to 200 (Kline, 2023). For a model with a small number of factors (i.e., less than five) and high variable factor loadings (i.e., greater than 0.70), a sample size of approximately 100 to 200 may be sufficient to obtain reliable parameter estimates and good model fit (Kline, 2023). This study includes only four factors, with all factor loadings greater than 0.7. Therefore, a sample size of 175 meets the standard requirements and is fully adequate for CFA analysis. (2) The sample size aligns with the requirements for the sample-to-variable ratio. In structural equation modeling (SEM), variables refer to the independent variables involved in the paths pointing to any endogenous variable (Hair et al., 2018). The minimum sample-to-variable ratio is 5:1, with a recommended ratio of 15–20:1 (Hair et al., 2018). In this study, six independent variables are involved in the paths pointing to any endogenous variable. Based on the recommended ratio, a sample size of at least 90 is required. From this standard, the study sample size adequately meets the analysis requirements. Several existing studies in related fields have survey samples of around 170, and these sample data have been used for CFA and SEM (Huang & Chen, 2022; Saari et al., 2024; Sahoo & Vijayvargy, 2021). Therefore, the use of CFA analysis in this study is appropriate. The results in Table 2 show that the four-factor model exhibits superior fit compared to the single-factor model ($\chi^2 =$

Table 2
Results of confirmatory factor analysis.

Model	χ^2	*df*	χ^2/df	IFI	TLI	CFI	RMSEA
Four-factor model: DBS, IP, GDC, GI	457.810	368	1.244	0.983	0.981	0.982	0.037
Three-factor model: DBS, IP, GDC + GI	907.543	371	2.446	0.896	0.885	0.895	0.091
Two-factor model: DBS, IP + GDC + GI	1074.280	373	2.880	0.864	0.851	0.863	0.104
One-factor model: DBS + IP + GDC + GI	2798.872	374	7.484	0.528	0.485	0.525	0.193

Note: DBS for digital business strategy, IP for institutional pressure, GDC for green dynamic capability, GI for green innovation.

2798.872, *df* = 374, RMSEA = 0.193, IFI = 0.528, TLI = 0.485, CFI = 0.525) and other alternative models (Podsakoff et al., 2003).

Fourth, the marker variable technique was adopted as an additional step to effectively exclude or minimize significant common method bias. The respondents' tenure was used as the marker variable, as it was theoretically unrelated to the focal variables in this study (Yang et al., 2024). Correlation coefficients between the marker variable and the key variables are all insignificant, with the highest correlation coefficient being r = 0.122. This indicates no evidence of common method bias (Lindell & Whitney, 2001). Collectively, these results show that common method bias is unlikely to significantly affect the study results.

Variable measurement

Digital business strategies

Digital business strategies were measured using the six-item scale developed by Ukko et al. (2019). This scale was also applied by Qiao and Liu (2024) and Yin et al. (2025). An example item from this scale is "Our company's management supports the utilization of digitality in our operations." All the items were assessed on a 7-point Likert scale (1 = "strongly disagree" to 7 = "strongly agree"). Based on the factor loading matrix, a regression algorithm was used to generate the composite score of digital business strategies. Subsequently, this factor score was incorporated into the regression analysis as a proxy variable (Qiao & Liu, 2024; Yin et al., 2025).

Green dynamic capabilities

The measurement of green dynamic capabilities was adapted from Chen and Chang (2013) and comprises seven items. An example item is "Our company has the ability to develop green technology." All seven items were assessed using a 7-point Likert scale (1 = "strongly disagree" to 7 = "strongly agree"). Following practice, a regression algorithm in factor analysis was used to generate the composite score of green dynamic capabilities. This score was incorporated into the regression analysis as a proxy variable (Chen & Chang, 2013).

Institutional pressures

The measurement of institutional pressures was adopted from a well-aligned three-dimensional scale, as outlined by Liao (2018), comprising 10 items. An example item is "It is important for our company to comply with stringent government regulations regarding the environment." In this study, institutional pressure was conceptualized to encompass regulatory, normative, and cognitive pressures (Jiang et al., 2024). Drawing on extant literature, it was operationalized using a 10-item Likert scale. This scale includes four items for regulative pressure, three for normative pressure, and three for cognitive pressure. The scale is derived from well-established research developed specifically for studies on environmental innovation and tested using samples of Chinese manufacturing firms (Liao, 2018). It aligns with the theoretical conceptualization of institutional pressure as a multi-dimensional construct and fits the research context of Chinese manufacturing firms engaging in green innovation. This scale was selected to maintain alignment with the theoretical framing of institutional pressure and the study's context, while ensuring consistency with existing research paradigms. Guided by established practice, all items were assessed on a 7-point Likert scale (1 = "strongly disagree" to 7 = "strongly agree"). For the analysis, the factor score generated by regression algorithm via factor analysis was incorporated into the regression model (Liao, 2018).

Green innovation

The measurement of green innovation was sourced from Song and Yu (2018) and includes six items. An example item is "Our company selects materials for product development that produce the least amount of pollution." All items were assessed on a 7-point Likert scale (1 = "strongly disagree" to 7 = "strongly agree"). We adopted this survey-based measurement of green innovation for the following considerations and justifications.

First, the survey-based measurement of green innovation is a valid, mainstream approach in the relevant literature, providing a robust basis for its adoption in this study. Survey-based measurements are widely used in environmental innovation, corporate sustainability, and green innovation management (Lajnef et al., 2025; Mamun, 2026; Mousa et al., 2025; Xie et al., 2024). When respondents have sufficient expertise and constructs are clearly defined, survey data accurately reflect corporate green innovation realities (Ashraf et al., 2024). Survey-based measurements are by no means a suboptimal choice but a recognized method in green innovation management research (Al Halbusi et al., 2025; Appiah, 2024; Xie et al., 2024).

Second, recent research has confirmed that patents classified by the Organization for Economic Co-operation and Development, World Intellectual Property Organization, and European Patent Office systems exhibit qualitatively and quantitatively consistent correlations with survey-based measurements of green innovation (Lambrecht et al., 2025). Notably, this positive association extends beyond German datasets to Italian samples, where survey-based green innovation measurements demonstrate an overall positive relationship with green patents and green trademarks (Lambrecht et al., 2025). This further validates the survey-based measurements' ability to capture the core dimensions of green innovation, aligning closely with well-established objective indicators. Thus, survey-based measurements are well-positioned to serve as a valid proxy for the established indicators.

Third, the survey-based measurement aligns strongly with this study's conceptualization of green innovation, which focuses on firms' green activities and capabilities rather than simply green outputs. Green innovation refers to organizational efforts to reduce pollution and energy consumption via innovative products and processes (Vo-Thai & Tran, 2025). It encompasses green product and process innovation (Lin et al., 2024; Singh et al., 2020; Song & Yu, 2018; Tian et al., 2023). Although valuable, green patents and renewable energy adoption (Lambrecht et al., 2025) cannot fully capture non-patentable activities or broader efforts, making survey-based measurement more compatible with the study's activity-oriented logic.

Fourth, the survey-based measurement excels in capturing the breadth of green innovation, which is ideal for this study's focus on diverse manufacturing industries. As a mainstream alternative (Xie et al., 2024), the survey-based measurement includes green product innovation efforts, such as pollution and material reduction, recyclability in product design or development, and green process innovation efforts, including resource consumption reduction and emission reduction in the manufacturing process (Song & Yu, 2018). The survey-based measurement addresses the limitation that green patents might not fully

reflect innovations across diverse industry samples (Lambrecht et al., 2025). It is particularly helpful for capturing green innovation information from small and medium-sized firms in the traditional manufacturing sector.

Fifth, the scale adopted in this study demonstrates strong contextual applicability to the Chinese context. Given that this study focuses specifically on Chinese manufacturing firms, the scale is congruent with our research context and exhibits robust contextual fit. Notably, it has undergone rigorous testing and validation in prior studies conducted in the Chinese context (Song & Yu, 2018; Tian et al., 2023). This usage attests to the scale's cultural relevance and operational feasibility and ensures it effectively captures green innovation-related information from Chinese manufacturing firms.

Sixth, the survey-based measurement of green innovation exhibits robust reliability and validity. Its Cronbach's alpha is 0.903 and yields satisfactory CFA fit ($\chi^2/df = 1.487$, RMSR = 0.067, CFI = 0.994, IFI = 0.994, TLI = 0.985; Song & Yu, 2018), providing compelling evidence of its robustness. The factor score of green innovation—generated via a regression algorithm through factor analysis—was incorporated into the regression model as a proxy variable for analysis (Song & Yu, 2018). The control variables included in the study are firm size, measured by the number of employees (Zhang & Wang, 2022); firm age, assessed by the number of years in operation (Huang & Huang, 2024; Zhang & Wang, 2022); and R&D intensity, measured by the company's annual average R&D investment in the past three years (Qi et al., 2021).

Reliability and validity

First, the internal consistency reliability and composite reliability of the measurements were examined. As Table 3 shows, the results indicate that the Cronbach's α and composite reliability (CR) values of all the scales are above 0.7, suggesting a high level of internal consistency among the items within each scale (Hair & Alame, 2022; Johri et al., 2025). Second, the convergent and discriminant validity were examined. The results show that the minimum standardized factor loading of the measurement items is 0.705, surpassing the recommended threshold of 0.7 and confirming satisfactory levels of significant convergent validity (Hair et al., 2019). The average variance extracted (AVE) values of all the variables are greater than 0.5, and the square root of the AVE for each variable is larger than the correlations between that variable and the others (Table 4), suggesting adequate discriminant validity (Hair & Alame, 2022).

Table 3
Measures, reliability, and validity.

Variables	Items	Loadings	α	CR	AVE
Digital business strategy (Ukko et al., 2019)	Our company's management is familiar with digital tools	0.965	0.982	0.985	0.918
	Our company's management has a clear vision for utilizing digitality in the future	0.949			
	Our company's management supports the utilization of digitality in our company	0.961			
	Utilizing digitality in internal processes has become an important part of our business	0.961			
	Digitality is a natural part of our business	0.958			
	Digitality enhances our business	0.954			
Institutional pressure (Liao, 2018)	It is important for our company to comply with stringent government regulations on the environment	0.753	0.918	0.931	0.576
	The preferential tax policy has increased our company's willingness to implement environmental innovation	0.778			
	Implementing environmental innovation is beneficial for our company to receive the local government's favorable treatment	0.795			
	The environmental innovation of our company will be influenced by government funding	0.779			
	Environmental products have been widely adopted by our customers	0.761			
	The increasing environmental consciousnesses of suppliers have spurred our company to implement environmental innovation	0.771			
	Social media has a strong influence on our company's environmental innovation	0.775			
	Our main competitors have made large investments in environmental innovation	0.731			
	Our main competitors that have adopted environmental innovation have benefited greatly	0.705			
	Our main competitors that have adopted	0.735			

(*continued on next page*)

Empirical results

Descriptive statistics and correlation analysis

Table 4 presents the descriptive statistics and correlation analysis of the control variables and focal variables in this study. The correlation coefficients are all less than 0.8, and the variance inflation factors (VIFs) are all less than 5 (Kock, 2015). Based on the commonly used criteria in the existing literature, there is no serious multicollinearity issue among the research variables (Johri et al., 2025; Kock, 2015).

Regression analysis

A review of the literature on inverted U-shaped relationships and their mediation effect testing reveals that mainstream studies often adopt ordinary least squares hierarchical regression to test the hypotheses. Haans et al. (2015) suggested three conditions for testing an inverted U-shaped relationship. First, the coefficient of the quadratic term of the independent variable is negative and significant. Second, the slope of the curve is negative and significant when the independent variable takes its maximum value, and positive and significant when the independent variable takes its minimum value. Third, the turning point of the curve lies between the maximum and minimum values of

Table 3 (*continued*)

Variables	Items	Loadings	α	CR	AVE
	environmental innovation are more competitive				
Green dynamic capability (Chen & Chang, 2013)	Our company has the ability that can fast monitor the environment to identify new green opportunities	0.900	0.959	0.966	0.802
	Our company has effective routines to identify and develop new green knowledge	0.891			
	Our company has the ability to develop green technology	0.902			
	Our company has the ability to assimilate, learn, generate, combine, share, transform, and apply new green knowledge	0.895			
	Our company has the ability to successfully integrate and manage specialized green knowledge within the company	0.896			
	Our company has the ability to successfully coordinate employees to develop green technology	0.898			
	Our company has the ability to successfully allocate resources to develop green innovation	0.885			
Green innovation (Song & Yu 2018)	Our company chooses the materials of the product that produce the least amount of pollution for conducting the product development or design	0.873	0.935	0.949	0.755
	Our company uses the fewest amount of materials to comprise the product for conducting the product development or design	0.882			
	Our company would circumspectly deliberate whether the product is easy to recycle, reuse, and decompose for conducting the product development or design	0.877			
	The manufacturing process of our company reduces the consumption of water, electricity, coal, or oil	0.880			
	The manufacturing process of our company effectively reduces the emission of hazardous substances or waste	0.845			
	The manufacturing process of our company reduces the use of raw materials	0.857			

independent variable. Following these practices, Table 5 presents the results (Xie & Wang, 2025). For Model 3, after controlling for such factors as firm age, firm size, and R&D investment, the squared term of digital business strategies has a negative and significant effect on green innovation ($\beta = -0.461$, $p < 0.001$). The values of digital business strategies used in the regression analysis range from −2.672 to 1.996. When the value of digital business strategies is at its minimum, the slope is 2.428. When the value of digital business strategies is at its maximum, the slope is −1.877. Additionally, the turning point is −0.039, which falls within the range of digital business strategy values. Based on Haans's (2015) proposition on the inverted U-shaped relationship, it can be concluded that an inverted U-shaped relationship exists between digital business strategies and green innovation, supporting H1.

Similarly, for Model 5, after controlling for relevant factors, the squared term of digital business strategies exerts a significant negative effect on green dynamic capabilities ($\beta = -0.502$, $p < 0.001$). When digital business strategies take their minimum and maximum values, the corresponding slopes are 2.688 and −1.999, respectively. Meanwhile, the turning point is 0.005, which lies within the range of digital business strategy values. This result confirms an inverted U-shaped relationship between digital business strategies and green dynamic capabilities (Haans et al., 2015), supporting H2. For Model 6, when the influence of control variables is excluded, green dynamic capabilities have a strongly positive effect on green innovation ($\beta = 0.620$, $p < 0.001$), which strongly verifies H3.

Following the conventional practice in the related literature (Baquero, 2024; Shehzad et al., 2023; Xie & Wang, 2025), Baron and Kenny's (1986) four-step approach was employed to test the mediating effect of green dynamic capabilities. In the first step, we tested the effect of the independent variable on the dependent variable. The results show that digital business strategies significantly predict green innovation ($\beta = -0.461$, $p < 0.001$). In the second step, we tested the effect of the independent variable on the mediating variable. The results demonstrate that digital business strategies significantly predict green dynamic capabilities ($\beta = -0.502$, $p < 0.001$). In the third step, we tested the effect of the mediating variable on the dependent variable. The results show that green dynamic capabilities significantly predict green innovation ($\beta = 0.620$, $p < 0.001$). In the fourth step, we incorporated green dynamic capabilities into the model to test the mediating effect. The results from Model 4 reveal the significant influence of digital business strategies on green innovation ($\beta = -0.197$, $p < 0.01$). However, the coefficient of the squared term of digital business strategies decreases significantly from the original −0.461 ($p < 0.001$) to −0.197 ($p < 0.01$). This finding implies that green dynamic capabilities play a partial mediating role between digital business strategies and green innovation (Baquero, 2024). Further calculations show that green dynamic capabilities mediate 67.51% of the inverted U-shaped effect of digital business strategies on green innovation, confirming a partial mediation effect, thus supporting H4. Existing literature has introduced market intelligence response as a mediator when examining the relationship between digital business strategies and service innovation (Yin et al., 2025), or incorporated knowledge-based dynamic capability as a mediating variable for the relationship between digital business strategies and innovation performance (Zheng, 2024). By contrast, our research shifts focus to the relationship between digital business strategies and green innovation. We specifically clarify how manufacturing firms can leverage digital business strategies to enhance green innovation through green dynamic capabilities.

Following Cohen et al.'s (2014) approach to test the moderating effect of institutional pressures, Models 7, 8, and 9 were developed. The results show that, excluding the influence of control variables, the squared term of digital business strategies and the interaction term of squared digital business strategies and institutional pressures have significant negative effects on both green innovation ($\beta = -0.472$, $p < 0.001$; $\beta = -0.284$, $p < 0.01$) and green dynamic capabilities ($\beta = -0.480$, $p < 0.001$; $\beta = -0.240$, $p < 0.05$), supporting H5a and H5b

Table 4
Descriptive statistics of the variables and correlation analysis.

Variables	Mean	SD	1	2	3	4	5	6	7
Firm age	3.749	1.569	1						
Firm size	3.383	1.507	0.452**	1					
R&D input	3.137	1.408	0.215**	0.045					
Digital business strategy	4.434	1.339	−0.036	−0.043	0.041	1			
Institutional pressure	4.409	1.583	0.050	0.131	0.013	−0.191*	1		
Green dynamic capability	4.019	1.830	0.018	−0.041	0.097	0.066	0.032	1	
Green innovation	3.838	1.831	0.109	0.003	0.216**	0.022	0.191*	0.635**	1

Note:.
* $p < 0.05$,.
** $p < 0.01$.

Table 5
The results of hierarchical analysis.

	Model 1 GI	Model 2	Model 3	Model 4	Model 5 GDC	Model 6 GI	Model 7 GI	Model 8 GDC	Model 9 GI
Firm age	0.086	0.087	0.061	0.063	−0.004	0.072	0.062	−0.003	0.078
Firm size	−0.045	−0.045	−0.012	−0.003	−0.018	−0.011	−0.062	−0.050	−0.041
R&D input	0.199*	0.198*	0.132†	0.122*	0.019	0.140*	0.093	−0.007	0.098†
DBS		0.015	−0.036	−0.039	0.005		−0.036	−0.008	
DBS^2			−0.461***	−0.197**	−0.502***		−0.472***	−0.480***	
IP							0.542***	0.366***	0.244***
GDC				0.525***		0.620***			0.528***
DBS^2xIP							−0.284**	−0.240*	
GDCxIP									0.293***
R^2	0.052	0.030	0.234	0.441	0.235	0.419	0.400	0.303	0.515
F	3.136*	2.349†	11.605***	23.817***	11.679***	32.338***	17.577***	11.784***	31.804***
VIF (max)	1.319	1.320	1.323	1.383	1.323	1.319	3.135	3.135	1.320

Note:.
† $p < 0.10$,.
* $p < 0.05$,.
** $p < 0.01$,.
*** $p < 0.001$; the dependent variable for model 1, model 2, model 3, model 4, model 6, model 7, and model 9 is green innovation; the dependent variable for model 5 and model 8 is green dynamic capability; DBS for digital business strategy, IP for institutional pressure, GDC for green dynamic capability, GI for green innovation.

(Cohen et al., 2014; Shehzad et al., 2023). These results show that institutional pressures exert a reinforcing effect on the inverted U-shaped relationship between digital business strategies and green dynamic capabilities. Furthermore, they exert a reinforcing effect on the inverted U-shaped relationship between digital business strategies and green innovation. This implies that institutional pressures might not only enhance the positive effect of moderate digital business strategies on green innovation but also intensify the inhibitory effect of excessive digital business strategies on green innovation. The literature commonly recognizes institutional pressures as one of the driving factors for green innovation (Ren & Wang, 2023). Institutional pressures were not treated as contextual factors to examine how their interaction with digital business strategies influenced green innovation in prior studies. In the literature on digital business strategies and innovation, the identified boundary conditions include organizational memory level and dispersion (Yin et al., 2025), as well as entrepreneurial orientation and market turbulence (Zheng, 2024). However, these studies did not consider the impact of the institutional environment. By highlighting the role of institutional pressures in enhancing the effect of digital business strategies on green innovation, our study emphasizes the importance of integrating digital strategies and environmental pressures to drive green innovation (Akhtar et al., 2024). This finding shows that firms experiencing high institutional pressures can implement moderate digital business strategies to enhance their green dynamic capabilities, which in turn promotes their green innovation.

Meanwhile, our regression analysis results reveal that green dynamic capabilities and the interaction term of green dynamic capabilities and institutional pressures exert significant positive effects on green innovation ($\beta = 0.528, p < 0.001$; $\beta = 0.293, p < 0.001$), thus supporting H5c (Cohen et al., 2014; Shehzad et al., 2023). This result indicates that institutional pressures positively moderate the linear relationship between green dynamic capabilities and green innovation. Consistent with the dynamic capability literature, green dynamic capabilities enable firms to actively respond to environmental regulations, and thereby improve their green innovation (Yu et al., 2024). Unlike the literature that has positioned green dynamic capabilities as a mediator for the impact of external pressures on green innovation (Singh et al., 2022), this study emphasizes the importance of treating external pressures as a contextual factor that interacts with green dynamic capabilities to enhance green innovation. Specifically, under high institutional pressures, firms with strong green dynamic capabilities tend to actively engage in green innovation.

The visual representation of the moderating effect of institutional pressures is shown in Fig. 2 (Xie et al., 2023). Sub-graph (a) depicts the moderating effect of institutional pressures on the inverted U-shaped relationship between digital business strategies and green innovation. Sub-graph (b) shows the moderating effect on the inverted U-shaped relationship between digital business strategies and green dynamic capabilities. These graphs indicate that under high institutional pressures, the curves still open downwards, but the openings are narrower than the curves under low institutional pressures. This finding suggests that increased institutional pressures amplify the inverted U-shaped effect of digital business strategies on both green innovation and green dynamic capabilities. Sub-graph (c) illustrates the moderating effect of institutional pressures on the relationship between green dynamic capabilities and green innovation. The graph shows that as institutional pressures increase, the slope of the line becomes steeper, indicating a more pronounced positive effect of green dynamic capabilities on green innovation. Overall, these visual representations provide a clear and intuitive understanding of how institutional pressures moderate the relationships

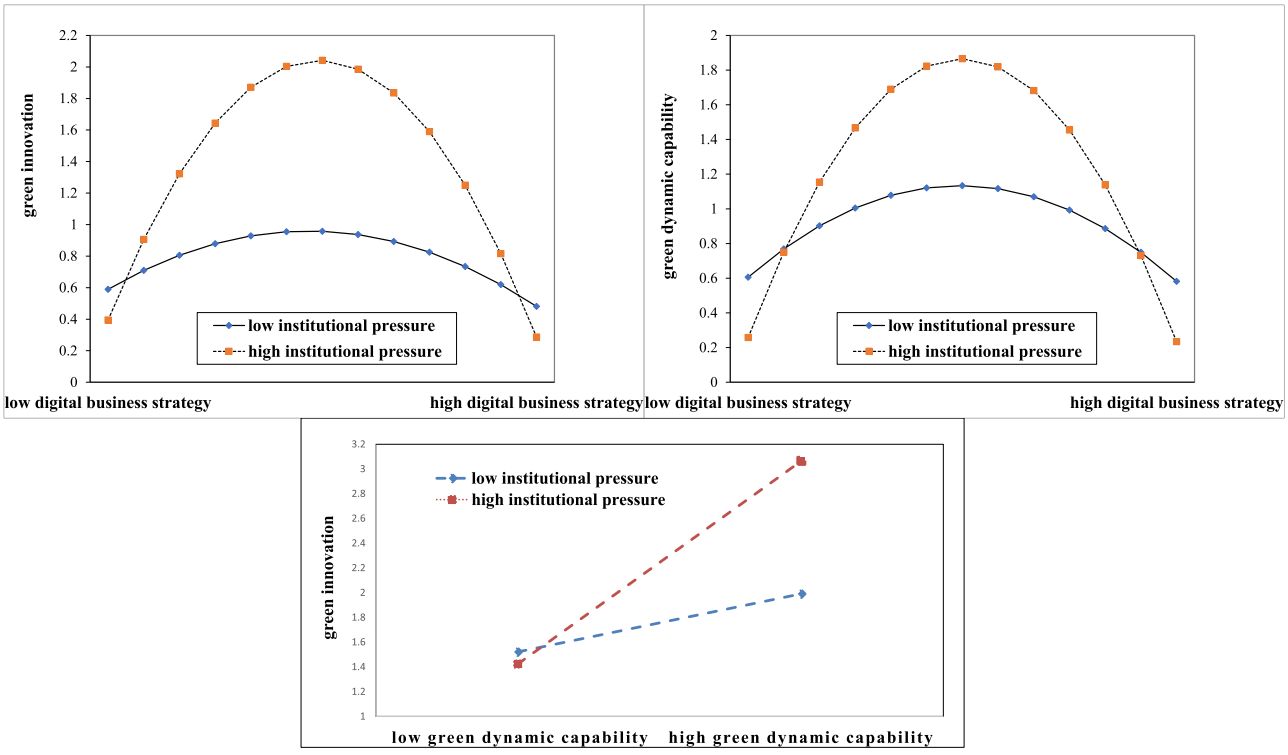

Fig. 2. The moderating effects.

examined in the study, enhancing the clarity and professionalism of the presentation.

Robustness test

We employed a combination of alternative measurement and estimation methods to test the robustness of the results. Specifically, consistent with Eikelenboom and Jong (2019), we used only one item, "Our company's management is familiar with digital tools," as the alternative measurement of the independent variable. We adopted Andrew Hayes's PROCESS with 5000 bootstrapped resamples and bias-corrected 95% confidence intervals as the alternative estimation method (Hayes et al., 2012). Model 59 was selected. The results in Table 6 (robustness test one) show the negative and significant effect of the squared term of digital business strategies on green dynamic capabilities ($\beta = -0.292$, $p < 0.001$) and green innovation ($\beta = -0.159$, $p < 0.01$), the positive effect of green dynamic capabilities on green innovation ($\beta = 0.449$, $p < 0.001$), the moderating effect of institutional pressures on the relationship between digital business strategies and green dynamic capabilities ($\beta = -0.100$, $p < 0.01$), and the linear relationship between green dynamic capabilities and green innovation ($\beta = 0.179$, $p < 0.001$); they are also consistent with the hypothesis testing results in terms of direction and significance. However, the moderating effect of institutional pressures on the relationship between digital business strategies and green innovation is not significant. Furthermore, the results of the moderated mediation analysis show that at values of low, medium, and high institutional pressures, the mediating effects of green dynamic capabilities are all significant ($\beta = -0.052$, $p < 0.05$; $\beta = -0.131$, $p < 0.05$; $\beta = -0.246$, $p < 0.05$).

We removed H5a, as the new estimation did not support it, and

Table 6
The results of robustness test.

Variables	Robustness test one						Robustness test two					
	Model 1 (DV: GDC)			Model 2 (DV: GI)			Model 3 (DV: GDC)			Model 4 (DV: GI)		
	Coefficients	LLCI	ULCI	Coefficients	LLCI	ULCI	Coefficients	LLCI	ULCI	Coefficients	LLCI	ULCI
Firm age	0.006	−0.145	0.156	0.073	−0.044	0.190	0.006	−0.145	0.156	0.073	−0.044	0.190
Firm size	−0.039	−0.188	0.109	−0.037	−0.152	0.079	−0.039	−0.188	0.109	−0.037	−0.152	0.078
R&D input	0.018	−0.118	0.154	0.086	−0.020	0.193	0.018	−0.118	0.154	0.086	−0.020	0.192
DBS	0.004	−0.138	0.146	−0.001	−0.111	0.110	0.004	−0.138	0.146	0.001	−0.104	0.105
DBS^2	−0.292***	−0.408	−0.176	−0.159**	−0.258	−0.061	−0.292***	−0.410	−0.174	−0.160**	−0.255	−0.065
GDC				0.449***	0.331	0.568				0.450***	0.333	0.567
IP	0.325***	0.149	0.502	0.295***	0.149	0.441	0.325***	0.149	0.502	0.292***	0.180	0.403
DBS^2xIP	−0.099*	−0.175	−0.023	−0.003	−0.072	0.067	−0.099**	−0.175	−0.023			
GDCxIP				0.179***	0.074	0.284				0.181***	0.090	0.272
R^2	0.262			0.561			0.262			0.561		
F	8.476***			23.440***			8.476***			26.529***		

Note: † $p < 0.10$,.
* $p < 0.05$,.
** $p < 0.01$,.
*** $p < 0.001$; DV for dependent variable, DBS for digital business strategy, IP for institutional pressure, GDC for green dynamic capability, GI for green innovation.

selected Model 58 to conduct the robustness test again. The values for digital business strategies range from −2.544 to 1.953. For green innovation, the results of the second robustness test show that the coefficient of the squared term of digital business strategies is negative and significant ($\beta = -0.160$, $p < 0.01$). For the minimum and maximum values of digital business strategies, the corresponding slopes are 0.815 and −0.624, respectively. The turning point is 0.003, which falls within the range of digital business strategy values. Consequently, the inverted U-shaped relationship between digital business strategies and green innovation (H1) is repeatedly supported (Haans et al., 2015). For green dynamic capabilities, the coefficient of the squared term of digital business strategies is negative and significant ($\beta = -0.292$, $p < 0.001$). For the minimum and maximum values of digital business strategies, the corresponding slopes are 1.490 and −1.136, respectively. The turning point is 0.007, well within the range of digital business strategy values. Thus, the inverted U-shaped relationship between digital business strategies and green dynamic capabilities (H2) is repeatedly supported (Haans et al., 2015). The results support the linear relationship between green dynamic capabilities and green innovation (H3), with a coefficient of $\beta = 0.450$ ($p < 0.001$). Furthermore, the results of the moderated mediation analysis reveal that at low, medium, and high levels of institutional pressures, the mediating effects of green dynamic capabilities are all significant, with $\beta = -0.052$ ($p < 0.05$), $\beta = -0.132$ ($p < 0.05$), and $\beta = -0.247$ ($p < 0.05$), respectively. Meanwhile, the direct effect of the squared term of digital business strategies on green innovation remains significant ($\beta = -0.160$, $p < 0.01$). Therefore, the partial mediating role of green dynamic capabilities (H4) is repeatedly supported. Additionally, the results indicate that the moderating effect of institutional pressures on the relationship between digital business strategies and green dynamic capabilities is significant ($\beta = -0.099$, $p < 0.05$). Furthermore, the linear relationship between green dynamic capabilities and green innovation is significant ($\beta = 0.181$, $p < 0.001$). Consequently, H5b and H5c are repeatedly supported and robust. This suggests that the effects hypothesized by H1, H2, H3, H4, H5b, and H5c are robust, whereas the moderating effect of institutional pressures on the inverted U-shaped relationship between digital business strategies and green innovation is subject to measurement and estimation method (Hayes et al., 2012; Mehralian et al., 2024). The robust model and effects are depicted in Fig. 3.

Configuration analysis

Regression analysis is a valuable method for testing causal relationship hypotheses, but it struggles to examine the potential interdependencies between antecedent variables and asymmetric causal relationships (Hu, 2025). Fuzzy-set qualitative comparative analysis (fsQCA) can overcome the limitations of survey-based measurement and precisely offset the deficiencies of regression analysis in these aspects, thereby explaining the multiple concurrent causal relationships of corporate green innovation (Lee & Choi, 2024). Therefore, combining fsQCA with traditional regression analysis aids understanding of causal patterns.

Variable calibration and data analysis

In this study, four variables were selected as antecedent conditions: digital business strategy, institutional pressure, green dynamic capability, and R&D input. This choice was mainly based on the following two considerations: First, the regression analysis theoretically analyzed and empirically tested the impact of digital business strategies, institutional pressures, and green dynamic capabilities on green innovation. Second, the results of correlation analysis show that R&D input has a significantly positive correlation with green innovation ($r = 0.216$, $p < 0.05$), whereas the relationships between firm age, firm size, and green innovation are not significant. Therefore, R&D input was incorporated as a potential antecedent condition (Mikalef & Pateli, 2017).

Before data calibration, we calculated the means of continuous variables, such as digital business strategy, institutional pressure, and green dynamic capability. The direct calibration method was adopted. Data calibration was conducted according to the standards of 95% (fully in), 50% (crossover point), and 5% (fully out), as Ragin (2008) proposed. After data calibration, we conducted a necessary condition analysis on all antecedents. The results show that none of the consistency levels exceed 0.9. This indicates that there are no absolute necessary conditions, and it is necessary to combine multiple antecedent conditions for configuration analysis (Dul, 2016).

Results of fuzzy-set qualitative comparative analysis

We used fsQCA 4.1 software to construct a truth table algorithm.

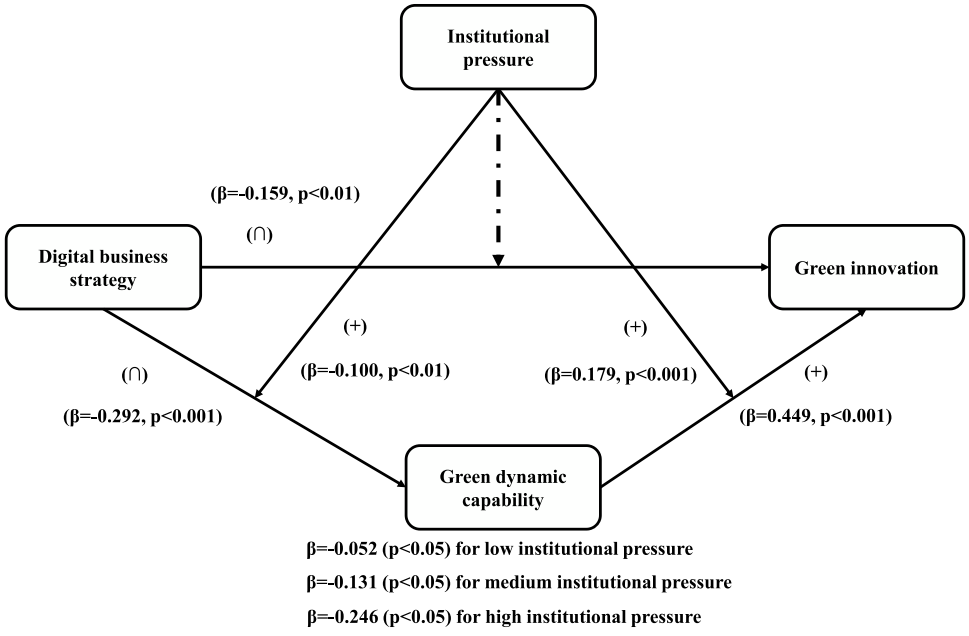

Fig. 3. Revised model after robustness test.

Based on the conventional practice in the related field, the consistency threshold was set at 0.8, the acceptable number of cases was set at 1, and proportional reduction in inconsistency scores were greater than 0.7 (Pappas & Woodside, 2021). The intermediate solution was used to determine the number of configurations leading to green innovation and the antecedent variables, and the parsimonious solution was used to determine the core conditions in the configurations (Pittino et al., 2025). Antecedent variables that appeared only in the intermediate solution but not in the parsimonious solution were identified as peripheral conditions, whereas those that appeared in both the intermediate solution and the parsimonious solution were identified as the core conditions (Pittino et al., 2025). Usually, there is a relatively strong causal relationship between core conditions and the outcome variable, and a relatively weak causal relationship between peripheral conditions and the outcome variable (Pappas & Woodside, 2021). Table 7 presents the results. Here, "●" indicates that the condition exists and serves as a core condition, and "⊗" indicates that the condition does not exist and serves as a core condition.

Table 7 presents the four configurations. Among them, two configurations could produce high green innovation. The solution coverage is 0.61, higher than 0.5 (Greckhamer et al., 2013). The solution consistency is 0.91, greater than 0.75 (Greckhamer et al., 2013), indicating that the configuration effect is good. The other two configurations produce non-high green innovation. The solution coverage is 0.64, and the solution consistency is 0.91, with an obvious configuration effect (Greckhamer et al., 2013). The four configurations could be interpreted as follows.

Configuration 1 (R&D investment * institutional pressure * green dynamic capability) reveals the path of knowledge accumulation-based green innovation. This configuration implies that under the mandatory regulation of institutional pressures, such as carbon emission policies, firms build a technical knowledge base through high R&D investment and activate their green dynamic capabilities. They conduct ecological reconstruction of knowledge assets (e.g., transformation of clean technology patents) to achieve green innovation. This configurational path receives partial support from a prior study, which proposed that knowledge enablers and knowledge processes form multiple configurations that drive improved green innovation (Shehzad et al., 2024). We further argue that the accumulation of knowledge, along with its efficacy in promoting firms' green innovation, depends on both external institutional pressures and internal green dynamic capabilities.

Configuration 2 (digital business strategy * institutional pressure * green dynamic capability) represents the path of digital empowerment-based green innovation. This configuration implies that well-designed environmental regulations and institutional pressures can encourage firms to adopt digital technologies and develop digital business strategies for green innovation through legitimacy empowerment, such as green certification incentives (Guo et al., 2025). When combined with the environmental insight function of green dynamic capabilities (Abbas, 2024), for instance, intelligent carbon footprint monitoring, firms achieve coordinated evolution of digital technologies and green goals, which leads to better green innovation. Studies on the influencing factors of green innovation have overlooked the interaction between institutional factors and resource factors (Xiao et al., 2023). Other studies have focused on green pressures, green technologies, and green knowledge (Bai et al., 2021) but have failed to examine the interactions between green pressures, digital strategies, and dynamic capabilities. However, our study emphasizes the importance of the interaction among digital strategies, dynamic capabilities, and institutional factors, as this interaction enables firms to leverage digital technologies to empower better green innovation under environmental pressures.

Configuration 3 (digital strategy * ~institutional pressure * ~green dynamic capability) presents the technical lock-in effect. This path reveals the implicit constraint function of institutional pressures. Existing studies indicate that pressures arising from environmental regulations influence the quality of green innovation (Zhu et al., 2023). Additionally, the impact of digitalization on green innovation depends on its interaction with the institutional environment (Zang et al., 2025a). Therefore, in the absence of institutional pressures, the one-sided expansion of digital business strategies causes technical paths to deviate from green innovation goals, eventually leading to non-substantive green innovation. Meanwhile, pressures from various stakeholders also affect green dynamic capabilities (Singh et al., 2022). This suggests that the lack of institutional pressures creates unfavorable conditions for green dynamic capabilities, which results in non-high green innovation. Overall, this configuration explains why the digital transformation of some firms is accompanied by the outcome of non-high green innovation.

Configuration 4 (institutional pressure * ~R&D investment * ~green dynamic capability) reflects the compliance dissipation mechanism. Although environmental regulations and institutional pressures are among the key drivers of firms' green innovation (Ren & Wang, 2023; Xiao et al., 2023), institutional pressures alone are insufficient if firms lack R&D capabilities and green dynamic capabilities. Green innovation depends not only on firms' green R&D investment but also on green dynamic capabilities, which help firms identify green opportunities, integrate, utilize, and reconstruct green resources (Xiao et al., 2023). When firms have insufficient R&D investment and lack green dynamic capabilities, institutional pressures can drive superficial or strategic compliance behaviors, such as the compilation of environmental protection reports, and fail to activate substantive green innovation (Zang et al., 2025a). This configuration underscores that promoting green innovation cannot rely solely on imposing green pressures, as it also requires focus on developing firms' R&D capabilities and green dynamic capabilities.

The analysis shows that the paths to green innovation exhibit a complementary and substitutable relationship. R&D investment and digital business strategies demonstrate functional equivalence in the context of green innovation, yet there are disparities in their mechanisms of action. This phenomenon of achieving the same outcome via different approaches resonates with the principle of equivalence in configurational theory (Fiss, 2011).

In addition to identifying the four abovementioned configurations, the fsQCA results provide strong supplementary validation of the regression analysis findings (Lee & Choi, 2024). First, the configuration results align with the regression analysis findings regarding the non-linear relationship between digital business strategies and green innovation. In configuration 2, digital business strategies exist together with institutional pressures and green dynamic capabilities, and the outcome is high green innovation, while in configuration 3, only a digital business strategy exists but the outcome is non-high green innovation. This contrast shows that the relationship between digital business strategies and green innovation is not a simple linear one, instead reflecting the non-linear characteristics of an inverted U-shaped relationship to an extent. When digital business strategies are combined with appropriate conditions, they promote strong innovation, but when the matching conditions are lacking, innovation weakens. Second, the configuration results are consistent with the regression analysis findings

Table 7
The results of fsQCA.

Configuration	High green innovation		Non-high innovation	
	1	2	3	4
R & D input	●			⊗
Digital business strategy		●	●	
Institutional pressure	●	●	⊗	●
Green dynamic capability	●	●	⊗	⊗
Raw coverage	0.52	0.51	0.46	0.44
Unique coverage	0.10	0.08	0.20	0.18
Consistency	0.93	0.93	0.91	0.93
Solution coverage	0.61		0.64	
Solution consistency	0.91		0.91	

in verifying the mediating role of green dynamic capabilities. In configuration 2, when digital business strategies and green dynamic capabilities co-exist, the outcome is high green innovation. In configuration 3, when digital business strategies exist but green dynamic capabilities do not, the outcome is non-high green innovation. In configuration 4, green dynamic capabilities do not exist, and the outcome is non-high green innovation. This shows that green dynamic capabilities are pivotal to the process of digital business strategies affecting corporate green innovation. Without green dynamic capabilities, achieving high green innovation is difficult, supporting the role of green dynamic capabilities as a mediating variable. Third, the results align with those from the regression analysis in confirming the moderating effect of institutional pressures on the inverted U-shaped relationship between digital business strategies and green innovation. In configuration 2, with institutional pressures and digital business strategies, the outcome is high green innovation. Meanwhile, in configuration 3, when digital business strategies exist but institutional pressures do not, the outcome is non-high green innovation. This indicates that when institutional pressures exist, they can work together with digital business strategies to promote high green innovation, supporting the positive moderating effect of institutional pressures on the inverted U-shaped relationship between digital business strategies and green innovation.

Discussion and implications

Discussion of results

This study offers empirical insights into the nuanced relationship between digital business strategies and green innovation, revealing a non-linear, inverted U-shaped pattern. This finding challenges the linear and optimistic portrayal of the impact of digitalization in prior research (Hassan et al., 2024; Wang et al., 2024c; Yang et al., 2024) and provides a more differentiated view. Specifically, this study corroborates and extends the recent scholarship that identifies an optimal inflection point in digital transformation for innovation outcomes beyond which returns diminish (Lu et al., 2025). We recognize that firms can benefit from moderate levels of digital business strategies for their green innovation. However, as highlighted in existing literature, excessive digitalization may induce unintended negative effects, such as crowding out or misallocating limited attention and resources (Shang et al., 2025). Therefore, we propose that excessive digital business strategies could also have an adverse effect on green innovation. This proposition aligns with the digital paradox in the relationship between enterprise digitalization and innovation performance (Li et al., 2024), indicating that excessive investment in digitalization may constrain firms' innovation performance.

Furthermore, our analysis indicates that digital business strategies and green dynamic capabilities share an inverted U-shaped relationship. First, we confirm that moderate levels of digital business strategies enhance firms' green dynamic capabilities, which aligns with prior studies proposing that digitalization facilitates firms' ability to perceive and seize opportunities and integrate and reconfigure resources (Llopis-Albert et al., 2021; Matarazzo et al., 2021). Second, we find that overemphasis on digital business strategies could cause green dynamic capabilities to decline. This outcome mirrors the findings of innovation management studies that report capability traps when firms overinvest in digitalization (Li et al., 2024; Zang et al., 2025b). Importantly, green dynamic capabilities exhibit a strong positive linear association with green innovation, reinforcing the theoretical arguments of dynamic capability theory that such capabilities are fundamental drivers of sustainable innovation (Chen et al., 2024) and performance (Ullah et al., 2025). The mediating role of green dynamic capabilities underscores that digital business strategies not only influence green innovation directly but also operate by enhancing firms' ability to integrate, reconfigure, and renew environmental knowledge and green resources. Studies on digital transformation and low-carbon technology innovation have observed a similar mechanism (Yang et al., 2023).

Institutional pressures significantly strengthen the curvilinear relationship between digital business strategies and green dynamic capabilities, as well as the linear link between green dynamic capabilities and green innovation. This finding resonates with institutional theory (DiMaggio & Powell, 1983) and a recent empirical study confirming that institutional pressures act as catalysts of managerial environmental concern that focus managerial attention and resource allocation on sustainability goals (Shivani et al., 2025). The result implies that when institutional pressures are high, firms usually leverage more digital technologies and resources to shape green dynamic capabilities, which contribute significantly to green innovation. This aligns well with the sustainability literature emphasizing the role of environment-related institutional push in driving firms toward greener practices (Singh & Joshi, 2024).

Finally, the fsQCA results validate and extend the regression findings (Bai et al., 2021) by revealing two distinct configurational paths toward high green innovation. One centers on digital strategy empowerment, which combines digital business strategy, green dynamic capability, and institutional pressure. The other path relies on substantial R&D investment as a substitute for digital business strategy. However, none of these single factors serves as either a sufficient or necessary condition for achieving high green innovation. This finding aligns with the tenets of the configuration perspective for green innovation (Cui et al., 2025; Yin, 2023) and a recent study emphasizing the coupling and interaction of internal and external factors to form different configurations in achieving sustainability (Li & Che, 2024). Additionally, consistent with Cui et al. (2025), who uncovered three configurational patterns leading to non-high radical green innovation, our study further identifies two more configurations that result in non-high green innovation. The results underscore the importance of balancing digital business strategies, fostering green dynamic capabilities, and responding to institutional pressures to enhance green innovation. These insights are critical for firms seeking to navigate a complex landscape in which digital transformation intersects with sustainability goals.

This study has dual relevance. Theoretically, it advances a nuanced understanding of the non-linear relationship between digital business strategies and green innovation, thereby challenging the prevailing linear assumptions in existing literature (Hassan et al., 2024; Wang et al., 2024c; Yang et al., 2024). By identifying green dynamic capabilities as a core mediating mechanism and institutional pressures as a critical boundary condition, this research addresses a gap in the literature by extending the application of the dynamic capability view and institutional theory to the context of digitally enabled green innovation. The findings offer actionable guidance for firms, governments, and industry associations. They highlight that blind investment in digitalization is insufficient for firms. Instead, firms should prioritize cultivating green dynamic capabilities while closely monitoring external institutional trends to optimally leverage digital business strategies for achieving sustainability goals. For governments and industry associations, the results underscore the need for differentiated roles: Governments could strengthen targeted institutional pressures (e.g., policy incentives, regulatory standards) to guide firms' digital-sustainability alignment, while industry associations could guide firms to prioritize the implementation of digital business strategies, recommending that policymakers or regulatory authorities implement tailored regulatory strategies for distinct types of firms.

Theoretical implications

First, our research contributes to the literature by uncovering an inverted U-shaped relationship between digital business strategies and green innovation, a finding that challenges the traditional linear perspective. Previous studies have assumed a positive, linear association between digital initiatives and innovation outcomes, suggesting that

increased digitalization fosters higher levels of green innovation (Fang & Li, 2024). However, some scholars have found that excessive digital transformation might result in resource misallocation, strategic misalignment, and increased operational complexity, which could undermine firms' green technology innovation performance (Xu et al., 2025). Similarly, our study finds that although a moderate level of digital business strategies could enhance green innovation, excessive focus could lead to a saturation point, where additional digital efforts do not yield increased green innovation but may instead lead to resource dilution, attention distractibility, and information overload. Theoretically, our study extends the digitalization paradox by providing empirical evidence for the inverted U-shaped relationship (Gao et al., 2025; Qi et al., 2025). This relationship introduces a dynamic in which the positive effects of digital business strategies on green innovation are not indefinite but curbed by the law of diminishing returns. This refined comprehension offers a pragmatic and nuanced perspective on the intricate interplay between digital strategies and their capacity to foster sustainable innovation practices. By acknowledging the existence of an optimal digitalization level beyond which benefits plateau and may reverse, our study corrects the oversimplified assumptions of prior research, fostering a balanced and realistic approach to strategically leveraging digital technologies for environmental stewardship and innovation.

Second, our study extends the dynamic capabilities view by identifying green dynamic capabilities as a mediator in the relationship between digital business strategies and green innovation. This aligns with and extends scholarship that has discussed the role of dynamic capabilities in innovation outcomes (Mikalef et al., 2019). However, our research explicitly specifies this mechanism within the context of green innovation. Unlike the previous mediating mechanism of dynamic capabilities in the linear relationship between digital capabilities and innovation outcomes (Liu & Wang, 2025; Xie & Wang, 2025), we reveal a more complex, non-linear mediating mechanism of green dynamic capabilities in the inverted U-shaped relationship between digital business strategies and green innovation. This not only challenges the existing narrative but also forges a new direction for investigating how digital business strategies can be optimally leveraged to foster green innovation, thereby contributing to the digitalization paradox literature.

Third, this study makes a significant contribution to the literature on institutional pressures by examining their contextual role in the relationships among digital business strategies, green dynamic capabilities, and green innovation. Existing research suggests that the impact of digital technology on corporate innovation activities varies across different institutional environments (Zhang et al., 2023). This highlights the need to incorporate institutional theory to better understand how the interaction between the institutional environment and corporate digitalization influences firms' innovative behaviors (Zang et al., 2025a). However, the literature has primarily focused on the separate impacts of institutional pressures or digital business strategies on green innovation (Singh & Joshi, 2024), overlooking their interaction effect. The present study addresses this gap by examining how these factors collectively influence green innovation outcomes. Consequently, our findings offer valuable theoretical insights into how digital business strategies shape green innovation under conditions of varying institutional pressure intensity.

Fourth, this study contributes significant theoretical value to the configurational literature on green innovation, as it identifies four novel configurations that lead to high or non-high green innovation. It explicitly integrates digital business strategies, green dynamic capabilities, institutional pressures, and R&D investment into a holistic analytical framework and identifies two novel configurations driving high green innovation in the process. This addresses the relative fragmentation in existing research, which focuses on partial factors. Although prior studies have explored the critical roles of environmental pressures (Cui et al., 2025), digital infrastructure (Li et al., 2023b), stakeholder networks (Bai et al., 2021), and knowledge management (Shehzad et al., 2024), our research uniquely identifies two distinct configurations that drive high green innovation. The first is a knowledge accumulation-based path, characterized by the combination of R&D investment, institutional pressure, and green dynamic capability. The second is a digital empowerment-based path, composed of the interactions between digital business strategy, institutional pressure, and green dynamic capability. This dual-path insight enriches the literature by explicitly linking digital transformation (Liu & Wang, 2025) and knowledge accumulation mechanisms (Shehzad et al., 2024), which were previously examined in isolation. Furthermore, the study breaks new ground by uncovering two distinct mechanisms that lead to non-high green innovation. This addresses a critical oversight in existing configurational research, which primarily focuses on high-performance paths. The technical lock-in effect configuration, involving digital business strategy alongside the absence of institutional pressure and green dynamic capability, reveals how such misalignment stifles green innovation. This dynamic was not examined in Cui et al.'s (2025) analysis of non-high radical green innovation configurations. Similarly, the compliance dissipation mechanism configuration, characterized by institutional pressure combined with the lack of R&D investment and green dynamic capability, explains how external pressures fail to drive green innovation when not accompanied by internal R&D resources and green dynamic capabilities. This finding complements Li and Che's (2024) focus on high-performance synergies by illuminating the failure scenarios that arise from misaligned internal and external factors.

Practical implications

First, firms must strive to achieve a balance that maximizes the advantages of digital business strategies for fostering green innovation. Excessive emphasis on a digital business strategy may inadvertently cause attention on green innovation to decline, whereas the absence of such a strategy may constrain the potential for green innovation. Consequently, firms should devise clear digital business strategic plans and integrate green innovation goals into their digital business strategies to ensure strategic synergy between both dimensions (Chen et al., 2025). Furthermore, firms should consistently evaluate the effectiveness of their digital business strategies and green innovation endeavors. By establishing key performance indicators, such as a count of green innovation achievements and the efficacy of digital technology applications, firms can quantify and assess the results of their strategic implementation. Based on these evaluations, firms should make the necessary adjustments to their digital business strategies and adopt a balanced approach to navigate the multifaceted impact of digitalization, thereby facilitating the achievement of green innovation (Hou et al., 2024).

Second, managers are advised to embed the cultivation of green dynamic capabilities into three key practices: formulating digitalization strategies, designing training programs, and collaborating with partners. Enhancing green dynamic capabilities could serve as a vital bridge between digital business strategies and green innovation, playing a pivotal role in advancing firms' green innovation and sustainable development efforts (Guo, 2023). Specifically, firms should foster green dynamic capabilities into the formulation and implementation of digital business strategies to bolster their green dynamic capabilities by adopting tailored digital strategies. Furthermore, they should organize regular internal training sessions and invite green technology experts to deliver workshops, thereby enhancing employees' insights into green markets and trends as well as their skills in integrating and utilizing green resources. Additionally, firms could actively forge partnerships with external entities, such as universities and research institutions (Secundo et al., 2025), to tap into expert resources in the fields of green technology, products, or markets. This would augment firms' capabilities to identify and capitalize on green opportunities, while also reinforcing the reconfiguration of their green resources and capabilities.

Third, the moderating influence of institutional pressures offers

practical implications for both governments and firms. By formulating and enforcing environmental protection regulations and providing preferential policies, governments can effectively steer firms toward prioritizing environmental protection and increasing green investments, urging them to focus on green and sustainable development during their digital transformation (Wu et al., 2023b). Governments should constantly refine the system of environmental protection regulations, clarify firms' responsibilities and obligations toward environmental protection, and enforce penalties for violations to create a deterrent effect. Simultaneously, governments could formulate a range of green incentive policies, including tax reductions, green subsidies, green bonds, and green credit to offset the cost of green investment (Huang et al., 2025) and encourage firms to engage in green innovation through digital business strategies. Firms should actively explore and implement digital business strategies, as this could effectively address institutional pressures, enhance firms' green dynamic capabilities, and foster green innovation. However, in contexts of high institutional pressures, it is prudent to avoid overreliance on investments in digital business strategies. The confluence of immense institutional pressures and excessive digital business strategies may weaken green dynamic capabilities and diminish green innovation efficiency.

Fourth, industry associations should establish a comprehensive situational diagnosis system with the following functions. When firms' R&D intensity is low and their R&D investment is at a low membership degree, the system should prompt such firms to prioritize the implementation of digital business strategies, and supplement their digital infrastructure and digital capabilities to avoid insufficient green innovation. When firms exist in an area with strong institutional pressures (configuration 2), the system should prompt these firms to enhance the agility of their institutional response by building a digital platform. Industry associations, as institutional intermediaries, play a key role in aggregating business issues and bringing them to the attention of policymakers (Yao et al., 2022). Therefore, this system should help industry associations further recommend that policymakers or regulatory authorities implement tailored regulatory strategies for distinct types of firms. For example, for firms with high R&D investment (configuration 1), performance-based regulations, such as green patent subsidies, could be applied. For firms leading in digitalization (configuration 2), green niche policies could be implemented. For firms with low R&D capabilities or low green dynamic capabilities (configurations 3 and 4), the system may suggest strengthening process supervision to prevent symbolic compliance.

Limitations and future research

First, this study employs cross-sectional survey data for testing the research model. This method is commonly used in digital business strategy research (Yin et al., 2025; Zheng, 2024) but has inherent limitations. Owing to the absence of a temporal dimension, the method restricts the ability to draw strong causal inferences or observe changes over time. In future research, the use of longitudinal data can enable stronger causal conclusions and a more comprehensive understanding of the dynamic effects. Another limitation pertains to the measurement items for green innovation. Although these items demonstrate strong reliability and validity, they do not capture objective outcomes, such as green patents, or quantifiable improvements in environmental performance (Zhang & Shi, 2024). Future research should integrate such objective metrics to offer a more comprehensive validation of the relationships examined in this study.

Second, this study is constrained by its focus on a single national context, with the research sample limited to Chinese manufacturing firms. This limits the generalizability of the findings to other sectors or countries with distinct institutional environments, especially as significant disparities exist in the development levels of the digital economy and institutional maturity across countries. To address these limitations, future research should adopt a comparative analytical approach across diverse economies. This approach should encompass both developed economies with mature market institutions and emerging economies characterized by distinct regulatory contexts. It would facilitate a deeper exploration of how digital business strategies, environmental regulations, and green innovation interact across varied settings. In turn, this would uncover more nuanced insights and strengthen the generalizability of the research findings. Additionally, future research could extend this framework to the service sector, following the examples of Khan et al. (2025) and Pan and Yang (2024). The service sector features operational models, resource dependencies, and environmental impact pathways distinct from those of the manufacturing sector. In manufacturing, green innovation often centers on tangible improvements in production processes, material efficiency, or product design. In this context, digital business strategies typically enable data-driven optimization of energy use or waste reduction in the factory. By contrast, the service sector relies on intangible assets, digital platforms, and human capital. This implies that the pathways of each sector to green innovation may be distinct. Thus, future research could extend the framework to the service sector to investigate the unique mechanisms through which digital business strategies promote green innovation.

Third, this study has limitations related to the moderator analysis. The measurement of institutional pressures relies on survey data from a single scale, and the moderating effect of institutional pressures may be sensitive to measurement and estimation methods. To address this limitation, future research could strengthen the validity of the moderating role by adopting mixed-methods measurement. For example, combining subjective scales with objective indicators, such as policy text analysis, third-party institutional evaluation reports, or an index (Shi & Mai, 2025) could help cross-validate the results. Furthermore, beyond institutional pressures, other contextual factors, such as firm ownership, market competition, and industry type, may also influence the focal relationships. Incorporating them into the analytical framework in future research would help clarify how institutional pressures interact with these factors to influence the focal relationships, providing a more comprehensive understanding of the phenomenon.

Conclusions

This study investigates the complex role of digital business strategies in fostering green innovation among manufacturing firms. Transcending linear assumptions, this analysis reveals curvilinear, inverted U-shaped relationships between digital business strategies and two key outcomes: green innovation and green dynamic capabilities. This pivotal finding indicates that although an appropriate level of digitalization acts as a catalyst for sustainability efforts, excessive pursuit of digitalization can lead to diminishing returns. This study further uncovers the mediating mechanism of green dynamic capabilities, through which the benefits of digital business strategies are partially translated into green innovation outcomes. Moreover, this study demonstrates that institutional pressures function as critical positive moderators: They strengthen not only the inverted U-shaped relationship between digital business strategies and green innovation but also that between digital business strategies and green dynamic capabilities, as well as the linear relationship between green dynamic capabilities and green innovation. This underscores the importance of the external institutional environment in improving firms' focus and guiding their digital investments toward green objectives. The application of fsQCA enriches these findings by identifying two distinct configurational paths to high green innovation: a digital empowerment-based path (leveraging digital business strategies, institutional pressures, and green dynamic capabilities), and a knowledge accumulation-based path (where high R&D investment substitutes for digital business strategies, paired with institutional pressures and green dynamic capabilities). This study offers empirical evidence that firms can achieve superior green performance through diverse strategic portfolios.

CRediT authorship contribution statement

Xiaoyong Zheng: Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Jiaqi Zhong:** Writing – review & editing, Investigation. **Wei Pi:** Writing – review & editing, Resources, Data curation.

Declaration of competing interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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