

Research on Digitalization to Facilitate the Development of Green Technology Innovation in Enterprises

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ABSTRACT

In the context of the rapid development of the digital economy, whether enterprise digitalization can promote green technological innovation has attracted the attention of academia. Existing studies lack a unified standard for measuring the level of enterprise digitalization and have not comprehensively and deeply examined the micro pathways through which enterprise digitalization affects green technological innovation. Unlike previous research, this paper not only measures the level of enterprise digitalization based on intangible asset data but also conducts a more refined textual analysis of the annual reports of listed companies. It uses the proportion of digital-related word frequency in the "Performance Review" section of the "Management Discussion and Analysis" to measure the actual level of enterprise digitalization and tests the constructed indicators using big data from online recruitment. On this basis, the paper examines the impact of digitalization on green technological innovation in heavily polluting industries and explores the micro mechanisms using detailed patent application data of listed companies. The study finds that digitalization in heavily polluting industries can significantly promote green technological innovation. This conclusion remains robust after a series of robustness tests, including IV estimation, counterfactual analysis, and changes in estimation methods.

KEYWORDS

Enterprise Digitization; Green Technology Innovation; Knowledge Integration; Information Sharing.

1. INTRODUCTION

Green technological innovation is an important driving force for transforming the economic development model and achieving green and sustainable development[1]. It is also a crucial support for China to realize the goals of "carbon peak" and "carbon neutrality." In 2021, the State Council of China issued the "Action Plan for Carbon Peak Before 2030," emphasizing that green and low-carbon technological innovation is a key task for the "carbon peak" action. It proposed strengthening the dominant position of enterprises in innovation[2-4], supporting enterprises in undertaking major national green and low-carbon scientific and technological projects, and accelerating the green and low-carbon technological revolution. Exploring the influencing factors of green technological innovation from multiple dimensions, such as its nature and characteristics, can provide references for China to achieve the goals of "carbon peak" and "carbon neutrality" and green and sustainable development[5]. Moreover, the wave of digital development is sweeping the globe today. Seizing the opportunities of digital development is crucial for enhancing the core competitiveness of China's economy and promoting high-quality economic development. Against the backdrop of the rapid development of the digital economy, an increasing number of enterprises are leveraging emerging digital technologies to undergo digital transformation and enhance their digitalization levels. Since 2020, policies to support enterprise digital transformation, such as the "Special Action Plan for Digital

Empowerment of Small and Medium-sized Enterprises" and the "Notice on Accelerating the Digital Transformation of State-owned Enterprises," have been successively introduced. Digitalization of enterprises has become an important direction for future enterprise reform and transformation[6]. Therefore, examining whether digitalization can promote green technological innovation in enterprises can provide theoretical references for China's digital economy development.

Some studies have conducted preliminary explorations and analyses of the relationship between enterprise digitalization and green technological innovation[7]. El-Kassar and Singh (2019) used micro-survey data from 215 companies and found through empirical analysis that the application of big data in enterprises would affect their green innovation activities, thereby further influencing their competitive advantages. However, the study by El-Kassar and Singh (2019) did not comprehensively analyze and empirically test the mechanisms through which enterprise digitalization affects green technological innovation[8-10]. Building on this, Mubarak et al. (2021) empirically tested the mechanisms through which Industry 4.0 technologies influence corporate green innovation behavior and found that Industry 4.0 technologies can motivate open innovation practices through efficient information transmission and knowledge accumulation, which in turn encourages enterprises to engage in more green innovation activities[11-12].

Nevertheless, the above studies lack a unified standard for measuring the level of enterprise digitalization and do not analyze or empirically test the micro pathways through which enterprise digitalization affects green technological innovation. Unlike existing research, first, this paper constructs a more refined indicator of enterprise digitalization based on textual analysis and tests the quality of the constructed digitalization indicator using big data from online recruitment. Second, based on the characteristics of green technological innovation, this paper explores the pathways through which digitalization affects green technological innovation, thereby providing a more comprehensive and in-depth mechanism discussion from a micro perspective to understand the relationship between digitalization and green technological innovation. Third, to address the endogeneity issue between enterprise digitalization and green technological innovation, a series of robustness tests are conducted. Fourth, this paper further investigates the heterogeneity of the impact of enterprise digitalization on green technological innovation for enterprises with different characteristics.

In terms of measurement indicators, this paper not only constructs an indicator to measure the level of enterprise digitalization based on intangible asset data details, as in the research by Qi et al. (2020), but also constructs a more refined indicator of enterprise digitalization based on textual analysis. In fact, the use of textual analysis to measure the level of digitalization has been widely applied in the literature (Zhao, 2021). However, the identification of digital-related word frequency in annual reports in the above literature is relatively crude. Unlike existing studies, this paper distinguishes whether the word frequency appears in the "Performance Review" or "Future Outlook" section of the "Management Discussion and Analysis" when counting the number of digital-related word frequencies. The "Performance Review" is a reflection of the work completed by the enterprise in the previous year, and the number of digital word frequencies in it can better reflect the actual level of enterprise digitalization. Using this indicator for empirical analysis also helps to further exclude the influence of other factors on the estimation results and more accurately identify the impact of digitalization on green technological innovation. In addition, no existing literature has tested the quality of digitalization indicators using multiple datasets. To test the reliability of data quality, this paper tests the constructed digitalization indicator based on 94,531 online recruitment data entries from listed companies.

In terms of mechanism identification, this paper empirically tests the micro mechanisms through which enterprise digitalization promotes green technological innovation, in combination with the characteristics of green technological innovation. It is found that enterprise digitalization mainly promotes green technological innovation by enhancing the level of information sharing and knowledge integration within enterprises. Specifically, first, compared with general technological

innovation, green innovation related to enterprise production and low-carbon management processes requires the integration of information on resource consumption, environmental impact, and manufacturing systems. This poses higher demands on the information-sharing capabilities of enterprises. Enterprise digitalization can enhance the level of information sharing within and outside the enterprise (Goldfarb and Tucker, 2019; Qi and Xiao, 2020), thereby promoting the transmission and exchange of resource and environment-related information and, in turn, promoting green technological innovation. Second, from a knowledge perspective, green innovation is essentially an interdisciplinary and cross-field innovation activity. It involves the creation, integration, and diffusion of knowledge in different fields such as enterprise production, pollution reduction, and energy control within the organization. Relying solely on knowledge in a single technological field within the enterprise is unlikely to achieve effective green innovation (Yu et al., 2019; Mubarak et al., 2021). Enterprise digitalization can promote collaborative innovation (Zhang, 2019), thereby achieving the integration and reconstruction of various types of knowledge across different technological fields and motivating green technological innovation in enterprises.

2. THEORETICAL ANALYSIS AND RESEARCH HYPOTHESIS

2.1. Enterprise Digitalization and Green Technological Innovation

According to the Natural Resource-Based View (NRBV) theory, internal organizational elements of a firm, such as its technological capabilities, are the foundation for its green technological innovation and the construction of a sustained competitive advantage (Yang and Chai, 2015). Factors such as innovation financial resources, human resources, technological resources, and knowledge resources all have an impact on a firm's capacity for green technological innovation (Bi et al., 2014). Among these, innovation technological resources refer to a firm's ability to improve existing technologies and independently complete technological innovation (Bi et al., 2014), which has a significant positive impact on a firm's R&D capabilities (Schoenecker and Swanson, 2002).

Based on this, enterprise digitalization may influence a firm's green technological innovation by optimizing its innovation technological resources. First, enterprise digitalization facilitates the exchange and integration of internal and external information, strengthening the integration and sharing of information, thereby enhancing a firm's innovation capabilities (Subramaniam and Youndt, 2005). Second, the application of digital technology at the firm level can expand the scope of innovation resource allocation, encouraging firms to engage in collaborative innovation, which in turn can improve their ability to independently innovate based on existing technologies and thus optimize their innovation technological resources. In summary, this paper posits that enterprise digitalization can enhance a firm's green innovation level by optimizing its innovation technological resources.

2.2. Mechanisms Through Which Enterprise Digitalization Affects Green Technological Innovation

In light of the characteristics of green technological innovation, this paper further analyzes the specific mechanisms through which digitalization affects green technological innovation. Scholars generally agree that green innovation not only requires the integration of information on resource consumption and manufacturing systems but also places higher demands on a firm's information-sharing capabilities. Moreover, it involves the integration of knowledge across different technological fields within and outside the firm. Relying solely on past technical experience and knowledge accumulation in a single technological field is insufficient for green innovation (Yu et al., 2019). Enterprise digitalization can generate information-sharing and knowledge-integration effects, promoting the optimization of innovation technological resources and enhancing the level of green technological innovation.

Information-Sharing Effect: Enterprise digitalization can accelerate the delivery and feedback of information within the organizational structure, facilitating the sharing of information related to the internal and external environment and resources, thereby encouraging firms to engage in green technological innovation activities. Information sharing includes both internal and external dimensions. Internal information sharing refers to the transmission and integration of information among different organizational units within the firm. Through the exchange and integration of information across departments, firms can better integrate their internal resources (Carr and Kaynak, 2007). External information sharing focuses on the communication and collaboration between the firm and external market participants. Numerous studies have shown that information sharing has a significant impact on firm technological innovation (Mooi and Frambach, 2012; Kulangara et al., 2016). Brynjolfsson and Hitt (2003) found that internal information sharing within a firm can generate complementary innovations through the effective integration of internal resources. Subramaniam and Youndt (2005) demonstrated that information sharing among employees can enhance a firm's innovation capabilities. In particular, green innovation in production and management processes requires the integration of resource consumption and environmental impact information from various stages of manufacturing and management systems, placing higher demands on a firm's information-sharing capabilities. Biondi et al. (2002) showed that information sharing plays an important role in promoting green R&D innovation in small and medium-sized enterprises. Therefore, enhancing a firm's information-sharing capabilities can facilitate the sharing of environmental and resource-related information among manufacturing, management, and R&D departments, accelerate the sharing of internal and external environmental resource information, strengthen communication among R&D personnel, optimize the firm's innovation technological resources, and promote green technological innovation.

Enterprise digitalization helps to promote information sharing within firms (Qi and Xiao, 2020). Goldfarb and Tucker (2019) found that enterprise digitalization promotes real-time information sharing, giving firms greater production flexibility and supply chain coordination capabilities. In summary, this paper argues that enterprise digitalization can help firms integrate internal and external resources by enhancing their information-sharing capabilities, thereby optimizing their innovation technological resources and encouraging green innovation.

Knowledge-Integration Effect: Enterprise digitalization can facilitate the integration of R&D resources and knowledge, optimize the firm's innovation technological resources, and effectively promote green innovation activities. From a knowledge perspective, green innovation is essentially a complex knowledge activity involving the creation, integration, and diffusion of knowledge across different technological fields related to production and pollution reduction within the organization. Relying solely on past technical experience and knowledge in a single technological field is unlikely to achieve effective green innovation. During the green innovation process, firms need to continuously integrate knowledge from multiple technological fields, manage and effectively utilize internal and external knowledge, and master the mainstream technologies, new concepts, and development trends of green innovation (Yu et al., 2019). Therefore, knowledge integration is an effective pathway and important mechanism for manufacturing firms to achieve green innovation (Strambach, 2017).

The foundational technologies of enterprise digitalization help to promote knowledge integration. Zhang (2019) found that the application of digital technology expands the space for innovation resource allocation and promotes collaborative innovation activities involving multiple innovation entities such as firms, universities, and research institutes across regions and fields. Mubarak et al. (2021) showed that Industry 4.0 technologies can promote open innovation in firms, thereby encouraging green innovation activities. In summary, this paper argues that the application of digital technology at the firm level can facilitate the integration and sharing of R&D resources, help integrate and restructure various knowledge elements across different technological fields, and thus enhance the level of green technological innovation.

2.3. Heterogeneity in the Impact of Enterprise Digitalization on Green Technological Innovation

From the Perspective of Corporate Environmental Investment Levels: Enterprise digitalization can optimize a firm's technological innovation resources, thereby encouraging green technological innovation. However, this incentive effect varies among firms with different levels of environmental investment. If a firm does not prioritize environmental investment, even if digitalization optimizes its technological innovation resources, it is unlikely to engage in green technological innovation. Conversely, if a firm values environmental investment, digitalization is more likely to facilitate the completion of green technology R&D, shorten the green innovation development cycle, and accelerate the application of green innovation outcomes. Therefore, this paper posits that for firms with higher levels of environmental investment, the incentive effect of digitalization on green technological innovation is greater.

From the Perspective of Regional Environmental Regulation Intensity: Firms located in regions with stricter environmental regulations face greater environmental pressure and have stronger incentives to engage in green innovation activities. Therefore, the application of digital technology can have a more significant impact on green technological innovation for these firms. In contrast, firms in regions with weaker environmental regulations face less environmental pressure and lack the incentive for green innovation, resulting in a weaker incentive effect of digitalization on green innovation.

3. RESEARCH DESIGN

The financial data of listed companies used in this paper are sourced from the CSMAR (China Stock Market & Accounting Research Database) provided by the Guotai - An Data Service Center, and the data on the number of invention patents are from the Incopat database. The sample period spans from 2011 to 2018. Based on the environmental protection industry classification management directory for environmental verification of listed companies by the Ministry of Environmental Protection, we screened out companies in heavily polluting industries among the listed firms. The primary reason for selecting companies in heavily polluting industries for this study is that these industries are the key focus of China's environmental protection authorities, and green technological innovation is of vital importance to the long - term development of companies in these sectors.

The data were filtered as follows: (1) companies that have been delisted were excluded; (2) companies with missing data were excluded; (3) samples with negative book values of equity were excluded; (4) based on relevant accounting standards, samples with abnormal debt - to - asset ratios were excluded.

This paper uses the proportion of green patents to total patents to measure a firm's green innovation. Compared with the absolute number of patents, using a relative indicator can eliminate the impact of other unobservable factors, thereby alleviating potential endogeneity issues in the empirical analysis. Based on the IPC (International Patent Classification) codes published in the Green Patent List by the World Intellectual Property Organization (WIPO), green innovations are identified. The types of patents include invention patents, utility model patents, and design patents. Since design patents are not classified under the IPC system, this paper only considers invention patents and utility model patents. Among them, invention patents are more creative and technologically advanced, while utility model patents have a lower degree of innovation and only protect the shape and structure of products.

Currently, measuring the level of enterprise digitalization is a challenge in relevant research, and there are mainly three approaches in the existing literature. First, Qi et al. (2020) measured the degree of enterprise digitalization by the proportion of the amount related to the digital economy in the detailed items of intangible assets at the end of the year to the total amount of intangible assets. Second, a large number of studies have used the frequency or proportion of digital-related keywords in annual reports to measure the digital transformation or digitalization level of enterprises (Zhao, 2021; Yuan

et al., 2021). Third, some studies have obtained data on the digitalization level of enterprises through questionnaires (Liu et al., 2020). This paper constructs a variable to measure the level of enterprise digitalization by referring to the first method and further tests it based on the second method.

4. RESULTS

Green technological innovation is a crucial driving force for transforming the economic development model and achieving green development. Against the backdrop of the rapid development of the digital economy, the digitalization level of enterprises is continuously increasing. Therefore, it is of great significance for China's economic transformation and high-quality development to study whether enterprise digitalization can promote green technological innovation. This paper employs micro-data of listed companies in heavily polluting industries in China from 2011 to 2018, constructs more refined indicators to measure the level of digitalization, and examines the impact of digitalization on corporate green innovation and its mechanisms.

The findings are as follows: (1) Digitalization of enterprises in heavily polluting industries can significantly enhance their level of green technological innovation, with a more pronounced effect on green invention patents that contain a higher degree of innovation. This conclusion remains robust after a series of robustness tests, including IV estimation, counterfactual analysis, and changes in estimation methods. (2) Mechanism analysis indicates that enterprise digitalization mainly promotes green innovation through the effects of information sharing and knowledge integration. (3) Heterogeneity analysis shows that for enterprises with higher levels of environmental investment and those located in regions with stricter environmental regulations, the incentive effect of digitalization on green innovation is greater.

This paper clarifies the relationship between enterprise digitalization and green technological innovation, which has important policy implications for promoting sustainable development and digital transformation of enterprises in China. (1) The government should accelerate the application of digital technologies in enterprise production and other processes to empower sustainable development through digitalization. This study shows that digitalization can motivate enterprises to engage in green technological innovation, achieving integration and unification of enterprise development and sustainable production. Therefore, government departments should encourage enterprises to promote data processing technologies such as cloud computing and blockchain in production, management, and innovation processes, implement digital simulation and big data analysis in R&D innovation and energy-saving management, and build a sustainable development R&D innovation system based on digital technology to empower enterprise environmental governance and intelligent green production through digitalization. (2) Enterprises should utilize digital technologies to strengthen the construction of internal and external information-sharing platforms to enhance their information-sharing capabilities. This study shows that enterprise digitalization can promote green technological innovation by enhancing information-sharing levels. Therefore, enterprises should strengthen the application of digital technologies in various links such as production manufacturing, energy consumption control, and supply chain, rely on digital technologies to achieve sharing of knowledge and information within and outside the enterprise, improve the efficiency of green technological innovation, and support green development with digital technologies. (3) Relevant departments should encourage the construction of new types of industry-university-research innovation open platforms and incorporate more innovation entities such as enterprises, universities, research institutes, individuals, and groups into an interconnected innovation ecosystem. This study shows that knowledge integration plays an important role in the technological innovation process of enterprises. Based on this, relevant departments should use digital technologies to further promote the networking and ecological development of innovation organizational methods and facilitate collaborative innovation among industry, academia, and research. (4) Against the backdrop of the rapid development of the digital economy, environmental protection departments

should actively guide enterprises to rely on digital technologies to carry out green technological innovation. This study shows that external factors such as environmental regulations can affect the green innovation incentive effect generated by enterprise digitalization. Therefore, the government can better guide and encourage enterprises to invest in environmental protection and governance through various incentive measures such as tax and financial subsidies and administrative means such as issuing standards and relevant regulations.

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