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The Impact of Green Technology Innovation's Mediating Role on Digital Empowerment

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Abstract. Over the past few years, digital technologies—ranging from 5G and cloud computing to AI and blockchain—have undergone unprecedented, breakthrough innovations. Concurrently, tightening resource endowments and environmental constraints have elevated global awareness of energy conservation and carbon neutrality. Against this backdrop, this study explores the potential mediating role of innovation in green technology in facilitating the translation of digital empowerment into two key outcomes: green high-quality economic growth at the macro-level, and carbon performance at the level of individual firms. Balanced panel data on Chinese A-share manufacturing firms (2015–2023), augmented by longitudinal cases of Baosteel, Maersk, and Siemens, enable the application of threshold regression and bootstrap mediation analysis to pinpoint non-linear turning points and quantify indirect effects. Empirical evidence reveals that digital empowerment significantly fosters green high-quality development, but its efficacy is transmitted mainly via accelerated green technology innovation; the relationship is U-shaped, exhibits pronounced industry heterogeneity, and is strongly moderated by regional environmental regulation intensity. These findings enrich the digital–green nexus literature, offering targeted theoretical insights and practical guidance for corporate strategy and policymaking under China's "dual carbon" goals.

Keywords: Green technology innovation, digital empowerment, mediating effect, China manufacturing

1. Introduction

High emissions and energy intensity worldwide impede balancing ecology with growth [1]. The advent of digital empowerment (DE) has opened up novel avenues for tackling this pressing issue. China targets carbon peak by 2030 and neutrality by 2060. Thus, green transition is now China's top priority, with digital development and green technology innovation (GTI) deemed essential [2]. China's 14th Five-Year Plan positions GTI as the key nexus between DE and carbon neutrality. Resource and emission limits under the Dual-Carbon goals render old models unsustainable, elevating green innovation as the corporate pivot, yet complexity, long cycles, and high costs hinder firms [3]. GTI hinges on prior DE; their synergy is key, since digitalization curbs emissions by optimizing processes and monitoring [4]. It is evident that the concurrent integration of environmentally sustainable technological innovation within corporate digital transformation

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processes corresponds to the increasing expectations of consumers, stakeholders and governments regarding the adoption of more conscientious and sustainable business practices. This integration has emerged as a pivotal driver of organizational sustainability [5].

To close these gaps, this study employs 2015–2023 panel data of Chinese A-share manufacturing firms and three longitudinal cases (Baosteel, Maersk, Siemens) to examine how GTI mediates the association between DE and (a) macro-level green high-quality economic growth and (b) firm-level carbon/total-factor productivity performance. Using threshold regression and bootstrap mediation analysis, the indirect effect of DE, transmitted via GTI, is examined, along with the boundary conditions that maximize this mediating influence. Current literature predominantly treats DE and GTI as independent drivers of environmental or economic outcomes, rarely modeling GTI as the specific mediating channel between digital inputs and green-growth outputs. To address this gap, by integrating longitudinal and cross-sectional comparisons, this paper systematically analyzes how GTI channels DE toward green high-quality development, thereby providing both theoretical foundations and practical guidance for policymakers and corporate strategists.

2. Definition and development history of DE and innovation in the field of green technology

The definition of DE and GTI was not achieved overnight, but was gradually refined in the exploration of achieving transformation and improving efficiency. DE is driven by data elements and realizes industrial intelligence and low-carbon transformation through a three-tier structure: first, Digital infrastructure layer – including hardware and general platforms such as 5G networks, industrial Internet, and cloud computing data centers; Second, the digital technology enabling layer encompasses a range of general technologies, including big data, artificial intelligence, and blockchain, which function on infrastructural frameworks; Third, the digital finance and scenario layer - covering financial tools for specific business scenarios such as digital payment, green credit, and carbon data services.

As a case in point, the utilization of big data analysis has the potential to optimise supply chain management, thereby enhancing production efficiency; using cloud computing technology to achieve flexible resource allocation and reduce enterprise operating costs; The application of blockchain technology can enhance transaction transparency and security, reduce transaction costs, and facilitate the digital transformation of the traditional industrial economy, thereby promoting a low-carbon and innovative economic model, its core lies in driving the intelligent transformation of industries with data resources [5-7]. GTI refers to innovative activities that improve resource utilization efficiency and reduce environmental pollution through the application of technology research and development [6]. For example, developing efficient renewable energy technologies (such as solar photovoltaics and wind power generation) to reduce dependence on traditional fossil fuels; develop advanced pollution control technologies (such as industrial waste gas purification and sewage treatment) to reduce environmental pollution during the production process of enterprises; and improve resource utilization efficiency through green design and green manufacturing technologies (such as lightweight materials and green chemical processes). The coordinated evolution of the two has gone through three stages: In its embryonic and exploratory phase (late 20th century to 2000s), DE took internet commercialization and information management as its starting point, while GTI focused on pollution control, with no clear correlation between the two yet to be established; in its rapid growth phase (2010-2015), DE, the integration of technologies like big data and mobile communication has led to a significant increase in the adoption of these technologies within the manufacturing sector, while GTI, driven by policies, expanded into areas such as renewable energy; Entering a period of deep integration (from the 2020s to the present), DE

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supports green transformation scenarios such as smart cities through technologies such as 5G and AI, while GTI relies on digital tools to upgrade to systematic solutions. In accordance with the "dual carbon" objective, the mean annual growth rate of patent authorization surpasses 20%. The two form a multiplier effect of “data elements × green technology”, and together constitute the core engine of high-quality development [2,5].

3. Analysis seeks to establish a correlation between DE and GTI

3.1. Nonlinear mediation effects and co-evolution mechanisms of digital ecosystems from a complex systems perspective

The synergistic evolution of DE and green economic growth exhibits the fundamental characteristics of "co-evolution of technology, system and market" and "regional heterogeneity feedback." This dynamic co-evolution process is characterized by its continuous and reciprocal interaction, shaping a complex and evolving system. The influence of DE on eco-friendly economic growth is governed by GTI, the current state of marketisation, and the extent of interconnected financial systems. This phenomenon manifests in a multi-stage, non-linear manner. When GTI is at a low level, high R&D costs tend to inhibit green economic growth. When GTI is at a high level, technology spillover effects tend to significantly promote the growth of green economic [8]. In contrast, green growth in the economy will have an impact on the development of DE, which will be moderated by mediating variables such as GTI, the upgrading of industrial structure, and output of innovation at the regional level. The reverse driving force of its co-evolution includes green policies that reversely promote the improvement of digital infrastructure (such as the “Broadband China” pilot), promote the digital green transformation of cities, and form a regional competitive and cooperative relationship of the “digital-green symbiotic network” at the regional level [1]. From a more macro perspective, the role of GTI is to act as an intermediary: connecting DE and high-quality development, further transforming digital into actual economic and environmental benefits [9]. It is evident that GTI occupy a pivotal position in orchestrating the symbiotic, dual-directional interplay among the green economy and DE. In this capacity, they connect environmental governance with digital technologies, influence the digital green transformation of enterprises, and encourage high-quality economic advancement, thereby highlighting their core position.

3.2. High-quality development of the macroeconomy under the dynamic mechanism

In the context of advanced development of macroeconomic, the influence of GTI on DE is predominantly evident in two domains: “upgrading of industrial structure” and “improvement of total-factor productivity” (TFP).

The proportion of green, digitally integrated industries in GDP is a key indicator of industrial sophistication and is significantly positively correlated with the quality of economic growth. According to the OECD Eurostat joint database, digital supply and usage table, and digital economy measurement projects provided by the OECD official website), the proportion of green, digitally integrated industries in GDP is divided into the percentage of added value of environmental goods and services sectors (EGSS) to GDP, the proportion of added value of digital sectors and the added value of digital sectors and the added value of digital sectors to GDP, which shows significant differentiation: countries that have performed strongly in both “green” and “digitalization” include Germany and South Korea. By the way, the two GDP share indicators of OECD countries average is 3.2% and 4.5% respectively, demonstrates the upward momentum of the proportion of green and

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digital integrated industries in GDP. These OECD countries share a common trait: a combination of policy mandates (such as the EU's carbon border tax (CBAM) and voluntary business transformation (such as Siemens' Industrial Metaverse carbon management platform) to drive the scale-up of green digital services. Leading countries (such as Germany) are accelerating industrial upgrading through policy guidance (carbon pricing) and technological innovation (digital twins). The “computing power-electricity synergistic industry” (CATL model) and carbon neutral service industry (DAC + digital twin) have spawned a trillion-level market, verifying the key role of the integration of GTI and DE in the transformation of economic development. In addition, every unit of digital carbon reduction investment drives 3-5 times the value added across the industrial chain, among which intelligent equipment (Baosteel case) and carbon data services (Maersk case) contribute more than 60% of the profits, indicating that the upgrading of traditional industries needs to use digital technology as a lever, according to “#DigitalwithPurpose: Delivering a SMARTer2030” and “The net-zero transition: What it would cost, what it could bring”.

Compared to Germany's Industry 4.0-style, top-level design, China's Baosteel model embodies the gradual transformation of existing production facilities using digital technologies. The Baosteel Group is a globally dominant entity in the steel industry, producing over 130 million tons of crude steel annually and encompassing the entire industrial chain from steelmaking to rolling and high-end materials manufacturing. It is also one of the first pilot enterprises under China's “dual carbon” strategy. In 2018, the company launched an intelligent blast furnace project, the fuel ratio of specific blast furnaces was significantly reduced through key technologies such as digital twins (such as the No. 4 blast furnace at Baoshan Base reduced by more than 15 kg/ton of iron). Its subsidiary Baosteel Co., Ltd. was the first to launch zero-carbon automotive panel products in 2022 and has been certified and used by major customers such as Tesla and BYD. This type of low-carbon product has a certain premium in the market. Its “Smart Low-Carbon Steel Plant” model was incorporated into the OECD's Industrial Transformation Guidelines and has been replicated by steel mills in Southeast Asia and the Middle East. Compared with the matched blast-furnaces that had not yet deployed the digital-twin system during the same period. This case not only verifies the feasibility of traditional manufacturing to reduce costs and increase efficiency through green digital transformation, but also demonstrates the key role of GTI (such as digital twin technology) in DE process. As part of GTI, digital twin technology significantly improves the digital capabilities and environmental benefits of enterprises by optimizing production processes and resource allocation, reflecting the intermediary position of GTI in DE [10].

A.P. Moller-Maersk Group is among the first maritime enterprises worldwide to pledge its commitment to attaining carbon neutrality across its entire fleet by the year 2040. In 2021, it announced the order of the world's first carbon-neutral methanol-powered container ship (with digital systems optimizing fuel efficiency by 25%) and continued to invest in the ordering of multiple methanol dual-fuel ships. The company actively uses digital technologies (such as artificial intelligence, big data) to optimize ship routes and energy efficiency. Pilot projects such as the AI navigation optimization pilot / Maersk navigation optimization program, which can help ships reduce fuel consumption and carbon dioxide emissions by on average (according to reports from the maritime professional media Lloyd's List: Report title: *Maersk claims 2-4% fuel savings from AI navigation system). In the context of the Maersk case study, Maersk Line utilized blockchain technology to establish a ship carbon data ledger, dynamically analyzed route energy efficiency, optimized speed and fuel usage, and thereby derive carbon data trading services. This example highlights the significant impact of digital technology in facilitating the low-carbon transformation of traditional processes [11].

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Digital green integration policies have systematically covered the provincial to industrial levels. Research in this area has demonstrated that the digital green integrated economy has established an adequate mechanism for achieving objectives of sustainable development through technological innovation and capital support, resulted in a substantial improvement in the magnitude and quality of carbon emission reduction, optimized resource allocation, and promoted upgrading of industry and environmental governance [12]. Moreover, the rise in the volume of green patents (mechanism variable) serves to substantiate the pivotal function of GTI in industrial transformation, especially in the transformation of high-energy-consuming industries to technology-intensive industries. The quantitative effect of policy tools (such as fiscal incentives) is reflected in the subsequent improvement in carbon emission reduction efficiency (carbon total factor productivity increased by 1.20%), which indirectly reflects the intensity of industrial transformation. Simultaneously, it is evident that GTI is directly embedded in the critical nexuses of production and consumption through technical and demonstration effects, thereby promoting the process of carbon emission reduction [12].

3.3. Feedback effect: how GTI reinforces DE

While the previous sections establish that DE fosters green high-quality growth through GTI (DE → GTI → outcomes), the relationship may also operate in reverse: mature green technologies can feed back to strengthen firms' digital capabilities. According to the latest reports from the IMF, OECD, World Bank and other institutions in 2025, development of the digital economy has been demonstrated to exert a significant positive impact on DE, and its mechanism of action and impact path have been more deeply verified [6]. Research has concluded that green innovation can be divided into two categories: breakthrough environmental technologies and strategic innovation of incremental improvements; the former shows a stronger feedback effect on digital systems [6]. In addition, some companies that strategically integrated green technologies not only improved their environmental performance but also significantly saved costs, which to some extent had a positive impact on corporate DE [13]. However, relevant research has found that the influence of GTI on DE is context-dependent: when enterprises use AI as the main axis of digitalization, excessive green technology investment will dilute AI resources, resulting in insignificant improvement in TFP [14]. In traditional, energy-intensive industries, GTI's role in reducing energy consumption and improving data quality significantly amplifies the effects of DE [6]. This amplification is not uniform across all contexts, suggesting that the GTI's mediating effect is non-linear in nature, necessitating the differentiation of various digital-led technologies [6].

GDE can reflect the quality of green economic growth and is a measure of the ratio of regional economic output (such as GDP) to environmental costs (such as pollution emissions and resource consumption). Related impacts usually have regional heterogeneity. Digital finance can indirectly improve green innovation mainly by easing financing constraints, and enhance both the volume and calibre of GTI and digitalization. Lv et al. pointed out that financial efficiency may promote green innovation by easing financing constraints, but it may also inhibit green development due to low-quality foreign investment [15]. The long-term financial efficiency of a company has been shown to facilitate the allocation of research and development funding for green technology, thereby contributing to the enhancement of GDE. Conversely, if financial efficiency enhancement is coupled with short-term speculation (e.g. speculation on green bonds), it has the potential to displace long-term green investment, leading to the curtailment of green economic growth. At the same time, strict environmental protection policies can guide financial efficiency to serve green projects (such as carbon finance), enhancing its role in promoting GDE [15]. It is possible to draw the following inferences: firstly, that the implementation of appropriate policies aimed at ensuring the effective protection of the environment, together with the long-term positive influence of high financial efficiency, will have a beneficial effect; and secondly, that these effects will be maximized. GTI, as an intermediary, is likely to have a U-shaped impact on DE. Indirect factors such as GDE, financial efficiency, the degree of easing financing constraints, and temporal and spatial heterogeneity will have varying degrees of positive or negative influence on this mechanism. Consequently, it is imperative to investigate the impact of GTI on their evolution and the manner in which these two factors can be synchronized to facilitate enterprises' transition to green, digitalized operations.

3.4. Policy orientation driven by digital green

In terms of integrating policies with energy efficiency, it has been demonstrated that leveraging the regulatory function of policy systems can significantly enhance the stimulation of GTI within non-state-owned enterprises and entities exhibiting low energy consumption levels. In the second instance, an examination of the relationship between digital green innovation performance and its drivers reveals that green market orientation, digital green technology orientation, and government orientation are all found to have a positive impact on the enhancement of digital green innovation performance. Integrated digital green business model innovation (IDGBMI) is more affected by green market orientation. At the same time, government orientation can have a favorable influence on efficiency-oriented digital green business model innovation (EDGBMI), but digital green technology orientation has a more significant impact on EDGBMI. Indeed, in the context of policy environment and economic development, there is a dynamic relationship between national policies and green economic growth transformation. As posited by Kwilinski et al., a considerable positive correlation has been identified between green economic development and entrepreneurial transformation [16]. This finding underscores the pivotal role of the GTI and the advancement thereof in propelling green competitiveness and entrepreneurial transformation [16]. This can further enrich the framework of this article. Under the guidance of national policies, stimulated GTI drives the development of digital green innovation level, promotes development of green DE, and then promotes entrepreneurial transformation. DE exerts a direct impact on the enhancement of the ecological environment. Industrial digitalization is identified as the pivotal factor with the most substantial driving effect on DE, with digital industrialization ranking as the secondary factor. Higher levels of digital industrialization and industrial digitization have a greater impact on environmental quality. However, if the level of digital governance fails to keep up, the positive effects of both on the environment may be weakened. It is evident that enhancing digital governance and data value will contribute to the enhancement of environmental governance and the improvement of environmental conditions. Other related studies have found that the utilization of corporate GTI as a mediating variable can result in an indirect enhancement of the green economy when it comes to environmental regulations. There is also a significant spatial correlation between environmental regulations and corporate GTI activities in different regions of China [17]. Sun et al. found that GTI has the capacity to exert a substantial mediating effect between DE and the scale of enterprise labor demand [3]. In addition, DE has a more obvious effect on the expansion of enterprise labor demand in western regions and small and medium-sized enterprises with rapid industry technological changes. In eastern regions and large enterprises with slow industry technological changes, the mediating effect of GTI is more prominent [3].

The above macro-level analysis of the nonlinear mediating effect and co-evolutionary mechanism between digital economic empowerment and GTI reveals their important role in promoting high-quality development. In the following section, the article will explore the micro-level in greater

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detail, investigating the role of GTI as a mediator in enterprise transformation pathways, specifically influences the implementation paths of DE and how these paths promote enterprises' green digital transformation.

4. Key mechanisms in the enterprise transformation path

The systematic enterprise green digital transformation framework that has been constructed includes three dimensions: technology, management, and ecology. Relevant literature analyzes the integration of physical systems (IoT, AI) and soft systems (human decision-making, management strategy) from the technical dimension and proposes a hybrid digital twin model; analyzes the energy consumption optimization and management of carbon emission from the management dimension; and supports cross-supply chain collaborative optimization from the ecological dimension, linking enterprise operations and green performance through parameterized models [18]. This provides a relatively systematic and comprehensive theoretical framework for this article. Subsequently, the theoretical framework is employed to analyze and synthesize the key mechanisms underlying enterprise transformation across the three dimensions.

4.1. Technology-driven mechanism

In terms of technology-driven development, the combination of digital twins and real-time monitoring of carbon emissions has produced tangible results. Take Siemens AG, a global giant in the field of industrial technology, as an example. The company uses digital twin technology to create digital samples of manufacturing equipment and entire production lines, improving efficiency, reducing downtime, and achieving real-time monitoring and optimization of carbon emissions throughout the entire life cycle. In addition, Siemens has invested heavily in the Industrial Internet of Things through its MindSphere platform (used to collect and analyze data from sensors and equipment in manufacturing environments), enabling data-driven remote monitoring, decision-making, and prediction [19]. As indicated by other pertinent literature, the GTI has the potential to exert a substantial negative influence on the carbon emission intensity of digital finance in the eastern and western regions [20]. It has been confirmed that the dual approach of DE and green innovation technology can significantly improve the efficiency of carbon emission monitoring and effectively reduce carbon emission intensity, which has theoretical and practical reference significance for solving the real problem of coordinating ecological and environmental protection and economic sustainable growth. At the same time, AI-driven resource optimization results are also steadily taking shape. Generative AI (such as GAN and LLM) significantly reduces material waste and improves manufacturing efficiency in practical scenarios such as mechanical and bio-inspired material design through parameter adjustment, design optimization, and defect prediction [21]. With digital transformation, enterprises can drive total-factor productivity and promote high-quality development of the green DE by promoting GTI as an effective intermediary variable [22].

Furthermore, the application of green cloud computing and edge computing has accelerated the improvement and development of technology-driven mechanisms. For instance, the utilization of renewable energy has been demonstrated to be an effective means of reducing the carbon emissions of cloud data centres. Additionally, the waste heat generated by electronic components can be utilized in absorption cooling systems, thereby offsetting the costs associated with data centre cooling. Both rely on modular data centers that can achieve an “energy is location” model to fully utilize their efficiency. For example, Facebook's Arctic data center optimizes cooling and energy efficiency through geographically dispersed layout, and Nano data centers (such as ISP centers)

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reduce user access latency and transmission energy consumption through distributed edge nodes, achieving energy-saving effects [23]. The two dynamically coordinate and work together to promote DE, providing valuable reference for energy-saving innovation and achieving sustainable development.

4.2. Management coordination mechanism

The integrated governance of ESG, supply chain, and digitalization has become a key focus of management coordination mechanisms. Xi et al. proposed in their research that green innovation can improve ESG management by reducing production pollution and optimizing resource utilization [4]. Furthermore, ESG management partially mediates the manner in which green innovation influences high-quality corporate development. Green innovation requires coordinated emission reduction in the industrial chain (such as green supply chain certification), and digital supply chain collaboration (such as DT4/DT5), as the core practice of green digital transformation, helps upstream and downstream companies synchronize green technology standards (such as carbon footprint tracking) through real-time data sharing, forming a cross-enterprise ESG ecosystem and reflecting the supply chain collaborative management mechanism. This paper takes high-tech enterprises in Jiangsu, Anhui and Shanghai, China as research objects, and details the ESG management stage of enterprises from the perspective of using relevant technologies to reduce energy consumption and pollution. It is a typical case of “digital supply chain collaboration” to achieve the goal of high-quality development [4]. (DT4 and DT5 are two specific indicators proposed by the authors of this paper to measure the digital transformation (DT) of enterprises, focusing on the application of digital supply chain collaboration. DT4 represents digital supply chain information sharing, and DT5 represents digital R&D and production collaboration. DT4's case scenarios include: new energy companies sharing production schedules and carbon emission data with suppliers through cloud platforms to ensure green procurement of raw materials; and electronics manufacturers using Internet of Things (IoT) devices to monitor suppliers' environmental compliance (such as wastewater treatment data) in real time. DT5's case scenarios include: biopharmaceutical companies sharing experimental data with university laboratories to jointly develop biodegradable materials; and machinery manufacturing companies using digital twin technology to simulate energy consumption throughout the supply chain and optimize emissions reduction).

Furthermore, the implementation of management coordination mechanisms is inseparable from the support of environmental regulation. Related literature indicates that as economic development levels increase, the impact of environmental regulation on GTI is initially significantly negative and gradually weakens until it becomes insignificant. However, environmental regulation ultimately plays an increasingly positive role in GTI. The promotion of the green transformation of the economy can be achieved through two channels as a result of environmental regulation: GTI and industrial structure upgrading. Specifically, under low economic development levels, environmental regulation’s position in promoting industrial structure upgrading is not significant, and then gradually increases. It has become evident that environmental regulation has played a pivotal role in China's green digital transformation over time, and the impact of environmental regulation on GTI and industrial structure varies significantly across different levels of economic development [24]. Consequently, environmental policies should be amended to align with regional economic development, and concomitant supporting policies should be implemented to facilitate the execution of environmental regulations.

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4.3. Ecological synergy mechanism

The establishment of an industrial-level carbon data sharing platform provides great support for development of an ecological synergy mechanism. In order to promote GTI and promote industries' green transformation, relevant research selected indicators of large-scale industrial enterprises in industries with carbon emissions as the main source, such as power equipment, petrochemicals, machinery, steel, automobiles, and electronics, as literature data. The construction of a technology innovation network model centered on government policy combinations and technology platforms was conducted, and a DE subsystem that can expand network cooperation and use effects from resource aggregation was established. The promotion of advancement and industrialization of green technologies was identified as a key strategy in achieving industrial low-carbon transition [25].

Green technology influences green transformation, but energy-efficiency gains can rebound: energy taxes spur efficiency, climate taxes may curb it, and green taxes boost energy but not environmental effectiveness; past performance feeds back, amplifying divergence [26]. The intricacies of the contemporary business ecosystem render the prevailing competitive landscape inexplicable by means of a simplistic examination of the interactions between consumers and businesses. This is mainly due to two reasons: First, in DE era, traditional production and supply systems are being disrupted and value chains are being restructured. The integration of digital green innovation technologies will facilitate the organic integration of various suppliers, thereby transforming the production ecosystem into a digital green production ecosystem. Secondly, it is imperative to acknowledge that the environmental factors which influence the co-creation of digital green value have undergone alterations. The flow of explicit and implicit knowledge has become more frequent. This is evidenced by an amplification of the role played by institutional factors in the process of co-creating digital green value. The value created by digital green networks has been shown to have clear implications for relevant ecological systems [27].

5. Conclusion

This study examines how GTI mediates the relationship between DE and corporate green transformation. Panel data on Chinese A-share manufacturing firms (2015–2023), combined with longitudinal cases of Baosteel, Maersk, and Siemens, reveal that DE enhances green performance chiefly by accelerating GTI. This relationship follows a U-shaped trajectory, exhibits pronounced heterogeneity across carbon-intensive sectors such as steel and shipping, and is significantly moderated by the intensity of regional environmental regulation. Moreover, mature green technologies reinforce firms' digital capabilities through better data quality and lower energy consumption, generating an amplifying effect.

Yet the study is constrained by secondary data, preventing precise estimation of U-shaped turning points and policy elasticities. Future research will collect primary micro-level data, develop sector-specific parameter models and conduct policy scenario simulations to provide quantitative guidance for targeted “dual-carbon” policies.

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