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Original Research Article

Can artificial intelligence enhance traditional energy firm green innovation? Based on signal transmission theory

Xiao Yan *
School of Economics and Management, Inner Mongolia Normal University, Hohhot, 010011, China

Abstract: As digitalization and intelligence gain increasing prominence, numerous studies have investigated their influence on green innovation and related domains. This paper conducts a comprehensive literature review along horizontal and vertical dimensions. The vertical analysis distinguishes between early and recent research, while the horizontal examination focuses on four key aspects: grounded theories, measurement methodologies for digitalization and intelligence, underlying mechanisms, and innovative approaches. Several critical gaps are identified: the lack of comprehensive theoretical foundations leading to uncertainty in theoretical frameworks (whether linear or U-shaped relationships), oversimplified quantitative methodologies (primarily relying on keyword screening in strategy data), and limited innovative perspectives (predominantly mechanism-focused). Through the novel lens of signal transmission theory, this study proposes an 'Intelligence-ESG-green innovation' theoretical framework. The research contributes new evidence toward resolving theoretical framework uncertainties regarding the relationship between digitalization (intelligence) and green innovation.
Keywords: intelligence; green innovation; ESG; signal transmission theory

1. Introduction

Global environmental challenges, including climate change and energy crises, pose significant threats to the sustainable development of human society (Gozgor & Paramati, 2022). These challenges stem from traditional production methods characterized by high energy consumption, substantial pollution, and inefficient processes (Abbas & Najam, 2024). Consequently, firms, particularly those in the traditional energy sector, must enhance their green innovation initiatives to promote energy conservation and carbon reduction. The rapid expansion of the global digital economy and intelligent technology adoption has led firms to actively promote emerging production models driven by digital technology, with artificial intelligence at their core (Sirin & Yilmaz, 2024). This emerging paradigm creates new opportunities for firm green innovation, including applications such as machine learning algorithms for real-time dynamic detection.

In the AI-centered technological revolution, green innovation serves not only as an essential measure to address environmental challenges but also as a crucial pathway for traditional energy firms to strengthen their competitive advantages. Chinese traditional energy enterprises must optimize their energy structure and ensure energy security in response to the "dual carbon"strategy, which necessitates improvements in safe, green production and resource utilization efficiency. Intelligent construction represents an effective approach for these enterprises to adapt to this strategy and achieve transformation.

Previous research on firm artificial intelligence and green innovation primarily draws upon resource-based view and dynamic capability perspectives (Feng et al., 2024; L. Guo et al., 2025; Lin & Zhu, 2025; Y. Liu et

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2251-2608(P)

al., 2025), with some studies incorporating human capital theory and institutional theory (Lin & Zhu, 2025; Q. Liu et al., 2025), alongside innovation theories. This paper extends beyond these established frameworks by applying signal transmission theory to analyze the relationship between firms' intelligence levels and their green innovation performance.

The remainder of this paper is structured as follows. Section 2 present prior literature reviews. Section 3 is for related theories and research hypothesis. Section 4 is the conclusion and future research.

2. Prior literatures reviews

This review begins with an examination of literature on digitization and green innovation, followed by studies on intelligence and green innovation, as early research did not distinguish intelligence from digitization. The analysis encompasses both historical research and detailed examination of recent studies.

2.1. Prior literatures on firm digitalization and green innovation

Earlier research on the impact of digitalization on green innovation exhibits two distinct characteristics. First, the theoretical framework demonstrates inconsistency. Some studies indicate that digitalization enhances green innovation (D. Li & Shen, 2021; Wei et al., 2021), while others suggest a U-shaped relationship (Peng et al., 2022).

Second, the definition of digitalization lacks consistency (Gradillas & Thomas, 2023). They identify six distinct definitions for digitalization, with measurements insufficient to capture all digitization elements.

Recent research exhibits several characteristics, as shown in Table 1. Most studies develop theoretical hypotheses based on resource-capability theories: including resource-based views (Fang & Li, 2024; M. Guo et al., 2025; Y. Li et al., 2025; Song et al., 2025) and dynamic capability theory (M. Guo et al., 2025; Xia & Chen, 2025), positioning firm digitalization as a resource or capability. Additionally, most studies measure the digitalization index through firm annual reports (Fang & Li, 2024; Y. Li et al., 2025; Song et al., 2025; Xia & Chen, 2025), with some utilizing intangible assets items (M. Liu et al., 2025), primarily through digitalization keyword screening methods. Few studies employ questionnaire survey methods(M. Guo et al., 2025) . Regarding novelty, some studies contribute through theoretical framework construction (M. Guo et al., 2025; Song et al., 2025), incorporating institutional theory and dynamic capability theory with resource-based view; others through variable perspectives (M. Liu et al., 2025; Xia & Chen, 2025), distinguishing between radical or incremental green innovation and application or invention-oriented approaches; most through exploration of intermediate mechanisms (M. Guo et al., 2025; Y. Li et al., 2025; M. Liu et al., 2025; Song et al., 2025; Xia & Chen, 2025).

A paper (Tang et al., 2023) employs a multi-dimensional fixed effect model to explore that digital transformation significantly promotes firm green innovation through its effects on innovation, ‘learning by doing' mechanism and spillover effects, formation of innovation cooperation networks, and alleviation of financial constraints. This work is conducted mostly on innovation theory. Referring to resource-based view, institutional theory, stakeholder theory, another work (Dou & Gao, 2023) investigates impact of firm digital transformation on green technology innovation from the perspectives of asymmetric effects and structural breakpoints. A research (Fang & Li, 2024) takes 2,908 China A-share listed companies as sample, and explores the impact

ISSN: 2424-8460(O)
2251-2608(P)

of firm digitalization on its green innovation performance, based on resource-based view, natural resource-based theory and dynamic capability theory. They employ text data analysis and entropy weight method to measure the digitalization level of enterprises, by screening in firm annual reports the digitalization keywords and constructing a comprehensive index by entropy weight method. These three mechanisms (local intellectual property protection, firm's financial status, and national "Internet+"policies) further strengthen their relationship.

A research (M. Liu et al., 2025) measures firm digitalization by proportion of intangible assets related to the digital economy, and confirms that firm digitalization significantly enhances the quantity and quality of green innovation, with a stronger effect on quality. Organizational slack plays a mediating role in this process. They obtain this result based on resource constraint theory and organizational theory, and China listed company data of 2013-2020. One paper (Xia & Chen, 2025) explores the impact of digital transformation on green dual innovation (green exploratory and exploitative innovation) of China's A-share listed companies from 2016 to 2023, based on innovation theory and dynamic capability theory, and analyzes the mediating role of R&D investment and the dual moderating effect of government subsidies. The digitalization is measured by the frequency of keywords related to digital technology in firm's annual reports. One more work (Y. Li et al., 2025) employs the same method to measure digitalization, with a focus on the mechanism of government subsidies and the heterogeneity of non-state-owned firms, examining the relationship between digitalization and green innovation. Another paper (Song et al., 2025), referring to Resource-Based View (RBV) and institutional theory, analyzes the impact of digital technology resource on green innovation, as well as the moderating effects of institutional environment and organizational characteristics. This article constructs firm digitalization indicators for digital keywords in annual reports from two dimensions of application breadth and depth. Based on resource-based theory and dynamic capability theory, a research (M. Guo et al., 2025) observes the impact of digital technology on enhancing the resilience of green innovation in Chinese manufacturing enterprises, and analyzes the mechanism of absorptive capacity.

Table 1. Researches on digitalization and green innovation.

Prior works	Theories for models	Methods for digitalization	Mechanisms	Novelties
(Tang et al., 2023)	Innovation theory	Keywords screening in annual report (52 policy document in 10 years)	Technological innovation effect, Innovation cooperation network, Alleviate financial constraints	Construct a multi-dimensional digital transformation index system
(Dou & Gao, 2023)	Resource-Based View, Institutional Theory, Stakeholder Theory	Keywords screening in annual report (key words from prior works)	Threshold effects of firm human capital, industry competition, and regional institutional quality	1. Micro-level digital transformation 2. Introduce asymmetric effects and structural breakpoint perspectives
(Fang & Li, 2024)	Resource-based view, Natural Resources theory, Dynamic capability theory	Keywords screening in annual report	National 'Internet+' policy, local intellectual property protection, firm financial status	1. More comprehensive measurement of digitalization (annual report MD&A) 2. Multi-level mechanism (national, province and firm level)
(M. Liu et al., 2025)	Resource constraint theory, Organizational Theory	Keywords screening in firm intangible assets detailed items	Organizational slack	1. Green innovation classification (quantity and quality) 2. Novel mechanism factors

ISSN: 2424-8460(O)
2251-2608(P)

(Xia & Chen, 2025)	Innovation theory, Dynamic capability theory	Keywords screening in annual report	R&D, Government subsidy	1.Green innovation classification (incremental and radical) 2. Novel mechanism factors
(Song et al., 2025)	Resource-Based View, Institutional theory	Keywords screening in annual report	Institutional environment, Organizational characteristics	1. Institutional theory for model construction 2. Novel mechanism factors
(M. Guo et al., 2025)	Resource-based theory, Dynamic capability theory	Questionnaire survey data	Absorptive capacity, Environmental regulation	1. Dynamic capability theory for model construction 2. Novel mechanism factors
(Y. Li et al., 2025)	Resource-based view, Collaborative innovation theory	Keywords screening in annual report	Government subsidy	1. Interactive effect 2. Different owner-ship heterogeneous

Table 1. (*continued*)

2.2. Prior literatures on firm artificial intelligence and green innovation

Research examining the relationship between artificial intelligence and green innovation has evolved from focusing on regional and industry-level intelligence to analyzing micro-level firm intelligence and its impact on green innovation. The methodological approaches for measuring firm-level artificial intelligence primarily fall into two categories: keyword analysis (Feng et al., 2024; L. Guo et al., 2025; Y. Liu et al., 2025) and the use of policy exogenous variables in annual reports as quasi-natural experiments (Lin & Zhu, 2025; Q. Liu et al., 2025). The development of intelligent keywords partially stems from existing literature and expert consultation methodologies (Feng et al., 2024) . The majority of firm-level intelligence studies employ resource-based theory and dynamic capability theory to establish theoretical frameworks. Further details are presented below and in **Table 2.**

Table 2. Researches on artificial intelligent and green innovation.

	Theories for modelling	Method for artificial intelligent	Mechanism	Novelties
(Yang et al., 2022)	Innovation theory, regional development imbalance theory, Environmental Economics Theory	Entropy Weight Method for Manufacturing Industry	Green technology innovation capability, Green Technology Efficiency and Green Technological Progress	Construct a multi-dimensional intelligent manufacturing evaluation system
(Feng et al., 2024)	Dynamic Capabilities Theory, Absorptive Capacity Theory, Technological Innovation Theory	Keyword screening in annual report (Keywords selection through literature review and expert consultation)	Dynamic capabilities (absorption, innovation, adaptability)	1. Novel measurement for artificial intelligence 2. Three dimensions for Dynamic capabilities
(L. Guo et al., 2025)	Schumpeter innovation theory, Resource-Based View, Dynamic Capability Theory	Keyword screening in annual report (key word from prior work)	data-driven decision-making, enhancing human-AI collaboration and reducing information asymmetry	1. Firm Technology Upgrade Perspective 2. Types of Green Innovation New mechanism
(Lin & Zhu, 2025)	Resource-Based View, innovation theory, Institutional theory	Policy as quasi-natural experiment	R&D, ESG score	1. Constructing an exogenous policy evaluation framework 2. New mechanism
(Q. Liu et al., 2025)	Innovation theory, Human capital theory, Institutional theory	Policy as quasi-natural experiment	Human Capital Structure, Total Factor Productivity	1. Constructing an exogenous policy evaluation framework 2. New mechanism

ISSN: 2424-8460(O)
2251-2608(P)

(Y. Liu et al., 2025)	Resource-Based View, Dynamic Capability Theory, Innovation theory	Keyword screening in annual report (key word from prior work)	High-skilled labor and R&D investment	1. Micro-level analysis for artificial intelligence 2. New mechanism Refinement of 3. Heterogeneity Analysis

Table 2. (*continued*)

Yang et al. (2022) demonstrate that intelligence in China's manufacturing industry significantly promotes green innovation performance through technological advancement and cost reduction mechanisms. Their analysis focuses on industry-level intelligence measurements. Feng et al. (2024) develop a micro-level firm intelligence measurement using keyword search methodology, revealing that AI adoption substantially enhances firm green innovation efficiency, particularly in non-state-owned enterprises and high-tech companies. Y. Liu et al. (2025) demonstrate that artificial intelligence technology strengthens green innovation capabilities in Chinese listed companies, with pronounced effects in heavily polluting, non-technology-intensive, and highly competitive firms, achieved through skilled labor absorption and increased R&D investment. Their methodology measures AIT application through AI keyword frequency in company annual reports. L. Guo et al. (2025) analyze the enhancement of green innovation performance through firm-level artificial intelligence, measured via annual report keyword screening. Weng (2025) identifies a positive correlation between artificial intelligence technology adoption and firm ESG performance, with green innovation serving as a crucial mediating factor. Q. Liu et al. (2025) employs China's "National Artificial Intelligence Innovation Development Pilot Zone"establishment as a quasi-natural experiment, utilizing a multi-period double difference (DID) model to examine artificial intelligence's impact on firm green development. Lin & Zhu (2025) analyze China's AI Innovation Development Pilot Zone policy from 2019 through a multi-period double difference approach, revealing significant promotion of green innovation in pilot area firms through increased R&D investment.

3. Theories and hypothesis development

3.1. Intelligence and green innovation

While existing literature predominantly employs resource-based theory and related frameworks to examine the influence of artificial intelligence on green innovation, this paper extends the theoretical framework by incorporating signal transmission theory to analyze the relationship between firm intelligence level and green innovation development.

According to resource-based view (Barney, 2000) and natural resource-based view (Hart & Dowell, 2011), which extends the former by incorporating environmental factors, organizations establish competitive advantages through valuable, rare, and difficult-to-replicate tangible and intangible resources and capabilities. Recent research(Annarelli et al., 2021) identifies firm digitalization as a dynamic capability, serving as a crucial foundation for sustainable development. This capability enables organizations to identify and capitalize on opportunities by effectively sensing market changes and adapting accordingly. Organizations continuously acquire new knowledge, adapt to emerging technologies, and efficiently integrate internal and external resources to drive innovation in products, services, and processes.

ISSN: 2424-8460(O)
2251-2608(P)

Signal transmission theory suggests that firm digitalization (or intelligence) enhances operational transparency and visibility of environmental and social responsibility achievements (Lo & Kwan, 2017), thereby reducing information asymmetry, transaction costs, and interaction costs with stakeholders (Wang & Esperança, 2023). Through digital and intelligent transformation, organizations can improve operational transparency and minimize information asymmetry with external investors. Transaction costs encompass expenses beyond commodity prices that buyers and sellers incur during transactions. Digital transformation enables organizations to optimize supply chain management and establish enduring partnerships, reducing bargaining and supervision costs. Big data analysis facilitates precise supply-demand matching, lowering information search and negotiation costs. Furthermore, intelligence capabilities demonstrate organizational technical prowess (including production automation, supply chain digitalization, and AI-driven R&D). Stakeholders (consumers, investors, partners) typically associate high intelligence with technological advancement and management efficiency. Consumers may perceive intelligent organizations as better equipped to deliver high-quality, value-added products. AI, functioning as predictive technology, enables organizations to learn more effectively from big data, expanding investment opportunities through reduced product development costs (Babina et al., 2024).

Additionally, organizational digitalization and intelligence reduce information asymmetry for investors. Investors perceive intelligent organizations as having enhanced market competitiveness and risk resilience. Specifically, the widespread adoption of artificial intelligence across industrial chain components facilitates data sharing and mutual supervision among organizations, reducing information concealment opportunities(Bai et al., 2025) , thus minimizing information asymmetry and financing constraints. This attracts increased investment, supporting resource-intensive green innovation initiatives.

Global energy transition requirements and energy security enhancement have prompted traditional energy companies to pursue intelligent transformation. In the electricity sector, digital twin technology enables comprehensive data analysis and rapid intelligent decision-making in digital power systems. In oil and gas operations, AI technology enhances exploration success rates and production efficiency across multiple stages, including exploration, production, and processing. Intelligence, a subset of digitization, focuses on implementing artificial intelligence, machine learning, and related technologies to emulate human cognitive capabilities. This analysis leads to the following hypothesis.

Hypothesis 1: Traditional energy firms intelligence transformation promotes their green innovation.

3.2. Intelligence, ESG and green innovation

ESG performance enhances the promotional effect of intelligence on green innovation through two mechanisms: resource coordination capability and external legitimacy.

Resource allocation theory (Resource Orchestration to Create Competitive Advantage.Pdf, n.d.) indicates that when digitalization processes are embedded within organizations, they effectively allocate and integrate digital resources, enhance operational efficiency, and provide timely digital resources for addressing environmental challenges such as low-carbon production (Lu et al., 2024; Warner & Wäger, 2019). Organizations with superior ESG performance typically maintain more comprehensive environmental management systems, demonstrate bet-

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2251-2608(P)

ter resource allocation efficiency, and more effectively integrate artificial intelligence technology with green innovation objectives. This integration includes applying AI data analysis to emission reduction planning, thereby enhancing organizational green innovation performance.

Strong ESG performance communicates organizational commitment to sustainable development, enhances stakeholder recognition of green innovation initiatives, and amplifies intelligence-driven green innovation outcomes. Intelligence technologies (including AI and big data) serve as essential tools for green innovation, such as optimizing energy allocation in smart grids and monitoring real-time energy consumption. Superior ESG performance magnifies these "intelligence + green innovation"effects. Organizations with strong ESG performance demonstrate greater motivation to direct intelligent technologies toward environmental objectives rather than merely cost reduction. Additionally, ESG credibility facilitates intelligent green innovation implementation. For instance, when waste management organizations develop intelligent waste classification systems using IoT technology, representing intelligence-enhanced green innovation, these solutions achieve greater consumer engagement and recognition. This analysis supports the following hypothesis.

Hypothesis 2: Traditional energy firms' ESG performance can strengthen the positive effect of intelligence on green innovation.

4. Conclusion and future research

This paper examines contemporary research on the relationship between digital intelligence and green innovation, identifying a gap in research from the signal transmission theory perspective. Based on signal transmission theory and established frameworks (resource-based theory, dynamic capability theory, etc.), this study proposes two theoretical hypotheses concerning the intelligent enhancement of green innovation and its moderating effect on ESG levels.

Current research examining the relationship between digitalization (intelligence) and green innovation demonstrates three distinct characteristics. First, the majority of studies utilize resource-based theory and dynamic capability theory to analyze digitalization and intelligence as resources or capabilities. Second, the measurement methodology for digitalization or intelligence primarily employs keyword search techniques in annual reports, assessing digitalization or intelligence strength through firm strategy. Third, contemporary research predominantly investigates the mechanism pathways between these elements.

Future research directions should prioritize two aspects. First, researchers should develop quantitative measurement methods that extend beyond keyword searches in annual reports. Additionally, they should investigate quantitative intelligence and digitalization intensity across production, operation, and sales domains, rather than limiting scope to corporate strategy. Second, the transformation towards or intensity of digitalization and intelligence extends beyond organizational strategic resources and core capabilities, serving as a vehicle for organizational image that transmits specific signals and information to external stakeholders.

This paper offers significant contributions while acknowledging certain limitations. The research contributes by providing new evidence to address theoretical framework uncertainties between digitalization (intelligence) and green innovation. The primary limitation lies in the incomplete comprehensiveness of literature collection

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2251-2608(P)

and review. Future work will focus on empirically testing the proposed hypotheses.

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About the author

Xiao Yan*, School of Economics and Management, Inner Mongolia Normal University; 20200020@imnu.edu.cn.

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