

# The Impact of Digital Technology Application on Logistics Enterprise ESG Performance in VUCA Environment: Base on the Moderated Mediation Model

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## **Abstract**

Against the backdrop of "dual-carbon" goals, the Environmental, Social, and Governance (ESG) performance of logistics enterprises has emerged as a critical factor influencing their competitive advantage and sustainable development. This study investigates the relationship between digital technology application and ESG performance in logistics enterprises, with a particular focus on the mediating role of green innovation and the moderating effect of the VUCA (Volatility, Uncertainty, Complexity, and Ambiguity) environment. Using empirical data from A-share listed logistics companies in China, we employ quantitative analysis methods to test our theoretical framework. The findings reveal that digital technology application significantly enhances both the ESG performance and green innovation capabilities of logistics enterprises. Moreover, green innovation demonstrates a significant positive effect on ESG performance and serves as a crucial mediating mechanism between digital technology application and ESG performance. Additionally, our results indicate that the VUCA environment positively moderates the relationship between digital technology application and ESG performance, with stronger VUCA conditions amplifying the positive impact of digital initiatives. This research contributes to understanding the digital transformation pathway for improving corporate sustainability in the logistics sector and provides practical implications for enterprises seeking to enhance their ESG performance through digital innovation.

**Keywords:** Digital Technology Application; Logistics Enterprise; ESG Performance; VUCA Environment; Moderated Mediation Model

## **Introduction**

The global logistics industry is facing unprecedented challenges in carbon emissions reduction, with the sector accounting for approximately 11% of global CO<sub>2</sub> emissions (IEA, 2021). With the increased global focus on carbon emissions, logistics companies are at a crossroads of transformation as major energy and emissions users. The implementation of environmental protection policies and rising consumer demand for green products have created both challenges and opportunities for logistics companies. Against this backdrop, logistics companies must enhance their environmental, social responsibility and governance (ESG) performance to adapt to the requirements of sustainable development and improve market competitiveness.

Despite growing attention to ESG performance in logistics, significant research gaps remain. First, while previous studies have examined various determinants of ESG performance (Smith & Johnson, 2022), the specific role of digital technology in enhancing ESG metrics remains understudied, particularly in the logistics sector. Second, the mechanisms through which digital transformation influences ESG performance are not well understood, especially

regarding the potential mediating role of green innovation (Wang et al., 2023). Third, there is limited empirical evidence on how environmental dynamism affects the relationship between digital technology adoption and ESG performance in logistics firms (Zhang & Liu, 2023). The current global VUCA environment has further exacerbated the uncertainty and complexity of business operations. This dynamic environment requires logistics organizations to have greater adaptability and flexibility to cope with market volatility and uncertainty. In such an environment, the application of digital technology has become a key tool for transformation and upgrading. The use of technologies such as Big Data, Artificial Intelligence, and Internet of Things not only improves the operational efficiency and customer service level of enterprises, but also promotes their performance in terms of social responsibility and sustainable development.

## Research Objectives

1) To investigate the impact mechanism of digital technology application on logistics enterprises' ESG performance by analyzing empirical data from A-share listed logistics companies in China, verifying the specific role of digital technology application in promoting the improvement of logistics enterprises' ESG performance.

2) To examine the mediating effect of green innovation between digital technology application and ESG performance, exploring how digital technology application indirectly enhances ESG performance through improving enterprises' green innovation capabilities.

3) To explore the moderating effects of the VUCA environment (uncertainty and complexity) on the relationship between digital technology application and ESG performance, testing whether and how the impact of digital technology application on ESG performance varies under highly uncertain and complex environmental conditions.

## Literature Review and Research Hypothesis

### 1. Analysis of the Mechanism of the Impact of Digital Technology Application on ESG Performance and Hypothesis Formulation

In terms of behavioral motivation, digital technology application promotes the ability and willingness of logistics enterprises to fulfill their environmental, social and governance responsibilities. Stakeholder theory suggests that logistics enterprises obtain economic resources from different stakeholders, and relatively, logistics enterprises feedback economic benefits to these subjects through the fulfillment of various types of responsibilities. In terms of behavioral outcomes, the application of digital technology improves the ability of logistics firms to fulfill their environmental, social, and governance responsibilities (Fichman et al., 2014; Wang & Jiang, 2014; Zhong & Ma, 2022), which includes promoting sustainable development by enhancing operational efficiency, optimizing resource utilization, enhancing transparency, and improving technological innovation (Zhong et al., 2023).

It has been well documented that the application of digital technology can promote corporate ESG performance, and Chang et al.'s (2021) study shows that digital finance and high ESG performance can enhance corporate financing efficiency. Using data envelopment analysis (DEA) and panel data analysis methods, this study finds a mutually reinforcing relationship between digital finance and ESG performance. Belousova et al.'s (2022) study examines how digital business services (DBS) firms can reduce GHG emissions through the

implementation of energy efficiency improvement measures. This study analyzed ESG disclosures of DBS companies based on the Refinitiv dataset and found that these companies significantly improved their environmental performance by implementing digitalization measures. The study by Wei (2023) examines how corporate digital transformation can significantly improve ESG performance. The research methodology included a fixed-effects model, and the study found that digital transformation can significantly contribute to corporate performance. Further research found that this driving effect was more pronounced in state-owned enterprises and digitized enterprises.

However, in recent years, studies have also found that digital technology adoption may negatively impact firms' ESG performance. A study by Klumpp & Loske (2021) noted that increased IT system dependency due to digitalization negatively impacts retail logistics efficiency. The study used Network Data Envelopment Analysis (NDEA) methodology to assess the impact of IT disruptions on the efficiency of retail logistics operational processes. Belousova et al. (2022) also observed that despite the progress made by DBS firms in reducing GHG emissions, the improvement in environmental performance was not significant. The article empirically examines the impact of corporate digital transformation on ESG performance based on panel data of Chinese A-share listed companies from 2013-2020. Wang & Guo (2023), on the other hand, find that the impact of digital transformation on ESG performance may be more complex. They conclude that the degree of digital transformation is significantly related to ESG performance in an "inverted U-shape", a finding that remains robust after a series of tests, including propensity score matching, instrumental variables, and variable replacement measures.

Although studies have revealed the challenges posed by digitalization, such as reliance on IT systems and potential limitations in improving environmental performance, in general, most studies have concluded that digital technology adoption has a significant positive impact on the ESG performance of logistics firms, especially in terms of improving operational efficiency, promoting technological innovation, and enhancing corporate transparency. To summarize, this study concludes that digital technology application can provide a driving force for logistics companies' ESG performance, and therefore proposes the following hypotheses:

H1: Digital technology application can significantly enhance ESG performance of logistics enterprises.

## **2. Analysis of green innovation intermediation mechanisms and formulation of hypotheses**

### ***Impact of digital technology applications on green innovation***

Based on the theory of Natural Resource-Based View (NRBV), it can be seen that the internal elements including the technological capability of logistics enterprises are the basis for them to innovate and maintain competitive advantages, and logistics enterprises cannot innovate without the support of technological resources, knowledge resources, human resources and capital, and the application of digital technology lays a relevant foundation for green technological innovation of logistics enterprises (Guo & Quan, 2022).

The positive impact of digital technology application on green innovation is mainly reflected in the promotion of sustainable development and environmentally friendly industries through technological innovation. Digital transformation helps companies utilize resources more efficiently and achieve the dual goals of environmental protection and economic growth

(Jiang et al., 2023; Huang et al., 2022). From the viewpoint of technology and subject knowledge of innovation activities, green innovation activities involve product design and production, manufacturing process upgrading, energy saving and emission reduction, etc., which involves multiple and complex processes, and therefore requires in-depth combination of multi-disciplinary technologies to empower green innovation. The application of digital technology in logistics enterprises can significantly improve the data mining ability and information decision-making ability of logistics enterprises, and at the same time will improve the information sharing and knowledge integration ability of logistics enterprises, help logistics enterprises to deeply couple the knowledge under different fields, enhance the knowledge reorganization efficiency of the innovation process, and then improve the green technology innovation ability of logistics enterprises. In addition, the application of digital technology can play a role in promoting the accumulation of financial and human resources of logistics enterprises and laying a material foundation for green innovation.

However, some studies have seen the potential negative impact of digital technology application on green innovation. Chen & Shen (2022) used static panel model, panel threshold model and spatial Durbin model to conduct an empirical study, and found that in the region with a lower level of digital innovation, the application of digital technology increases the carbon emissions of the industry, but with the increase in the level of digital innovation, its application inhibits carbon emissions and shows the effect of reducing carbon emissions. the effect of reducing carbon emissions.

To summarize, this study concludes that digital technology application can enhance the green innovation of logistics enterprises, and therefore proposes the following hypothesis:

H2: The application of digital technology can significantly enhance the green innovation of logistics enterprises.

### ***The Impact of Green New on Corporate ESG Performance***

Green innovation has a significant impact on firms' ESG performance, and it is seen as a key way to improve firms' ESG (performance by promoting environmentally friendly technologies and practices, as well as sustainable development through improved social responsibility and governance transparency (Xu et al., 2021).

There are a number of reasons why more green innovations by logistics firms can positively impact their ESG performance, which reflects the importance of sustainable development and social responsibility. From an environmental perspective, green innovation in logistics firms usually involves reducing resource consumption, lowering waste emissions and minimizing negative impacts on the ecosystem. This helps to mitigate the environmental footprint of logistics firms, reduce greenhouse gas emissions, and protect natural resources and ecosystems (Chen & Jia, 2020). These environmental initiatives help to improve the environmental reputation of logistics firms. From a social perspective, green innovation may involve initiatives to improve labor conditions, provide social support, and engage in community development. This can help enhance employee satisfaction, attract and retain talent, and improve the reputation of logistics firms at the social level. From a corporate governance perspective, green innovation usually requires a higher level of governance and transparency to ensure efficient allocation of resources and compliance. This helps to reduce firms' risks, prevent misconduct, and enhance investor and stakeholder trust (Wojtas et al., 2017; Bumgardner & Buehlmann, 2022). From a sustainability perspective, green innovation usually involves long-term sustainability goals such as reducing resource waste, improving

efficiency, and combating climate change. These goals help logistics firms to maintain sound operational and financial performance in the long term, in line with the long-term perspective of ESG. From an investor and stakeholder perspective, more and more investors, consumers and stakeholders are interested in the ESG performance of logistics companies. By actively pursuing green innovation, logistics enterprises can fulfill these needs and attract more investments and customers. In summary, green innovation in logistics enterprises not only helps to mitigate environmental and social problems, but also helps to improve the ESG performance of logistics enterprises and enhance their sustainability and competitiveness. Therefore, this study proposes the following hypotheses:

H3: Green innovation can significantly improve ESG performance of logistics enterprises.

#### ***Mediating effects of green innovation***

The above analysis suggests that the use of digital technology by logistics firms has the potential to both improve the firm's ESG performance and contribute to increasing the firm's green innovation capability, which in turn can further improve the firm's ESG performance. Therefore, green innovation may play a mediating role in the impact of digital technology application on firms' ESG performance. On the one hand, logistics enterprises are able to improve the level of digital technology application by utilizing digital resources, and can also more fully integrate green-related knowledge, information and technology resources to improve the environmental supervision and resource utilization efficiency of logistics enterprises (Cui et al., 2022), thus enhancing the green innovation ability of logistics enterprises (Wang et al., 2023); on the other hand, logistics enterprises can both On the other hand, logistics enterprises can not only accelerate the mutual exchange of internal knowledge and information technology through digital empowerment, but also form an innovative knowledge co-creative network with external logistics enterprises (Subramaniam & Youndt, 2005), which can promote the green technological innovation of logistics enterprises.

To summarize, the higher the degree of digital technology application in logistics enterprises, the more they can fully integrate digital resources with green innovation development, thus enhancing the green technology innovation capability of logistics enterprises, reducing the green production cost of logistics enterprises, and improving the green production efficiency of logistics enterprises, which will help logistics enterprises to achieve better ESG performance. Therefore, this study proposes the following research hypotheses:

H4: Green innovation plays a significant mediating role between digital technology application and ESG performance.

### **3. Analysis of the mechanisms and hypotheses for the environmental moderating effects of VUCA**

In an environment fraught with uncertainty (VUCA), digital technology applications can provide more data, analytics, and real-time insights to help logistics organizations better understand and respond to complex environmental challenges. This enhances the impact of digital technologies on ESG (environmental, social and governance) performance, enabling logistics companies to take more flexible and rapid steps to adapt to change and improve ESG performance as they are better able to track, manage and report on sustainability-related information and data.

First, logistics companies face challenges that may involve climate change, social instability, regulatory changes, and rapidly evolving consumer expectations, which require faster and more precise decisions and actions to respond. Digital technology applications (e.g., big data analytics, artificial intelligence, IoT, etc.) can provide logistics companies with key insights that can help them better identify risks, opportunities, and trends to better meet ESG objectives. Digital technologies can also improve efficiency and reduce costs, for example through resource optimization and energy management, which can help improve environmental performance. Second, in a VUCA environment, digital technology applications can also help logistics companies better address governance challenges. Digital technologies can help logistics companies better understand consumer needs and expectations and improve their products and services. At the same time, digital technologies can enhance risk management, compliance and transparency, which can help prevent misconduct, safeguard company reputation, and improve governance performance. Digital technology applications can also drive innovation, develop new sustainable business models and solutions, and further improve ESG performance. Sun et al. (2022) argue that digital technologies can drive innovation in the field of renewable energy, improve energy efficiency, reduce carbon emissions, and meet environmental goals. At the same time, digital technologies can also promote social inclusion and improve social performance by digitizing education, healthcare, and financial services. In summary, the VUCA environment strengthens the impact of digital technology applications on ESG performance, enabling logistics firms to better adapt to complex sustainability challenges and improve their sustainability and competitiveness, so this study proposes the following hypothesis:

H5: VUCA environment positively moderates the relationship between digital technology application and ESG performance, i.e., the stronger the VUCA environment, the greater the impact of digital technology application on ESG performance.

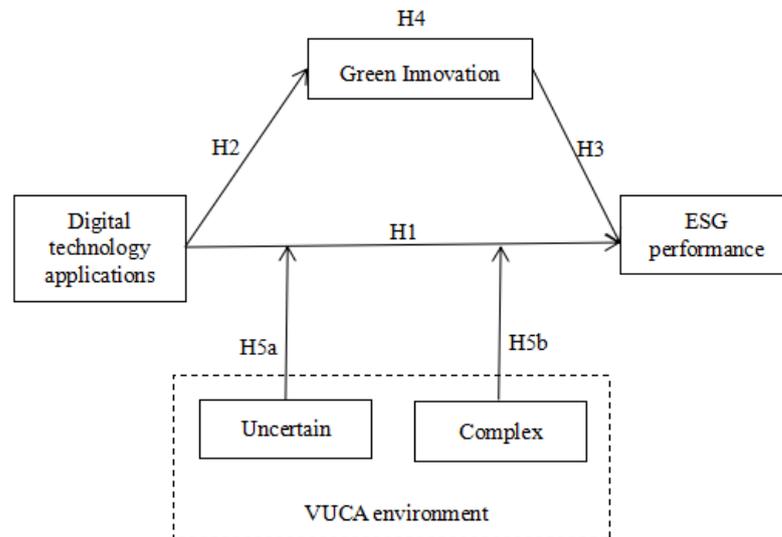
Further, VUCA is divided into two secondary indicators according to its meaning, and the following two segmentation hypotheses are proposed:

H5a: Uncertainty positively moderates the relationship between digital technology application and ESG performance, i.e., the stronger the VUCA environment, the greater the impact of digital technology application on ESG performance.

H5b: Complexity environment positively moderates the relationship between digital technology application and ESG performance, i.e. the stronger the VUCA environment, the greater the impact of digital technology application on ESG performance.

As a result, the research framework of this study is shown in Figure 1.

**Figure 1**



*Research framework diagram*

## Research Methodology

### 1. Sample selection and data sources

This study selects listed companies in the logistics category in China from 2009-2022. The CSI ESG rating and Bloomberg ESG rating data come from the Wind database; the green patent data come from the State Intellectual Property Office (SIPO) and WIPO Green Patent List; and the data on the application of digital technology by enterprises refer to Wu et al. (2021), which refers to 76 digitization-related word frequencies in the five dimensions of artificial intelligence technology, big data technology, cloud computing technology, blockchain technology, and the use of digital technology. Statistics are conducted. The economic data at the enterprise level are obtained from the Cathay Pacific Database (CSMAR). In the process of data collection and cleaning, the data are processed as follows. First, listed enterprises with ST and PT are excluded. Second, samples with gearing ratio greater than 100% are removed. Third, the missing data of relevant variables are removed. Fourthly, the data are shrink-tailed at 1% and 99% quartiles.

### 2. Variable Description

#### *Explanatory variable*

This study uses the CSI ESG ratings to measure corporate ESG performance. This system categorizes ESG performance into nine grades: from AAA to C, with a score of 9 to 1 assigned accordingly.

#### *Explanatory variable*

Referring to Wu et al. (2021), this study counted 76 digitization-related word frequencies in five dimensions: artificial intelligence technology, big data technology, cloud computing technology, blockchain technology, and digital technology use, and then used the number of word frequencies plus one to take the natural logarithm to measure the enterprise digital technology application (Dig). In addition, in order to verify the reliability of the

conclusions, this study also refers to Zhao et al. (2021), which counts 99 digitization-related word frequencies in the four dimensions of digital technology application, Internet business model, intelligent manufacturing, and modern information system, and then uses the word frequency plus 1 to take the natural logarithm to measure the enterprise digital technology application (Dig1).

**Intermediary variable**

This study uses the total number of green patents granted by firms plus one to take the natural logarithm (Pat) to measure firms' green innovation.

**Moderator variable**

**Uncertainty.** The difference in the level of environmental uncertainty not only stems from the firm's own operating conditions, but also is closely related to the development of the industry in which it operates, so this study draws on the practices of Shen et al. (2012) and Hu & Zheng (2021) to use the data of listed companies' sales revenues over the past five years to estimate the abnormal sales revenues over the past five years through regression, respectively, as in Eq. 1.

$$Sale_{it} = \varphi_0 + \varphi_1 Year_{i,t} + \varepsilon_{i,t} \quad (1)$$

Where *Sale* represents the sales revenue, *Year* represents the year, and the residual term  $\varepsilon$  is the abnormal sales revenue; calculate the standard deviation of the listed company's abnormal sales revenue in the past five years, and then divide it by the average of the sales revenue in the past five years, so as to get the listed company's unindustry-adjusted environmental uncertainty as in Equation 2.

$$UN_{it} = \frac{std(\varepsilon_{i,t-1}, \varepsilon_{i,t-2}, \varepsilon_{i,t-3}, \varepsilon_{i,t-4}, \varepsilon_{i,t-5})}{mean(Sale_{i,t-1}, Sale_{i,t-2}, Sale_{i,t-3}, Sale_{i,t-4}, Sale_{i,t-5})} \quad (2)$$

This study uses the median unindustry-adjusted environmental uncertainty of all listed companies in the annual logistics industry as the value of the industry's environmental uncertainty for that year *UN*.

**Complexity.** This study measures uncertainty in an organization's external environment: drawing on Laise & Overbeck (2005) and Kerber et al. (2009), a diversity indicator, the Herfindahl Index, is used to measure the degree of complexity in the environment faced by firms. The Herfindahl Index (HHI) is one of the most widely used indicators for measuring the complexity of an industry. and its calculation is shown in Equation 3.

$$COM = HHI = 1 - \sum_{i=1}^n P_i^2 \quad (3)$$

Where  $P_i$  is the share of revenue of firm *i* in the operating revenue of the listed company. *COM* the larger the index, the higher the degree of diversification and the higher the degree of complexity of the environment faced by the firm.

**Control variable**

In this study, firm size (Size), gearing ratio (Lev), return on total assets (Roa), equity concentration (Top1), firm growth (Growth), share of tangible assets (Tang), and share of independent directors (Indep) are selected as control variables. The detailed definition of each variable is shown in Table 1.

**Table 1** Variable Definition

Category of variables	Variable Symbol	Variable Definition
Explained Variables	ESG	Firms' ESG performance, obtained by assigning values using the CSI ESG score
Explanatory Variables	Dig	Digital technology application = $\ln(\text{total number of digitized feature words in annual reports of enterprises} + 1)$
Mediating variable	Inno	Green Innovation = $\ln(\text{total number of green patents granted} + 1)$
Moderating variable	UN	Uncertainty
	COM	Complexity
	Size	Enterprise size = $\ln(\text{total assets})$
	Lev	Gearing ratio = $\text{total liabilities} / \text{total assets}$
	Roa	Return on total assets = $\text{net profit} / \text{total assets}$
	Top1	Equity Concentration = proportion of shares held by the first largest shareholder
Control Variables	Growth	Enterprise Growth = Operating Revenue Growth Rate
	Tang	Tangible Assets Ratio = $\text{Tangible Assets} / \text{Total Assets}$
	Indep	Percentage of independent directors = $\text{Number of independent directors} / \text{size of directors}$

### 3. Model design

First, this study constructs the following regression model to verify the impact of digital technology application on corporate ESG performance.

$$ESG_{it} = \pi_0 + \pi_1 Dig_{it} + \pi_2 Controls_{it} + Firm_i + Year_t + \varepsilon_{it} \quad (4)$$

Among them, the explanatory variable is firms' ESG performance (ESG) and the explanatory variable is digital technology adoption (Dig). The control variables (Controls) include firm size (Size), gearing ratio (Lev), return on total assets (Roa), equity concentration (Top1), firm growth (Growth), share of tangible assets (Tang), and share of independent directors (Indep). The variables and are firm fixed effects and year fixed effects, respectively.

Second, this study constructs the following model to verify the impact of corporate green innovation on corporate ESG performance.

$$ESG_{it} = \delta_0 + \delta_1 Inno_{it} + \delta_2 Controls_{it} + Firm_i + Year_t + \varepsilon_{it} \quad (5)$$

In this case, the explanatory variable remains corporate ESG performance (ESG), the explanatory variable is corporate green innovation (Inno), and the control variables are consistent with model (4) and will not be repeated.

Third, this study intends to use a three-step approach to verify whether green innovation plays the role of a mediating variable in the impact of digital technology adoption on corporate ESG performance. Specifically, based on model (4), model (6) and model (7) are developed.

$$Inno_{it} = \alpha_0 + \alpha_1 Dig_{it} + \alpha_2 Controls_{it} + Firm_i + Year_t + \varepsilon_{it} \quad (6)$$

$$ESG_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_2 Inno_{it} + \beta_3 Controls_{it} + Firm_i + Year_t + \varepsilon_{it} \quad (7)$$

In model (6), the explanatory variable is the mediator variable of this study enterprise green innovation (Inno), the explanatory variable is digital technology application (Dig), and the control variables are consistent with model (4) and will not be repeated. In model (7), it is the explanatory variable of this study (Dig) and the mediator variable (Inno) together to do regression on the explanatory variable (ESG).

Fourth, this study sets up model (8) to test whether the VUCA environment plays a moderating effect between digital technology adoption and corporate ESG performance.

$$ESG_{it} = \mu_0 + \mu_1 Dig_{it} + \mu_2 VUCA_{it} + \mu_3 Dig_{it} \times VUCA_{it} + \mu_4 Controls_{it} + Firm_i + Year_t + \varepsilon_{it} \quad (8)$$

In model (8), the explanatory variable is firms' ESG performance, and the core explanatory variable is the interaction term between digital technology adoption and VUCA environment (Dig×VUCA), if the estimated coefficient of the interaction term is significantly positive, then it can be shown that VUCA environment positively moderates the relationship between Dig and ESG. Specifically, the VUCA environment includes uncertainty (UN) and complexity (COM).

## Results

### 1. The Impact of Digital Technology Adoption on Corporate ESG Performance

After substituting the data into model (4) for regression in this study, the regression results are shown in Table 2. As can be seen from the table, column (1) is the estimation result without adding control variables and the estimated coefficient of digital technology application (Dig) is significantly positive at 1% level (0.146; t=3.967), which tentatively indicates the accuracy of hypothesis H1. Column (2) is the estimation result of adding all control variables and the regression result of model (1), and it can be learned that the estimated coefficient of digital technology application (Dig) is still significantly positive at 1% level (0.135; t=3.581), which indicates that digital technology application contributes to the improvement of the ESG performance of the logistics enterprises while keeping other variables unchanged and the hypothesis H1 of the present study has been formally verified. For the control variables, the estimated coefficient of enterprise size (Size), for example, is 0.264, which is also significant at the 1% level, indicating that the larger the size of the enterprise, the higher the level of corporate ESG performance

**Table 2** Regression results on the impact of digital technology adoption on corporate ESG performance

VARIABLES	(1) ESG	(2) ESG
Dig	0.146*** (3.967)	0.135*** (3.581)
Size		0.264*** (3.391)
Lev		-0.091 (-0.345)

Roa		3.516*** (4.828)
Top1		1.122** (2.527)
Growth		-0.076 (-1.337)
Tang		0.475 (1.273)
Indep		2.696*** (5.069)
Constant	3.384*** (34.721)	-4.678** (-2.453)
Firm/Year FE	YES	YES
Observations	971	971
R-squared	0.590	0.621

Note: t-statistics are in parentheses and \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ , as in the following tables.

## 2.The Impact of Corporate Green Innovation on Corporate ESG Performance

After substituting the data into model (5), the estimation is carried out and the regression results are shown in Table 3. According to the estimation results in the table, it can be learned that the estimated coefficient of corporate green innovation (Inno) is significantly positive at the 5% level (0.096;  $t=2.26$ ), which indicates that corporate green innovation contributes to the improvement of the ESG performance of logistics companies, while keeping other variables constant, and the hypothesis of this study, H3, is verified.

**Table 3** Regression results on the impact of corporate green innovation on corporate ESG performance

VARIABLES	(1) ESG
Inno	0.096** (2.260)
Size	0.298*** (3.797)
Lev	-0.206 (-0.764)
Roa	3.448*** (4.672)
Top1	1.345*** (3.007)
Growth	-0.064 (-1.124)

Tang	0.425 (1.123)
Indep	2.375*** (4.484)
Constant	-5.020** (-2.580)
Firm/Year FE	YES
Observations	971
R-squared	0.618

### 3. Mediation effect test

In order to test whether green innovation plays the role of a mediating variable between digital technology adoption and firms' ESG performance, this study substitutes the data into models (6) and (7), and performs the estimation, and the regression results are shown in Table 4. As can be seen from the table, column (1) is the estimation result of the first step and the regression result of model (4), which will not be repeated. Column (2) is the regression result of digital technology application (Dig) on enterprise green innovation (Inno), which is the result of model (6), at this time, the estimated coefficient of digital technology application is significantly positive at 5% level (0.072;  $t=2.361$ ), indicating that the digital technology application can significantly improve the level of green innovation of logistics enterprises, and the hypothesis of this study, H2, is verified. Column (3) shows the estimation results of model (7), and it can be found that the estimated coefficient of green innovation (Inno) is significantly positive (0.084;  $t=1.98$ ) at the 5% level, which indicates that green innovation plays a mediating effect between digital technology application and ESG performance of logistics enterprises, and that the digital technology application improves ESG performance of logistics enterprises by increasing the level of green innovation of the enterprises, and the present research hypothesis H4 is verified.

**Table 4** Regression results on the mediating effects of green innovation

VARIABLES	(1) ESG	(2) Inno	(3) ESG
Dig	0.135*** (3.581)	0.072** (2.361)	0.129*** (3.376)
Inno			0.084** (1.980)
Size	0.264*** (3.391)	0.196*** (4.271)	0.248*** (3.157)

(continued)

**Table 4** Regression results on the mediating effects of green innovation (continued)

Lev	-0.091 (-0.345)	0.659*** (3.234)	-0.147 (-0.553)
Roa	3.516*** (4.828)	0.483 (0.738)	3.475*** (4.760)
Top1	1.122** (2.527)	-1.574*** (-3.961)	1.255*** (2.807)
Growth	-0.076 (-1.337)	0.014 (0.295)	-0.077 (-1.364)
Tang	0.475 (1.273)	-0.381 (-0.895)	0.507 (1.376)
Indep	2.696*** (5.069)	2.041*** (4.523)	2.524*** (4.679)
Constant	-4.678** (-2.453)	-4.429*** (-3.736)	-4.305** (-2.243)
Firm/Year FE	YES	YES	YES
Observations	971	971	971
R-squared	0.621	0.595	0.623

#### 4. Moderating effects test

In order to test whether the VUCA environment (including uncertainty and complexity) plays a moderating effect between digital technology adoption and firms' ESG performance, this study substitutes the data into model (8) and the estimation results are shown in Table 5. As can be seen from the table, column (1) is the estimation result of uncertainty (UN) as a moderating variable, and the estimated coefficient of the interaction term of digital technology application and uncertainty (Dig×UN) is significantly positive at the 5% level (0.371;  $t = 2.318$ ), which indicates that uncertainty positively moderates the relationship between digital technology application and ESG performance, i.e., the stronger the VUCA environment, the greater the digital technology application has a greater impact on ESG performance, and hypothesis H5a of this study is tested. Column (2) shows the estimation results of complexity (COM) as a moderating variable, and the estimated coefficient of the interaction term of digital technology application and complexity (Dig×COM) is significantly positive at 1% level (0.197;  $t = 3.226$ ), which indicates that complexity positively moderates the relationship between digital technology application and ESG performance, i.e., the stronger the VUCA environment is, the more digital technology application has an impact on ESG performance, the stronger the impact of digital technology application on ESG performance, and the hypothesis H5b of this study is tested.

**Table 5** *Regression results for the moderating effects of uncertainty and complexity*

VARIABLES	(1) ESG	(2) ESG
Dig	0.093** (2.176)	-19.561*** (-3.203)
UN	-0.893** (-2.041)	
Dig×UN	0.371** (2.318)	
COM		-0.764*** (-3.423)
Dig×COM		0.197*** (3.226)
Size	0.254*** (3.284)	0.259*** (3.332)
Lev	-0.082 (-0.306)	-0.088 (-0.334)
Roa	3.493*** (4.820)	3.483*** (4.425)
Top1	0.966** (2.113)	1.079** (2.392)
Growth	-0.076 (-1.344)	-0.077 (-1.342)

(continued)

**Table 5** *Regression results for the moderating effects of uncertainty and complexity (continued)*

Tang	0.466 (1.247)	0.491 (1.321)
Indep	2.665*** (5.016)	3.122*** (5.527)
Constant	-4.264** (-2.233)	71.663*** (3.236)
Firm/Year FE	YES	YES
Observations	971	971
R-squared	0.623	0.624

## **Conclusions and Implications**

### **1. Conclusions**

By analyzing the empirical data of A-share listed logistics companies, this study clarifies that digital technology application plays a positive role in promoting the ESG performance of logistics companies. From the perspective of digital technology application, the findings confirm a positive relationship between technology investment and corporate performance in environmental protection, social responsibility, and governance efficiency. In addition, green innovation, as a new organizational practice and an embodiment of the results of technology investment, plays a significant mediating role between digital technology adoption and ESG performance, further cementing the link between technology and performance.

In the context of the VUCA era, the characteristics of uncertainty and complexity are more prominent, and the results of this study suggest that these characteristics not only fail to attenuate the positive impact of digital technology adoption on ESG performance, but further strengthen it, suggesting that firms should be more flexible in adopting digital technologies to adapt to and take advantage of this new business environment.

### **2. Implications**

**Implications for logistics enterprises:** Logistics enterprises should actively embrace digital transformation and take technological innovation and the application of digital technology as the core strategy for improving ESG performance. At the same time, enterprises need to continuously promote green innovation in the process of technology application and form an internal driving mechanism for green development to ensure that they can continuously improve their ESG performance in the VUCA era.

**Implications for policymakers:** The government and relevant industry authorities should formulate and implement policies to encourage logistics enterprises to carry out digitalization, especially investing in technological upgrading and green innovation, and to reduce the risks and costs of enterprise transformation through tax incentives and financial support. At the same time, policymakers should fully consider and study the new features of the VUCA environment to provide a more flexible and forward-looking development environment for enterprises.

**Implications for investors and stakeholders:** The results of this study can provide decision-making references for investors and other stakeholders. Logistics companies with a high level of digital technology application are more likely to improve their ESG performance, which not only represents the future development potential of the company, but also meets the current social expectations for green and sustainable development. Investors can take the degree of digitization and ESG performance of companies as important considerations when making investment decisions.

**Implications for academics:** This study proposes and validates the relationship between digital technology application and ESG performance, and its significance in the VUCA era, which provides a new perspective and research basis for subsequent studies in related fields. Future research can further explore the specific impact of different types of digital technologies or specific application scenarios on the ESG performance of logistics firms, as well as the changes in the relationship under different cultural and economic conditions.

In summary, this study not only theoretically enriches the association between digital technology application, green innovation and ESG performance, but also provides concrete guidance and suggestions for logistics enterprises and related policy making from a practical perspective. In the grand context of the "dual-carbon" era, the digital transformation and ESG performance improvement of logistics enterprises have become more and more important and urgent, especially in the current volatile global business environment, enterprises need to use digital technology to improve their adaptability and competitiveness.

## Suggestion

### 1. Practical Implications

Based on our empirical findings, we propose several practical suggestions for different stakeholders in the logistics industry:

First, logistics enterprises should strengthen their digital transformation initiatives with a focus on ESG performance enhancement. Specifically, they should: (1) develop systematic digital transformation strategies that integrate ESG objectives into their core business processes; (2) establish digital platforms that facilitate green innovation and sustainable operations; and (3) implement comprehensive performance measurement systems that track both digital capabilities and ESG outcomes. Moreover, enterprises should invest in employee training programs to build digital competencies while fostering ESG awareness throughout the organization.

Second, policy makers should create a supportive environment for digital-driven ESG development in the logistics sector. We recommend: (1) designing targeted incentive policies that encourage digital technology adoption and green innovation; (2) establishing standardized ESG evaluation criteria specific to the logistics industry; and (3) developing regulatory frameworks that promote sustainable digital transformation while ensuring fair competition. Furthermore, government agencies should consider providing financial support mechanisms to help smaller logistics firms overcome digital transformation barriers.

Third, industry stakeholders, including investors and financial institutions, should adapt their strategies to accommodate the digital-ESG nexus. They should: (1) incorporate digital capability assessments into their ESG investment frameworks; (2) develop specialized financial products supporting digital-green initiatives; and (3) promote industry-wide collaboration on digital sustainability projects.

### 2. Future Research Directions

Our study suggests several promising avenues for future research:

First, theoretical extensions could explore: (1) additional theoretical frameworks beyond stakeholder theory and NRBV to explain the digital-ESG relationship; (2) more nuanced interactions between different ESG dimensions in the context of digital transformation; and (3) the development of comprehensive models that capture the complexity of digital-driven sustainability in logistics.

Second, methodological improvements should focus on: (1) adopting mixed-method research approaches to provide deeper insights into the digital-ESG relationship; (2) developing more sophisticated measures of digital technology application; and (3) incorporating alternative ESG rating systems to enhance the robustness of findings.

Third, emerging research areas warrant investigation, including: (1) the differential impacts of specific digital technologies (AI, blockchain, IoT) on various ESG components; (2) cross-cultural comparisons of digital-ESG transformation strategies; (3) the role of organizational culture in facilitating digital-driven ESG improvements; and (4) the long-term sustainability impacts of digital transformation in the logistics sector.

### 3. Limitations

While our study provides valuable insights, several limitations should be noted for future research consideration: (1) our sample is limited to Chinese A-share listed logistics companies, which may affect the generalizability of findings to other contexts; (2) the measurement of digital technology application relies on keyword frequency, which may not fully capture the complexity of digital transformation; and (3) the study period might not fully reflect the most recent technological developments and their impact on ESG performance.

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