Asia Pacific Economic and Management Review
ISSN(O):3005-9275
ISSN(P):3005-9267
Vol. 2 No.5 (2025)

The Impact of Technological Innovation on Environmental Governance in the Logistics Industry

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Abstract: This article uses relevant data from 30 provinces, autonomous regions, and municipalities in China from 2014 to 2023 as research samples to empirically test the impact of technological innovation on logistics industry environmental governance. The results show that: (1) the benchmark regression results show that technological innovation has a positive impact on logistics industry environmental governance. (2) The results of the mediation effect test show that new quality productivity and market mechanisms play a partial mediating role in the relationship between the two. (3) Heterogeneity tests indicate that technological innovation has a more significant impact on the environmental governance of the logistics industry in the eastern region than in the central and western regions.

Keywords: Technological Innovation; Logistics Industry; Environmental Governance; New Quality Productivity; Market Mechanism
Published: Sept 13, 2025
DOI: https://doi.org/10.62177/apemr.v2i5.635

Introduction

With the deepening of globalization and the explosive growth of e-commerce, modern logistics has become a critical infrastructure supporting efficient socio-economic operations, reaching unprecedented scales and complexities. This transportation-dependent industry is inevitably closely linked to energy consumption and environmental emissions. According to assessments by the United Nations Environment Programme (UNEP), transportation-related carbon dioxide emissions account for a significant proportion, particularly in freight logistics, where its environmental impact increasingly becomes an unavoidable bottleneck in sustainable development [1]. Traditional logistics management and environmental governance models are predominantly characterized by "end-of-line solutions" or difficult trade-offs between efficiency and environmental protection. Their strategies for addressing environmental challenges demonstrate insufficient timeliness and depth, making governance effectiveness prone to stagnation.

In this era, cutting-edge technological clusters represented by big data analytics, AI-driven decision support, IoT real-time monitoring, automated equipment applications, and new energy power technologies are profoundly reshaping the operational logic and environmental interactions within the logistics industry. The precision insights and optimization potential embedded in these advanced technologies provide innovative pathways for transforming environmental governance paradigms. Empowered by technology, logistics systems have achieved unprecedented operational visualization and holistic optimization—from micro-level real-time vehicle path planning and multimodal transport coordination to macro-level network design and green energy deployment strategies—achieving an unprecedented integration of technology and environmental objectives. Consequently, carbon intensity, air pollutant emissions, and total resource consumption in logistics processes have been systematically reduced. A new form of green logistics productivity, centered on intelligentization, is rapidly taking shape. It should be emphasized that this technology-driven governance transformation represents not merely an upgrade of specific emission reduction tools, but a comprehensive leap in the logistics industry's ecological niche and developmental logic. This transition profoundly reveals the empowering value of technological innovation for green development, while also requiring us to conduct in-depth analysis and systematic evaluation of the internal mechanisms and practical effects of technology-enhanced environmental governance. Only through such efforts can the logistics industry secure strategic initiative in high-quality development amidst the global green and low-carbon transition wave.

1.Literature review

The logistics industry serves as a cornerstone sector supporting national economic operations [2-3], while maintaining supply chain resilience, it has also triggered significant energy consumption and pollutant emissions. Current research generally regards technological innovation as the key pathway to reconcile efficiency improvements in logistics with environmental protection. Systematic academic understanding reveals that technology demonstrates multidimensional penetration in reshaping governance paradigms and optimizing environmental performance within logistics systems. In transportation, advanced digital applications show the most notable effect on reducing carbon footprints. Intelligent dispatching systems leverage big data and AI algorithms to integrate real-time order information, road network data, weather conditions, and vehicle status, enabling global dynamic route planning. This not only reduces idle rates but also substantially enhances route efficiency, with empirical evidence demonstrating substantial emission reduction potential [4]. Meanwhile, advancements in green energy vehicle technologies are progressively replacing traditional fossil fuel power chains. Multiple domestic and international case studies confirm that hydrogen fuel cell trucks and electric trucks show scalable application potential in short-haul cargo collection and urban collaborative delivery, effectively reducing nitrogen oxides (NOx) and fine particulate matter (PM2.5) emissions [5-7]. Notably, debates persist in this field, with scholars proposing critical reflections on the carbon accounting boundaries of electric vehicles' entire life cycle and infrastructure adaptability [8].

The intensification and automation of logistics storage operations have profoundly transformed energy structures and land-use efficiency. Automated three-dimensional warehouses, equipped with intelligent stacker cranes, shuttle vehicles, and high-speed sorting systems, achieve exponential improvements in space utilization. This not only reduces land requirements but also decreases average energy consumption per storage operation [9]. Smart logistics park management systems utilize IoT sensors to precisely regulate cold storage temperatures and equipment status, while integrating distributed energy solutions like rooftop photovoltaic panels. These innovations significantly reduce overall indirect environmental costs in operational processes [10].

Innovative technologies for packaging focus on closed-loop management of material flows. Lightweight designs and the substitution of traditional high-density polyethylene (HDPE) packaging with renewable bio-based materials have become research hotspots. Empirical studies demonstrate that modified cellulose and polylactic acid (PLA) exhibit exceptional value in significantly reducing packaging pollution loads [11]. More importantly, fundamental innovations in logistics information system architectures drive environmental governance toward global optimization. The integrated logistics environment platform combining big data, artificial intelligence, and cloud computing enables real-time monitoring of energy consumption, emissions, and waste throughout the entire supply chain, providing data-driven support for precise decision-making [12].

The academic community has reached a consensus: Technological innovation systematically reduces environmental externalities in the industry by restructuring operational models across logistics sectors. However, the practical penetration of these technologies remains constrained by cost pressures, standardization barriers, and policy coordination levels. Exploring the compatibility between green technologies and market incentive mechanisms will be the key direction for future research breakthroughs.

2.Research hypotheses

2.1 Technological innovation and environmental governance of logistics industry

Technological innovation is recognized as a pivotal driver for advancing green transformation and environmental governance in the logistics sector [13]. Theoretically, it optimizes logistics operations through multidimensional approaches, effectively reducing environmental footprints. At the technological application level, intelligent path planning and vehicle scheduling systems powered by big data analytics, IoT, and AI dynamically capture real-time multi-source data including road conditions and order information. This enables scientific optimization of transport routes, loading efficiency, and driving speeds, significantly cutting ineffective mileage while enhancing output efficiency per unit of transportation resources. These innovations directly reduce fuel consumption and emissions. On the equipment front, the industrial adoption of new energy vehicles like electric trucks and hydrogen-powered trucks fundamentally replaces traditional fossil fuels with clean energy. By shifting carbon emissions at their source, these solutions achieve substantial reductions in logistics-related carbon footprints. With the ongoing development of charging/hydrogen refueling infrastructure and improvements in battery endurance, their emission-reduction potential will continue to grow.

At the meso-level operational management, the establishment of blockchain-powered logistics traceability platforms and digital supply chain management systems has significantly enhanced information transparency and collaborative capabilities among enterprises across supply chain nodes. These systems not only enable precise monitoring of resource flow paths to optimize warehouse layouts and inventory levels, thereby reducing redundant storage energy consumption, but also encourage companies to adopt eco-friendly packaging and collaborate on co-loading operations. Through resource sharing, these practices effectively mitigate systemic environmental burdens. On a macro level, technological innovation profoundly reshapes logistics industry structures and organizational models, giving rise to innovative business formats like shared logistics platforms and “Internet+” logistics. Leveraging digital capabilities, these models facilitate the integration and efficient coordination of social logistics resources, consolidating fragmented transportation demands while substantially improving facility utilization rates. This evolution objectively achieves optimized overall transportation demand and large-scale low-carbon operations through systematic resource optimization.

Based on the above theoretical analysis, this study puts forward hypothesis 1: Technological innovation has a significant positive promoting effect on environmental governance in logistics industry.

2.2 On the mediating role of new qualitative productive forces

The core characteristics of new-quality productivity manifest as an industrial paradigm transformation driven by data elements, supported by advanced technologies, and aimed at enhancing total factor productivity [14]. Within this research framework, it serves as a crucial intermediary bridging technological innovation and environmental governance. Theoretically, technological innovations such as AI algorithms, clean energy equipment, and digital twin systems first stimulate the formation of new-quality productivity through restructuring the structure of productive factors. For instance, IoT technology collects real-time data on transportation energy consumption and emissions, while AI-optimized engines dynamically adjust logistics routes, transforming traditional experience-driven models into algorithm-driven decision-making systems. This process drives qualitative upgrades in labor elements (e.g., driver operational efficiency), work objects (e.g., cargo consolidation methods), and working tools (e.g., new energy vehicles) within logistics systems, forming a new productivity combination centered on “data + computing power + green technology”. The emergence of new-quality productivity signifies a profound transformation in logistics resource utilization—from scale expansion to lean operations, and from reliance on factor inputs to technology-driven empowerment. Building on this foundation, new-quality productivity generates environmental governance effectiveness by reconstructing logistics paradigms. Its core mechanisms are manifested in two aspects: First, data intelligence-driven precise supply-demand matching (e.g., shared cloud warehouse systems) and dynamic resource scheduling (e.g., network-wide collaborative transportation networks) systematically reduce vehicle idling rates, warehouse vacancy rates, and packaging waste. On the other hand, the high-intensity application of new energy equipment technologies (such as large-scale operation of hydrogen fuel cell trucks) requires support from advanced infrastructure maintenance capabilities (like smart hydrogen refueling station networks) and green supply chain management systems (including real-time carbon footprint tracking). This exemplifies the industrial organization-level manifestation of new-quality productivity. The resulting digitalized, collaborative, and low-carbon logistics ecosystem directly reduces both energy intensity and total emissions per unit of logistics service.

Based on the above theoretical analysis, this study puts forward hypothesis 2: new quality productivity plays a significant mediating role between technological innovation and environmental governance of logistics industry.

2.3 The mediating role of market mechanisms

The impact of technological innovation on environmental governance in the logistics industry can only achieve scale effects through effective market mechanisms. Market mechanisms transform technological innovation potential into practical drivers for environmental governance through three dimensions: price signals, competitive pressure, and institutional incentives. This mediating role fundamentally reshapes the behavioral logic of micro entities and industrial structures, guiding technological innovations to unleash systemic value in green development. Theoretical analysis shows that technological innovation primarily triggers market transmission through the mechanism of green premium formation. When IoT real-time monitoring technology is applied to transportation vehicles, it enables precise quantification of energy consumption and emission data per shipment, allowing enterprises to internalize environmental cost accounting. This data supports verifiable carbon footprints, thereby establishing a differentiated pricing basis in carbon emission trading markets. Logistics companies gain carbon quota surpluses by adopting low-emission technologies (e.g., hydrogen-powered trucks), with direct transactional benefits significantly enhancing the return on investment for eco-friendly technology adoption and stimulating equipment renewal initiatives. Meanwhile, end consumers' willingness to pay premium for low-carbon logistics (e.g., "green delivery" options on e-commerce platforms) further motivates enterprises to build clean technology moats. This market demand-driven technological iteration forms a positive feedback loop under competitive market pressures.

The deeper mediating mechanism manifests through the restructuring of competitive order dynamics. Digital platforms like intelligent logistics matching systems dismantle information barriers in traditional transportation markets, enabling real-time algorithmic matching between cargo orders and optimal low-carbon carriers. The dramatic increase in transport pricing transparency compels enterprises to optimize management and upgrade technologies to reduce unit costs. Green technologies, with their cost-effective advantages in fuel efficiency and penalty reduction, have evolved from optional solutions into essential competitive requirements. Government-led green subsidies and environmental tax reductions further amplify this effect—such as subsidies for urban joint distribution center construction, which incentivize companies to consolidate fragmented transportation resources while simultaneously reducing regional traffic pollution. This synergy between institutional frameworks and technological innovation shifts environmental governance from passive compliance to proactive value creation.

Based on the above theoretical analysis, this study puts forward hypothesis 3: market mechanism plays a significant mediating role between technological innovation and environmental governance of logistics industry.

3.Study design

3.1 Data sources and selection

This paper selects the relevant data of 30 provinces, autonomous regions and municipalities in China from 2014 to 2023 as the research sample, and conducts tail trimming on the sample data. The data sources are provincial statistical yearbooks, Wind database and CNRDS database.

3.2 Variable definitions

3.2.1 Interpretation of variables

Technological innovation (denoted as TI). Following the approach of Zou Zhiming and Chen Xun [15], we selected the number of patent grants and adopted logarithmic transformation as an indicator to measure the technological innovation level of each province.

3.2.2 The variable to be explained

Environmental governance in the logistics industry (denoted as EG). Following the approach of Friday's seventh [16], the global entropy weighting method was adopted for measurement based on the environmental governance indicators constructed by them.

3.2.3 Moderating variables

The first mediating variable in this paper is new quality productivity (denoted as New). Referring to the evaluation system of Lu Jiang et al. [17], the development level of new quality productivity is measured by principal component analysis.

The second mediating variable in this paper is the market mechanism (denoted as MM), which is measured according to Guo Liting's [18].

3.2.4 Control variables

In this paper, urban and rural residents income gap (Ingap), government intervention ability (Govn), industrial structure (Stru), urbanization level (Lr) and other variables are taken as control variables.

3.3 Model construction

3.3.1 Benchmark regression models

To test hypothesis 1, we construct the following model,

$EGit = \beta 0 + \beta 1TIit + mCit + \tau i + \mu t + \varepsilon it$ （1） （1）

Among them, EGit is the explained variable, representing environmental governance, i represents province, t represents year, TIit is the explanatory variable, representing technological innovation, Cit is a series of control variables, where μt is the time fixed effect, τi is the individual fixed effect of province, and εit is the random disturbance term.

3.3.2 Mediating effect model

To test hypothesis 2 and hypothesis 3, we construct mediation effect models (2) and (3), (4) and (5) respectively.

$Newit = \gamma 0 + \gamma 1TIit + mCit + \tau i + \mu t + \varepsilon it$ （2） （2）

$EGit = \delta 0 + \delta 1TIit + \delta 2Newit + mCit + \tau i + \mu t + \varepsilon it$ （3） （3）

$MMit = \gamma 0 + \gamma 1TIit + mCit + \tau i + \mu t + \varepsilon it$ （4） （4）

$EGit = \delta 0 + \delta 1TIit + \delta 2MMit + mCit + \tau i + \mu t + \varepsilon it$ （5） （5）

Newit and MMit are the new quality productivity and market mechanism respectively, and other variables are the same as model (1).

4.Empirical results and analysis

4.1 Benchmark regression results

The regression results of the benchmark model are shown in column (1) of Table 1. The positive regression coefficient of technological innovation indicates that technological innovation plays a positive role in promoting environmental governance in the logistics industry, and hypothesis 1 is verified.

Table 1 Results of benchmark test regression and mediation effect regression

variable	EG	EG	New	EG	MM
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
TI	2.29*** (6.81)	1.57** (2.47)	1.32*** (5.16)	1.25*** (3.86)	2.16*** (4.26)
New		2.74*** (4.87)			
MM				1.49*** (3.69)	
_cons	1.391* (1.85)	2.31* (1.92)	3.54*** (2.87)	1.87 (1.12)	2.46* (1.67)
N	300	300	300	300	300
controlled variable	YES	YES	YES	YES	YES
The province and time are fixed	YES	YES	YES	YES	YES
Adj-R2	0.916	0.932	0.873	0.864	0.816

4.2 Moderator variable test

The regression results of the mediating effects between new-quality productivity and market mechanisms are presented in columns (2) and (3), and columns (4) and (5) of Table 1. In column (2), the coefficient of new-quality productivity on environmental governance in the logistics industry is significantly positive. In column (3), technological innovation shows a significant positive correlation with new-quality productivity. This indicates that new-quality productivity partially mediates the relationship between technological innovation and environmental governance in the logistics industry, further validating Hypothesis 2. Similarly, Hypothesis 3 has also been preliminarily tested.

To further confirm the mediating effects of new quality productivity and market mechanism, this study employed two testing methods: Bootstrap and Sobel. The results showed that both direct and indirect effect coefficients were significantly positive, indicating that the analysis of mediating effects between new quality productivity and market mechanism was robust.

4.3 Robustness tests

4.3.1 Replace the core explanatory variables

This study employs a method of replacing the core explanatory variable measurement approach to ensure the robustness of research findings. Following Ma Jinli's [19] methodology, technological innovation is measured by the logarithm of per capita patent grants per province (denoted as TII). As shown in Column (1) of Table 2, all regression coefficients remain significantly positive at the 1% level, indicating that Research Hypothesis 1 remains valid after adopting the revised core explanatory measurement approach.

4.3.2 Lagged two explanatory variables

This paper refers to the method of Ban Yunchao et al. [20] and adopts the method of replacing the explanatory variables with two periods of lag. The regression results are shown in column (2) of Table 2, and the regression coefficients are positive and significant at the level of 1%, so hypothesis 1 of this study is still valid.

Table 2 Regression results of robustness test

variable	**EG**	**EG**
	(1)	**(2)**
TII	2.85*** (5.68)	
L2.TI		3.54* (1.76)
_cons	3.25* (1.89)	4.43*** (4.19)
N	300	300
controlled variable	YES	YES
The province and time are fixed	YES	YES
Adj-R2	0.927	0.919

4.3.3 Endogeneity tests

This study employs the one-period lagged core explanatory variable as instrumental variables (IV), which satisfies both correlation and exogeneity assumptions. The over-identification test rejects the weak instrument hypothesis through the SW-F test, confirming valid instrument variables. As shown in Table 3, the Anderson LM statistic rejects the insufficient identification hypothesis at the 5% significance level. The F-test for first-stage regression yields a value significantly greater than 10, while the Sargan statistic reaches 8.546, failing to reject the null hypothesis, thereby confirming exogeneity. Second-stage regression results demonstrate that the coefficient of technological innovation is significantly positive, with its significance and sign consistent with the benchmark regression. This indicates that Hypothesis 1 remains supported after controlling for endogeneity.

Table 3 Endogeneity tests

variable	TI	EG
	First	Second
	(4)	(6)
LTI	0. 72*** (5.84)	
TI		1.59*** (3.96)
N	300	300
controlled variable	YES	YES
The province and time are fixed	YES	YES
Adj-R2		0.894

4.4 Heterogeneity tests

The impact of technological innovation on environmental governance in the logistics industry may vary across regions due to differences in their endowments. This study examines the relationship between technological innovation and environmental governance in logistics from a geographical perspective, categorizing China's regions into three zones: eastern, central, and western. As shown in columns (1), (2), and (3) of Table 4, technological innovation has a more significant impact on environmental governance in eastern China compared to central and western regions. This disparity may stem from the eastern region's advanced economic development and higher technological capabilities, which amplify the effect of technological innovation on environmental governance in logistics.

Table 4 Regression results of heterogeneity test

Variables	EG（east）	EG（central section）	EG（west）
	(1)	(2)	(3)
TI	0.28*** (5.59)	0.24** (2.49)	0.26* (1.94)
_cons	4.27* (1.89)	1.59 (0.57)	2.32* (1.63)
N	132	99	99
controlled variable	YES	YES	YES
The province and time are fixed	YES	YES	YES
Adj-R2	0.915	0.863	0.785

5 Conclusions and recommendations

5.1 Conclusions

This study employs panel data from 30 Chinese provinces, autonomous regions, and municipalities between 2014 and 2023 to investigate the impact of technological innovation on environmental governance in the logistics sector. The findings reveal three key conclusions: (1) Technological innovation significantly enhances environmental governance within the logistics industry; (2) New-quality productive forces and market mechanisms partially mediate the relationship between technological innovation and environmental governance in logistics; (3) Eastern China demonstrates more pronounced positive effects of technological innovation on environmental governance in its logistics sector compared to central and western regions.

5.2 Recommendations

First, based on empirical research revealing the key drivers and impact pathways of technological innovation in China's logistics industry environmental governance, future policy design should emphasize targeted measures and mechanism coordination to maximize innovation dividends. The primary strategy is to implement regional differentiated empowerment. Given that eastern regions demonstrate more significant catalytic effects in technological innovation, they should be encouraged to fully leverage their pioneering advantages in digitalization and intelligentization. Priority should be given to promoting deep integration of emerging technologies like artificial intelligence, big data, and IoT in green warehousing, smart scheduling, and multimodal transport, aiming to establish benchmark technology-intensive green logistics demonstration zones. Simultaneously, efforts should intensify to guide advanced technologies, management models, and spillover effects to orderly transfer and diffuse to central and western regions. The central government and developed areas can enhance the intelligence and informatization levels of logistics infrastructure in central and western regions, as well as professional talent reserves, through fiscal transfers, tax incentives, and establishing paired technical support platforms. This will help resolve bottlenecks constraining technological innovation efficiency, thereby driving coordinated regional development and overall enhancement of green governance capabilities.

Second, it is imperative to strengthen the synergistic efforts between two key intermediary pathways: new productive forces and market mechanisms. As new productive forces constitute an effective intermediary, policies should explicitly position the R&D, transformation, and application of green technologies in logistics as a strategic direction for developing new productive forces. Significantly increase fiscal support for research and development of low-energy-consuming equipment (such as electric trucks, hydrogen fuel cell vehicles), recyclable packaging materials, intelligent warehousing systems, and high-efficiency path optimization algorithms. Build an integrated ecosystem combining "industry, academia, research, application, and finance" to accelerate technological iteration and industrialization. Simultaneously, fully leverage the mediating efficacy of market mechanisms. It is urgent to expedite the establishment and deepening of a national carbon emission trading market, explore incorporating logistics transportation into mandatory emission control, significantly increase pollution emission costs, and establish a robust cost-driven mechanism. Deepen green finance practices by encouraging financial institutions to develop diversified financing tools such as green credit and green bonds tailored for the logistics industry, providing tangible cost advantages for enterprises adopting advanced clean technologies. Improve the green logistics standards system and certification framework to enhance the market recognition and premium pricing power of eco-labels, guiding consumers to choose environmentally friendly logistics services, thereby effectively bridging the supply side of technological innovation with the demand side of market needs.

Third, strengthening foundational support and environmental safeguards for technological application is indispensable. It is crucial to enhance comprehensive support throughout the entire process of new technology adoption in logistics enterprises, particularly SMEs. This requires integrated measures including fiscal incentives, financial support, and information services to reduce initial investments and risks during digital transformation and green upgrades. Continuous efforts should focus on improving nationwide logistics infrastructure through digitalization, standardization, and green connectivity. Key priorities include unifying interface standards for information platforms and establishing robust data-sharing mechanisms, thereby providing stable physical and digital foundations for large-scale implementation of advanced technologies. The legal framework must be updated promptly to reflect evolving technological demands, with enhanced legal protections for data security, platform economy regulation, and innovation outcomes. Clear demarcation of environmental protection responsibilities will create a stable and predictable institutional environment that maximizes the potential of technological innovation within green governance frameworks.

Funding

no

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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