

Article

The Impact of Enterprise Technological Innovation on Environmental Performance—An Industry Perspective

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Abstract: With the ongoing advancements in the modern industrial economy, the global ecological environment is encountering a multitude of challenges, prompting the increasing dissemination and global acknowledgment of the concept of sustainable development. Governments have formulated green development strategies aimed at incentivizing enterprises to enhance their environmental performance and mitigate environmental risks. This study utilizes a research sample comprising 3313 firm-level environmental performance scores and primary business data for 276 Chinese enterprises from 2007 to 2017. Based on the empirical evidence from the fixed-effects model, it is evident that technological innovation overall enhances the environmental performance and reduces the environmental risks of Chinese enterprises. Heterogeneity analysis reveals that internal innovation within Chinese enterprises exhibits heterogeneous impacts on environmental performance. The study shows that, compared to enterprises in the primary and tertiary industries, technological innovation in the enterprises of China's secondary industry has a greater impact on enhancing environmental performance. Furthermore, within the secondary industry, the positive impact of technological innovation on environmental performance is more pronounced for the traditional sectors. Based on these findings, government authorities should actively encourage technological innovation among enterprises and formulate differentiated environmental policies tailored to different enterprises and industries. This research holds significant implications for the implementation of green strategies, enhancement of enterprise competitiveness, achievement of long-term sustainability, and improvement of global ecological environmental quality.



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1. Introduction

The advancement of modern industrial society has brought about a series of issues to the global ecological environment, such as increased carbon emissions, excessive consumption of energy resources, destruction of green vegetation, and climate change. Ecological and environmental risks are closely interconnected with every aspect of enterprises' production and operation. Pearce et al. (1989) [1] first introduced the concept of a "green economy", emphasizing the comprehensive assessment of products and services by enterprises in production and operation to promote the harmonious coexistence of economy and environment. Subsequently, the concept of green development has gradually been promoted and widely recognized globally.

Over the years, countries worldwide have continuously focused on environmental issues, with a series of agreements such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol being successively signed. Simultaneously, the governments of various countries are increasingly emphasizing the coordinated development of the industrial economy and ecological environment, and have formulated green development strategies, as emphasized by Chang and Hu (2019) [2]. For example,

the European Union officially launched its green economy development strategy in March 2009; Japan issued a draft policy titled “Green Economy and Social Transformation” in April 2009; and China actively advocated the “dual-carbon” strategy of “carbon peak” and “carbon neutrality” in September 2020. The current international consensus is to implement the ESG (Environmental, Social, and Governance) corporate social responsibility system, encouraging enterprises to enhance environmental performance and commit to promoting the long-term sustainable development of the economy and society.

As countries increasingly emphasize the coordinated development of industries and ecological environments, more and more entrepreneurs are realizing that the traditional extensive economic growth model, which focuses solely on economic profit growth, high energy consumption, and high pollution, is insufficient for meeting the long-term needs of sustainable development. Enterprises should pay more attention to improving the environment while pursuing economic growth (Lv et al., 2021 [3]) and consider green development as one of the key strategies for their businesses, gradually transitioning towards long-term sustainable and high-quality growth. Integrating environmental strategies into the overarching enterprise development strategy and engaging in green technological innovation activities, while entailing substantial initial investments and yielding relatively subdued short-term economic benefits, ultimately proves advantageous in the long term by reducing energy consumption, regulating pollutant emissions, and mitigating environmental losses throughout production and operational processes (Luo et al., 2019 [4]), thus enhancing environmental performance, boosting economic benefits, and promoting the long-term sustainable development of enterprises (Albort-Morant et al., 2018 [5]; Liang et al., 2022 [6]; Tung and Baird, 2023 [7]).

The research on factors influencing enterprise environmental performance is currently a focal point of academic discussion. Research on the relationship between the environmental performance and innovation of enterprises is gradually gaining prominence. Previous studies have indicated that environmental innovation exhibits characteristics of longtermism and high uncertainty (la Hiz et al., 2019 [8]). However, although scholars generally hold a positive view of the impact of green technological innovation on environmental performance (Wang et al., 2021 [9]; Liang et al., 2022 [6]; Tung and Baird, 2023 [7]), there are still divergences in opinions and a lack of consensus. Here, “green technological innovation” refers to the development of healthy, green products with low energy consumption through resource recycling and utilization based on the foundation of the harmonious and stable development of society, economy, and ecology, also known as “green innovation” or “technological innovation” in the following text.

This study focuses on the relationship between enterprise green technological innovation and environmental performance. Utilizing the environmental performance scores and primary business data of 276 Chinese enterprises from 2007 to 2017, the study systematically demonstrates the significant role of green technological innovation in enhancing enterprise environmental performance and reducing environmental risks from an industry perspective. The study first explores whether green technological innovation can overall enhance enterprise environmental performance. The results indicate that the impact of enterprise green technological innovation on environmental performance is significantly positive on an overall level, with a coefficient of 0.161, and the impact of innovation intensity on environmental risk management efficiency is also robustly and significantly positive, with a coefficient of 0.111.

Due to significant differences in production modes among enterprises in different industries, this study, from an industry perspective, further elucidates the heterogeneity of the impact of innovation on environmental performance across various industries and sectors. Based on the classification of the 3 industries by the National Bureau of Statistics of China, we categorize all 276 enterprises into the primary industry represented by agriculture, the secondary industry symbolized by manufacturing, and the tertiary industry represented by services. It is found that in the primary industry, the role of enterprise green technological innovation in enhancing its environmental performance is not significant,

whereas in the secondary industry, green technological innovation has the most positive effect on reducing environmental risks and improving environmental performance. Empirical results further reveal that the impact of green technological innovation intensity on enterprise environmental risk management efficiency is most significant in the secondary industry, with a coefficient of 0.119, and the impact of green technological innovation on enterprise environmental performance is weakly positively correlated, as well.

To further explore the mechanisms of its effects, we divide the enterprises in the secondary industry into two categories based on traditional and non-traditional sectors. It is found that in the traditional sectors of the secondary industry (primarily encompassing traditional manufacturing sectors), increasing technological investments is advantageous for enhancing enterprise environmental performance, reducing environmental risks, and strengthening competitiveness, with coefficients reaching 0.252 and 0.172 at the levels of innovation and innovation intensity, respectively, higher than the average coefficients of the secondary industry, tertiary industry, and all-enterprise sample. However, in the non-traditional sectors of the secondary industry (primarily encompassing emerging sectors), the effect of green innovation on environmental performance is not significant enough. This further indicates that the positive impact of technological innovation on environmental performance is primarily driven by innovations in the traditional sectors of the secondary industry, and technological advancements in manufacturing have the most significant impact on environmental protection.

The marginal contributions of this study can be summarized as follows:

Firstly, there is a limited amount of empirical research in the current academic literature concerning the relationship between green technological innovation and environmental performance. This study investigates the impact of green technological innovation on environmental performance from the perspective of firm-level, providing evidence supporting the relationship between enterprise innovation and environmental performance. Previous studies have largely examined the relationship between technological innovation and environmental performance and energy utilization from a macro perspective (e.g., Guo and You, 2024 [10]; Zhang et al., 2024 [11]; Yin and Zeng, 2024 [12]; Lasisi et al., 2022 [13], etc.). This study complements and enhances the existing literature by focusing on Chinese firm-level samples.

Secondly, current research on environmental risks largely focuses on the environmental performance of specific industries (e.g., Liang, Zhang, and Qiang, 2022 [6], etc.). By adopting an industry-based approach, this study reveals the heterogeneity of the impact of innovation on environmental performance across various industries and sectors, which is relevant to the conclusion drawn by Padgett and Galan (2010) [14] that research and development (R&D) intensity positively affects corporate social responsibility, and this relationship is significant in the manufacturing industry. This analysis aids in exploring and evaluating the environmental characteristics of enterprises within various industries.

Thirdly, this study offers insights for enterprises in selecting green strategies and assists governments in formulating policies related to green economies. By contributing to the sustainable development of the national economy and offering pathways for global ecological optimization, this research is of significant importance for advancing green development within enterprises and enhancing the global ecological environment.

2. Literature Review

As environmental awareness among individuals continues to rise, enterprises are striving to achieve a balance between performance and environmental responsibility. Empirical studies on the relationship between green technological innovation and environmental risks are scarce in the existing literature. Palmer et al. (1995) [15] suggest that different enterprises possess varying levels of research and development (R&D) capabilities. When the environmental innovation capability of a business is insufficient and the cost of enhancing technologies related to environmental performance is high, a proper balance needs to be struck between operational costs and financial returns. Scholars like Bhattacharya

(2017) [16] have observed that environmental technological innovation constitutes a long-term unique investment, distinct from traditional tangible asset investments. Due to the long timespan required for technological innovation investments, the effects may not be quickly visible in the short term. Cheng et al. (2019) [17] use panel quantile methods to analyze data from OECD countries, studying the impact of renewable energy and technological innovation on carbon emissions, and conclude that patent development has a minimally positive impact on reducing carbon emissions.

However, these viewpoints have been challenged by numerous scholars. Scholars have conducted relevant theoretical studies regarding the relationship between technological innovation, environmental performance, and business conditions, primarily building upon three theoretical aspects and assumptions, namely the Porter hypothesis, the Resource-Based View (RBV), and the Natural Resource-Based View derived from the Endogenous Growth Theory (EGT).

The Porter hypothesis (Porter et al., 1995 [18]) emphasizes that effective environmental management can drive technological innovation, counterbalance the production costs associated with environmental investments, strengthen the market profit-making capacity of companies, and gain competitive advantages in the market. This theory suggests that a company's overall strength and innovation capability are closely related and depend on the performance of innovation activities in terms of cost savings (Porter, 1991 [19]; Porter et al., 1995 [18]; Banerjee and Gupta, 2018 [20]). The Resource-Based Theory (Wernerfelt, 1984 [21]) suggests that an enterprise's development and success depend not only on external factors, but also on internal characteristics. The theory proposes that the heterogeneity of an enterprise's resources determines differences in competitiveness and advocates for enterprises to transform their characteristic tangible and intangible resources into unique capabilities that are difficult for other enterprises to imitate, enabling them to sustain a competitive advantage in the long term. Given the theory's clear recognition of the importance of intangible resources such as technology and reputation, it helps in analyzing green technological innovation and environmental performance. The Classic Endogenous Growth Theory points out that economic growth is influenced by internal factors such as technological progress, capital accumulation, and improvement in labor quality. Accordingly, enterprises investing in research and development (R&D) can promote technological progress, thereby enhancing their effective utilization of natural resources (Romer, 1990 [22]; Helpman, 1992 [23]). Combining the Resource-Based View (RBV), Hart (1995) [24] introduces the Natural Resource-Based View (NRBV), which explores the relationship between resource utilization and long-term sustainable performance, emphasizing that the ecological environment is a constraining factor that enterprises must consider in their competitiveness and advocating for them to focus on long-term sustainable development rather than short-term profits.

Building upon the theoretical foundation above, a wave of empirical literature has emerged in academia focused on studying the relationships between technological innovation and environmental risks, environmental performance, and sustainable development. Some studies have discussed the impact of environmental risks on the technological innovation of enterprises (e.g., Li and Li, 2022 [25]), while our study focuses on the relevant literature regarding the influence of technological innovation on environmental performance and sustainable development (e.g., Wu, Zhang, and Wang, 2024 [26]). Most research findings in recent years suggest that the technological innovation of enterprises has positive externalities, benefiting firm environmental performance and long-term competitiveness (Wang et al., 2021 [9]; Liang et al., 2022 [6]; Tung and Baird, 2023 [7]); however, some studies have identified a U-shaped relationship between them.

Academics extensively discuss the relationship between environmental risks and the technological innovation of enterprises. For instance, Barney (1991) [27] delves into the interconnection between the sustainable competitive advantage and resources of enterprises earlier. Drawing upon the Resource-Based View (RBV) theory and the Porter hypothesis, the study analyzes the potential of enterprises' resources to generate sustain-

able competitive advantages and discusses the potential impacts across different business domains. Furthermore, the study outlines four key metrics for evaluating the resources of an enterprise for sustainable competitive advantages, including rarity, value, imitability, and substitutability. Ghisetti and Quatraro (2017) [28], using environmental productivity as an assessment indicator for enterprise environmental performance, find that sectors with higher levels of green technology exhibit superior environmental performance. They highlight that research and development (R&D) investments related to environmental protection serve as the primary driver for enhancing environmental performance of an enterprise. Tung and Baird (2023) [7] propose that technological innovation can broaden the strategic development pathways of businesses, enabling them to explore innovative products and processes that meet environmental regulatory requirements while increasing profits. Opazo-Basáez, Monroy-Osorio, and Marić (2024) [29] empirically find that the individual and simultaneous deployment of green technological innovation positively impact both organizational and environmental performance using a sample of 354 medium-sized manufacturing firms in Spain. Sahoo, Kumar, and Upadhyay (2023) [30], based on survey data from 283 Indian manufacturers and using structural equation modeling, demonstrate that green technological innovation facilitates the transformation of green knowledge management towards improving firm environmental performance.

In recent years, China has adopted “dual carbon” as a national strategy, leading to the emergence of a significant body of literature in the Chinese market focusing on the relationship between technological innovation and environmental performance. Wu et al. (2024) [26] empirically examine the concept of technological innovation based on the Porter Hypothesis framework using a sample of 850 listed companies in China from 2010 to 2019. They find that technological innovation can simultaneously enhance both firm and environmental performance and extend the Porter Hypothesis by revealing the forms through which technological innovation influences environmental performance, as well as the conditions that maximize the impact of technological innovation on environmental performance. Zhao and Cheng (2019) [31] posit that technological innovation is a crucial means for improving enterprise environmental performance and achieving green development. This study suggests that proactively introducing green technologies and leveraging them to enhance environmental governance post facto are two key pathways for a business to improve environmental performance through technological innovation. Moreover, recent literature has viewed technological innovation as a mechanism for enhancing firm environmental performance through digital transformation. For instance, Jin, Lei and Wu (2023) [32] suggest that technological innovation serves as a crucial intermediary channel for digital investments to promote firm environmental performance, highlighting a significant U-shaped relationship between technological innovation and environmental performance. Song et al. (2024) [33] substantiate through theoretical and empirical analysis that the upgrading of technology drives resource reallocation, thus enhancing the environmental performance of the industry. Therefore, the upgrading of green technologies is considered one of the significant pathways for enterprises to enhance environmental performance through digital transformation.

Based on the Natural Resource-Based View (NRBV), a large amount of literature suggests that enterprise technological innovation enhances resource utilization efficiency and resilience, reduces carbon emissions, and plays a positive role in improving enterprise environmental performance. Liang, Zhang, and Qiang (2022) [6] empirically investigate the impact of technological innovation on the environmental performance of 136 energy companies in China using panel data from 2009 to 2019, indicating that technological innovation significantly enhances the environmental performance of energy companies, leading to a 0.056% improvement in environmental performance and a 0.015% reduction in carbon emission intensity. Zhang and Fu (2022) [34] conduct a two-stage analysis of industrial data in Guangdong, China, from 2000 to 2018, showing that the transfer technology strategy of foreign-funded enterprises elevates their imitative innovation levels, leading to improved energy efficiency. Cagno et al. (2015) [35] conduct an empirical study

on 71 small and medium-sized manufacturing enterprises in Italy, revealing that internal research and innovation practices in manufacturing enterprises have a positive impact on enhancing energy efficiency. At the national and macro levels, Zhang et al. (2024) [11] reveal that technological progress can actively drive the simplification of energy consumption structures, serving as a key factor in mitigating emerging global climate risks. Mensah et al. (2018) [36] examine the impact of innovation on carbon emissions in 28 OECD (Organisation for Economic Co-operation and Development) countries from 1990 to 2014, indicating that innovation plays a critical role in mitigating carbon emissions in most OECD countries. Dong et al. (2020) [37] find that the main reasons for the growth in carbon emissions over the past 20 years are the decrease in energy intensity and the increase in income. Li et al. (2021) [38] utilize panel data from 69 countries spanning from 1996 to 2011 to investigate the significant inverted U-shaped relationship between innovation and carbon emissions in China. Furthermore, other studies, such as Melnyk et al. (2003) [39], Sagar and Holdren (2002) [40], Fei et al. (2014) [41], and Sohag et al. (2015) [42], also have consistently provided evidence for the significant role of technological progress in enhancing energy efficiency.

Past literature has also examined the mutual relationship between technological innovation and long-term sustainable development, suggesting that innovation enhances an enterprise's long-term competitiveness. Utilizing longitudinal panel data from 1989 to 2009, Chakrabarty and Wang (2012) [43] find that multinational corporations with higher levels of R&D intensity and internationalization demonstrate stronger competitiveness in terms of sustainable development. Banerjee and Gupta (2018) [20] empirically study the impact of Environmental Sustainable Practices (ESP) on R&D intensity among 42 countries from 2002 to 2013 based on an integrated dataset. The findings suggest that environmental sustainable practices can enhance an enterprise's R&D intensity, encourage more innovation, and facilitate improvements in environmental performance. Le (2022) [44] conducts a survey among 469 senior managers in enterprises, utilizing structural equation modeling to demonstrate the mediating role of enterprise social responsibility and green innovation in enhancing the sustainable performance of small and medium-sized enterprises.

3. Methodology and Data

3.1. Sample Overview

According to the ISO 14001 [45] environmental management system, enterprise environmental performance can be defined as the measurable ecological environment management effect achieved by an enterprise by controlling the environmental factors in its production and operation process based on environmental objectives, policies, and indicators. Environmental factors refer to the activities, products, or services produced during the production and operation processes that can interact with the ecological environment. The effectiveness of the ecological environment management system refers to the comprehensive performance of enterprises by strengthening environmental management behaviors. External environmental pressure factors include environmental regulations, tax policies, market pressures, corporate social responsibility, and internal environmental pressures such as business scale, internal governance structure, technological level, and financial status, collectively influencing the environmental management behaviors and environmental performance of enterprises. Green technological innovation and R&D investments play crucial roles in promoting the environmental performance of enterprises.

In this study, we utilize the Refinitiv Thomson Reuters ASSET4 ESG (Environmental, Social Responsibility, Corporate Governance) database to obtain variables and data pertaining to enterprise characteristics and environmental performance. Firstly, this database provides robust data support for numerous research papers (Aouadi and Marsat, 2018 [46]; Gonenc and Scholtens, 2017 [47]; Graafland, 2019 [48]). Secondly, the Refinitiv database offers ESG (i.e., environmental, social responsibility, and corporate governance) scores for enterprises, which are based on publicly available, verifiable reporting data reflecting the ESG performance of enterprises. Refinitiv ASSET4 holds an advantage over other ESG databases, as all of its data is publicly available and transparent, allowing scholars to gain

deeper insights through the study of this database. Lastly, Refinitiv collects and computes over 450 company-level indicators, including 186 highly comparable indicators, to assist in the scientific assessment and evaluation of environmental performance for enterprises. Thomson Reuters compiles environmental performance and fundamental operating data from the annual reports and sustainability reports of enterprises, and the Refinitiv ASSET4 database uses a multi-step process to create scoring metrics and convert the numerical values of key indicators into scores ranging from 0 to 100 (Liu, 2020 [49]). These scores indicate an enterprise's position and performance compared to all other enterprises in the Refinitiv ASSET4 database.

More precisely, we utilize a sample encompassing 3313 observations from 276 firms across 33 industries in China spanning from 2007 to 2017 to investigate the influence of enterprise technological innovation on environmental performance. We obtain environmental performance scores and key business data from the Refinitiv Thomson Reuters ASSET4 ESG database. In our regression analysis, we define the enterprise environmental performance score (E) and its proportion in the overall ESG score as proxy variables for environmental performance and environmental risk management efficiency, respectively, serving as the primary dependent variables in the models. Additionally, we designate the enterprise green technological innovation score (PI) and its proportion in the overall ESG score as proxy variables for technological innovation and technological innovation intensity, respectively, serving as the primary independent variables in the models.

3.2. Model and Method

Using panel multiple regression analysis, this paper makes a comparative study on the innovation effect of enterprise environmental risk and tests the impact of enterprise technological innovation on enterprise environmental performance and enterprise environmental risks separately. According to the model selection, we first compare the mixed-effect model with the fixed-effect model through F-tests, suggesting the existence of individual effects, favoring the fixed-effects model over the mixed-effects model. Then, we compare the fixed effect and random effect through the Hausman test. Finally, we choose the fixed-effect model as the main empirical model for this study.

(i) Basic model

We construct the following equation:

$$\log(E)_{i,t} = \alpha + \beta_1 \log(PI)_{i,t-1} + \beta_k (\text{firm}_{\text{controls}})_{i,t-1} + \delta + \varepsilon_{i,t} \quad (1)$$

where E is a dependent variable, which is the environmental performance score of the enterprise i in year t. PI is a subjective score to measure the enterprise's management commitment and its effectiveness in supporting the R&D of products or services in year $t - 1$. PI reflects an enterprise's capacity to reduce the environmental costs and burdens of its customers, thereby creating new market opportunities through innovation in green technologies. The regression coefficient β_1 serves to reflect the impact of enterprise innovation on environmental performance. According to the practice in Dyck (2018) [50], we should control the variable, including the emission reduction score, energy saving score, leverage ratio, return on assets, price to book ratio, etc. δ is introduced as a fixed effect of year, industry, and sector. The annual output change at the sector level can affect the environmental performance of enterprises. It is expected that the sector effect can capture the time-varying effect of environmental risk and ESG at the sector level. Similarly, changes in the level of industrial policy can affect the technological innovation and its intensity of enterprises. We also control the fixed effect of the industrial level in the regression. Therefore, the environmental performance impact of enterprise technological innovation is controlled in specific sectors of specific industries every year. According to the results of Alam et al. (2019) [51], it takes a period of time for technological innovation to realize achievement transformation. Considering that the impact of enterprise technological innovation on environmental performance cannot take effect immediately and that the

industrial transformation of technological innovation requires a certain amount of time, we therefore treat both the independent and control variables as lagged by one year.

(ii) Robustness testing model (Ratio model)

In the robustness test, the concept of enterprise technological innovation intensity is introduced. We define the ratio of enterprise technological innovation score to ESG as innovation intensity, designated as PI/ESG. We assess risk management capability by utilizing the enterprise environmental performance score (E) and define the environmental risk management efficiency as the ratio of environmental performance to ESG score, designated as E/ESG.

$$(E/ESG)_{i,t} = \alpha + \beta_1(PI/ESG)_{i,t-1} + \beta_k(\text{firm}_{\text{controls}})_{i,t-1} + \delta + \varepsilon_{i,t} \quad (2)$$

We validate the impact of enterprise technological innovation intensity on the effectiveness of environmental risk management using Equation (2), employing the same estimation method as outlined in Equation (1).

For convenience, we designate Equation (1) as the basic model and Equation (2) as the ratio model. We regard the ratio model described in Equation (2) with relative variables as a robustness assessment of the basic model articulated in Equation (1) with absolute variables, suggesting that the ratio model may more accurately depict the influence of enterprise innovation on environmental conservation compared to the basic model.

In addition to statistical significance, economic significance should also be discussed in the empirical report. Economic meaning has different expressions. We employ a method that links the mean and standard deviation of the independent variable. Consequently, economic significance is defined as the estimated coefficient multiplied by the ratio of the sample standard deviation of the independent variable to its mean, which represents the response of the dependent variable to the change of the standard deviation of the independent variable (Alam et al., 2019 [51]).

3.3. Variable Definition

The meanings of the main variables used in this study are summarized as follows:

ESG: environmental, social responsibility, and corporate governance performance

E: environmental performance

E/ESG: environmental performance ratio

PI: enterprise technological innovation score

PI/ESG: enterprise technological innovation intensity

RR: resource reduction score

ER: environmental reduction score

ROA: return on asset

Leverage: leverage

MTBV: market to book value

Table 1 presents the results of the descriptive statistical analysis for the variables.

Table 1. Descriptive statistical analysis.

VARIABLES	Mean	sd	min	P50	max
Ln (E)	3.4024	0.7010	2.1412	3.4087	4.5473
Ln (ESG)	3.6149	0.4088	2.0631	3.6462	4.3832
E/ESG	0.9202	0.4555	0.2380	0.8548	2.7245
Lag (lnPI)	3.5450	0.6449	2.6174	3.3193	4.5811
Lag (PI/ESG)	3.5501	0.5072	3.2375	3.2865	4.5833
Lag (RR)	36.2870	27.1940	7.1700	28.1450	93.2800
Lag (ER)	35.2374	25.8050	7.4000	23.5150	94.6800
Lag (ROA)	4.8426	5.0336	−37.1900	3.9400	49.5000
Lag (Leverage)	62.0559	205.0203	0.0000	30.5950	5.1e+03
Lag (MTBV)	0.5655	0.6794	−0.8440	0.5128	7.2477

4. Empirical Results

This study firstly examines the impact of enterprise technological innovation on environmental performance and risk management; secondly investigates the heterogeneity of the influence of enterprise technological innovation on environmental performance across different industries; and further discusses the heterogeneous effects of technological innovation on environmental performance among various sub-sectors within the same industry.

4.1. The Impact of Technological Innovation on Environmental Performance

Table 2 presents the regression results onfor the impact of enterprise green technological innovation on enterprise environmental performance. The empirical findings demonstrate a significant positive effect of innovation on environmental performance. Column (1) of Table 2 reports the coefficient estimate of the baseline model. It indicates that after adding the fixed effect of year, industry, and sector, the impact coefficient of enterprise technological innovation on environmental performance is 0.221. After controlling additional key variables related to firm characteristics, the coefficient for innovation on environmental performance is 0.161 (as shown in column [6] of Table 2). Further interpretation of the economic significance is 3.05% (calculated as $100 \times 0.6449 / 3.4024 \times 0.161$), suggesting that a one-standard-deviation increase in enterprise technological innovation leads to a 3.05% growth in enterprise environmental performance. The higher the degree of innovation, the better the environmental performance and risk control capability of enterprises. From column (2) to column (6), we progressively introduce RR, ER, ROA, Leverage, and MTBV as control variables in the regression analysis, and the facilitating effect of technological innovation on environmental performance remains statistically significant. Additionally, we also find that RR and Leverage have significant positive implications for enhancing the environmental performance of enterprises.

Table 2. The impact of technological innovation on enterprise environmental performance.

	(1)	(2)	(3)	(4)	(5)	(6)
	y1	y2	y3	y4	y5	y6
VARIABLES	lne	lne	lne	lne	lne	lne
Lag.lnpi	0.221 *** (0.0577)	0.160 ** (0.0618)	0.156 ** (0.0615)	0.161 ** (0.0626)	0.162 ** (0.0623)	0.161 ** (0.0622)
Lagrr		0.00780 *** (0.00114)	0.00708 *** (0.00131)	0.00707 *** (0.00131)	0.00708 *** (0.00130)	0.00722 *** (0.00131)
lager			0.00188 (0.00139)	0.00189 (0.00139)	0.00181 (0.00140)	0.00161 (0.00140)
lagroa				−0.00401 (0.00481)	0.000916 (0.00482)	0.000587 (0.00466)
lagleverage					0.000202 *** (3.80e−05)	0.000174 *** (3.81e−05)
lagmtbv						0.0455 (0.0292)
Year F.E.	YES	YES	YES	YES	YES	YES
Industry F.E.	YES	YES	YES	YES	YES	YES
Constant	2.526 *** (0.224)	2.553 *** (0.240)	2.536 *** (0.235)	2.551 *** (0.236)	2.504 *** (0.236)	2.493 *** (0.236)
Observations	686	686	686	686	686	686
R-squared	0.550	0.593	0.594	0.595	0.600	0.602

The standard deviation is reported in parentheses, *** $p < 0.01$, ** $p < 0.05$.

To validate the robustness of the aforementioned conclusions, we introduce the concepts of enterprise technological innovation intensity and environmental risk management efficiency. We define innovation intensity as the ratio of the technological innovation score to the ESG score, and environmental risk management efficiency as the ratio of the environmental performance score to the ESG score. Subsequently, we construct a ratio model and

employ the same panel data regression analysis method. The results are shown in Table 3. It is evident that technological innovation intensity also has a significant positive impact on enterprise environmental risk management efficiency. Column (1) of Table 3 presents the estimated coefficients of the baseline model. The results indicate that when adding fixed effect of year, industry, and sector, the coefficient of technological innovation intensity on environmental risk management efficiency is 0.0945. By gradually introducing RR, ER, ROA, Leverage, and MTBV as control variables, the promoting effect of technological innovation intensity on environmental risk management efficiency remains statistically significant. Furthermore, we observe that RR and Leverage also hold significant positive implications for enhancing the environmental performance of enterprises. When all control variables are included, the coefficient of technological innovation intensity on environmental risk management efficiency is 0.111 (as shown in column [6] of Table 3), with an economic significance of 11.31% (calculated as $100 \times 0.9372 / 0.9202 \times 0.111$). This implies that each increase of one standard deviation in enterprise technological innovation intensity leads to an 11.31% growth in enterprise environmental risk management efficiency.

Table 3. The impact of technological innovation intensity on enterprise environmental risk management efficiency.

	(1)	(2)	(3)	(4)	(5)	(6)
	y1	y2	y3	y4	y5	y6
VARIABLES	Enviratio	Enviratio	Enviratio	Enviratio	Enviratio	Enviratio
laginnintensity	0.0945 *** (0.0348)	0.108 *** (0.0360)	0.112 *** (0.0349)	0.113 *** (0.0352)	0.113 *** (0.0352)	0.111 *** (0.0348)
lagrr		0.00475 *** (0.000696)	0.00398 *** (0.000765)	0.00398 *** (0.000766)	0.00399 *** (0.000764)	0.00416 *** (0.000777)
lager			0.00200 ** (0.000922)	0.00201 ** (0.000919)	0.00198 ** (0.000922)	0.00173 * (0.000920)
lagroa				−0.00148 (0.00257)	0.000161 (0.00288)	−0.000236 (0.00279)
lagleverage					6.71e−05 *** (2.33e−05)	3.18e−05 (2.33e−05)
lagmtbv						0.0567 *** (0.0180)
Year F.E.	YES	YES	YES	YES	YES	YES
Industry F.E.	YES	YES	YES	YES	YES	YES
Constant	0.839 *** (0.104)	0.711 *** (0.107)	0.674 *** (0.106)	0.685 *** (0.107)	0.670 *** (0.107)	0.657 *** (0.105)
Observations	686	686	686	686	686	686
R-squared	0.439	0.484	0.489	0.489	0.491	0.497

The standard deviation is reported in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2. Industry Perspective Analysis of Technological Innovation and Environmental Performance

Considering the differences in production modes among enterprises in different industries, this study investigates the industrial heterogeneity of the impact of technological innovation on environmental performance. The industry classification in this study is based on the three industry classification methods of the National Bureau of Statistics of China. The primary industry refers to agriculture, forestry, animal husbandry, and fishery (excluding agricultural, forestry, animal husbandry, and fishery services). The secondary industry refers to mining (excluding mining support activities), manufacturing (excluding the metal product, machinery, and equipment repair industries), electricity, heat, gas, the water production and supply industry, and the construction industry. The tertiary industry is the service industry, referring to industries other than the primary industry and the secondary industry. Based on the classification of the three industries by the National Bureau of Statistics of China, we categorize all 33 industries into three groups based on their industrial characteristics.

According to the three industries, the panel regression analysis is carried out by using the basic model. Table 4 reports the results. Column (1) shows the results of 276 enterprises in 33 industries including all three industries, and columns (2)–(4) present the results of the primary industry, secondary industry, and tertiary industry. The technological innovation by enterprises in the primary industry has a negative impact on the improvement of environmental performance, while technological innovation by enterprises in the tertiary industry has a significantly positive effect on enhancing environmental performance. In the secondary industry, technological innovation does not have a significant impact on environmental performance, generating only a weak positive effect. Therefore, in the primary industry, encouraging technological innovation to enhance enterprise environmental performance, reduce enterprise environmental risks, and promote the sustainable development of both enterprises and the ecosystem may not be the most optimal choice.

Table 4. Industry perspective analysis of technological innovation and environmental performance.

	(1)	(2)	(3)	(4)
	y1	Primary	Secondary	Tertiary
VARIABLES	lne	lne	lne	lne
lagpi	0.161 ** (0.0622)	−0.826 *** (2.38e−06)	0.114 (0.0819)	0.251 *** (0.0825)
lagrr	0.00722 *** (0.00131)	0.0136 *** (1.00e−08)	0.00819 *** (0.00146)	0.00498 (0.00294)
lager	0.00161 (0.00140)	0.0267 *** (4.65e−08)	0.00132 (0.00174)	0.00212 (0.00295)
lagroa	0.000587 (0.00466)	−0.0546 *** (4.17e−08)	−0.00140 (0.00474)	0.0284 (0.0200)
lagleverage	0.000174 *** (3.81e−05)	0.0142 *** (2.49e−08)	0.000149 *** (3.62e−05)	−0.000477 (0.000638)
lagmtbv	0.0455 (0.0292)	1.219 *** (8.37e−07)	0.0521 * (0.0292)	0.0447 (0.102)
Year F.E.	YES	YES	YES	YES
Industry F.E.	YES	YES	YES	YES
Constant	2.493 *** (0.236)	3.554 *** (6.24e−06)	2.887 *** (0.270)	1.936 *** (0.295)
Observations	686	14	472	200
R-squared	0.602	1.000	0.613	0.608

The standard deviation is reported in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

We utilized the ratio model in Equation (2) to investigate the impact of technological innovation intensity on environmental risk management efficiency, and the results are displayed in columns (2)–(4) of Table 5. Empirical evidence indicates that in the primary industry, the technological innovation intensity of enterprises has a significant negative impact on the efficiency of environmental performance, with a coefficient of −0.793. For enterprises in the tertiary industry, the coefficient of technological innovation intensity on environmental performance efficiency is 0.0853, but it is not statistically significant. In the secondary industry, the impact of technological innovation intensity on environmental performance efficiency is significantly positive, with a coefficient of 0.119, higher than the corresponding coefficient of all Chinese enterprises at 0.111. This further confirms that the role of technological innovation in the primary industry in improving environmental performance is not prominent; hence, enhancing environmental performance by raising technological levels may not be effective. Instead, our focus should be on exploring the positive implications of technological innovation in the secondary and tertiary industries for enhancing environmental performance efficiency.

Table 5. Industry perspective analysis of technological innovation intensity and environmental risk management efficiency.

	(1)	(2)	(3)	(4)
	y1	Primary	Secondary	Tertiary
VARIABLES	Enviratio	Enviratio	Enviratio	Enviratio
laginnintensity	0.111 *** (0.0348)	−0.793 *** (1.14e−07)	0.119 *** (0.0405)	0.0853 (0.0685)
lagrr	0.00416 *** (0.000777)	0.00927 *** (1.47e−09)	0.00510 *** (0.00108)	0.00263 (0.00157)
lager	0.00173 * (0.000920)	0.0187 *** (8.78e−09)	0.000692 (0.00126)	0.00281 (0.00195)
lagroa	−0.000236 (0.00279)	−0.0403 *** (7.68e−11)	0.000275 (0.00313)	0.00843 (0.0111)
lagleverage	3.18e−05 (2.33e−05)	0.0205 *** (1.14e−08)	3.55e−05 (2.41e−05)	−0.000431 (0.000431)
lagmtbv	0.0567 *** (0.0180)	0.686 *** (8.04e−08)	0.0674 *** (0.0194)	−0.00254 (0.0572)
Year F.E.	YES	YES	YES	YES
Industry F.E.	YES	YES	YES	YES
Constant	0.657 *** (0.105)	−0.0697 *** (5.14e−07)	0.864 *** (0.100)	0.476 *** (0.142)
Observations	686	14	472	200
R-squared	0.497	1.000	0.521	0.496

The standard deviation is reported in parentheses, *** $p < 0.01$, * $p < 0.1$.

4.3. Second Industry Segmentation of Technological Innovation and Environmental Performance

The analysis above indicates that the impact of technological innovation on the environment is more significant in the secondary industry. To further explore the relevant sources, we divide the secondary industry into traditional and emerging sectors and investigate the environmental effects of technological innovation on different types of secondary industrial enterprises. Table 6 reports the results using the basic model of Equation (1). Column (1) represents the impact of technological innovation on environmental performance for all enterprises in the secondary industry. Column (2) displays the empirical results for the traditional sectors in the secondary industry, such as manufacturing, transportation, mining, oil, and energy. Column (3) shows the emerging sectors in the secondary industry, such as bio-pharmaceutical science, electronic information, and new materials. The empirical results demonstrate that for traditional sectors in the secondary industry, the enhancement effect of enterprise technological innovation on environmental performance is significantly strengthened, with a coefficient reaching 0.252, much higher than the average level of all Chinese enterprises and enterprises in the tertiary industry. Its significance changes from being insignificant at the overall level of the secondary industry to significant at the 1% level. Column (3) reveals that in the high-tech and emerging sectors of the secondary industry, there is no significant correlation between technological innovation and environmental performance.

To further examine the robustness of the above conclusions, we utilize the ratio model of Equation (2) to investigate the relationship between the technological innovation intensity of enterprises and environmental risk management efficiency within sub-sectors of the secondary industry. The results are presented in Table 7. Column (2) presents the results of the traditional sectors in the secondary industry, with a coefficient of 0.172, which remains significant at the 1% level and is higher than the corresponding coefficient of all enterprises in the secondary industry. Column (3) reports the results of the emerging sectors in the secondary industry, with a coefficient of 0.006, which is not statistically significant.

Table 6. Second industry segmentation of technological innovation and environmental performance.

	(1)	(2)	(3)
	Secondary	Traditional	Nontraditional
VARIABLES	lne	lne	lne
lagpi	0.114 (0.0819)	0.252 *** (0.0838)	−0.111 (0.131)
lagrr	0.00819 *** (0.00146)	0.00833 *** (0.00166)	0.00773 *** (0.00278)
lager	0.00132 (0.00174)	0.00143 (0.00172)	−0.000864 (0.00276)
lagroa	−0.00140 (0.00474)	−0.000893 (0.00690)	−0.000285 (0.00877)
lagleverage	0.000149 *** (3.62e−05)	0.000673 (0.000952)	8.69e−05 (8.84e−05)
lagmtbv	0.0521 * (0.0292)	0.0540 (0.0334)	0.111 (0.0716)
Year F.E.	YES	YES	YES
Industry F.E.	YES	YES	YES
Constant	2.887 *** (0.270)	2.372 *** (0.256)	2.782 *** (0.378)
Observations	472	281	191
R-squared	0.613	0.635	0.628

The standard deviation is reported in parentheses, *** $p < 0.01$, * $p < 0.1$.

Table 7. Secondary industry segmentation of technological innovation intensity and environmental risk management efficiency.

	(1)	(2)	(3)
	Secondary	Traditional	Nontraditional
VARIABLES	Enviratio	Enviratio	Enviratio
laginnintensity	0.119 *** (0.0405)	0.172 *** (0.0300)	0.00628 (0.0787)
lagrr	0.00510 *** (0.00108)	0.00455 *** (0.00123)	0.00507 ** (0.00187)
lager	0.000692 (0.00126)	0.00101 (0.00132)	−0.00173 (0.00200)
lagroa	0.000275 (0.00313)	−0.00225 (0.00433)	0.00368 (0.00625)
lagleverage	3.55e−05 (2.41e−05)	0.000732 (0.000620)	2.91e−05 (5.81e−05)
lagmtbv	0.0674 *** (0.0194)	0.0719 *** (0.0211)	0.109 ** (0.0492)
Year F.E.	YES	YES	YES
Industry F.E.	YES	YES	YES
Constant	0.864 *** (0.100)	0.777 *** (0.0947)	0.179 (0.138)
Observations	472	281	191
R-squared	0.521	0.533	0.574

The standard deviation is reported in parentheses, *** $p < 0.01$, ** $p < 0.05$.

The empirical results indicate that in using the basic model represented by Formula (1) or the ratio model represented by Formula (2), the technological innovation of enterprises in China's secondary industry belonging to the emerging industries with high technology does not have a significant impact on environmental performance. If the emerging high-tech industries are separated from the secondary industry, the role of technological innovation by enterprises in environmental performance would be significantly enhanced. This may be attributed to the high technological level of the high-tech industries in China's

secondary industry, which exhibit low dependence on the environment. Therefore, further enhancement of enterprise technological innovation may not lead to a substantial improvement in environmental performance. Traditional industries in China's secondary industry present greater room for improvement in their technological innovation capabilities. Simultaneously, traditional sectors exhibit strong environmental dependence. Green technological innovation aids in reducing pollutant emissions and lowering environmental risks, thereby improving environmental performance. Hence, it is recommended that regulatory authorities focus more on the traditional sectors and implement differentiated measures when formulating policies related to the green economy.

4.4. Further Explanation of Industry and Sector Heterogeneity

The heterogeneity of technological innovation across different industries is determined by the distinctive characteristics of these industries. The effects of technological innovation behaviors in different industries on environmental performance such as carbon emissions and energy efficiency vary, being related to both the stage characteristics of industrial economic development and ecological footprint disparities. Fundamentally, this stems from the distinctive production methods of these three major industries. The differences in the impact of enterprise innovation on environmental performance across different industries can be explained through three dimensions.

Firstly, the three major industries are at different stages of development. The global industries are in a dynamic state of continual upgrading and transformation. Kuznets (1985) [52] summarizes the basic pattern of industrial upgrading as follows: The proportion of the primary industry gradually decreases, the proportion of industrial output in the secondary industry first rises and then falls again, and the growth rate of the proportion of output in the service industry in the tertiary industry gradually accelerates. Agriculture, as an early-stage industry, has a relatively mature development pattern. Developing countries, represented by China, have also completed industrial transformation in modern times. Meanwhile, countries worldwide are starting to reflect on the environmental costs brought about by the rapid development of the secondary industry and are pushing for a new round of industrial transformation and upgrading, seeking technological innovation in the secondary industry, while the proportion of the service industry is showing an increasing trend. The mature development of the secondary industry and new technological innovations strengthens the effectiveness of green technological innovation. However, the relatively slow pace of green technological innovation in the mature primary industry and the emerging tertiary industry means that the impact of green technological innovation on environmental performance is significant in the secondary industry and weaker in the primary and tertiary industries.

Secondly, the three major industries exhibit distinct characteristics in their ecological footprints. The concept of the "Ecological Footprint" was initially introduced by Wackernagel and Rees (1996) [53], referring to the amount of productive land and water area required to produce the resources and absorb the waste for a specific population under prevailing conditions. This concept reveals the demand for natural resources by people to meet a certain living standard. Numerous scholars have conducted research on the topic of the ecological footprint and found that among the three major industries, the secondary industry has the highest ecological footprint, with the footprint of the tertiary industry gradually surpassing that of the primary industry. Therefore, there is a relatively high consumption of natural resources in the production processes of the secondary industry, providing significant room for improvement and making technological innovations in the secondary industry more likely to yield significant results.

Thirdly, the heterogeneity of the empirical results is led by the differences in industrial production methods. Most of the primary industry operations take place in nature, and excessive technological interventions may exert certain pressures on the environment. Therefore, relatively lower technological input is required. In the tertiary industry, in which businesses primarily provide services, direct engagement in resource input for

production activities is limited, leading to less room for environmental improvement and making it challenging for innovation to manifest tangible environmental effects. However, in the secondary industry, in which industrial production predominates, the nature of its production processes inherently poses significant negative environmental impacts. Increasing technological inputs and enhancing technological levels can aid in reducing the environmental erosion and destruction caused by the production processes, thereby making technological innovation beneficial for enhancing environmental performance.

Additionally, technological innovation has been shown to effectively enhance the environmental performance of traditional manufacturing enterprises; however, its facilitative impact on non-traditional manufacturing enterprises is not significant. Years of large-scale traditional industrial production have adversely affected the ecological environment, prompting China to elevate green and sustainable development to a strategic priority. A series of policies have been introduced to advance the process of technological innovation development, with a trend towards the transformation of industrial sectors into service-oriented industries gradually gaining consensus. It is observable that non-traditional manufacturing enterprises (or emergent enterprises) already possess a relatively high level of technological capability; continued technological innovation in the short term cannot significantly contribute to marginal improvements in enterprise environmental performance. This empirical finding also partially corroborates the view of a U-shaped relationship between technological innovation and environmental performance, as found in the literature.

5. Conclusions and Recommendation

This study on the impact of technological innovation on the environmental performance of enterprises holds significant importance for implementing green strategies, contributing to enhancing the competitiveness of enterprises, achieving long-term sustainable development, and improving the quality of the global ecological environment. Drawing upon 3313 environmental performance scores and main business data from 276 enterprises across 33 industries in China from 2007 to 2017, the study investigates the influence of technological innovation on environmental performance in enterprises. Empirical results demonstrate that technological innovation exerts a significant overall positive incentive effect on environmental performance. The findings of this study offer potential avenues and directions for reducing environmental risks for enterprises.

This study explores the heterogeneity of the impact of green technological innovation on environmental performance from an industry perspective. The research reveals that technological innovation in the primary industry does not contribute significantly to improving environmental performance. In the secondary industry, increasing technological investment and enhancing technological capabilities are beneficial for reducing environmental risks and enhancing environmental performance. Particularly in the traditional secondary industry, increasing technological investment shows significant improvement in the environmental performance of enterprises, while in the emerging secondary industry, the impact of technological innovation on environmental performance is not significant. With the continuous enrichment of enterprise data in the future, we can further investigate industrial technological innovation and environmental performance of more enterprises in China and other countries and further validate the effectiveness of technological innovation in actual production. This study discusses specific pathways for enterprises to engage in environmental innovation and provides decision-making references for the government to formulate related environmental policies.

Governments should foster enterprise technological innovation to enhance environmental performance, strengthen the capacity for environmental risk management, and support long-term sustainable development. Greater emphasis should be placed on supporting technological innovation in the secondary and tertiary industries. It is crucial to significantly increase support for technological innovation investments in the secondary industry to enhance the scientific and technological strength of enterprises and facilitate environ-

mental improvements. Within the secondary industry, particular focus should be placed on traditional manufacturing enterprises. It is advocated that these enterprises look towards the distant future, courageously advance technological innovation and revolution, transform their production methods and profit models, vigorously integrate new technologies, and construct new ecosystems. Concurrently, it is also advised that during the operational process, policymakers should segment industries and formulate personalized measures.

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