frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 11 December 2024
DOI 10.3389/fmars.2024.1518619

OPEN ACCESS

EDITED BY
Xuemei Li,
Ocean University of China, China

REVIEWED BY
Yusheng Zhou,
Hong Kong Polytechnic University, Hong Kong SAR, China
Yun Cao,
Guangxi University, China

*CORRESPONDENCE
Changrong Wang
changrongwang@qdu.edu.cn

RECEIVED 28 October 2024
ACCEPTED 22 November 2024
PUBLISHED 11 December 2024

CITATION
Wang C and Dong X (2024) Has green innovation in marine-related enterprises reduced environmental pollution? —a perspective based on executives' environmental awareness.
Front. Mar. Sci. 11:1518619.
doi: 10.3389/fmars.2024.1518619

Has green innovation in marine-related enterprises reduced environmental pollution? —a perspective based on executives' environmental awareness

Changrong Wang[1]* and Xiaopeng Dong[2]

[1]Business School, Qingdao University, Qingdao, Shandong, China, [2]Faculty of Business Economics and Statistics, University of Vienna, Vienna, Austria

This study investigates the direct impact of green innovation in marine-related enterprises on pollution emissions, addressing a significant gap in existing research regarding the role of executives' environmental awareness factor. Using a sample of 2,580 marine-related firm-year observations from the 2008-2022 period, we find that green innovation and improved environmental awareness among management can significantly reduce water pollution and air pollutants in enterprises and reduce the environmental problems caused by marine-related businesses. Moreover, enhancing environmental awareness within management can effectively substitute for the inhibitory effects of green innovation on pollution emissions. We conduct a heterogeneity test, and it proves that the inhibitory effects of green innovation and executives' environmental awareness vary across industries and ownership types. These findings contribute to the literature on the sustainable development of marine enterprises.

KEYWORDS

green innovation, marine-related enterprises, air pollution emissions, water pollution emissions, environmental awareness

1 Introduction

With the global emphasis on sustainable development, corporate green innovation has gradually become a research hotspot. Green innovation not only helps companies improve their competitiveness, but also contributes to environmental protection. This paper will review the relevant literature and explore the relationship between green innovation of marine enterprises and corporate air pollution and water pollution, as well as the impact of senior executives' environmental awareness on environmental pollution of marine enterprises, and the substitution effect of senior executives' environmental awareness on corporate green

innovation on environmental pollution. It empirically tests whether green innovation of marine enterprises can effectively reduce the emission of air pollution and water pollution, the impact of senior executives' environmental awareness on environmental pollution of marine enterprises, and analyzes its impact mechanism and implementation path, so as to effectively reduce the negative impact of enterprises on the environment and promote corporate pollution reduction and green development.

Green innovation is generally defined as the adoption of environmentally friendly technologies and sustainable methods in products, processes and management to reduce negative impacts on the environment (Porter and Van der Linde, 1995). According to the definition of the EPA (Environmental Protection Agency), green innovation emphasizes achieving a win-win situation of economic benefits and environmental protection by improving resource efficiency, reducing waste and pollution. Guinot et al., (2022) pointed out that green innovation also includes the positive initiatives of enterprises in social responsibility and environmental management, covering all aspects from raw material procurement to product life cycle. Through green innovation, the innovation of enterprise production processes or technologies is used to reduce pollutant emissions (Li et al., 2018). The characteristics of corporate green innovation include low energy consumption, high resource utilization and low emissions, which enable enterprises to maximize environmental benefits while pursuing economic benefits. According to Zhang (2023), green innovation can be divided into technological innovation, management innovation and market innovation. Technological innovation is mainly reflected in the application of new materials and new processes. Management innovation includes the optimization of organizational structure, decision-making process and other aspects. Market innovation refers to the adoption of environmentally friendly practices in product positioning and marketing strategies. These forms of innovation help reduce resource consumption and pollution emissions.

Green innovation has attracted the attention of scholars. Existing research mainly focuses on the driving factors of enterprises implementing green innovation, the implementation path of green innovation, and its impact on enterprise performance. The driving factors of enterprises implementing green innovation can be divided into external factors and internal factors. External factors include government tax incentives and subsidies, demand of consumers for environmentally friendly products and market competition intensity (Zhang, 2023; Wang et al., 2021). Internal factors include management support and corporate green culture (Cheng B. et al., 2024; Chang and Chen, 2013; Huang and Li, 2017; Singh et al., 2020). Management's attention makes enterprises more inclined to green projects in resource allocation and promotes the development of green technology (Xie et al., 2022). Shaping corporate culture is also a key influencing factor. Besides, Wan et al. (2022) found that successful green innovation usually adopts multiple paths in parallel. For example, enterprises can achieve green goals through technology research and development, cooperative innovation and marketing. When choosing an implementation path, enterprises must comprehensively consider their resources, market demand and technical capabilities. Scholars have proven the significant role of green innovation in promoting corporate performance. According to Wang et al. (2021), green innovation companies are usually able to gain higher brand recognition and customer loyalty in the market, thereby increasing sales. In addition, Xie et al. (2022) pointed out that green innovation promotes the long-term sustainable development of enterprises by improving their financial flexibility. Green innovation can also reduce the operating costs of enterprises by reducing waste disposal costs (Chen et al., 2024).

From the perspective of how to reduce corporate pollution emissions, scholars try to explore how corporate technological innovation, management innovation, and environmental management systems can impact corporate pollution emissions. Technological innovation is an important part of corporate green innovation. Cohen and Winn (2007) prove that technological innovation enables companies to adopt cleaner production processes and reduce pollutant emissions during the production process. Many companies have significantly improved environmental issues by introducing energy-saving equipment and environmentally friendly materials. Besides, from the perspective of management, management innovation further promotes the development of enterprises in a green direction by improving resource utilization efficiency and employees' environmental awareness (Tseng et al., 2021). An effective management system can help companies better implement green innovation and ensure the implementation of environmental protection measures. For example, establishing an environmental management system (EMS) can help companies systematically identify and manage environmental impacts, thereby reducing pollution.

In summary, it can be found that there is little existing research on the impact of corporate green innovation behaviors on corporate environmental pollution emissions and sustainable development (Vergara and Agudo, 2021). A literature review summary table is shown in Table 1. Most scholars focus on the driving factors of green innovation and the relationship between green innovation and corporate performance. Some scholars focus on studying the impact of corporate culture and strategy on their environmental performance (Masud et al., 2019). Some scholars also focus on technological innovation to improve resource efficiency and thereby alleviate the negative relationship between economic growth and the environment (Tang et al., 2022). The exploration of the relationship between corporate green innovation behavior and specific corporate pollution emission data has been ignored. Limited studies have focused on the marine-related enterprises regarding their relationship.

Marine-related enterprises are an important part of China's economic development. The industrial chain of marine-related enterprises includes upstream marine equipment manufacturing and marine material manufacturing, midstream marine fisheries, marine oil and gas industry, marine transportation industry, etc., and downstream marine product reprocessing and marine product wholesale and retail. As enterprises pay more and more attention to the development and utilization of marine resources, it also brings about the problems of competition for marine resources and damage to the marine environment. Marine enterprises may emit

TABLE 1 Literature summary table.

Summary	Author	Content
Green Innovation definition and its advantages	Porter and Van der Linde, 1995; Zhang, 2023	Adoption of environmentally friendly technologies; Green innovation can be divided into technological innovation, management innovation and market innovation
	Guinot et al., 2022; Li et al., 2018	Positive initiatives of enterprises; Reduce pollutant emissions
The driving factors of enterprises implementing green innovation	Zhang, 2023; Wang et al., 2021	External factors include government tax incentives and subsidies, demand of consumers for environmentally friendly products and market competition intensity
	Cheng B. et al., 2024; Chang and Chen, 2013; Huang and Li, 2017; Singh et al., 2020	Internal factors include management support and corporate green culture
Green innovation promote corporate performance	Wang et al., 2021; Xie et al., 2022	Green innovation companies gain higher brand recognition and customer loyalty in the market, thereby increasing sales
Reduce corporate pollution emissions	Cohen and Winn, 2007	Technological innovation enables companies to adopt cleaner production processes and reduce pollutant emissions
	Tseng et al., 2021	Management innovation further promotes the development of enterprises in a green direction by improving resource utilization efficiency

various pollutants during production and operation, including wastewater, waste gas, solid waste, etc. If these pollutants are directly or indirectly discharged into the ocean without proper treatment, they will pollute the marine environment (Wang et al., 2023). For example, the exhaust gas emitted by ships during navigation contains sulfur oxides (SOX) and nitrogen oxides (NOX). These gases will pollute the atmosphere and eventually settle into the ocean, affecting the marine ecosystem. A large amount of organic waste and chemicals may be generated during marine aquaculture. If these wastes and chemicals are directly discharged into the ocean without treatment, they will cause water pollution and affect the health of the marine ecosystem. Accidents may occur during marine transportation and operations, such as oil spills and chemical spills, which will cause serious pollution to the marine environment. Therefore, studying how to reduce the pollution emissions of marine enterprises is of great significance to protecting the marine environment and reducing regional pollution.

Although existing research supports innovation and effective management systems to advance the company's pursuit of green strategy, no definitive evidence has been found that increased green innovation of marine-related enterprises suppresses corporate environmental pollution, and there is no research combining executive environmental awareness with corporate green innovation to explore the substitution effect of executive environmental awareness in the impact of corporate green innovation on corporate pollution emissions. As a result, this study focuses on the following research question: Will a company's green innovation behavior reduce its pollution emissions? Does the increase in environmental awareness among executives reduce the company's environmental pollution emissions? Does executive environmental awareness have a substitute effect on the impact of green innovation on corporate environmental pollution? What are the differences in this impact under different ownership and industries?

This study significantly complements and expands the existing literature regarding the role of green innovation in marine-related enterprises, executive environmental awareness, and the substitution effect of executive environmental awareness on the relationship between green innovation and corporate pollution emissions. We further conducted heterogeneity tests to explore the differences in the impact of industry and ownership differences on environmental pollution. Firstly, from the perspective of the corporate strategy, we use data to empirically test and prove the direct negative impact of green innovation behavior of marine-related enterprises on air pollution and water pollution. Secondly, from the perspective of executive consciousness, the importance of executive environmental awareness in influencing corporate pollution emissions is revealed. Management of enterprises with higher environmental awareness tends to be more inclined to take proactive environmental protection measures, such as investing in green technology and reducing emissions, while enterprises with lower executive environmental awareness may only be satisfied with complying with the minimum legal requirements. In addition, we have demonstrated that executive environmental awareness can replace the inhibitory effect of corporate green innovation on environmental pollution and promote green development of enterprises. Thirdly, from the perspective of industry and ownership, through heterogeneity testing, we find that the impact of green innovation and executive environmental awareness on corporate pollution behavior varies across different industries and ownership levels. These findings help us to have a more comprehensive understanding of the mechanisms and driving factors of environmental pollution in marine-related enterprises and further develop green development measures for marine-related enterprises.

2 Theoretical background and hypothesis development

2.1 Green innovation behavior of marine enterprises and enterprise pollution emissions

Green innovation refers to innovation in resource utilization, energy consumption and pollutant emissions to achieve a win-win situation between economic growth and environmental protection. This includes the research and development and application of clean energy technology, the promotion of energy-saving and emission reduction technology, and the practice of circular economy. These measures help improve resource utilization efficiency, reduce resource waste, and reduce pollutant emissions by reducing energy consumption. Green technology innovation can reduce environmental pollution, save energy, and achieve green and sustainable development, which is coordinated with environmental protection and corporate competitiveness (Tariq et al., 2017; Abbas & Sağsan, 2019); Many scholars have proved that corporate green innovation can help enterprises gain competitive advantages in the industry and thus improve corporate performance. Green innovation is of great significance in improving corporate performance, gaining competitive advantages and promoting improved labor relations (Aguilera-Caracuel and Ortiz-de-Mandojana, 2013; Meles et al., 2023). Andersen and Massa (2000) found that ecological modernization helps improve the competitive advantage of enterprises, reduce raw material costs and corporate pollution. Tian et al. (2023) analyzed sample data of small and medium-sized enterprises in the manufacturing industry and used the theory of ecological modernization to prove that technological innovation can promote corporate environmental performance. Technological breakthroughs can help improve resource efficiency, thereby reducing corporate environmental pollution. Improving resource efficiency can eliminate environmental pollution (Khan et al., 2021). Green innovation is closely related to sustainable development, but in practice, enterprises still face many challenges. High R&D costs and market risks often make it difficult for enterprises to obtain substantial returns in the short term (Dangelico & Pujari, 2010). Xie et al. (2022) found through a study of heavily polluting enterprises that enterprises often optimize product design during the green innovation process. In the short term, the capital investment in green innovation will reduce the value of the enterprise, but it is an important way for heavily polluting enterprises to achieve green transformation. Wang et al. (2022)'s research shows that the effectiveness of pollution discharge fees on corporate green technology innovation has been significantly improved. The increase in pollution discharge fees can reduce pollution emissions.

From the perspective of macro-policy guidance, Zhang (2023) emphasized that government policy support plays a key role in corporate green innovation. Policies guide enterprises to adopt low-emission technologies and encourage green innovation through measures such as fiscal subsidies and tax exemptions, further promoting the internal application of environmental protection and green technologies in enterprises, thereby creating competitive advantages for enterprises, increasing market share, and promoting the sustainable development of the industrial chain. Many scholars have discovered the role of environmental regulations in promoting corporate green innovation by studying macro-environmental regulatory policies. Yang & Wang (2021) further showed that the implementation of environmental regulations can significantly improve the green innovation efficiency of enterprises and reduce corporate environmental pollution. Moreover, this effect has significant differences in the green innovation efficiency of different regions, indicating that the effectiveness of environmental regulation varies in different regions. Zhang et al. (2022) found through research on Chinese enterprises that when enterprises face more stringent environmental supervision, they are more motivated to innovate green technologies to meet environmental standards and reduce pollution emissions. Chen et al. (2023a) further pointed out that the implementation of environmental regulations not only promotes corporate green innovation, but also promotes corporate environmental investment in digital transformation. This means that enterprises not only reduce pollution emissions through technical means, but also improve their environmental performance through organizational structure and management innovation. Therefore, enterprises need to reduce the barriers to implementing green innovation through government support, cross-industry cooperation, so as to achieve the goal of sustainable development (Shahin et al., 2024).

Air pollution mainly comes from industrial emissions, transportation, and construction. Enterprise green innovation can significantly reduce air pollution emissions by improving technical level and management capabilities. Enterprises that adopt clean production technology can usually reduce the emission of harmful gases, thereby improving air quality. Clean production is a major measure of environmental innovation strategy and an inevitable choice for industrial sustainable development (Halynska et al., 2019). Marine enterprises often need to consume a lot of resources and energy in the production process, resulting in the emission of a large amount of waste gas, wastewater and other pollutants. Through green technology innovation, enterprises can improve resource utilization efficiency, adopt cleaner energy and production processes, and reduce the generation of pollutants from the source. Therefore, this paper proposes hypothesis 1.

Hypothesis 1: Green innovation of marine enterprises can inhibit air pollution.

Water pollution mainly comes from industrial wastewater discharge, agricultural runoff and urban sewage. Enterprises can effectively reduce the occurrence of water pollution through green innovation. Khan et al. (2022) pointed out that the use of advanced wastewater treatment technology and measures to recycle water resources can significantly reduce the water pollution emissions of enterprises. Marine enterprises face great challenges in water pollution control, and green innovation can promote enterprises to develop and apply advanced pollution control technologies. For example, marine enterprises can reduce the toxic and harmful substances discharged in their production process and reduce damage to the marine ecosystem by developing new wastewater treatment technologies or using low-pollution raw materials (Yang & Wang, 2021). In addition, advanced pollution control technologies can also improve the efficiency of pollutant recovery

and reuse, further reducing emissions. Therefore, this paper proposes the following hypothesis 2.

Hypothesis 2: Green innovation of marine enterprises can inhibit water pollution emissions.

2.2 Corporate management's environmental awareness and corporate environmental pollution

Executive environmental awareness refers to the understanding of the importance, interest, attitude and impact of environmental protection by corporate top managers (Li et al., 2022). This awareness not only affects a company's environmental policy but also directly affects its environmental performance. Top managers are influenced by their values, feel they are influential and capable, and often implement social responsibility strategies in enterprises (Kutzschbach et al., 2021). The environmental awareness of senior executives can effectively promote the green innovation of enterprises, thereby affecting the pollution emissions of enterprises.

From a macro policy perspective, scholars have found that government environmental supervision is an important external factor that promotes corporate executives to strengthen environmental awareness. Research by Zhu et al. (2022) shows that environmental supervision can significantly improve the environmental governance motivation of enterprises, especially among large enterprises and heavily polluting enterprises. Government environmental regulations can effectively improve the green innovation of enterprises, and environmental investment plays an intermediary role. Enterprises should improve environmental awareness to improve corporate social responsibility, establish a positive environmental image, and accelerate the development of cleaner production technologies and green products to improve green innovation performance (Lin et al., 2015; Chen et al., 2023b).

From the perspective of internal corporate decision-making, Jiménez-Parra et al. (2018) pointed out that there is a significant relationship between corporate social responsibility (CSR) and the reduction of air pollution. The study also found that environmental innovation is the link between corporate sustainable development practices and pollution. Key mechanisms for emissions reduction. Research by Yu et al. (2022) pointed out that the Environmental Accountability System (EAS) policy played an important role in promoting companies to reduce sulfur dioxide emissions. The study found that executives of private companies and labor-intensive companies pay more attention to environmental issues when faced with strict government regulation, thereby adjusting the company's production and operation models to reduce pollutant emissions and promote the optimization of the local environment. The research of Latan et al. (2018) found that environmental uncertainty and executive commitment jointly affect the environmental performance of enterprises. If executives can make proactive environmental decisions in the face of uncertain environmental policies, companies will be able to reduce pollution emissions while improving economic benefits. Research also shows that environmental management accounting (EMA) is an effective tool to help corporate executives cope with environmental uncertainties. It can help companies identify and manage environmental risks and reduce pollution emissions. Research by Baba (2007) pointed out that although SMEs are inferior to large enterprises in terms of resources and technology, the environmental leadership of executives can significantly affect the environmental performance and pollution emissions of small and medium-sized enterprises (SMEs) through the implementation of environmental management practices. Research shows that when executives proactively support environmental management practices, companies are better able to reduce pollution and improve environmental performance. The study also points out that if executives can embed environmental awareness into corporate culture, small and medium-sized enterprises will make significant progress in reducing pollution emissions and improving environmental performance. Among small and medium-sized enterprises (SMEs), executives' environmental awareness has an equally significant impact on corporate pollution emissions. In addition, Da Silva (2019) research emphasizes the importance of executives' environmental awareness to employee environmental education. The environmental awareness of senior executives can not only affect the environmental performance of the company, but also improve the environmental awareness of employees through environmental education and training, thereby promoting the improvement of the company's overall environmental management level and further reducing pollution emissions.

From the perspective of executive experience, existing research has demonstrated the impact of manager experience on managers' values and cognitions, which in turn affects their attention to green and social responsibility. He et al. (2024) studied the impact of CEOs' early-life experience on corporate green innovation and proved their positive relationship. Quan et al. (2023); Choi et al. (2023) and Javed et al. (2023) found that CEOs with overseas study background, CEOs with childhood experiences of natural disasters and female CEOs were more willing to promote corporate green innovation, and Fulfill corporate social responsibilities. Based on Impression theory, Marquis and Tilcsik (2013) proved that personal experience can affect the psychological cognition and behavior of executives. Executives who have experienced environmental pollution pay more attention to environmental protection in corporate strategic decisions (Lu, 2020) and are more likely to promote green innovation and reduce environmental pollution (Guo et al., 2023; Liu & Li, 2022). Therefore, the personal characteristics, environmental protection experience and environmental awareness of executives can affect the company's social responsibility fulfillment and corporate environmental strategy. Based on the above analysis, this article proposes the following hypothesis 3 and hypothesis 4.

Hypothesis 3: Executives' environmental awareness has an inhibitory effect on environmental pollution of marine-related enterprises

Hypothesis 4: Executive environmental awareness has a substitution effect on the negative relationship between green innovation and environmental pollution in marine-related enterprises.

3 Research design

3.1 Data sources

The research object of this paper is China's marine-related listed companies from 2008 to 2022. The list of A-share listed companies comes from the China Stock Market & Accounting Research(CSMAR)database. Referring to the research of Li and Cao (2022), listed companies whose business scope includes keywords such as ocean, marine engineering, marine equipment, marine information services, marine shipbuilding industry, shipbuilding industry, marine public services, marine biology, offshore, marine-related, and marine transportation in the business registration information of enterprises are selected as the research objects of this paper. On this basis, this paper carried out the following screening: First, ST companies and PT companies were eliminated; secondly, samples of companies with missing values and abnormal data were eliminated. In order to eliminate the influence of extreme values, the sample data was subjected to 1% tail shrinkage. Finally, 2580 sample data of 190 A-share listed companies were selected. The industry classification of marine-related sample companies is shown in Figure 1 below. The green innovation data in this paper refers to the method of Wang and Wang (2021), and the green patent data of listed companies are obtained from the China Research Data Service Platform. They are matched with the international green patent list released by the World Intellectual Property Organization (WIPO) in 2010, and the corresponding patent classification numbers are extracted to obtain the green patent data of listed companies. The financial data of other companies are obtained from the CSMAR database and the author's manual collection and collation.

3.2 Models

This paper uses stata17.0 to process the data. By establishing a fixed effect regression model, we study the impact of corporate green innovation and executives' environmental awareness on corporate pollution emission intensity, and construct models (1) to (6). Where Total Air $\text{Pollution}_{i,t}$ and Total Water $\text{Pollution}_{i,t}$ are the dependent variables that represent the air pollution and water pollution emissions of enterprises; $\text{GreenInnovation}_{i,t}$ and $\text{Environmentalconscious}_{i,t}$ are the independent variables that denote the corporate green innovation behaviors and executive environmental awareness, respectively; $\text{Controls}_{i,t}$ is a set of control variables. Measurement of variables is represented in Table 2: Variables and definitions.

Models (1) and (2) respectively test the impact of corporate green innovation on corporate air pollution emissions and water pollution emissions. To test H1 and H2, we estimate the following model (1) and model (2):

$$\text{Total Air Pollution}_{i,t} = a_0 + a_1 GreenInnovation_{i,t} + a_2 controls_{i,t} + \varepsilon_{i,t}$$

$$\text{Total Water Pollution}_{i,t} = a_0 + a_1 GreenInnovation_{i,t} + a_2 controls_{i,t} + \varepsilon_{i,t}$$

Models (3) and (4) respectively test the impact of executives' environmental awareness on corporate air pollution emissions and water pollution emissions. To test H3, we estimate the following model (3) and model (4):

$$\text{Total Air Pollution}_{i,t} = a_0 + a_1 EnvironmentalConscious_{i,t} + a_2 controls_{i,t} + \varepsilon_{i,t}$$

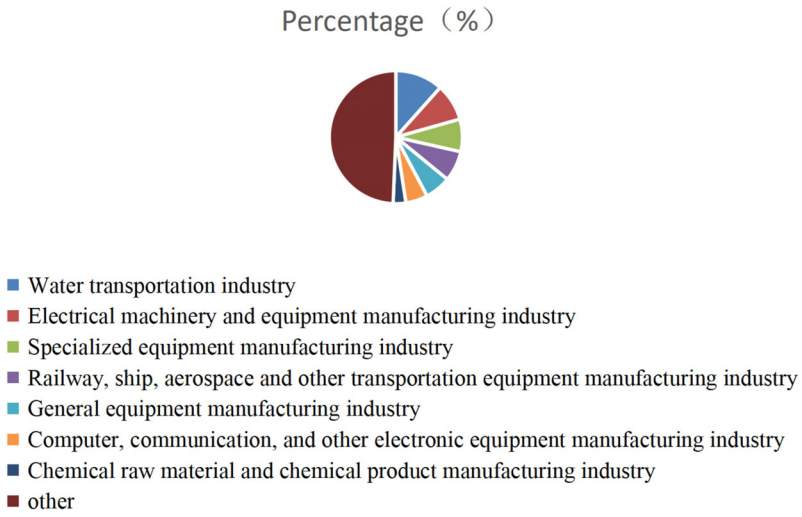

FIGURE 1
Industry classification of sample data.

TABLE 2 Variables and definitions.

Variable Type	Variable name	Symbol	Definitions
Dependent Variables	Total Water pollution	TWP	Total Water pollution=(chemical oxygen demand+ammonia nitrogen emissions+total nitrogen+total phosphorus)/total asset * 10000
	Total Air pollution	TAP	Total gas pollution=(sulfur dioxide+nitrogen oxides+particulate matter)/total asset * 10000
Independent Variables	Greeninnovation	GI	Natural logarithm of (Number of green invention patent applications+number of green utility model applications+1)
	Environmental Conscious	EC	8 environmental management disclosures, Environmental Protection Concept;Environmental Protection Goal;Environmental Protection Management System;Environmental Protection Education Training; Environmental Protection Special Act;Environmental Protection Emergency response mechanism for incidents;Environmental Protection Honor Reward;ThreeSimultaneity; Assign a value of 1, otherwise 0
Control Variables	Top Ten Holders Rate	TopTen	The shareholding ratio of the top ten shareholders (%)=the sum of the shareholding ratios of the top ten shareholders
	Seperation	SP	Separation rate of ownership and control =the difference between the actual controller's control and ownership of the listed company
	Income Tax Rate	TAXR	Income Tax Rate of the Company
	Rate of Return on Common Stockholders' Equity	ROE	Net profit/Average balance of shareholders' equity; Average balance of shareholder equity=Closing balance of shareholder equity
	Cash Equivalents Turnover	CASH	Operating income/end of period cash and cash equivalents balance
	Environmental Protection Subsidiary	SUB	Environmental subsidies/total assets, environmental subsidies: green subsidies received by enterprises.

$$\text{Total Water Pollution}_{i,t} = a_0 + a_1 EnvironmentalConscious_{i,t} + a_2 controls_{i,t} + \varepsilon_{i,t}$$

On the basis of models (1) to (4), models (5) and (6) add the multiplication term of green innovation and executives' environmental awareness (GI×EC) to test the substitution effect of executives' environmental awareness on the relationship between corporate green innovation and environmental pollution. To test H4, we estimate the following model (5) and model (6):

$$\text{Total Air Pollution}_{i,t} = a_0 + a_1 GreenInnovation_{i,t} + a_2 EnvironmentalConscious_{i,t} + a_3 GreenInnovation_{i,t} \times EnvironmentalConscious_{i,t} + a_4 controls_{i,t} + \varepsilon_{i,t}$$

$$\text{Total Water Pollution}_{i,t} = a_0 + a_1 GreenInnovation_{i,t} + a_2 EnvironmentalConscious_{i,t} + a_3 GreenInnovation_{i,t} \times EnvironmentalConscious_{i,t} + a_4 controls_{i,t} + \varepsilon_{i,t}$$

3.3 Variables

3.3.1 Dependent variable

The dependent variable of this paper is the environmental pollution emission intensity of marine enterprises. The calculation of pollution emission intensity of listed marine enterprises refers to the research of Mao et al. (2022) and Ren and Li (2024). Through Python crawling the annual reports of marine enterprises and government reports and other documents, the pollution emission data of marine sample enterprises are collected. Enterprise pollution emissions include waste gas pollution emissions and wastewater pollution emissions. Waste gas pollution emissions are the sum of three pollutants including sulfur dioxide, nitrogen oxides and smoke. Wastewater pollution emissions are the sum of chemical oxygen demand, ammonia nitrogen emissions, total nitrogen and total phosphorus pollution emissions. First, calculate the total amount of water pollution emissions and air pollution emissions, and then use the total amount of water pollution emissions/total assets of the enterprise × 10000 and the total amount of air pollution emissions/total assets of the enterprise × 10000 to measure the water pollution emission intensity and air pollution emission intensity of the enterprise. Specific environmental pollutants are shown in Table 3 below.

3.3.2 Independent variables

The independent variable of this paper is corporate green innovation. Referring to the existing research of Li and Zheng (2016) and Wang and Wang (2021), the number of green patent applications is used as a proxy variable to measure the green innovation behavior of enterprises. The number of green patent applications is the sum of the number of green invention patent applications and the number of green utility model patent applications. This paper adds 1 to the number of green patent applications and takes the natural logarithm to represent the

TABLE 3 Environmental pollution details.

Dependent variable (environmental pollution intensity) Water pollution	Water pollution	Water pollution1	Chemical oxygen demand
		Water pollution2	Ammonia nitrogen emissions
		Water pollution3	Total nitrogen emissions
		Water pollution4	Total phosphorus emissions
		Total Water pollution	Total water pollution = chemical oxygen demand + ammonia nitrogen emissions + total nitrogen + total phosphorus
	Air pollution	Air pollution1	Sulfur dioxide
		Air pollution2	Nitrogen oxides
		Air pollution3	Smoke
		Total Air pollution	Total air pollution = sulfur dioxide + nitrogen oxides + smoke

green innovation behavior (GI) of the enterprise. The larger the value of GI, the more the enterprise pays attention to the application of green research and development and green patents, that is, the enterprise tends to develop green innovation.

The environmental awareness index of executives refers to the research of existing scholars (Li et al., 2023), selects a series of keywords, and uses the intensity of environmental information disclosure behavior as a proxy variable for whether corporate executives have environmental awareness. The data on environmental management disclosure comes from the CSMAR database. The following 8 environmental management disclosure contents are Environmental Protection Concept - Disclosure of the company's environmental protection concept, environmental policy, environmental management organizational structure, circular economy development model, green development, etc., assigned a value of 1, otherwise 0. Environmental Protection Goal - discloses the company's past environmental protection goal completion and future environmental protection goals, with a value of 1, otherwise 0. Environmental Protection Management System - discloses the company's formulation of a series of management systems such as environmental management systems, systems, regulations, responsibilities, etc., with a value of 1, otherwise 0. Environmental Protection Education and Training - discloses the company's participation in environmental protection-related education and training, with a value of 1, otherwise 0. Environmental Protection Special Act - discloses the company's participation in environmental protection special activities, environmental protection and other social welfare activities, with a value of 1, otherwise 0. Environmental Protection Emergency response mechanism for incidents-Disclose the company's establishment of an emergency mechanism for major environmental emergencies, the emergency measures taken, the treatment of pollutants, etc., with a value of 1, otherwise 0. Environmental Protection Honor Reward-Disclose the honors or rewards the company has received in environmental protection, with a value of 1, otherwise 0. Three Simultaneity (The 'Three Simultaneous' System)-Disclose the company's implementation of the "Three Simultaneous" system (When enterprises carry out new construction, renovation, and expansion projects, facilities for preventing and controlling pollution and other public hazards must be designed, constructed, and put into operation simultaneously with the main project), with a value of 1, otherwise 0. And add the above 8 indicators to get the index of executives' environmental awareness. The larger the index is, the more attention the company pays to the disclosure of environmental management, that is, the stronger the executives' environmental awareness is.

3.3.3 Control variables

Control variables data are obtained from the CSMAR database. This paper selects Top Ten Holders Rate, Seperation, Income Tax Rate, Cash Equivalents Turnover, ROE, Environmental Protection Subsidiary as control variables. Based on the research of existing scholars (Chen & Chen, 2024), and based on the government subsidy data in the notes to the financial statements of enterprises, multiple words related to green environmental protection are selected, including "green", "clean", "environmental protection", "energy saving", "emission reduction", "circulation", "pollution", "waste gas", "desulfurization", "denitrification", "boiler", "dust removal", etc., and the data of corporate environmental protection subsidies are obtained by merging and sorting. Definitions of control variables are shown in Table 2.

4 Analysis of empirical results

4.1 Descriptive statistics

Table 4 is the descriptive statistics of the main variables. From Table 4, we can see that the maximum value of the green innovation value of the sample data of marine enterprises is 5.753, the average value is 0.862, and the minimum value is 0. This shows that there are huge differences in the strategic choices of green innovation among different marine enterprises. The maximum values of the total water pollution intensity and air pollution intensity of marine enterprises are 3.039 and 4.408, while the environmental pollution emission value of some marine enterprises is 0, which shows that the negative impact of different marine enterprises on the environment in their operations is very different.

TABLE 4 Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
TWP	2850	.017	.072	0	3.039
Waterpollution1	2850	.002	.006	0	.233
Waterpollution2	2850	.005	.021	0	.895
Waterpollution3	2850	.007	.031	0	1.298
Waterpollution4	2850	.003	.015	0	.614
Airpollution1	2850	.005	.022	0	.786
Airpollution2	2850	.008	.037	0	1.561
Airpollution3	2850	.012	.051	0	2.061
TAP	2850	.025	.109	0	4.408
GI	2850	.862	1.212	0	5.753
EC	2850	1.614	1.982	0	8
TopTen	2850	60.503	16.007	14.6	100
SP	2850	4.563	7.463	0	58.142
TAXR	2850	.156	.624	-12.283	18.436
ROE	2850	.022	2.196	-50.082	90.705
CASH	2850	8.087	20.981	.003	794.846
SUB	2850	0	.003	0	.108
Public Attention	2301	5.019	1.058	0	7.151

4.2 Basline regression results and analysis

4.2.1 Green innovation and environmental pollution of marine-related enterprises

Based on Formula 1 and Formula 2, Table 5 shows the impact of green innovation of marine-related enterprises on water pollution and air pollution. Columns 1 and 2 report the impact of corporate greenness on water pollution. Based on column 1, column 2 adds control variables. Columns 3 and 4 report the impact of corporate green innovation on air pollution. Column 4 adds relevant control variables based on column 3. The data results in columns 1 and 2 show that before and after adding control variables, the impact of green innovation of marine-related enterprises on water pollution is -0.0024 and -0.0023 respectively, with significant negative correlations at the 1% and 5% levels respectively. The regression results in columns 3 and 4 show that the impact of green innovation of marine-related enterprises on air pollution before and after adding control variables is significantly negatively correlated at the 1% and 5% levels, respectively, and the correlation coefficients are -0.0037 and -0.0034 respectively. It shows that green innovation by marine-related enterprises will effectively reduce the company's water pollution and air pollution emissions, thereby benefiting the improvement of environmental pollution and optimizing the environment. This further proves Hypothesis 1 and Hypothesis 2 of this article, that is, the green innovation of marine-related enterprises is negatively related to the intensity of water pollution and air pollution. Green innovation by marine enterprises will improve their green efficiency, thereby reducing pollution emissions during production and operation, and promoting green development of enterprises.

TABLE 5 The limpact of green innovation on water pollution and air pollution.

	TWP	TWP	TAP	TAP
	(1)	(2)	(3)	(4)
GI	-0.0024***	-0.0023**	-0.0037***	-0.0034**
	(-3.4891)	(-2.5747)	(-3.3589)	(-2.5337)
TopTen		-0.0007***		-0.0010***
		(-3.6990)		(-3.6378)
SP		-0.0006*		-0.0009*
		(-1.7741)		(-1.7870)
TAXR		-0.0013		-0.0020
		(-1.5851)		(-1.5210)
ROE		0.0192**		0.0278**
		(2.1757)		(2.1712)
CASH		-0.0001**		-0.0002**
		(-2.2152)		(-2.2260)
SUB		0.1792		0.2261
		(1.4113)		(1.4533)
_cons	0.0458***	0.0984***	0.0721**	0.1502***
	(2.7066)	(4.0747)	(2.5701)	(3.8639)
Industry	Yes	Yes	Yes	Yes
N	2850	2850	2850	2850
adj. R2	0.1235	0.5202	0.1365	0.5070

t statistics in parentheses.
*p < 0.10, **p < 0.05, ***p < 0.01.

4.2.2 Environmental awareness and environmental pollution of marine-related enterprises

Table 6 shows the regression results of the impact of executives' environmental awareness on water pollution. Columns 1 to 4 respectively report the impact of executives' environmental awareness on different water pollutants. The four water pollutants are chemical oxygen demand, ammonia nitrogen emissions, total nitrogen and total phosphorus. The results show that executives' environmental awareness is negatively related to these four water pollution elements, and they are all significantly negatively correlated at the 5% level. Column 5 shows the impact of executives' environmental awareness on the total number of water pollutants. There is a significant negative correlation at the 5% level, which proves hypothesis 3 of this article. Executives' environmental awareness has a negative effect on corporate environmental pollution. This shows that the stronger the environmental awareness of executives, the higher their sense of social responsibility, and the more likely they are to choose corporate development strategies that optimize the environment.

TABLE 6 The impact of environmental conscious on water pollution.

	Waterpollution1	Waterpollution2	Waterpollution3	Waterpollution4	TWP
	(1)	(2)	(3)	(4)	(5)
EC	-0.0001**	-0.0002**	-0.0004**	-0.0002**	-0.0009**
	(-2.5826)	(-2.1358)	(-2.2435)	(-2.0677)	(-2.2356)
TopTen	-0.0001***	-0.0002***	-0.0003***	-0.0001***	-0.0007***
	(-3.6089)	(-3.5971)	(-3.6228)	(-3.6392)	(-3.6377)
SP	-0.0000	-0.0002*	-0.0003*	-0.0001**	-0.0006*
	(-1.3476)	(-1.9683)	(-1.8677)	(-2.0388)	(-1.9131)
TAXR	-0.0001*	-0.0004*	-0.0006*	-0.0003	-0.0015*
	(-1.8887)	(-1.7717)	(-1.7211)	(-1.6504)	(-1.7533)
ROE	0.0015**	0.0057**	0.0082**	0.0039**	0.0192**
	(2.2312)	(2.1811)	(2.1620)	(2.1709)	(2.1747)
CASH	-0.0000	-0.0000**	-0.0001**	-0.0000**	-0.0001**
	(-1.1410)	(-2.1850)	(-2.2485)	(-2.4296)	(-2.1906)
SUB	0.0031	0.0597	0.0887	0.0470	0.1986
	(0.4319)	(1.4807)	(1.5078)	(1.4171)	(1.5218)
_cons	0.0076***	0.0275***	0.0428***	0.0207***	0.0986***
	(5.4418)	(4.0055)	(3.9368)	(3.9167)	(4.0844)
Industry	Yes	Yes	Yes	Yes	Yes
N	2850	2850	2850	2850	2850
adj. R2	0.4427	0.5339	0.5090	0.4909	0.5198

t statistics in parentheses.
*p < 0.10, **p < 0.05, ***p < 0.01.

Table 7 shows the regression results of the impact of executives' environmental awareness on air pollution emissions. Columns 1 to 3 are sulfur dioxide, nitrogen oxides, and particulate matter pollutants in air pollution respectively. Column 4 is the sum of the previous three pollutants. It can be found from Table 7 that executives' environmental awareness has a negative impact on different air pollutants and total air pollutants. The coefficients of executives' environmental awareness on sulfur dioxide, nitrogen oxides, and particulate matte and total air pollution are -0.0003, -0.0004, -0.0006, and -0.0013 respectively, and are significantly negatively correlated at the 5% level. This shows that senior executives' environmental awareness has an inhibitory effect on corporate air pollution, and once again proves hypothesis 3, that is, the higher the senior executives' environmental awareness, the more likely they are to reduce air pollution and promote corporate green development. When executives' environmental awareness increases, they are more willing to make socially and environmentally responsible decisions and are therefore more likely to adopt green development strategies and reduce corporate pollution emissions.

4.2.3 The substitute role of environmental awareness

Based on Formula 5 and Formula 6, Table 8 is the regression coefficient table of the substitution effect of environmental awareness. On the basis of columns 1 and 3, columns 2 and 4 add the multiplication term of Green Innovation and Environmental Conscious (GI × EC) respectively to test the substitution effect of environmental awareness on green innovation. From columns 2 and 4, the regression coefficients between GI and EC and the water pollution emissions and air pollution emissions of marine-related companies are significantly negative, indicating that the green innovation of marine-related companies and the improvement of executives' environmental awareness can inhibit Enterprise pollution emissions once again prove Hypothesis 1 to Hypothesis 4. Further analysis, we found that the regression coefficient between the multiplication term of Green Innovation and Environmental Conscious (GI × EC) and the company's environmental pollution emission intensity is positive and has a significant positive correlation at the 10% level, indicating that environmental awareness will replace Green innovation affects the pollution emission intensity of Marine-related enterprises. Therefore, it is proved that in suppressing environmental pollution emissions, the improvement of executives' environmental awareness can replace the impact of corporate green innovation behaviors on pollution emissions, proving the substitution effect of executives' environmental awareness. As a subjective influencing factor, executives' environmental awareness can also inhibit corporate pollution emissions. Therefore, executives' environmental awareness may replace the inhibitory effect of

TABLE 7 The impact of environmental conscious on air pollution.

	Airpollution1	Airpollution2	Airpollution3	TAP
	(1)	(2)	(3)	(4)
EC	-0.0003**	-0.0004**	-0.0006**	-0.0013**
	(-2.1268)	(-2.0949)	(-2.1404)	(-2.1289)
TopTen	-0.0002***	-0.0003***	-0.0005***	-0.0010***
	(-3.6340)	(-3.4565)	(-3.6155)	(-3.5762)
SP	-0.0002*	-0.0003*	-0.0004*	-0.0009*
	(-1.9466)	(-1.8920)	(-1.9123)	(-1.9217)
TAXR	-0.0004	-0.0008*	-0.0010*	-0.0021*
	(-1.5425)	(-1.7598)	(-1.6747)	(-1.6820)
ROE	0.0049**	0.0099**	0.0130**	0.0278**
	(2.1771)	(2.1665)	(2.1702)	(2.1701)
CASH	-0.0000**	-0.0001**	-0.0001**	-0.0002**
	(-2.3711)	(-2.1127)	(-2.1811)	(-2.2019)
SUB	0.0467*	0.0642	0.1444	0.2553
	(1.6751)	(1.6058)	(1.4834)	(1.5898)
_cons	0.0311***	0.0489***	0.0705***	0.1505***
	(3.7492)	(3.8682)	(3.9051)	(3.8715)
Industry	Yes	Yes	Yes	Yes
N	2850	2850	2850	2850
adj. R2	0.4540	0.5233	0.5125	0.5066

t statistics in parentheses.
*p < 0.10, **p < 0.05, ***p < 0.01.

TABLE 8 The substitute role of environmental awareness.

	TWP	TWP	TAP	TAP
	(1)	(2)	(3)	(4)
GI	-0.0020**	-0.0029***	-0.0031**	-0.0045***
	(-2.3628)	(-2.7358)	(-2.3387)	(-2.6671)
EC	-0.0006*	-0.0011**	-0.0009	-0.0017**
	(-1.6959)	(-2.1247)	(-1.6004)	(-2.0385)
GI×EC		0.0004*		0.0006*
		(1.8627)		(1.8243)
TopTen	-0.0007***	-0.0007***	-0.0010***	-0.0010***
	(-3.7175)	(-3.7254)	(-3.6554)	(-3.6625)
SP	-0.0006*	-0.0006*	-0.0009*	-0.0009*
	(-1.7787)	(-1.8033)	(-1.7915)	(-1.8158)
TAXR	-0.0014	-0.0014	-0.0020	-0.0020
	(-1.6367)	(-1.6353)	(-1.5691)	(-1.5687)
ROE	0.0192**	0.0192**	0.0278**	0.0278**
	(2.1745)	(2.1742)	(2.1700)	(2.1696)
CASH	-0.0001**	-0.0001**	-0.0002**	-0.0002**
	(-2.1897)	(-2.1770)	(-2.2014)	(-2.1889)
SUB	0.1846	0.1888	0.2340	0.2406
	(1.4362)	(1.4459)	(1.4863)	(1.5002)
_cons	0.0995***	0.1001***	0.1517***	0.1528***
	(4.1345)	(4.1310)	(3.9163)	(3.9136)
Industry	Yes	Yes	Yes	Yes
N	2850	2850	2850	2850
adj. R2	0.5201	0.5201	0.5069	0.5069

t statistics in parentheses.
*p < 0.10, **p < 0.05, ***p < 0.01.

corporate green innovation on environmental pollution, further promote corporate green development, reduce pollution, and improve environmental problems caused by the operation of marine-related enterprises.

4.3 Endogeneity test

In order to avoid the endogeneity problem of the independent variable. This paper selects two stage least square (2sls) to test the endogeneity problem (Sheikhi et al., 2022). Based on the research of Wang & Zhao (2018), Yin et al. (2022), and Liu (2022), this paper selects public environmental attention as an instrumental variable. Because the higher the public environmental attention, the more likely it is to guide enterprises to optimize their corporate image through green innovation, so public environmental attention can affect corporate green innovation behavior. However, as a subjective public choice, public environmental attention can hardly directly affect the pollution emission intensity of enterprises. It ensures that the instrumental variable (Public Attention) meets the exogenous conditions. The natural logarithm of the daily average of Baidu search index + 1 is taken as the proxy variable for public environmental attention. The specific approach is as follows: Search for "environmental pollution" and "smog" as keywords in the Baidu search index, and obtain the average daily search volume for the terms "environmental pollution" and "smog" in the regions where the listed companies are located. Add them up and add one to take the natural logarithm, which is used as a proxy variable (Public Attention) for the degree of public attention in the regions where the listed companies are located.

Table 9 shows the results of 2sls. Column 1 shows the regression results of the first stage. The coefficient of Public Attention is positive and significantly positively correlated at the 1% level, indicating that the higher the Public Attention, the more it can motivate enterprises to carry out green innovation. Columns 2 and 3 report the results of the second stage with water pollution and air pollution as dependent variables, respectively. The coefficients of GI in columns 2 and 3 are -0.071 and -0.111, respectively, and are significantly negatively correlated at the 1% level, which once again proves Hypothesis 1 and Hypothesis 2. The EnvironmentalConscious (EC) coefficient is significantly negatively correlated at the 1% level, which once again proves Hypothesis 3. The regression coefficient of GI×EC is significantly positively correlated at the 1% level, demonstrating the substitution effect of environmental awareness, proving Hypothesis 4 again, and proving the robustness of the previous baseline regression and environmental awareness substitution results.

The F-statistics of the first stage is 41.92, and in Table 10, Shea's partial R-squared for the first stage model is 0.0180, which is below 0.05. The F-statistics and Shea's partial R-squared show that the instruments are correlated with the potentially endogenous variable (Javorcik & Li, 2013), so the instrumental variable does not exhibit weak instrumental variable problem.

TABLE 9 The results of instrumental variables estimation.

	First-stage	Second-stage	Second-stage
	(1)	(2)	(3)
VARIABLES	GI	TWP	TAP
Public Attention	0.067***		
	-4.14		
GI		-0.071***	-0.111***
		(-3.06)	(-3.10)
EC	-0.161***	-0.015***	-0.023***
	(-14.63)	(-3.69)	(-3.71)
GI×EC	0.214***	0.015***	0.023***
	-51.7	-2.99	-3.03
TopTen	-0.003**	-0.001***	-0.001***
	(-2.27)	(-5.86)	(-5.83)
SP	-0.003	0	0
	(-1.48)	(-0.42)	(-0.47)
TAXR	0.038	0	-0.001
	-1.04	(-0.14)	(-0.09)
ROE	-0.001	0.020***	0.029***
	(-0.16)	-30.33	-28.39
CASH	-0.001	0	0
	(-1.22)	(-0.73)	(-0.75)
SUB	1.326	0.332	0.453
	-0.24	-0.62	-0.55
Constant	0.551***	0.115***	0.178***
	-5.35	-5.46	-5.46
Observations	2,301	2,301	2,301
R-squared	0.591	0.027	

t-statistics in parentheses.
*p < 0.10, **p < 0.05, ***p < 0.01.

4.4 Robustness check

Table 11 shows the robustness test results of this article. This article chooses to use Green Invention Patent to replace the total number of green patent applications in the baseline regression. The symbol in the regression is GI2 as the proxy variable for green innovation. GI2 represents the quality of green innovation. The calculation method is the number of green invention patent applications + 1, taking the natural logarithm (Wang and Wang, 2021). The dependent variables reported in columns 1 and 2 are water pollution and air pollution, respectively. It can be found that when the proxy variable of green innovation becomes green innovation quality (GI2), the impact of green innovation quality and executives' environmental awareness on water pollution and air pollution is still significantly negatively correlated at the 1% level. The coefficient of the multiplication term (GI2×EC) of green quality and

TABLE 10 Shea's partial R-squared.

Variable	Shea's partial R-sq.	Shea's adj. partial R-sq.
GI	0.0180	0.0154

TABLE 11 Regression results: alternative green innovation measure.

	TWP	TAP
	(1)	(2)
GI2	-0.0037***	-0.0057***
	(-2.7071)	(-2.5959)
EC	-0.0010**	-0.0015**
	(-2.0912)	(-1.9862)
GI2×EC	0.0005**	0.0007*
	(1.9926)	(1.9214)
TopTen	-0.0007***	-0.0010***
	(-3.7152)	(-3.6521)
SP	-0.0006*	-0.0009*
	(-1.8063)	(-1.8180)
TAXR	-0.0014*	-0.0021
	(-1.7070)	(-1.6372)
ROE	0.0192**	0.0278**
	(2.1744)	(2.1699)
CASH	-0.0001**	-0.0002**
	(-2.1770)	(-2.1888)
SUB	0.2059	0.2666*
	(1.5970)	(1.6851)
_cons	0.1016***	0.1550***
	(4.1553)	(3.9316)
Industry	Yes	Yes
N	2850	2850
adj. R2	0.5202	0.5070

t statistics in parentheses.
*p < 0.10, **p < 0.05, ***p < 0.01.

environmental awareness is still significantly positive. This result is consistent with the results of the baseline regression, proving that green innovation quality and executive environmental awareness will reduce corporate pollution, as well as the environmental awareness. substitution effect. This once again proves the robustness of the assumptions of this article and the previous results.

5 Heterogeneity analysis

5.1 Heterogeneous effects of the manufacturing industry and non-manufacturing industry

Due to different industry characteristics, manufacturing and non-manufacturing industries have different emissions and concerns about environmental pollution (Xu et al., 2021). To further analyze the heterogeneity of the manufacturing and non-manufacturing industries of Marine-related enterprises, Table 12 reports the differences in regression results between the manufacturing and non-manufacturing industries. Columns 1 and 3 report the regression results of Marine-related manufacturing companies. Columns 2 and 4 report the regression results of non-manufacturing marine-related enterprises. The comparison results show that the negative impact of green innovation on pollution emissions is more significant among marine-related manufacturing companies. However, among non-manufacturing marine-related companies, executives' environmental awareness has a stronger inhibitory effect on corporate pollution emissions, and the substitution effect of environmental awareness is also more significant. Perhaps due to the characteristics of marine-related manufacturing enterprises, the manufacturing industry is more likely to emit pollutants during the manufacturing process. Under the supervision of environmental protection regulatory authorities, green innovation is more necessary. Therefore, green innovation in manufacturing enterprises plays an important role in reducing pollution emissions, while the impact of executives' environmental awareness is less significant.

5.2 Heterogeneous effects of State-owned enterprises and non-state-owned enterprises

According to the nature of enterprise equity, this article further divides Marine-related enterprises into State-owned enterprises and Non-state-owned enterprises for heterogeneity analysis. The results are shown in Table 13. Columns 1 and 3 present the regression results of state-owned Marine-related enterprises. Columns 2 and 4 present the regression results of non-state-owned Marine-related enterprises. The comparison shows that compared with non-state-owned enterprises, in state-owned Marine-related enterprises, green innovation and senior executives' environmental awareness play a more significant role in optimizing corporate environmental pollution. State-owned enterprises usually have stronger policy execution and resource allocation capabilities. Thus, more green innovation resources can be invested to promote the optimization of environmental pollution. Different stakeholders influence non-state-owned enterprises, so the factors that affect their ecological pollution emissions are more diverse.

6 Conclusions and suggestions

6.1 Research conclusions

Enterprise green innovation is a complex and multidimensional activity, and its successful implementation depends on multiple driving factors and effective implementation paths. Although there are many challenges, the long-term benefits of green innovation cannot be ignored. This paper conducts an empirical analysis based on the data of marine enterprises from 2008 to 2022 and finds that corporate green innovation is a crucial way to deal with air and water pollution. Enterprises can effectively reduce environmental pollution and enhance sustainable development capabilities through

TABLE 12 Manu and non-Manu industry differences.

	Manufacturing industry	Non-manufacturing industry	Manufacturing industry	Non-manufacturing industry
	TWP	TWP	TAP	TAP
	(1)	(2)	(3)	(4)
GI	-0.0025**	-0.0019*	-0.0037**	-0.0027
	(-2.1279)	(-1.6677)	(-2.1193)	(-1.6421)
EC	-0.0001	-0.0008**	-0.0000	-0.0012**
	(-0.1747)	(-2.5669)	(-0.0399)	(-2.5202)
GI×EC	-0.0000	0.0004**	-0.0000	0.0007**
	(-0.0097)	(2.2077)	(-0.1174)	(2.2102)
TopTen	-0.0006***	-0.0004**	-0.0009***	-0.0006**
	(-3.9729)	(-2.0099)	(-3.9589)	(-2.0050)
SP	-0.0006	-0.0002	-0.0009	-0.0004
	(-1.6491)	(-0.5921)	(-1.5838)	(-0.7259)
TAXR	-0.0006	-0.0002	-0.0008	-0.0005
	(-1.2636)	(-0.8324)	(-1.1882)	(-0.9680)
ROE	0.0227***	0.0001	0.0330***	-0.0000
	(2.6383)	(0.2019)	(2.6376)	(-0.0312)
CASH	-0.0002***	-0.0001	-0.0003***	-0.0002
	(-2.7823)	(-1.1060)	(-2.7174)	(-1.1595)
SUB	0.1414	0.4588	0.1716	0.8378
	(1.4123)	(0.6957)	(1.5482)	(0.7383)
_cons	0.0622***	0.0357***	0.0914***	0.0551***
	(4.9875)	(3.0123)	(5.0399)	(3.0540)
Industry	Yes	Yes	Yes	Yes
N	1559	1291	1559	1291
adj. R2	0.6251	0.1378	0.6247	0.1404

t statistics in parentheses.
*p < 0.10, **p < 0.05, ***p < 0.01.

technological innovation and management optimization. And the enhancement of executives' ecological awareness can also promote enterprises to reduce pollution, thereby promoting the harmonious development of enterprises and the environment. Further analysis found that executives' environmental awareness has a substitution effect on the relationship between green innovation and environmental pollution. It proves that executives' environmental awareness can replace the green innovation of marine enterprises to inhibit environmental pollution emissions. It fully proves the effectiveness and importance of executives' ecological awareness.

Through heterogeneity testing, this paper finds that the impact of marine enterprise green innovation and executives' environmental awareness on corporate environmental pollution emissions differs among different industries and ownership types. The negative impact of green innovation and senior executives' environmental awareness on environmental pollution is more significant in state-owned enterprises. Comparing manufacturing and non-manufacturing companies, we can find that in the manufacturing industry, green innovation has a more significant inhibitory effect on pollution emissions, but in the non-manufacturing industry, executives' environmental awareness has a more significant inhibitory effect on environmental pollution. This is due to the characteristics of the manufacturing enterprises themselves, the constraints of the government's environmental protection regulatory authorities, and the environmental protection emission reductions carried out in the daily production of the manufacturing industry. Based on this study, further research in the future will include the impact of macro factors (fiscal and taxation policies) and micro factors (corporate public reputation, capital holdings) on the green strategies and pollution emissions of marine-related companies.

TABLE 13 State-owned and Non-state-owned enterprises differences.

	State-owned enterprises	Non-state-owned enterprises	State-owned enterprises	Non-state-owned enterprises
	TWP	TWP	TAP	TAP
	(1)	(2)	(3)	(4)
GI	-0.0016***	-0.0018	-0.0024***	-0.0025
	(-4.1994)	(-1.3800)	(-4.1326)	(-1.3265)
EC	-0.0005***	-0.0013	-0.0007**	-0.0020
	(-2.7455)	(-1.4400)	(-2.4728)	(-1.4125)
GI×EC	0.0002***	0.0002	0.0002**	0.0003
	(2.8219)	(0.5332)	(2.5941)	(0.4939)
TopTen	-0.0002***	-0.0006***	-0.0002***	-0.0008***
	(-3.7022)	(-3.3455)	(-3.5602)	(-3.2224)
SP	0.0001*	-0.0007*	0.0001*	-0.0011
	(1.8876)	(-1.8210)	(1.8831)	(-1.5909)
TAXR	-0.0000	-0.0011	-0.0001	-0.0016
	(-0.3183)	(-1.4644)	(-0.4791)	(-1.4372)
ROE	0.0001	0.0318***	0.0002	0.0461***
	(0.3249)	(27.4292)	(0.2925)	(27.7719)
CASH	0.0000**	0.0003*	0.0000**	0.0005*
	(2.3462)	(1.7496)	(2.2567)	(1.7966)
SUB	0.0217**	0.4445***	0.0301*	0.4675**
	(2.2428)	(3.3166)	(1.9148)	(2.3564)
_cons	0.0205***	0.0610***	0.0306***	0.0968***
	(4.4913)	(4.0434)	(4.5192)	(4.2615)
Industry	Yes	Yes	Yes	Yes
N	1585	1265	1585	1265
adj. R2	0.2278	0.8647	0.2411	0.8645

t statistics in parentheses.
*p < 0.10, **p < 0.05, ***p < 0.01.

6.2 Suggestions

First, enterprises should strengthen the environmental awareness of executives so that management can fully understand the importance of sustainable development and its impact on the long-term development of enterprises. Then the management can prioritize environmental factors in the decision-making process, and then take more active environmental protection measures, thereby enhancing the competitiveness of enterprises in the market. Second, the government should actively formulate incentive mechanisms to encourage corporate executives to take action to protect the environment by providing tax incentives and financial subsidies. This policy support can not only reduce the economic burden of enterprises in green technology investment, but also stimulate the environmental protection motivation of enterprises, and encourage more enterprises to make a difference in environmental protection. Third, enterprises should also establish and improve environmental protection performance monitoring and evaluation mechanisms and regularly evaluate and provide feedback on the implementation effect of green innovation strategies. This monitoring mechanism can help companies promptly identify and correct problems in the implementation process, ensuring the effectiveness and sustainability of environmental protection measures. Finally, the participation of the public and investors is also an essential factor in promoting corporate environmental protection behavior. By encouraging the public and investors to monitor and provide feedback on corporate environmental performance, companies can more consciously assume environmental protection responsibilities and increase their enthusiasm for environmental protection. This transparent supervision mechanism not only enhances the social responsibility of companies, but also

promotes improvements in environmental protection. In summary, by implementing the above suggestions, marine companies can effectively reduce environmental pollution while promoting green development, positively contribute to achieving sustainable development goals, and thus achieve a win-win situation of economic benefits and environmental protection.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

CW: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. XD: Data curation, Formal analysis, Writing – original draft.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This article is a phased research result of the Social Science Planning Project of Shandong Province "Research on the relationship between the power evolution of entrepreneurs in the mixed-ownership reform of state-owned enterprises in Shandong Province and the upgrading of enterprise environmental innovation under the background of green and low carbon (22DGLJ04)".

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

Abbas, J., and Sağsan, M. (2019). Impact of knowledge management practices on green innovation and corporate sustainable development: A structural analysis. *J. Cleaner Prod.* 229, 611–620. doi: 10.1016/j.jclepro.2019.05.024

Aguilera-Caracuel, J., and Ortiz-de-Mandojana, N. (2013). Green innovation and financial performance: An institutional approach. *Organ. Environ.* 26, 365–385. doi: 10.1177/10860266135079

Andersen, M. S., and Massa, I. (2000). Ecological modernization—origins, dilemmas and future directions. *J. Environ. Policy Plann.* 2, 337–345. doi: 10.1080/714852820

Baba, H. N. (2007). Environmental management elements and corporate environmental performance of SMEs in Malaysia. *Soc. Manage. Res. J.* 4, 109–118. doi: 10.24191/smrj.v4i2.5140

Chang, C. H., and Chen, Y. S. (2013). Green organizational identity and green innovation. *Manage. Decision* 51, 1056–1070. doi: 10.1108/MD-09-2011-0314

Chen, J. H., and Chen, J. H. (2024). Digital transformation and corporate green technology innovation - Empirical evidence based on heavy polluting enterprises. *Management Science and Engineering* 13, 1043. doi: 10.12677/mse.2024.136112

Chen, H., Zhu, H., Sun, T., Chen, X., Wang, T., and Li, W. (2023a). Does environmental regulation promote corporate green innovation? *Empirical evidence Chin. carbon capture companies. Sustainability* 15, 1640. doi: 10.3390/su15021640

Chen, K. Q., Zhao, S., and Zhu, Q. W. (2023b). Executive environmental awareness and ecological innovation of small and medium-sized enterprises—the regulation of institutional pressure and organizational slack. *J. Changzhou Univ. (Social Sci. Edition)* 24, 52–61. doi: 10.3969/j.issn.2095-042X.2023.01.006

Cheng, B., Li, Z., Qiu, B., and Xiong, T. (2024). Does collective decision-making promote SOEs' green innovation? *Evidence China. J. Business Ethics* 191, 481–500. doi: 10.1007/s10551-023-05495-w

Cheng, Q., Lin, A. P., and Yang, M. (2024). Green innovation and firms' financial and environmental performance: the roles of pollution prevention versus control. *J. Account. Econ.* 101706. doi: 10.1016/j.jacceco.2024.101706

Choi, D., Shin, H., and Kim, K. (2023). CEO's childhood experience of natural disaster and CSR activities. *J. business ethics* 188, 281–306. doi: 10.1007/s10551-022-05319-3

Cohen, B., and Winn, M. I. (2007). Market imperfections, opportunity and sustainable entrepreneurship. *J. business venturing* 22, 29–49. doi: 10.1016/j.jbusvent.2004.12.001

Dangelico, R. M., and Pujari, D. (2010). Mainstreaming green product innovation: Why and how companies integrate environmental sustainability. *J Bus Ethics* 95, 471–486. doi: 10.1007/s10551-010-0434-0

Da Silva, R. F. (2019). Conscientização ambiental nas empresas: beneficios positivos para as organizações e para os trabalhadores. *Movendo Ideias* 24, 51–56. doi: 10.17648/movideias-v24n1-1372

Guinot, J., Barghouti, Z., and Chiva, R. (2022). Understanding Green Innovation: A Conceptual Framework. *Sustainability* 14(10), 5787. doi: 10.3390/su14105787

Guo, M., Wang, H., and Kuai, Y. (2023). Environmental regulation and green innovation: Evidence from heavily polluting firms in China. *Finance Res. Lett.* 53, 103624. doi: 10.1016/j.frl.2022.103624

Halynska, Iu., Kryvoruchko, O., and Kovalchuk, O. (2019). Organization of clean production projects and their impact on harmful gas emissions reduction. *Economic Ann.* 178, 12–20. doi: 10.21272/1817-9215.2019.3-12

He, N., Yang, J., and Ren, J. (2024). Pollution and green innovation: Evidence from CEOs' early-life experience. *Int. Rev. Economics Finance* 93, 65–79. doi: 10.1016/j.iref.2024.03.015

Huang, J. W., and Li, Y. H. (2017). Green innovation and performance: The view of organizational capability and social reciprocity. *J. business ethics* 145, 309–324. doi: 10.1007/s10551-015-2903-y

Javed, M., Wang, F., Usman, M., Gull, A. A., and Zaman, Q. U. (2023). Female CEOs and green innovation. *J. Business Res.* 157, 113515. doi: 10.1016/j.jbusres.2022.113515

Javorcik, B. S., and Li, Y. (2013). Do the biggest aisles serve a brighter future? Global retail chains and their implications for Romania. *J. Int. Economics* 90, 348–363.c. doi: 10.1016/j.jinteco.2012.12.004

Jiménez-Parra, B., Alonso-Martínez, D., and Godos-Díez, J. L. (2018). The influence of corporate social responsibility on air pollution: Analysis of environmental regulation and eco-innovation effects. *Corporate Soc. Responsibility Environ. Manage.* 25, 1363–1375. doi: 10.1002/csr.1645

Khan, S. A. R., Ponce, P., Yu, Z., Golpîra, H., and Mathew, M. (2022). Environmental technology and wastewater treatment: Strategies to achieve environmental sustainability. *Chemosphere* 286, 131532. doi: 10.1016/j.chemosphere.2021.131532

Khan, S. A. R., Yu, Z., Sarwat, S., Godil, D. I., and Shujaat, S. (2021). The role of block chain technology in circular economy practices to improve organisational performance. *Int. J. Logistics* 2, 1–18. doi: 10.1080/13675567.2021.1872512

Kutzschbach, J., Tanikulova, P., and Lueg, R. (2021). The role of top managers in implementing corporate sustainability—A systematic literature review on small and medium-sized enterprises. *Administrative Sci.* 11, 44. doi: 10.3390/admsci11020044

Latan, H., Jabbour, C. J. C., de Sousa Jabbour, A. B. L., Wamba, S. F., and Shahbaz, M. (2018). Effects of environmental strategy, environmental uncertainty and top management's commitment on corporate environmental performance: The role of environmental management accounting. *J. cleaner production* 180, 297–306. doi: 10.1016/j.jclepro.2018.01.106

Li, B., and Cao, G. (2022). Structural resilience change of China's marine economic network based on the data of sea-related a-share listed companies. *Prog. Geogr.* 41, 945–955. doi: 10.18306/dlkxjz.2022.06.001

Li, D., Huang, Y., and Qian, L. (2022). Potential adoption of robotaxi service: The roles of perceived benefits to multiple stakeholders and environmental awareness. *Transport Policy* 126, 120–135. doi: 10.1016/j.tranpol.2022.07.004

Li, D., Huang, M., Ren, S., Chen, X., and Ning, L. (2018). Environmental legitimacy, green innovation, and corporate carbon disclosure: Evidence from CDP China 100. *J. Business Ethics* 150, 1089–1104. doi: 10.1007/s10551-016-3187-6

Li, Y. B., Xia, Y., and Zhao, Z. (2023). The impact of executives' green cognition on corporate performance in heavily polluting industries: A moderated mediation effect model. *Sci. Technol. Prog. Countermeasures* 40, 11. doi: 10.6049/kjjbydc.2022030266

Li, W. J., and Zheng, M. N. (2016). Substantive innovation or strategic innovation? — The impact of macro-industrial policies on micro-enterprise innovation. *Economic Res.* 4, 60–73. doi: CNKI:SUN:JJYJ.0.2016-04-005

Lin, C. P., Tsai, Y. H., Chiu, C. K., and Liu, C. P. (2015). Forecasting the purchase intention of IT product: Key roles of trust and environmental consciousness for IT firms. *Technological Forecasting Soc. Change* 99, 148–155. doi: 10.1016/j.techfore.2015.06.034

Liu, Q. (2022). Can Esg performance improve the internationalization level of enterprises? Empirical evidence from Chinese listed companies. *J. Graduate Stud. Zhongnan Univ. Economics Law.* 6, 19–30.

Liu, M., and Li, Y. (2022). Environmental regulation and green innovation: Evidence from China's carbon emissions trading policy. *Finance Research Letters* 48, 103051. doi: 10.1016/j.frl.2022.103051

Lu, J. G. (2020). Air pollution: A systematic review of its psychological, economic, and social effects. *Curr. Opin. Psychol.* 32, 52–65. doi: 10.1016/j.copsyc.2019.06.024

Mao, J., Guo, Y. Q., and Cao, J. (2022). Financing platform debt and environmental pollution control. *Manage. World.* 10, 96–118. doi: 10.19744/j.cnki.11-1235/f.2022.0147

Marquis, C., and Tilcsik, A. (2013). Imprinting: Toward a multilevel theory. *Acad. Manage. Ann.* 7, 195–245. doi: 10.5465/19416520.2013.766076

Masud, M. A. K., Rashid, M. H. U., Khan, T., Bae, S. M., and Kim, J. D. (2019). Organizational strategy and corporate social responsibility: The mediating effect of triple bottom line. *Int. J. Environ. Res. Public Health* 16, 4559. doi: 10.3390/ijerph16224559

Meles, A., Salerno, D., Sampagnaro, G., Verdoliva, V., and Zhang, J. (2023). The influence of green innovation on default risk: Evidence from Europe. *Int. Rev. Economics Finance* 84, 692–710. doi: 10.1016/j.iref.2022.11.036

Porter, M., and Van der Linde, C. (1995). "Green and competitive: ending the stalemate," in *The Dynamics of the eco-efficient economy: environmental regulation and competitive advantage.* Edward Elgar Publishing, Belgium, vol. 33, 120–134.

Quan, X., Ke, Y., Qian, Y., and Zhang, Y. (2023). CEO foreign experience and green innovation: Evidence from China. *J. Business Ethics* 182, 535–557. doi: 10.1007/s10551-021-04977-z

Ren, X. C., and Li, Z. D. (2024). Can industrial robots promote pollution reduction in manufacturing enterprises? Based on empirical analysis of listed manufacturing enterprises in my country. *Reform of Economic System* 04, 108–115.

Shahin, V., Alimohammadlou, M., and Abbasi, A. (2024). Identifying and prioritizing the barriers to green innovation in SMEs and the strategies to counteract the barriers: An interval-valued intuitionistic fuzzy approach. *Technological Forecasting and Social Change* 204, 123408. doi: 10.1016/j.techfore.2024.123408

Sheikhi, A., Bahador, F., and Arashi, M. (2022). On a generalization of the test of endogeneity in a two stage least squares estimation. *J. Appl. Stat* 49, 709–721. doi: 10.1080/02664763.2020.1837084

Singh, S. K., Giudice, M. D., Chierici, R., and Graziano, D. (2020). Green innovation and environmental performance: The role of green transformational leadership and green human resource management. *Technological Forecasting Soc. Change* 150, 119762. doi: 10.1016/j.techfore.2019.119762

Tang, Y. M., Chau, K. Y., Fatima, A., and Waqas, M. (2022). Industry 4.0 technology and circular economy practices: Business management strategies for environmental sustainability. *Environ. Sci. pollut. Res.* 29, 49752–49769. doi: 10.1007/s11356-022-19081-6

Tariq, A., Badir, Y. F., Tariq, W., and Bhutta, U. S. (2017). Drivers and consequences of green product and process innovation: A systematic review, conceptual framework, and future outlook. *Technol. Soc.* 51, 8–23. doi: 10.1016/j.jclepro.2019.05.024

Tian, H., Siddik, A. B., Pertheban, T. R., and Rahman, M. N. (2023). Does fintech innovation and green transformational leadership improve green innovation and corporate environmental performance? A hybrid SEM–ANN approach. *J. Innovation Knowledge* 8, 100396. doi: 10.1016/j.jik.2023.100396

Tseng, C.-H., Chang, K.-H., and Chen, H.-W. (2021). Strategic Orientation, Environmental Management Systems, and Eco-Innovation: Investigating the Moderating Effects of Absorptive Capacity. *Sustainability* 13(21), 12147. doi: 10.3390/su132112147

Vergara, C. C., and Agudo, L. F. (2021). Fintech and sustainability: do they affect each other? *Sustainability* 13, 1–19. doi: 10.3390/su13137012

Wan, X., Wang, Y., Qiu, L., Zhang, K., and Zuo, J. (2022). Executive green investment vision, stakeholders'green innovation concerns and enterprise green innovation performance. *Front. Environ. Sci.* 10. doi: 10.3389/fenvs.2022.997865

Wang, M., Li, Y., Wang, Z., and Li, J. (2022). The heterogeneous relationship between pollution charges and enterprise green technology innovation, based on the data of chinese industrial enterprises. *Energies* 15, 1663. doi: 10.3390/en15051663

Wang, Y., Ouyang, Z., Lin, T. Y., and Chiu, S. H. (2021). "Does corporate green innovation enhance the persistence of financial performance? Evidence from Chinese listed corporations," in *Proceedings of the 2021 3rd International Conference on Management Science and Industrial Engineering (MSIE '21).* (New York, NY, USA: Association for Computing Machinery), 64–69. doi: 10.1145/3460824.3460835

Wang, X., and Wang, Y. (2021). Research on green credit policy to promote green innovation. *Manage. World* 37, 173–188.

Wang, Y. Z., and Zhao, J. (2018). Voting with money": the impact of public environmental concern on asset prices in different industries? *J. Manag. World.* 34, 46–57. doi: 10.3969/j.issn.1002-5502.2018.09.005

Wang, K., Wu, S. L., Gao, H., and Wang, C. Y. (2023). A study on the impact of air pollution on green technology innovation of listed companies in heavily polluting industries. *Journal of Management* 20(3), 400–10.

Xie, Z., Wang, J., and Zhao, G. (2022). Impact of green innovation on firm value: evidence from listed companies in China's heavy pollution industries. *Front. Energy Res.* 9, 806926. doi: 10.3389/fenrg.2021.806926

Xu, J., Jiang, Y., Guo, X., and Jiang, L. (2018). Environmental efficiency assessment of heavy pollution industry by data envelopment analysis and malmquist index analysis: empirical evidence from China. *Int. J. Environ. Res. Public Health* 18, 5761. doi: 10.3390/ijerph18115761

Yang, Y., and Wang, Y. (2021). Research on the impact of environmental regulations on the green innovation efficiency of Chinese industrial enterprises. *Polish J. Environ. Stud.* 30, 1433–1445. doi: 10.15244/pjoes/125767

Yin, Z. H., Chen, X., and Tian, L. (2022). The impact of public environmental concern on corporate green innovation. *Economic Theory Economic Management.* 42, 17. doi: 10.3969/j.issn.1000-596X.2022.07.004

Yu, H., Xu, J., Shen, F., Fang, D., and Shi, D. (2022). The effects of an environmental accountability system on local environmental governance and firms' emissions. *Economic Systems* 46(3), 100987. doi: 10.1016/j.ecosys.2022.100987

Zhang, G. (2023). Analysis of the impact of green innovation and corporate green performance. *Int. J. Energy* 3, 52–58. doi: 10.54097/ije.v3i3.012

Zhang, Z. F., Xu, H. D., Shan, S. S., Duan, H. Y., Lu, Y. Q., and Lyu, Y. P. (2022). Does ambient air quality standard contribute to green innovation of enterprises in China? Implications for environmental protection and public health. *Front. Public Health* 10. doi: 10.3389/fpubh.2022.997864

Zhu, Y. K., Gao, H. G., Ding, Q. N., and Hu, Y. N. (2022). Impact of local environmental target constraint intensity on the quality of enterprise green innovation. *China Population, Resources and Environment* 32(5), 106–119.