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GUIDING INNOVATION TOWARDS GREEN: THE PIVOTAL ROLE OF ENVIRONMENTAL REGULATIONS ON INNOVATION DIRECTION

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Abstract. Green innovation is a pivotal way to achieve both environmental and economic benefits. This study constructs an evolutionary game model to validate the Porter Hypothesis from the perspective of guiding innovation resources toward green innovation. The findings indicate that (1) Environmental regulation can reset the expected returns of different innovation directions. When the value gap between different innovation directions exceeds a certain threshold, innovation direction selection strategies will eventually evolve into a dispersed innovation mode. This not only directs innovation resources towards green but also avoids the problem of innovation direction congestion. (2) Environmental regulation should be positively proportional to the economic value gap of innovation directions and the extent of environmental tax reduction, and inversely proportional to the pollution emission gap. (3) Weaker environmental regulations should be implemented to maximize social benefits when the economic value and pollution emission gap are both small. This reduces compliance costs for innovators and achieves higher social benefits. Conversely, when the economic value gap is large, stronger environmental regulations should be implemented to alleviate innovation direction congestion, and ensure resource allocation for green innovation. Therefore, it is essential to reasonably adjust the environmental regulations to achieve a positive cycle of sustainable development. Additionally, heterogeneous environmental regulations should be designed and implemented for different industries and types of innovation.

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1. Introduction

With the rapid development of the global economy, the deterioration of the environment has constrained the achievement of sustainable development goals [1, 2]. Environmental quality, being a public good, suffers from ambiguous property rights, making it challenging to optimize through market mechanisms [3]. Consequently, governments should implement environmental regulations [4]. Appropriate environmental regulations can drive firms to innovate, reducing pollution and enhancing competitiveness simultaneously, thereby achieving a win–win scenario for both the environment and the economy [5]. In China, the environmental carrying capacity

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does not align with its economic development level, prompting the introduction of a series of environmental regulatory policies in recent years [6, 7].

Green innovation is crucial for promoting sustainable development of the environment and the economy [8, 9], as it improves environmental quality and fosters high-quality economic growth [10, 11]. Before economic development and environmental quality are decoupled, green innovation, compared to non-green innovation, typically offers lower economic value but higher ecological value. Additionally, green innovation presents dual externalities-technological and environmental-which often make it a less preferred choice for corporate innovation strategy [12, 13], which hinders the realization of sustainable development goals. Therefore, incentivizing green innovation remains a topic of in-depth exploration. Several researchers advocate for leveraging environmental regulation adjustments to promote the growth of green innovation [14–16].

Market failures often occur in the innovation sector, necessitating regulatory measures alongside market mechanisms to optimize the allocation of innovative resources [17]. Existing research has proposed solutions from intellectual property management like intellectual property protection and tiered patent systems [18, 19] to resolve market failures such as the limited acquisition of innovation benefits and the cumulative nature of innovation. However, the issue of congestion in innovation directions remains underexplored [20]. Innovation resources tend to cluster in high-return areas due to the winner-takes-all patent system. Once an innovator succeeds and patents their innovation, others working in the same area face large sunk costs if they are not the first to succeed. This situation, known as the "patent race" [21], leads to resource wastage as lower-return innovation areas receive little attention. This is akin to traffic management, where certain roads experience congestion while others remain underutilized. Addressing the failure in innovation direction allocation is crucial for maximizing social benefits.

Environmental regulation can be classified into command-and-control and market-driven types [6, 22, 23]. Market-driven environmental regulation aims to adjust corporate profitability and encourages companies to engage in innovation [24, 25]. Under this situation, there are two innovation direction strategic choices for companies: pursuing high-economic-value non-green innovation, which can increase revenue to offset regulatory costs, or focusing on high-environmental-value green innovation to reduce regulatory burdens. However, consistently opting for non-green innovation is unsustainable, on the one hand, deteriorating environmental quality harms the public interest and negatively impacts companies' ESG assessments, on the other hand, as environmental quality worsens, regulations will tighten, imposing stricter penalties on businesses. Therefore, macroeconomic policies should guide innovation resources toward green innovation, achieving a win–win scenario for both environmental and economic development.

The above analysis indicates that green innovation, despite its high social value, often becomes a sacrifice in the selection of innovation directions due to its relatively low economic value [12, 13]. Cui *et al.* (2022) argue that green innovation is primarily driven by environmental protection policies [15], which leads to a critical scientific question: Does environmental regulation guide the innovation resources flows toward green innovation, and if so, how? This study explores the question in three parts. First, we construct an evolutionary game model for the innovation direction selection process. This model identifies the equilibrium points, showing that the direction of innovation evolves into dispersed research mode if the value gap between two directions is above a certain range, the dispersed research mode means the innovators tend to research in different directions, which ensures that innovation resources flow toward green innovation while avoiding congestion issues. Second, we investigate the pathway of how environmental regulation resets the payoff gap between innovation directions, thereby steering innovative resources toward the green sector. Third, we analyze the optimal setup for environmental regulation under different innovation direction value gaps, aiming to maximize social benefits. This research provides both academic and practical contributions.

Academic contributions. Firstly, this paper demonstrates that the innovation direction will ultimately evolve into a dispersed research mode by constructing an evolutionary game model. This provides new insights into addressing market failures in the innovation direction congestion problem. Secondly, the paper extends the Porter hypothesis by providing a mechanism through which environmental regulation promotes green innovation from the perspective of innovative resource acquisition. Thirdly, the paper offers a theoretical foundation for heterogeneous environmental regulations to achieve maximum social benefits.

Practical contributions. Our study provides strategic insights for innovators to select the innovation directions as we found that the innovation direction selection is related to the value gap, innovation success rate, environmental regulation, and tax reduction extent. Additionally, our study provides practical optimization suggestions for the adjustment of environmental regulations. We use the environmental protection tax law of China as an example and draw upon OECD data to conduct simulation analyses, we offer advice on environmental regulations to maximize the social benefits, which emphasizes the central role of environmental regulation in promoting sustainable development.

The structure is as follows: Section 2 provides a literature review, offering a comprehensive overview of existing research. Section 3 details the construction of the evolutionary game model. Section 4 presents the evolutionary game analysis. Section 5 showcases the evolutionary game simulation. Section 6 offers discussion and recommendations.

2. Literature review

2.1. Environmental regulation and green innovation

Environmental regulation refers to the mandatory restrictions imposed by the government through legislation to protect the environment and promote the rational and effective use of resources. This includes but is not limited to, the imposition of pollution charges, environmental administrative penalties, environmental protection fiscal expenditures, and the formulation of environmental regulations [4]. Environmental regulations can be categorized into command-and-control and market-driven types [6,22,23]. Command-and-control environmental regulations are compulsory, utilizing tools such as production bans, nontransferable licenses, and enterprise closures. They offer the advantage of rapid implementation with significant short-term effects but tend to be less effective in motivating firms' independent innovation and incur high enforcement costs [26–28]. On the other hand, market-driven environmental regulations are more flexible, employing mechanisms like environmental taxes, technical standards, subsidies, and deposit refunds, which can effectively encourage firms to innovate independently and boost corporate vitality [24, 25]. However, their efficacy is subject to various influencing factors and their implementation outcomes are difficult to ensure, with inherent time lags [29, 30]. The Porter hypothesis posits that environmental regulation has an innovation offset effect, which can fully or partially compensate for the costs incurred by environmental regulation, and firms can enhance their competitiveness through increased innovation [5].

Green innovation encompasses technological advancements targeted at environmental management, pollution prevention, waste reduction, and energy conservation [31, 32]. By engaging proactively in green innovation, firms can not only comply with environmental regulations but also enhance energy efficiency and minimize waste [33, 34]. Research specifically investigates whether environmental regulations spur green innovation, with findings clustered into four categories:

① Promoting. Appropriate environmental regulation can motivate firms to innovate, exerting a significant positive effect on green innovation [35–43]. ② Inhibiting. Some studies contend that environmental regulation increases firms' costs, reduces their competitiveness, and hampers innovation by limiting available resources [44–46]. ③ Nonlinear relationship. Empirical research has identified a nonlinear impact of environmental regulation on green innovation. As environmental regulations become more stringent, their effect on green innovation demonstrates a U-shaped pattern, initially decreasing then increasing, or an N-shaped pattern, initially increasing, then decreasing, and increasing again [47–49]. ④ Indeterminate effects. This viewpoint suggests that the effect of environmental regulation on green innovation is uncertain, the relationship cannot be simply classified as promotive or inhibitive, as it may vary due to industry, time, and the type of environmental regulation, indicating heterogeneity in outcomes [4, 50, 51].

2.2. The factors of the innovation direction

Innovation is characterized by two main features. First, innovators have limited ownership over the value of their innovations [17, 52], leading early research to explore how to safeguard the innovators' profits, such as by strengthening intellectual property protection and increasing subsidies for innovative activities [53]. Second, innovation is sequential, the innovation process follows an order where preceding innovations can have a positive spillover effect on subsequent innovations, but the profits of subsequent innovators may encroach upon those of their predecessors. Existing research has also addressed how to balance this market failure, for instance, by establishing a tiered patent system to weigh the benefits of innovators at different stages [18].

Hopenhayn and Squintani (2021) found that even when innovators capture the full benefits of their innovations, inefficiency in innovation can still arise due to the unequal distribution of innovation resources across different research directions [20], resulting in a distortion of the direction of innovation [54]. This is because the high-return projects often attract more innovation resources, and under the patent system, the profits for innovators in a particular direction can plummet after the technological breakthrough (other innovators succeed ahead), leading to the wastage of innovation resources [20].

At present, there are relatively few researches on the innovation direction, mainly existing research primarily examines the distortion of innovation directions through theoretical models. Bryan & Lemus (2017) developed an innovation direction model based on horizontal spillover effects and the sequential nature of innovation [54], revealing that excessive intellectual property protection can distort innovation directions. Lee (2020) considered innovators and two research projects, finding that innovation resources might bypass projects with high innovation value but greater difficulty [55]. Moraga-González *et al.* (2022) constructed a market model with one leader and many challengers, where each challenger aims to become the market leader through innovation [56]. Their findings suggest that the allocation of innovation resources is influenced by factors such as project profitability, difficulty, and social value, leading firms to overinvest in projects with higher expected profits but underinvest in projects with high social value.

2.3. Literature commentary

The existing empirical studies on the impact of environmental regulation on green innovation are inconclusive [4], and the effect exhibits heterogeneity across regions, industries, and time periods. Wang *et al.* (2024) argue that environmental regulation is not necessarily more effective when it is stricter, rather, an appropriate intensity can improve firms' green decision-making [57]. Environmental regulation can influence firms' strategic choices in innovation direction by adjusting the expected returns. Most current research on innovation direction is theoretical and primarily explores the impact of innovation incentive policies on corporate innovation. However, the impact of environmental regulation on innovation direction remains underexplored.

Green innovation has dual positive externalities in terms of technology and the environment. On one hand, it is incentivized by intellectual property policies, for example, many countries have established fast-track mechanisms for green patents. On the other hand, it is motivated by environmental regulations [15]. We believe that innovation incentivized by environmental regulation can be categorized into two types: First, non-green innovation with high economic value and low ecological value, which offsets the costs imposed by environmental regulation by increasing corporate revenue. Second, green innovation with low economic value and high ecological value, which reduces the costs imposed by environmental regulation by minimizing pollution. It is essential to allocate innovation resources reasonably between these two types of innovation. Given the existence of the patent system, the selection of innovation direction is a game-theoretic process among enterprises.

Existing research often singularly explores the impact of environmental regulation on green innovation [38, 39], with few studies investigating how environmental regulation influences the allocation of innovation resources. In recent years, an increasing number of studies have employed evolutionary game models to analyze the impact of environmental regulation on strategic choices of agents [58, 59]. These include studies on corporate carbon emission strategies [59], collusion behavior between firms and third parties [60], environmentally friendly production behaviors [61, 62], and green supply chain optimization [63, 64].

Therefore, this study aims to use a two-player evolutionary game model to analyze the impact of environmental regulation on firms' innovation direction choices. It seeks to explore the optimal paths for the rational allocation of innovation resources under environmental regulation.

3. Innovation direction selecting game model construction

3.1. Description of the game

When ecological and economic development are not yet fully decoupled, non-green innovation brings high economic value but also leads to high pollution. Therefore, most countries are currently encouraging green innovation to improve environmental quality and achieve sustainable development [65].

The patent system is the primary method of intellectual property protection, designed to ensure exclusive returns for innovators to incentivize innovation. Once an innovator succeeds, they apply for a patent to secure long-term exclusive innovation returns, which creates a "winner-takes-all" scenario, where only the first successful innovator receives rewards. Other innovators, even if they have invested significantly in the same direction, incur sunk costs if they are not the first to succeed. This is the essence of the "patent race" [21].

Thus, the choice of innovation direction is a game between innovators. Suppose there are two innovators (Player 1 and Player 2). The direction chosen by one innovator affects the strategic choices of the other. Each innovator's choice of direction is interdependent, they adjust their strategies based on the other's behavior during the game, eventually evolving into stable strategies. This interdependence aligns with the characteristics of evolutionary game theory.

The two-player game for selecting innovation directions unfolds as follows: There are two modes for innovators to choose innovation directions, one is concentrated research, where both innovators research in the same direction. The other is dispersed research, where each innovator pursues a different direction separately. Due to the existence of the patent system, not all innovators will concentrate on a single high-value direction, which could lead to "innovation congestion" [20]. Instead, innovators will reasonably choose their directions based on the principle of maximizing individual returns.

3.2. Game assumptions

3.2.1. Game participants

Two innovators (Player 1 and Player 2) are the participants in this game. Both innovators rationally pursue the maximization of their own payoffs. They engage in a Nash game to select their innovation directions.

3.2.2. Game background

Assume there are two innovation directions: green innovation (Q_1) and non-green innovation (Q_2). If Q_1 succeeds, it generates an economic value of Z_L and an environmental pollution of P_L. If Q_2 succeeds, it generates an economic value of Z_H and an environmental pollution of P_H. Assume the national standard for environmental pollution is P_0, and it holds that $0 < Z_L < Z_H$, $0 < P_L < P_0 < P_H$. Additionally, assume constants k and j such that $Z_L = k * Z_H$ and $P_L = j * P_H$, where $0 < k <= 1$ and $0 < j <= 1$. The constants k and j represent the gaps in economic values and pollution emissions between the two innovation directions. The smaller the values of k and j, the greater the gaps in economic values and pollution emissions.

Market-driven environmental regulation can guide the innovation direction by resetting the expected returns. Typically, market-driven environmental regulation imposes taxes or fees at a multiple r of the pollution amount ($r > 0$). The larger the value of r, the higher the intensity of the environmental regulation. Additionally, if the pollution is below the national standard, it qualifies for a tax reduction to s times the original tax amount ($0 < s < 1$). If environmental regulations are implemented, the total values obtained upon success for Q_1 and Q_2 are denoted as R_1 and R_2, respectively. They can be formulated as follows:

$$R_1 = Z_L - r * s * P_L \tag{1}$$

		Player 2	
		Q_1	Q_2
Player 1	Q_1	(p*(1-p/2), p*(1-p/2))	(p, p*a)
	Q_2	(p*a, p)	(0,0)

FIGURE 1. Payoff matrix for innovator direction selecting game.

$$R_2 = Z_H - r * P_H. \tag{2}$$

Substituting $Z_L = k * Z_H$ and $P_L = j * P_H$, assuming $Z_H = m$ and $P_H = n$, we get:

$$R_1 = m * k - n * j * r * a \tag{3}$$

$$R_2 = m - n * r. \tag{4}$$

To simplify the analysis, we assume $R_2 = a * R_1$, where $a > 0$. The constant a represents the total value gap between the two innovation directions after adjusting for environmental regulation. If $a < 1$, a smaller value indicates a greater gap between the two directions. Conversely, if $a > 1$, a larger value indicates a greater gap.

3.3. Innovation direction strategies

In the process of selecting innovation directions, the two innovators can freely choose their innovation strategies based on their needs and the realization of innovation value. The selected result may be either concentrated or dispersed research. Assume the success rate for dispersed research is p, and its q for concentrated research. Drawing from Hopenhay and Squintani (2021), the relationship between p and q satisfies $1 > q > p > 0$, $q - p < q$, and $q = 2 * p - p\hat{}2 < 2 * p$ [20]. Assume that Player 1 selects (Q_1, Q_2) with probabilities $(x, 1 - x)$, and Player 2 selects (Q_1, Q_2) with probabilities $(y, 1 - y)$.

If they concentrated research on Q_1, due to the patent system, the first innovator to succeed will gain all the benefits. Therefore, the expected individual payoff when focusing on Q_1 is $(1/2) * q * R_1$, which equals to $p*(1-p/2)*R_1$. Under the purpose of guiding innovation resources toward green fields, we assume that if both innovators choose to research non-green innovation (Q_2), the expected individual payoff is zero.

In the case of dispersed research, the expected payoff for choosing Q_1 and Q_2 are $p*R_1$ and $p*R_2$, respectively, and $p * R_2$ equals $p * a * R_1$. Normalizing R_1 to 1, we obtain the payoff matrix for both innovators, as shown in Figure 1.

The payoff matrix indicates that when $a < (1-p/2)$, there is a unique Nash equilibrium, (Q_1, Q_1), suggesting that both players will focus on green innovation. This implies that when the value difference between the two innovation directions is small, innovators are willing to participate in a "patent race", even though the loser may face substantial sunk costs. Conversely, when $a > (1-p/2)$, there are two Nash equilibriums, (Q_1, Q_2) and (Q_2, Q_1), indicating that players will pursue dispersed research.

4. Analysis of the evolutionary game model

4.1. Evolutionarily stable strategy

Given that the selection of innovation directions is a long-term dynamic adjustment process, we adopt an evolutionary game model to analyze the dynamic evolution of game strategies. Based on the payoff matrix, when Player 1 chooses Q_1, the expected benefit for Player 1 to chooses Q_1 is M_{11}, to chooses Q_2 is M_{21}, thus, the average expected benefit for Player 1 is M_1.

$$M_{11} = y * (p * (1 - p/2)) + (1 - y) * p = p - \frac{p^2 * y}{2} \tag{5}$$

$$M_{21} = y * p * a + (1 - y) * 0 = y * p * a \tag{6}$$

$$M_1 = x * \left[p - \frac{p^2 * y}{2}\right] + (1 - x) * y * p * a. \tag{7}$$

The replication dynamic equation for Player 1 is $F(x)$:

$$F(x) = x * [M_{11} - M_1] = \frac{p * x * (x - 1) * (2 * a * y + p * y - 2)}{2}. \tag{8}$$

Similarly, the expected benefit for Player 2 to chooses Q_1 is M_{12}, to chooses Q_2 is M_{22}, the average expected benefit for Player 2 is M_2.

$$M_{12} = x * (p * (1 - p/2)) + (1 - x) * p = p - \frac{p^2 * x}{2} \tag{9}$$

$$M_{22} = x * p * a + (1 - x) * 0 = x * p * a \tag{10}$$

$$M_2 = y * [p - (p\hat{\ }2 * x)/2] + (1 - y) * x * p * a. \tag{11}$$

Thus, the replication dynamic equation for Player 2 is $F(y)$:

$$F(y) = y * [M_{12} - M_2] = \frac{p * y * (y - 1) * (2 * a * x + p * x - 2)}{2}. \tag{12}$$

By combining $F(x)$ and $F(y)$, and setting $F(x) = 0$ and $F(y) = 0$, we find that there are five equilibrium points in this evolutionary game system: $(0, 0)$, $(1, 0)$, $(0, 1)$, $(1, 1)$, and (x^*, y^*), where $x^* = y^* = 2/(2 * a + p)$.

According to the evolutionary game analysis method, and combined with the replication dynamic equations (8) and (12), we derive the Jacobian matrix (J):

$$J = \begin{vmatrix} \frac{p*(2*x-1)*(2*a*y+p*y-2)}{2} & \frac{p*x*(2*a+p)*(x-1)}{2} \\ \frac{p*y*(2*a+p)*(y-1)}{2} & \frac{p*(2*y-1)*(2*a*x+p*x-2)}{2} \end{vmatrix}$$

From the Jacobian matrix, we obtain the determinant $\det(J)$ and the trace $\operatorname{tr}(J)$:

$$\begin{aligned} \det(J) = -(&p\hat{\ }2 * ((4 * x + 4 * y - 12 * x * y) * x * y * a\hat{\ }2 + ((16 \\ &* y + 4 * p * y - 12 * p * y\hat{\ }2 - 8) * x\hat{\ }2 + (4 * p \\ &* y\hat{\ }2 - 16 * y + 16 * y\hat{\ }2 + 4) * x - 8 * y\hat{\ }2 + 4 * y) \\ &* a + ((-3 * x * y + x + y) * x * y * p\hat{\ }2 + (2 * (2 * x \\ &- 1) * (2 * y - 1) * (x + y)) * p - 4 * (2 * x - 1) * (2 * y - 1)))/4 \end{aligned} \tag{13}$$

$$\begin{aligned} \operatorname{tr}(J) = -(&p * (4 * x + 4 * y + 2 * a * x + 2 * a * y + p * x + p * y \\ &- 8 * a * x * y - 4 * p * x * y - 4))/2. \end{aligned} \tag{14}$$

Using the local stability of the Jacobian matrix J, we can determine the stability of the five equilibrium points in the evolutionary game between the two innovators and their stable strategies. When an equilibrium point satisfies $\det(J) > 0$ and $\operatorname{tr}(J) < 0$, the equilibrium point is in an equilibrium state. We compute the determinant and trace of the Jacobian matrix for each equilibrium point, as shown in Table 1.

We categorize the relationship between a and p into two scenarios and discuss the equilibrium state (Tab. 2).

TABLE 1. Analysis of local equilibrium results.

Equilibrium point	det(J)	tr(J)
$E_1(0,0)$	p^2	$2*p$
$E_2(1,0)$	$\frac{p^2*(2*a+p-2)}{2}$	$-\frac{p*(2*a+p)}{2}$
$E_3(0,1)$	$\frac{p^2*(2*a+p-2)}{2}$	$-\frac{p*(2*a+p)}{2}$
$E_4(1,1)$	$\frac{p^2*(2*a+p-2)^2}{4}$	$p*(2*a+p-2)$
$E_5(x^*,y^*)$	$-\frac{p^2*(2*a+p-2)^2}{(2*a+p)^2}$	0

TABLE 2. Equilibrium state analysis of equilibrium points.

	$a>(1-p/2)$			$a<(1-p/2)$		
Equilibrium point	det(J)	tr(J)	State	det(J)	tr(J)	State
$E_1(0,0)$	+	+	Unstable	+	+	Unstable
$E_2(1,0)$	+	–	ESS	–	–	Unstable
$E_3(0,1)$	+	–	ESS	–	–	Unstable
$E_4(1,1)$	+	+	Unstable	+	–	ESS
$E_5(x^*,y^*)$	–	0	Saddle Point			

From Table 2, it can be observed that $(1,0)$ and $(0,1)$ are two equilibrium points of the evolutionary game system for the innovation direction selection. This indicates that dispersed research by both innovators is the stable state. Points $(0,0)$ and $(1,1)$ are unstable, which implies that even if both innovators initially concentrate on a same direction, they will gradually evolve towards dispersed research. The point (x^*,y^*) is a saddle point in the evolutionary game system. The dynamic evolution process is shown in Figure 2.

Based on this, we discuss two scenarios.

Scenario one: $a>(1-p/2)$

As shown in Table 2, when $a>(1-p/2)$, the evolutionarygame system for innovation direction has two ESS points: $(1,0)$ and $(0,1)$, which indicate that dispersed research is the stable state in the evolutionary game. The points $(0,0)$ and $(1,1)$ are unstable, suggesting that even if both innovators initially engage in concentrated research in one single direction, they will evolve towards dispersed research. The point (x^*,y^*) is the saddle point of the system. The dynamic evolutionary process is illustrated in Figure 2a, where five equilibrium points form two distinct regions. The line E_1–E_5–E_4 serves as the boundary between strategies. If the initial state of the innovators is below E_1–E_5–E_4, the system tends to converge to point $E_2(1,0)$. Conversely, if the initial state is above this line, it converges to point $E_3(0,1)$. Over time, the system stabilizes into a state of dispersed research.

This finding has practical implications. Innovators consider their own and their competitors' capabilities when choosing innovation direction, ultimately evolving towards dispersed research. Specifically, if player 1 has stronger green innovation capabilities, such as more green patents or greater resource investment in green innovation, player 2 may opt for non-green innovation to achieve higher returns, thus relieving congestion in innovation.

Scenario two: $a<(1-p/2)$

When $0<a<(1-p/2)$, the evolutionary game system has a single ESS point at $(1,1)$. This suggests that when the value gap between different innovation directions is small, innovators prefer concentrated research

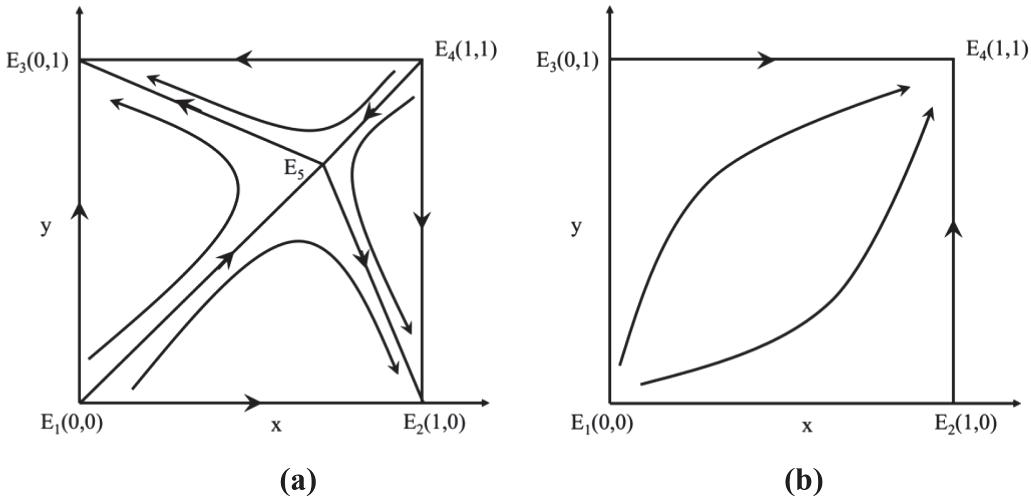

FIGURE 2. The dynamic evolution process.

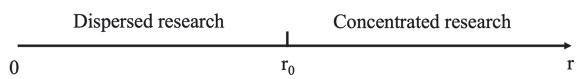

FIGURE 3. The innovation modes under different environmental regulation.

in green innovation, even if losers face sunk costs. The dynamic evolutionary process, illustrated in Figure 2b, shows that regardless of the initial state, the system converges to point $E_4(1,1)$. Over time, the system stabilizes into a state of concentrated research in green innovation.

This result also bears practical significance. When the value difference between green and non-green innovations is small, innovators tend to participate in patent races and adopt concentrated research strategies, whether for gaining legitimacy or to build a green image.

4.2. Adjustment strategy for environmental regulation

Given that $a = R_2/R_1 = (m - n * r)/(m * k - n * j * r * s)$, we can calculate the critical value of environmental regulation intensity as r_0.

$$r_0 = \frac{m * (k * (p-2) + 2)}{n * (j * s * (p-2) + 2)}. \tag{15}$$

The intensity of environmental regulation influences innovators' choices of innovation direction. As it is generally difficult to adjust environmental regulations in the short term, innovators must analyze the relationship between compliance costs for environmental protection and the sunk costs of participating in patent races to decide their innovation direction. The selecting in innovation direction under established regulation depends on r_0.

We discuss two scenarios, shown at Figure 3:

Scenario one: $r < r_0$

Innovators tend toward dispersed research. If regulation intensity is below the critical value, the compliance cost for environmental protection is relatively low. If Player 1 (or Player 2) has a higher green innovation capability, Player 2 (or Player 1) may opt for non-green innovation to avoid the patent race, choosing to incur the environmental compliance cost for greater exclusive innovation gains. This leads both innovators to spontaneously evolve towards dispersed research.

Scenario two: $r > r_0$

Innovators tend toward concentrated research. If regulation intensity exceeds the critical value, the compliance cost for environmental protection is relatively high. Even if Player 1 (or Player 2) has superior green innovation capability, Player 2 (or Player 1) may engage in green innovation to reduce compliance costs, joining the green patent race and accepting the risk of patent race failure to lower these costs.

Equation (15) indicates that the value of r_0 depends on parameters related to different innovation directions, resulting in varied impacts of established environmental regulations on different innovation paths. Since m, n, p are absolute parameters of the innovation direction and do not involve the comparison between the two innovation directions, we take the partial derivatives with respect to k, j, s:

$$\frac{\partial r_0}{\partial k} = -\frac{m*(2-p)}{n*(2-j*s*(2-p))} < 0 \tag{16}$$

$$\frac{\partial r_0}{\partial j} = \frac{m*s*(2-p)*(2-k*(2-p))}{n*(2-j*s*(2-p))^2} > 0 \tag{17}$$

$$\frac{\partial r_0}{\partial s} = \frac{j*m*(2-p)*(2-k*(2-p))}{n*(2-j*s*(2-p))^2} > 0. \tag{18}$$

From equations (16) to (18), it can be observed that r_0 is inversely proportional to the economic value difference k between innovation directions, and directly proportional to both the pollution emission difference j and the reduction intensity s. We assume that the initial state of r is at r_0. For innovation directions with a larger economic value gap (smaller k), a smaller pollution emission gap (larger j), and less reduction intensity (larger s), r_0 gets larger, thus leading $r < r_0$, environmental regulation tends to guide innovators towards dispersed research. Conversely, for directions with a smaller economic value gap (larger k), a larger pollution emission gap (smaller j), and greater reduction intensity (smaller s), r_0 gets smaller, leading $r > r_0$, here, environmental regulation tends to guide innovators towards concentrated research in green innovation.

5. Evolutionary game simulation

5.1. Innovation direction selection process

We selected the following parameter values for our simulation: $p = 0.5$, $j = 0.5$, $k = 0.5$, $s = 0.5$, $m = 500$, $n = 10$, $r = 2$. The reasons for these values are as follows:

Taking China's environmental protection tax law as an example, China's environmental tax is based on the pollution equivalent, with different amounts set for various pollutants. For instance, atmospheric pollutants are taxed at 1.2 to 12 yuan per pollution equivalent, and water pollutants are taxed at 1.4 to 14 yuan per pollution equivalent. Furthermore, for taxpayers whose emission concentrations of taxable atmospheric or water pollutants are below 30% of national and local standards, the tax is reduced to 75% of the original tax. If the emission concentrations are below 50% of the standards, a 50% tax reduction is applied. Based on these legal provisions, r can range from 1.2 to 14, and s can be 0.5 or 0.75. In this study, we set $r = 2$ and $s = 0.5$.

Since a significant difference in economic value and pollution emissions between the two directions would lack comparability, while a negligible difference would not effectively reflect directional choice, we select intermediate values, namely $j = k = 0.5$. The values for m and n are absolute quantities for innovation directions and are chosen with flexibility. Based on the OECD database, the proportion of environmental taxes to GDP ranges from 0.01% to 3.79%. This implies that $(n*r*(j*s+1))/(m*(k+1))$ should fall within this range. Thus, we set $m = 500$ and $n = 10$, resulting in the proportion of environmental tax to economic value as 3.33%. Therefore, the selected parameter values are consistent with real-world situations. Figure 4 shows the evolutionary trajectories simulation of x and y.

From Figure 4, it is apparent that the innovation strategies evolve towards $(0, 1)$ and $(1, 0)$, supporting the earlier evolutionary game analysis conclusion that innovators tend towards dispersed research. It should be noted

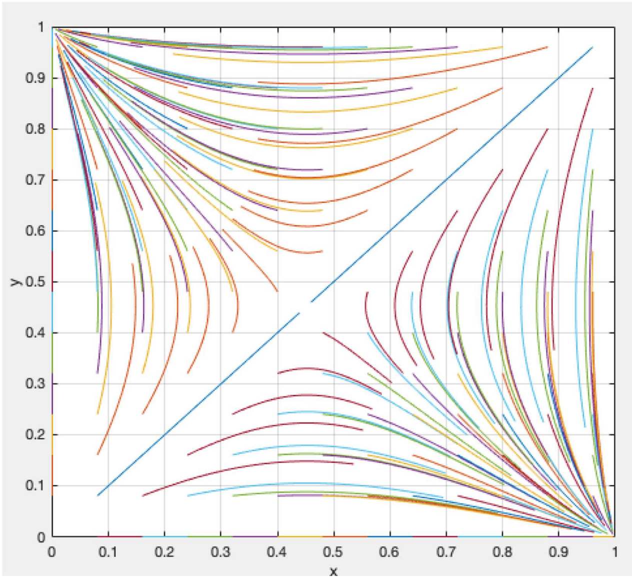

FIGURE 4. Simulation of innovation direction selection.

that since environmental regulation cannot increase indefinitely, there is no scenario of concentrated research after satisfying the aforementioned real-world value conditions. Therefore, the subsequent discussion will focus on the context of dispersed research.

5.2. Analysis of social benefits of innovations

Adjustments in environmental regulation not only need to guide the innovation direction but also aim to maximize social benefits. Since the innovation direction will gradually evolve into dispersed research, the social benefits at this stage can be represented as:

$$U = p * (R_1 + R_2) = p * \left(1 + \frac{m - n * r}{m * k - n * j * r * s}\right)_0 . \tag{19}$$

Therefore, the objective function is:

$$\max U = p * \left(1 + \frac{m - n * r}{m * k - n * j * r * s}\right)$$
$$\text{s.t.} \begin{cases} 0 < r < \frac{m*(k*(p-2)+2)}{n*(j*s*(p-2)+2)} \\ 0 < k < 1, 0 < j < 1, 0 < s < 1, 0 < p < 1, 0 < m, 0 < n. \end{cases} \tag{20}$$

As mentioned earlier, we set $p = 0.5$, $s = 0.5$, $m = 500$, and $n = 10$. We analyze how social benefits vary with j and k when r is set to 0.5, 1, 1.5, and 2. A higher value of r indicates stricter environmental regulation. The result is shown in Figure 5.

From Figure 5, we can draw the following conclusions:

Firstly, when the gaps in economic value and pollution emissions of the two innovation directions are relatively similar (*i.e.*, k and j are close to 1), the damage to environmental quality from economic activities is relatively low. Thus, the intensity of environmental regulation should be set at a low level. This can reduce compliance costs for firms and allow innovators to allocate more funds to innovation activities, which is beneficial to overall social benefits.

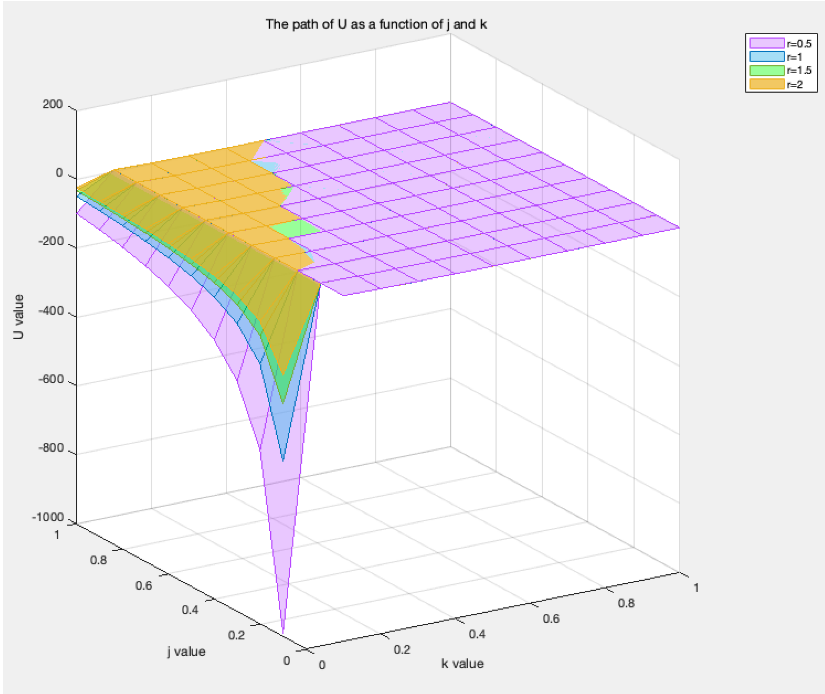

Figure 5. Simulation of social benefits.

Secondly, when there is a significant gap in the economic values of the two innovation directions (*i.e.*, k is close to 0), regardless of the pollution emissions gap, strict environmental regulation should be implemented to achieve higher social benefits. This is because, with a large disparity in economic value between the innovation directions, innovators are more willing to undertake the risk of failure. Consequently, innovation resources tend to concentrate on non-green innovation areas, neglecting green innovation. This not only leads to resource misallocation due to congestion in the innovation direction but also deteriorates the ecological environment. Therefore, strict environmental regulation should be implemented to correct the excessive inclination towards non-green innovation and maximize overall social benefits.

6. Discussion and recommendations

6.1. Results and discussion

6.1.1. Research findings

Current research on environmental regulation and innovation often focuses on testing the Porter Hypothesis [38, 46]. Most studies are empirical [4, 66] or analyze the game between governments and firms in setting environmental regulations and environmental protection behaviors [3, 63, 67, 68]. Few studies address the game process of innovation direction choices. Additionally, the definition of innovation is usually broad, with only some studies focusing on green innovation [6, 7, 69]. Cui *et al.* (2022) found that green innovation is primarily driven by environmental protection policies [15]. However, few studies detail the contribution of environmental regulation to the acquisition of green innovation resources.

The alleviation of innovation direction congestion has been a research hotspot in recent years [20, 54], aiming to optimize the allocation of innovation resources by guiding individual innovation behaviors [70]. Therefore, exploring how environmental regulation directs innovation resources toward green innovation is necessary.

Moreover, most studies suggest that adjustments in environmental regulation mainly depend on environmental quality [7]. Few studies, however, examine the role of environmental regulation in innovation direction selection from the perspective of innovation direction adjustments. Our study fills this research gap, providing new insights into environmental regulation adjustments and promoting a positive cycle of sustainable development through environmental regulation.

Overall, this study expands the Porter Hypothesis by demonstrating the contribution of environmental regulation to sustainable development by guiding innovation resources towards green innovation. It also supplements research on solving innovation direction congestion, providing academic significance. Combined with simulation analysis, we explain the necessity of optimizing environmental regulation to achieve maximum social benefits, presenting practical significance as well.

6.1.2. Limitations and future research

Although this study employs an evolutionary game model to analyze the game process of innovation direction selection by innovators, this method effectively reflects the evolution process of innovators' decisions on innovation direction [3, 58, 62]. It successfully simulates firms' innovation strategies and demonstrates that the long-term evolutionary result will stabilize in dispersed research, consistent with the findings of Hopenhay and Squintani (2021). However, due to the difficulty in finding cases of innovation direction during the simulation process, we used data from the Chinese environmental protection tax law and OECD database to perform the simulation analysis. This approach inputs real data into the model as accurately as possible, adding practical significance to the study.

Future research can further collect micro-enterprise data to analyze the process of innovators' choices in innovation direction, thereby providing more research evidence and recommendations for heterogeneous environmental regulation.

6.2. Policy recommendations

Firstly, it is essential to reasonably adjust environmental regulations. This will not only improve environmental quality but also guide innovation resources towards green innovation and achieve a positive cycle of sustainable development. Policymakers should evaluate the economic value and pollution emission gaps of innovation directions. They can then use these evaluations as a reference to optimize the environmental regulations. Additionally, dynamic adjustments in the reduction extents of environmental taxes and national pollution standards can reset the value gaps between innovation directions. This approach optimizes the allocation of innovation resources, avoids frequent regulatory changes, and reduces policy uncertainty. To increase the attractiveness of green innovation, policymakers can enhance its expected returns through incentives such as green innovation subsidies and fast-track green finance channels.

Secondly, it is crucial to design and implement heterogeneous environmental regulations for different industries and types of innovation. Policymakers should set varying regulatory standards based on industry characteristics and innovation categories. For innovation directions with a large economic value gap, higher environmental regulations should be applied to prevent resources from being excessively concentrated in non-green innovation. Conversely, when economic value and pollution emission gaps are smaller, lower environmental regulations should be implemented to reduce compliance costs for firms and achieve greater social benefits. Additionally, during the implementation process, tax reductions and other policy combinations can optimize the effect of environmental regulations on adjusting innovation directions. To ensure feasibility and acceptance, it is advisable to first conduct pilot programs in specific industries or regions. Accumulating practical experience in this way can facilitate gradual broader implementation.

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The website of the Ministry of Ecology and Environmental of the People's Republic of China: https://www.mee.gov.cn/ywgz/fgbz/fl/201811/t20181114_673632.shtml.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The research data associated with this article are included in the article.

References

[1] X.L. Ouyang, Q. Li and K.R. Du, How does environmental regulation promote technological innovations in the industrial sector? Evidence from Chinese provincial panel data. *Energy Policy* **139** (2020) 111310.

[2] H. Peng, N. Shen, H.L. Liao, H.Q. Xue and Q.W. Wang, Uncertainty factors, methods, and solutions of closed-loop supply chain – a review for current situation and future prospects. *J. Clean. Prod.* **254** (2020) 120032.

[3] H. Sun and G.K. Gao, Research on the carbon emission regulation and optimal state of market structure: based on the perspective of evolutionary game of different stages. *RAIRO-Oper. Res.* **56** (2022) 2351–2366.

[4] J. Liu, M. Zhao and Y. Wang, Impacts of government subsidies and environmental regulations on green process innovation: a nonlinear approach. *Technol. Soc.* **63** (2020) 101417.

[5] M.E. Porter and C. Vanderlinde, Toward a new conception of the environment-competitiveness relationship. *J. Econ. Perspect.* **9** (1995) 97–118.

[6] H. Peng, N. Shen, H. Ying and Q. Wang, Can environmental regulation directly promote green innovation behavior? – Based on situation of industrial agglomeration. *J. Clean. Prod.* **314** (2021) 128044.

[7] Y.Y. Chen, Z.Y. Yao and K. Zhong, Do environmental regulations of carbon emissions and air pollution foster green technology innovation: evidence from China's prefecture-level cities. *J. Clean. Prod.* **350** (2022) 131537.

[8] K.R. Du and J.L. Li, Towards a green world: How do green technology innovations affect total-factor carbon productivity. *Energy Policy* **131** (2019) 240–250.

[9] M.Y. Wang, Y.M. Li, Z.X. Cheng, C. Zhong and W.J. Ma, Evolution and equilibrium of a green technological innovation system: simulation of a tripartite game model. *J. Clean. Prod.* **278** (2021) 123944.

[10] X. Ji, M. Umar, S. Ali, W. Ali, K. Tang and Z. Khan, Does fiscal decentralization and eco-innovation promote sustainable environment? A case study of selected fiscally decentralized countries. *Sustain. Dev.* **29** (2021) 79–88.

[11] L. Wang, H.L. Chang, S.K.A. Rizvi and A. Sari, Are eco-innovation and export diversification mutually exclusive to control carbon emissions in G-7 countries? *J. Environ. Manage.* **270** (2020) 110829.

[12] M. Marino, P. Parrotta and G. Valletta, Electricity (de)regulation and innovation. *Res. Policy* **48** (2019) 748–758.

[13] D. Popp, Environmental policy and innovation: a decade of research. *Int. Rev. Environ. Res. Econ.* **13** (2019) 265–337.

[14] S. Shao, Z.G. Hu, J.H. Cao, L.L. Yang and D.B. Guan, Environmental regulation and enterprise innovation: a review. *Bus. Strategy Environ.* **29** (2020) 1465–1478.

[15] J. Cui, J. Dai, Z. Wang and X. Zhao, Does environmental regulation induce green innovation? A panel study of chinese listed firms. *Technol. Forecasting Soc. Change* **176** (2022) 121492.

[16] Y. Rubashkina, M. Galeotti and E. Verdolini, Environmental regulation and competitiveness: empirical evidence on the Porter Hypothesis from European manufacturing sectors. *Energy Policy* **83** (2015) 288–300.

[17] K.J. Arrow, Economic welfare and the allocation of resources for invention. To appear in: Social Science Electronic Publishing.

[18] I. Horstmann, G.M. Macdonald and A. Slivinski, Patents as information-transfer mechanisms – to patent or (maybe) not to patent. *J. Political Econ.* **93** (1985) 837–858.

[19] S. Scotchmer, Standing on the shoulders of giants – cumulative research and the patent-law. *J. Econ. Perspect.* **5** (1991) 29–41.

[20] H. Hopenhayn and F. Squintani, On the direction of innovation. *J. Political Econ.* **129** (2021) 1991–2022.

[21] N.C. Thompson and J.M. Kuhn, Does winning a patent race lead to more follow-on innovation? *J. Legal Anal.* **12** (2020) 183–220.

[22] D. Fullerton and G.E. Metcalf, Environmental controls, scarcity rents, and pre-existing distortions. *J. Publ. Econ.* **80** (2001) 249–267.

[23] J.X. Zhang, Y. Ouyang, P. Ballesteros-Perez, H. Li, S.P. Philbin, Z.L. Li and M. Skitmore, Understanding the impact of environmental regulations on green technology innovation efficiency in the construction industry. *Sustain. Cities Soci.* **65** (2021) 102647.

[24] K.W. Chang, L.L. Liu, D. Luo and K. Xing, The impact of green technology innovation on carbon dioxide emissions: the role of local environmental regulations. *J. Environ. Manage.* **340** (2023) 117990.

[25] Z.J. Liao, Content analysis of China's environmental policy instruments on promoting firms' environmental innovation. *Environ. Sci. Policy* **88** (2018) 46–51.

[26] O. Schilke, A micro-institutional inquiry into resistance to environmental pressures. *Acad. Manage. J.* **61** (2018) 1431–1466.

[27] E. Taoketao, T.W. Feng, Y.T. Song and Y. Nie, Does sustainability marketing strategy achieve payback profits? A signaling theory perspective. *Corporate Soc. Responsibility Environ. Manage.* **25** (2018) 1039–1049.

[28] J.P. Li, J.R. Huang and B.W. Li, Do command-and-control environmental regulations realize the win–win of "pollution reduction" and "efficiency improvement" for enterprises? Evidence from China. *Sustain. Dev.* **32** (2024) 3271–3292.

[29] W.M. Friske and M.A. Zachary, Regulation, new venture creation, and resource-advantage theory: an analysis of the US brewing industry. *Entrepreneurship Theory Pract.* **43** (2019) 999–1017.

[30] S.G. Ren, X.L. Li, B.L. Yuan, D.Y. Li and X.H. Chen, The effects of three types of environmental regulation on eco-efficiency: a cross-region analysis in China. *J. Clean. Prod.* **173** (2018) 245–255.

[31] Y.S. Chen, The driver of green innovation and green image – green core competence. *J. Bus. Ethics* **81** (2008) 531–543.

[32] T. Kong, T.W. Feng and C.M. Ye, Advanced manufacturing technologies and green innovation: the role of internal environmental collaboration. *Sustainability* **8** (2016) 1056.

[33] D.Y. Li, M. Huang, S.G. Ren, X.H. Chen and L.T. Ning, Environmental legitimacy, green innovation, and corporate carbon disclosure: evidence from CDP China 100. *J. Bus. Ethics* **150** (2018) 1089–1104.

[34] M. Tariq, Y.Z. Xu, K. Ullah and B.Y. Dong, Toward low-carbon emissions and green growth for sustainable development in emerging economies: Do green trade openness, eco-innovation, and carbon price matter? *Sustain. Dev.* **32** (2024) 959–978.

[35] A.B. Jaffe and K. Palmer, Environmental regulation and innovation: a panel data study. *Rev. Econ. Stat.* **79** (1997) 610–619.

[36] M. Hamamoto, Environmental regulation and the productivity of Japanese manufacturing industries. *Res. Energy Econ.* **28** (2006) 299–312.

[37] C.J. Li, A. Razzaq, M. Irfan and A. Luqman, Green innovation, environmental governance and green investment in China: exploring the intrinsic mechanisms under the framework of COP26. *Technol. Forecasting Soc. Change* **194** (2023) 122708.

[38] Z.M. Yan, Y. Yu, K.R. Du and N. Zhang, How does environmental regulation promote green technology innovation? Evidence from China's total emission control policy. *Ecol. Econ.* **219** (2024) 108137.

[39] N. Mahmood, Y.J. Zhao, Q.Q. Lou and J.Z. Geng, Role of environmental regulations and eco-innovation in energy structure transition for green growth: evidence from OECD. *Technol. Forecasting Soc. Change* **183** (2022) 121890.

[40] L.P. Wang, Y. Long and C. Li, Research on the impact mechanism of heterogeneous environmental regulation on enterprise green technology innovation. *J. Environ. Manage.* **322** (2022) 116127.

[41] X.M. Yin, D.D. Chen and J.Y. Ji, How does environmental regulation influence green technological innovation? Moderating effect of green finance. *J. Environ. Manage.* **342** (2023) 118112.

[42] N. Stojcic, Social and private outcomes of green innovation incentives in European advancing economies. *Technovation* **104** (2021) 102270.

[43] Z.Y. Jiang, Z.J. Wang and Y.Q. Zeng, Can voluntary environmental regulation promote corporate technological innovation? *Bus. Strategy Environ.* **29** (2020) 390–406.

[44] P. Chakraborty and C. Chatterjee, Does environmental regulation indirectly induce upstream innovation? New evidence from India. *Res. Policy* **46** (2017) 939–955.

[45] Y.J. Zhang, Y.L. Peng, C.Q. Ma and B. Shen, Can environmental innovation facilitate carbon emissions reduction? Evidence from China. *Energy Policy* **100** (2017) 18–28.

[46] R.H. Xie and T.S.H. Teo, Green technology innovation, environmental externality, and the cleaner upgrading of industrial structure in China – considering the moderating effect of environmental regulation. *Technol. Forecasting Soc. Change* **184** (2022) 122020.

[47] F.-X. Jiang, Z.-J. Wang and J.-H. Bai, The dual effect of environmental regulations' impact on innovation-an empirical study based on dynamic panel data of Jiangsu manufacturing. *Chin. Ind. Econ.* **7** (2013) 2013.

[48] Q. Zhou, Y.A. Song, N.N. Wan and X.L. Zhang, Non-linear effects of environmental regulation and innovation – spatial interaction evidence from the Yangtze River Delta in China. *Environ. Sci. Policy* **114** (2020) 263–274.

[49] J.X. Zhang, L. Kang, H. Li, P. Ballesteros-Pérez, M. Skitmore and J. Zuo, The impact of environmental regulations on urban Green innovation efficiency: the case of Xi'an. *Sustain. Cities Soc.* **57** (2020) 102123.

[50] Z.Y. Jiang, Z.J. Wang and X. Lan, How environmental regulations affect corporate innovation? The coupling mechanism of mandatory rules and voluntary management. *Technol. Soc.* **65** (2021) 101575.

[51] H.Y. Yu, J.C. Wang, J. Hou, B.L. Yu and Y.L. Pan, The effect of economic growth pressure on green technology innovation: Do environmental regulation, government support, and financial development matter? *J. Environ. Manage.* **330** (2023) 117172.

[52] J.A. Schumpeter, The Theory of Economic Development. McGraw-Hill (2008).

[53] T.P.T. Nguyen, F. Huang and X.W. Tian, Intellectual property protection need as a driver for open innovation: empirical evidence from Vietnam. *Technovation* **123** (2023) 102714.

[54] K.A. Bryan and J. Lemus, The direction of innovation. *J. Econ. Theory* **172** (2017) 247–272.

[55] K. Lee, The value and direction of innovation. *J. Econ.* **130** (2020) 133–156.

[56] J.L. Moraga-Gonzalez, E. Motchenkova and S. Nevrekar, Mergers and innovation portfolios. *Rand J. Econ.* **53** (2022) 641–677.

[57] M.M. Wang, X.Y. Chen, X.X. Zhu and K. Liu, Green innovation and product line decisions under environmental standard upgrading. *RAIRO-Oper. Res.* **58** (2024) 1703–1733.

[58] K. Kang, Y.J. Zhao, J. Zhang and C. Qiang, Evolutionary game theoretic analysis on low-carbon strategy for supply chain enterprises. *J. Clean. Prod.* **230** (2019) 981–994.

[59] X.N. Song, M. Shen, Y.J. Lu, L.Y. Shen and H.Y. Zhang, How to effectively guide carbon reduction behavior of building owners under emission trading scheme? An evolutionary game-based study. *Environ. Impact Assess. Rev.* **90** (2021) 106624.

[60] Y.C. Pan, W. Yang, N. Ma, Z.M. Chen, M. Zhou and Y. Xiong, Game analysis of carbon emission verification: a case study from Shenzhen's cap-and-trade system in China. *Energy Policy* **130** (2019) 418–428.

[61] W.T. Chen and Z.H. Hu, Using evolutionary game theory to study governments and manufacturers' behavioral strategies under various carbon taxes and subsidies. *J. Clean. Prod.* **201** (2018) 123–141.

[62] Q. Qi, Q.G. Bai, J.T. Xu and Q. Feng, A comparative study on a firm's optimal production decision considering risk aversion and carbon policies. *RAIRO-Oper. Res.* **57** (2023) 2025–2043.

[63] A. Paul and B.C. Giri, Green sustainable supply chain under cap and trade regulation involving government introspection. *RAIRO-Oper. Res.* **56** (2022) 769–794.

[64] C.H. Liao, Analysis of government subsidy strategies for blockchain-enabled green supply chains under competition. *RAIRO-Oper. Res.* **58** (2024) 4119–4143.

[65] C.L. Shu, K.Z. Zhou, Y.Z. Xiao and S.X. Gao, How green management influences product innovation in China: the role of institutional benefits. *J. Bus. Ethics* **133** (2016) 471–485.

[66] Y.S. Xu, Z.Y.Z. Dong and Y. Wu, The spatiotemporal effects of environmental regulation on green innovation: evidence from Chinese cities. *Sci. Total Environ.* **876** (2023) 162790.

[67] S.Y. Zhang, C.X. Wang, C. Yu and Y.J. Ren, Governmental cap regulation and manufacturer's low carbon strategy in a supply chain with different power structures. *Comput. Ind. Eng.* **134** (2019) 27–36.

[68] H.H. Song and Y. Wang, Enterprises' decision-making under government green subsidy and information asymmetry. *RAIRO-Oper. Res.* **56** (2022) 3871–3893.

[69] M.M. Guo, H.X. Wang and Y.C. Kuai, Environmental regulation and green innovation: evidence from heavily polluting firms in China. *Finan. Res. Lett.* **53** (2023) 103624.

[70] K.A. Bryan, J. Lemus and G. Marshall, R&D competition and the direction of innovation. *Int. J. Ind. Org.* **82** (2022) 102841.