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Original Research

Tripartite Coordinated Governance Evolutionary Game and System Simulation Study on the Ecological Environment in China's Pearl River Basin

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Abstract

The aim of this study is to dissect and enhance the tripartite collaborative governance mechanisms among polluting enterprises, the public, and government regulatory bodies within the scope of China's recent healthcare reforms. Through the lens of an evolutionary game model, this research seeks to understand the strategic evolutionary equilibrium among these actors and evaluate the impact of various incentives and penalties on their decision-making processes. Utilizing an evolutionary game model from a bounded rationality perspective, it investigates the strategic evolutionary equilibrium among the stakeholders and the influence of various factors on their strategic evolution. A critical equilibrium point E5(1,1,0) was identified, where enterprises adopt clean production strategies, the public engages in environmental governance, and the government exercises lenient regulatory strategies. Empirical analysis employing real-world data further substantiates the theoretical findings, showcasing how governmental bodies can drive clean production measures among polluting enterprises through economic incentives or penalties. The study outlines pivotal measures for achieving collaborative ecological governance in the Pearl River Delta region, such as establishing an information sharing platform, augmenting government regulation and enforcement, encouraging clean production in enterprises, enhancing public participation, and bolstering support for technological innovation. These measures could promote continuous environmental amelioration and sustainable development in the region. The findings offer both theoretical and practical insights for multifaceted environmental governance

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in China, illuminating the nuanced interplay among governmental bodies, industries, and the public in enhancing environmental standards and healthcare reforms.

Keywords: Pearl River Basin, government regulators, discharging enterprises, public, evolutionary game

Introduction

The Pearl River Basin in China, as a significant economic zone, has long been facing severe ecological and environmental challenges [1-4]. With China's rapid industrialization and urbanization in recent decades, environmental problems in the region have become increasingly serious, particularly water pollution. These issues primarily arise from the activities of polluting enterprises within the basin, with the public and government being crucial stakeholders in the remediation process. Driven by economic gains, these enterprises often neglect their environmental responsibilities, leading to the aggravation of water and air pollution issues [5-7].

Wang L. et al. [8] and Zhang Q. et al. [9] provide foundational insights into the environmental quality and human health risks associated with water pollution due to rapid urbanization in China. Building on this, Yang W et al.'s [10] evaluation of green development levels presents a stark contrast in regional ecological efforts, while Yang W. et al. [11] four-party evolutionary game model offers a nuanced understanding of regulatory compliance dynamics. Both studies underscore the complexity of ecological governance in regions like the Pearl River Basin, where the interplay of environmental degradation and health implications necessitates a strategic approach to governance. The escalating public demand for environmental accountability and the government's role in mediating interests underscore the urgency of our investigation into the tripartite relationships that could drive sustainable ecological policies, as also indicated by Lu Set et al.'s [12] findings on the health impacts of environmental factors. Concurrently, the level of public concern for environmental issues is escalating, demanding polluting enterprises take on more responsibilities to ensure the quality of life and health. The government plays a vital role in this interplay, tasked with the delicate balance of fostering economic growth while safeguarding environmental integrity. Additionally, the government needs to mediate between the interests of polluting enterprises and the public. Hence, investigating the tripartite game relationships in the ecological governance of the Pearl River Basin holds significant theoretical and practical implications for addressing this substantial challenge.

System simulation, as an effective research methodology, can model the game processes in complex systems and assess the impact of varying strategies on system performance [13-15]. Within the ecological governance of the Pearl River Basin, the game among polluting enterprises, the public, and the government encompasses multiple variables and factors, such as environmental policy formulation, apportionment of governance costs, and promotion of technological innovations. Through system simulation studies, it is feasible to delve into the dynamic evolution of the tripartite game, exploring the effects of different decisions on the efficacy of ecological governance. Moreover, simulation can provide decision-makers with decision support and risk assessment, providing a scientific basis for devising more effective policies and management strategies. The primary objectives of this paper are to meticulously analyze the collaborative governance mechanisms at play in the Pearl River Basin and to pinpoint sustainable strategies for mitigating ecological issues. By applying system simulation techniques, our goal is to delineate and propose actionable governance strategies that ensure environmental sustainability. This endeavor not only seeks to enhance governance outcomes but also aims to provide a methodological blueprint for environmental stewardship that can be replicated in similar ecological contexts globally.

Overview of the Pearl River Basin

The Pearl River Basin in China is one of the most significant economic regions in southern China, encompassing provinces such as Guangdong, Guangxi, Jiangxi, Hunan, and Fujian, with a total area of about 450,000 square kilometers. The basin is characterized by its mountainous terrain and abundant water resources, including the Pearl River and its tributaries, the Dongjiang River, the Beijiang River, and the Xijiang River. With diverse topographical features, including high mountains, hills, plains, and coastlines, and a developed river system, it stands as one of China's key concentrations of water resources. Situated in the subtropical climate zone, the basin enjoys a warm, humid climate, ample sunlight, and fertile land, enriching its ecological and environmental conditions. The geographical diversity of the Pearl River Basin embraces a wealth of natural resources and ecosystems, including the World Natural Heritage Site Danxia Mountain, national nature reserves, lakes, wetlands, and forests, each contributing to the unique and varied natural landscapes and fostering a rich biodiversity (Fig. 1).

However, the ecological environment of the Pearl River Basin faces severe challenges due to long-term industrialization and rapid population growth. The activities of numerous polluting enterprises have led to severe water pollution, deteriorated air quality, and land degradation. Problems such as water pollution, soil contamination, and air pollution are escalating, posing

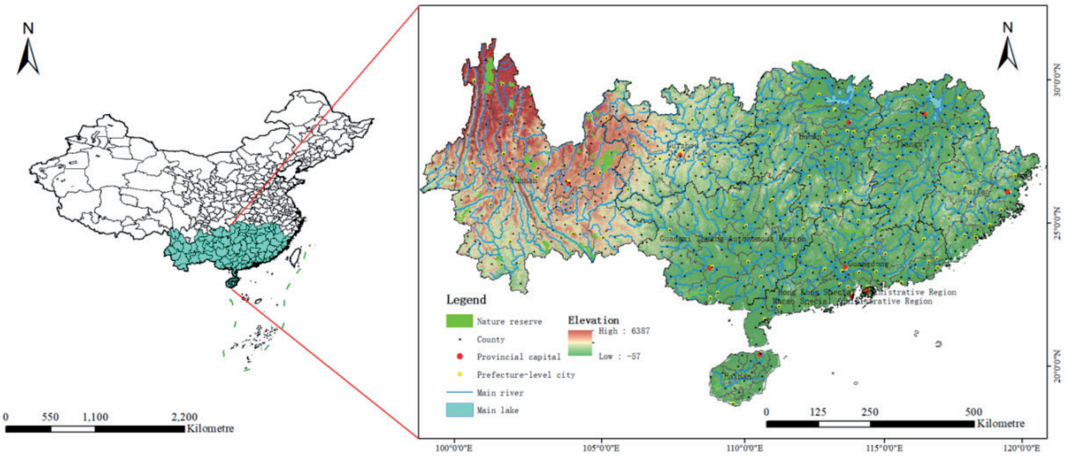

Fig. 1. Geographic location of the Pearl River Basin in China.

serious threats to the ecosystems and biodiversity within the basin. Issues of water scarcity, ecological degradation, and diminishing ecosystem functionality are in urgent need of resolution. Against this backdrop, the People's Government of Guangdong Province promulgated the "Regulations on Ecological and Environmental Protection of Guangdong Province" in 2022, aiming to bolster the ecological and environmental protection efforts in Guangdong Province. In 2023, the Ministry of Ecology and Environment, along with five other departments, jointly issued the "Water Ecological Environment Protection Plan for Key Basins", advocating for integrated management of water resources, water environment, and water ecology to propel the ecological protection and governance of crucial rivers, lakes, and reservoirs. The introduction of these governmental documents provides guidance and support for the ecological governance of the Pearl River Basin, laying a substantial foundation and context for research on the evolutionary game of collaborative governance. By delving into the tripartite game relationships, robust policy support can be rendered for formulating scientific policies and measures, thereby promoting ecological and sustainable development in the Pearl River Basin.

Literature Review

Studies on River Basin Ecological Governance and Game Theory in China

In recent years, an increasing number of Chinese scholars have shifted their focus towards water environment governance and ecological compensation mechanisms within river basins. Evolutionary game theory methodologies have been extensively employed in studies related to water environment governance across various basins. Chai et al. [16] explored cooperative mechanisms in water environment governance through a study conducted in the Dongting Lake Basin. Similarly, Yu et al. [17] investigated evolutionary cooperative issues in transboundary river basins. Wang et al. [18] examined the influencing factors and simulations of ecological compensation in river basins. Additionally, Yuan et al. [19] utilized prospect theory, system dynamics, and evolutionary game methods to study competitive strategic behaviors in cross-administrative regional water pollution issues within China. Jiang et al. [20] focused on the stability and influencing factors of incentive-compatible payments in ecological compensation within the Xin'anjiang River Basin. These studies hold significant implications for understanding and ameliorating water environment governance in river basins.

Moreover, some studies have delved into the ecological and economic environments of specific basins. Zhu et al. [21] studied the stresses and responses concerning the tourism economy and ecological environment in the Yangtze River Basin. He Qin [22] explored the cross-provincial river basin ecological compensation legal system, taking the Chishui River Basin governance as an example. You Bensheng et al. [23] proposed suggestions for establishing a modernized governance system to promote aquatic ecological health in the Tai Lake Basin. Wang Jiang and Wang Peng [24], along with Wang Youyun [25], employing dynamic evolutionary game models, demonstrated that inter-jurisdictional ecological collaborative governance in river basins is superior to territorial governance and proposed methods to implement such governance models.

Furthermore, several case-specific studies have yielded insightful observations for water environment governance in river basins. Fan Ting [26] centered her research on water pollution governance in the Yellow River Basin segment of Inner Mongolia's Zhungeer Banner. Zhan Cheng [27] studied the ecological protection compensation mechanisms in the Chishui River Basin. These case studies offer targeted suggestions and solutions for water environment governance in specific regional basins.

China is showing growing concern for the influencing factors, stability, and regional characteristics of water environment governance and ecological compensation mechanisms. These studies provide theoretical backing and practical insights for enhancing water environment governance in river basins. However, there is a continuing need for further research and exploration to refine the theories and practices concerning water environment governance in river basins.

Application of System Simulation Technology in Environmental Governance and Protection

In various facets of environmental governance and protection, system simulation technology in a myriad of aspects within environmental governance and protection, system simulation technology has emerged as a pivotal tool, enhancing comprehension of water resource management and ecological conservation. For example, a study by Alitane A. et al. [28] focused on water resource management in central Morocco, leveraging hydrological modeling as a pivotal tool for decision-making and underlining its essential role in sustainable water resource management. In a similar vein, Cardoso de Salis H.H. et al. [29] utilized hydrological modeling to delve into water resource management in urbanized karst regions, unveiling how scientific simulation can assist in formulating policies in such complex environments.

When considering the sustainable utilization of water resources, a multifaceted perspective is indispensable. Un Y. et al. [30] employed system dynamics models to explore the sustainable utilization of China's water resources, furnishing a crucial platform for a more integrated understanding. Building upon this, Wei F. et al. [28] implemented an integrated optimization method for simulating water resource allocation processes, aiming to spur sustainable urban development. Conversely, Xu H. et al. [31] developed a web-based decision support system, utilizing serious gaming techniques to collaboratively mitigate numerous water-related risks.

In the realm of ecological safety and differentiated management, Hu M. et al. [3] employed spatial analysis to investigate the spatial discrepancies in ecological safety in China's Pearl River Delta, emphasizing the importance of zonal management in ecological conservation. Subsequently, Liu G. et al. [32] explored how China could achieve low-carbon development through marine fisheries using system dynamics simulation analysis. Furthermore, Magnuszewski P. et al. [33] investigated the role of relational practices in water management through gamification, hinting at the potential of simulation and gaming in fostering collaborative governance practices. Additionally, for multi-scenario simulation of land use, Liu X. et al. [34] developed a future land use simulation model (FLUS) by amalgamating human and natural influences, thereby providing a methodological framework that considers various impacts. Concurrently, crucial research on environmental load has also been undertaken; for instance, the work of Zhou X.-Y. et al. [35] focused on industrial structure upgrades and spatial optimization based on water environmental carrying capacity.

The aforementioned studies illuminate the extensive application of system simulation in the realms of environmental governance and protection, encapsulating various aspects such as model establishment, decision support, resource allocation, risk mitigation, and land-use planning. The core objective of these studies is to advance the intelligent and scientific progression of environmental governance, adapting to the increasingly complex environmental challenges and societal demands.

International Research on River Basin Ecological Environment Governance and Game Theory

International studies concerning tripartite collaborative governance of river basin ecological environments encompass a variety of aspects, including water resource demand and ecosystem game dynamics, collaborative governance platforms and institutional design, model and game theory-based methodologies, as well as integrated management strategies and practices. These research endeavors provide invaluable theoretical and practical support towards achieving ecological preservation and sustainable development within river basins.

Initially, research conducted by Arfanuzzaman and Abu Syed [36], along with Ghadimi and Ketabchi [37], delved into the game dynamics between water resource demands and ecosystems, exploring the potential of collaborative water resource management through modeling and optimization methods. Their studies underscored the interrelationship between water demand and ecological preservation, furnishing a theoretical foundation for collaborative governance. Subsequently, research by Bell and Scott [38] and Karambelkar and Gerlak [39] focused on collaborative governance platforms and institutional design, comparing the implementation effects in various case studies. These studies unveiled the characteristics and merits/demerits of collaborative governance platforms and emphasized the significance of effective institutional design for realizing collaborative governance of river basin ecological environments. Additionally, Den Haan et al. [40] and Magnuszewski et al. [33] adopted model and game theory-based approaches, such as virtual river games and serious games, to explore cooperative river management and relational practices in water resource governance. These methodological approaches provide decision-makers with experimental and simulation platforms for understanding and evaluating the effects of various governance strategies. Furthermore, studies by Djosetro and Behagel [41] concentrated on cooperative governance in establishing locally supported coastal protection zones; Hand et al. [42] proposed a river-scape management framework from a socio-ecological perspective; Teague et al. [43] developed cooperative serious games for water resource planning and disaster mitigation; Wang et al. [44] explored integrated water resource management and modeling using the Canadian BoW River Basin as a case study; Xu et al. [31] developed a network-based decision support system for collaboratively mitigating multiple water-related risks. Feng B. et al. [45] analyzed the green supply chain finance credit market under government regulation through evolutionary game theory, offering new insights into the understanding of this market structure. In summary, research on tripartite collaborative governance of river basin ecological environments in China encompasses water resource demand and ecosystem game dynamics, collaborative governance platforms and institutional design, model and game theory-based methodologies, as well as integrated management strategies and practices. These studies provide invaluable theoretical and practical support towards achieving ecological preservation and sustainable development within river basins.

Evolutionary Model Assumptions and Model Description

Model Description

This study, taking the environmental protection of the Pearl River Basin as the research object, constructs an evolutionary game model involving three parties: polluting enterprises, the public, and governmental regulatory agencies. In the gaming process, the variables involved and the choices of game strategies influence and adjust each other, eventually forming a stable game equilibrium point. All variables used in the model and their meanings are presented in Table 1.

Firstly, polluting enterprises are subjected to government regulation and penalties. The variable ‘f’ represents the government fine, that is, the enterprises would be fined if they opt for a “pollution production” strategy under strict government supervision. Besides, enterprises also need to consider production costs (C_e) and reputation loss (P_g). Enterprises following a “clean production” strategy will gain additional benefits (H) and enterprise revenue (W_1), while those going for a “pollution production” strategy can only attain speculative profits (W_2).

Secondly, the public plays a significant role in environmental governance. The variable ‘C_p’ denotes the governance cost of public involvement in environmental management, which is the cost borne by the public to partake in environmental governance. Also, if enterprises choose a “pollution production” strategy, the public will suffer health loss (L_p), whereas a “clean production” strategy will bring about health benefits (M) and psychological benefits (K). Moreover, the public can influence the behavior of enterprises through the probability of reporting (P), i.e., the probability of the public reporting when enterprises are engaged in pollution production.

Lastly, the government regulatory departments play a directive and supervisory role in the game. Through rewarding expenditure (S), the government incentivizes enterprises to adopt a “clean production” strategy and encourages the public to partake in environmental governance through rewarding expenditure for the public (R). The government also needs to bear the remediation costs (C_1) for handling environmental pollution incidents and regulatory costs (C_2) when adopting a “strict supervision” strategy. On the flip side, if enterprises choose a “clean production” strategy, the government will obtain potential benefits (N).

In the broad context of exploring the ecological and environmental governance of the Pearl River Basin in China, a complex game relationship has emerged among polluting enterprises, the public, and government regulatory departments. Within this evolutionary game process, all three parties pursue their own interests and objectives while being influenced by the actions of the other two, culminating in a scenario requiring a balance among different decisions. Under the framework of this tripartite game evolution, polluting enterprises, the public, and government regulatory departments drive the progress of ecological and environmental governance in the Pearl River Basin through mutual influence and feedback. The logical relationships of the tripartite game evolution are illustrated in Fig.2.

Firstly, polluting enterprises, as the main bodies of pollution emissions, need to consider the regulatory requirements of government regulatory departments and the environmental awareness of the public when deciding on their emissions and governance measures. The degree of government regulation and public opinion reactions can potentially impact the operation and social reputation of enterprises. Secondly, the public, as beneficiaries and overseers of environmental governance, must recognize that their environmental consciousness and behavioral feedback not only affect the policy formulation of government regulatory departments, but also influence the operational decisions of polluting enterprises. The public can express their expectations for environmental protection through various channels, urging the government and enterprises to adopt more proactive environmental measures. Lastly, government regulatory departments, as the supervisors and guiders of ecological and environmental governance, are responsible for formulating corresponding environmental regulations and policies, overseeing the emission behaviors of enterprises, and enhancing the environmental awareness of the public through public publicity. The government can choose to set emission standards through laws and regulations, penalize enterprises that violate pollution regulations, and increase public environmental awareness and participation through public education and information disclosure.

Table 1. Variables and definitions of variables.

Gaming party	Variant	Variable	Definitions of variables
Polluting Companies	f	Government Fines	Enterprises adopting the "polluting production" strategy will be penalized by the government under strict supervision.
	C_e	Production Cost	The cost of clean production for the enterprise.
	P_g	Reputation Loss	If enterprises adopt a "polluting production" strategy with public involvement, there will be a reputational loss for the enterprise.
	W_1	Enterprise Revenue	Revenue for enterprises adopting a "clean production" strategy (W1>W2).
	W_2	Speculative Revenue	Revenue for enterprises adopting a "polluting production" strategy.
	H	Additional Revenue	Additional economic benefits are brought about by adopting a "clean production" strategy.
Public	C_p	Governance Cost	The cost of public participation in environmental governance.
	L_p	Health Loss	The public will be affected by environmental pollution if enterprises adopt a "polluting production" strategy.
	M	Health Benefits	The public will benefit from environmental improvement if enterprises adopt a "clean production" strategy.
	K	Psychological Benefits	The psychological benefits of public participation in environmental governance.
	P	Reporting Probability	The probability of the public reporting enterprises' polluting production (0<P<1).
Government Regulatory Authorities	S	Rewarding Expenditure to Enterprises	If enterprises adopt a "clean production" strategy under strict government supervision, they will receive environmental protection subsidies from the government.
	R	Rewarding Expenditure to the Public	Rewards for public participation in environmental governance when the government adopts a "strict supervision" strategy.
	C_1	Remediation Cost	The cost to the government of handling environmental pollution incidents caused by enterprises' polluting production.
	C_2	Supervision Cost	The cost of manpower, materials, and financial resources invested by the government in adopting a "strict supervision" strategy.
	N	Government Revenue	The potential benefits to the government if enterprises adopt "clean production" strategies.

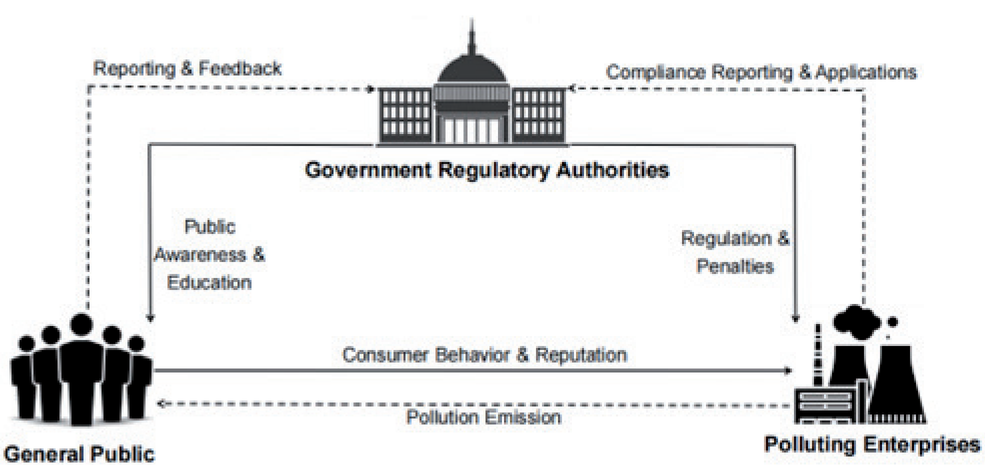

Fig. 2. Logic of the evolution of the tripartite game between emission enterprises, the public and government regulators.

Evolutionary Model Assumptions

The tripartite game entities in this study, namely, polluting enterprises, the public, and government regulatory departments, aim to maximize their own interests. The strategy each entity adopts hinges on the strategies chosen by the other two. This game is not a traditional, static, one-off interaction, but an evolving process where each boundedly rational individual in the three game groups adjusts its strategies based on past experiences, eventually converging to a stable point. To construct the game model, analyze the stability of strategies and equilibrium points, and understand the interplay of different factors, the following assumptions are made:

Assumption 1: Participating Entities. The regulation and remediation of pollution production require the joint participation of government health regulatory departments, polluting enterprises, and the public. This study constructs a tripartite evolutionary game model comprising "government regulatory departments," "polluting enterprises," and "the public," with all parties making strategy choices under the premise of bounded rationality.

Assumption 2: Enterprise Decision-Making. Polluting enterprises seek to maximize their total revenue in every decision-making instance. The enterprises weigh the fines, production costs, reputation losses, and possible revenues to decide between polluting or reducing pollution.

Assumption 3: Public Response. The public decides whether to report polluting enterprises based on psychological benefits, health losses, and governance costs. The health benefits are a direct result of the public's active participation in governance. The probability of reporting polluting enterprises, denoted as P, is directly proportional to psychological benefits and health losses.

Assumption 4: Government Actions. Government regulatory departments adjust incentivizing expenditures and regulatory costs based on the behavior of enterprises and the public. The government aims to maximize its benefits while ensuring the ecological environment of the basin is improved.

Assumption 5: Strategy Adjustment and Learning. During the game process, all parties adjust their strategies and learn from game outcomes and feedback. They strive to optimize their interests and adjust their strategic choices based on observations of others' behaviors. For instance, if an enterprise is frequently fined or suffers significant reputation loss, it might increase its environmental protection investment to reduce pollution.

Assumption 6: Dynamic Revenue and Cost. With the passage of time and advancement in technology, the production cost Ce of enterprises, the regulatory cost C2 of government, and the governance cost CP of the public may change, affecting the strategic choices of all parties in the game.

Assumption 7: Bounded Rationality of Stakeholders. As different game parties seek to maximize expected benefits under the premise of information asymmetry, a set of stable equilibrium strategies exists in the long-term evolution, whereby no greater benefit can be achieved through unilateral strategy changes when all parties adopt this set of strategies.

The evolutionary model proposed in this study is applicable for describing the evolutionary game process of tripartite collaborative governance in the ecological environment of the Pearl River Basin in China, to a certain extent reflecting the actual situation. However, the applicability of the model may be limited by real-world conditions and data, necessitating further research and verification.

Evolutionary Modeling and Analysis

Modeling

Setting the game model sewage enterprises set clean production as x and no clean production as $1–x$. The public's participation in environmental governance is Public participation in environmental governance is y The public does not participate in environmental governance $1–y$. The public does not participate in environmental governance. The willingness of government regulators to strictly regulate is z The willingness of government regulators to regulate loosely is $1–z$. The willingness of the government regulators to strictly regulate is The above x, y, $z \in (0,1)$ The above. Based on the above assumptions and variable definitions, the tripartite mixed-strategy game payoff-payoff matrix of sewage enterprises, the public and government regulators is established as shown in Table 2.

Game Model Analysis

(1) Benefits of cleaner production for sewage enterprises:

$$E_x = (W_1 - C_e + H + S)*y*z + (W_1 - C_e + H)*y*(1-z) + (W_1 - C_e + S + H)*(1-y)*z + (W_1 - C_e + H)*(1-y)*(1-z)$$

Gains from polluting production by emitters:

$$E_{1-x} = (W_2 - P*P_g - f)*y*z + (W_2 - P*P_g)*y*(1-z) + (W_2 - f)*(1-y)*z + (W_2)*(1-y)*(1-z)$$

The average earnings of the discharging companies are:

$$\bar{E} = xE_x + (1–x)E_{1–x}$$

The replication dynamic equation for the discharging firm is:

$$f_x = -x*(x - 1)*(H - C_e + W_1 - W_2 + f*z + S*z + P_g *P*y)$$

Table 2. Payoff payment matrix for the tripartite mixed-strategy game between sewage enterprises, the public and government regulators

Game participant		Public	Governments: Strict regulation (z)	Governments: Leniency regulation (1-z)
Corporations	Cleaner production (x)	Participation in environmental governance (y)	W_1 -C_e +H+S M+K-C_P +R N-R-C_2 -S	W_1 -C_e +H M+K-C_P N
		Non-involvement in environmental governance (1-y)	W_1 -C_e +H+S M N-C_2 -S	W_1 -C_e +H M N
	Contaminated production (1-x)	Participation in environmental governance (y)	W_2 -P*P_g -f K-C_P -L_P +R f-C_1 -C_2 -R	W_2 -P*P_g K-C_P -L_P -C_1
		Non-involvement in environmental governance (1-y)	W_2 -f -L_P f-C_1 -C_2	W_2 -L_P -C_1

(2) The benefits of public participation in environmental governance are:

$$E_y = (M + K\text{-}C_P + R)*x*z + (M + K\text{-}C_P)*x*(1\text{-}z) + (1\text{-}x)*z*(K\text{-}C_P - L_P + R) + (K\text{-}C_P - L_P)*(1\text{-}x)*(1\text{-}z)$$

The benefits of public non-participation in environmental governance are:

$$E_{1-y} = (M)*x*z + (M)*x*(1\text{-}z) + (1\text{-}x)*z*(-L_P) + (-L_P)*(1\text{-}x)*(1\text{-}z)$$

The average return to the public is:

$$\bar{E} = yE_y + (1-y)E_{1-y}$$

The equation for the replication dynamics of the public is:

$$f_y = -y*(y - 1)*(K - C_P + R*z)$$

(3) Gains from strict supervision by government regulators:

$$E_z = (N\text{-}R\text{-}C_2\text{-}S)*x*y + (N\text{-}C_2\text{-}S)*x*(1\text{-}y) + (f\text{-}C_1\text{-}C_2\text{-}R)*(1\text{-}x)*y + (f\text{-}C_1\text{-}C_2)*(1\text{-}x)*(1\text{-}y)$$

Gains from lax regulation by government regulators:

$$E_{1-z} = (N)*x*y + (N)*x*(1\text{-}y) + (-C_1)*(1\text{-}x)*y + (-C_1)*(1\text{-}x)*(1\text{-}y)$$

The average return for government regulators is:

$$\bar{E} = zE_z + (1-z)E_{1-z}$$

The equation for the replication dynamics of the government regulator is:

$$f_z = z*(z - 1)*(C_2 - f + f*x + R*y + S*x)$$

Equilibrium Analysis of Evolutionary Systems

TThe game process of government regulators, sewage enterprises, and the public is evolving, so the equilibrium point of the three-party game model is calculated by establishing a system of dynamic equations to replicate the three-party game model. The game process of government regulators, sewage enterprises, and the public is evolving, i.e., the probability of any strategy chosen by the three parties is time-dependent. According to the principle of stability of differential equations, when all dynamic equations are stable, it means that the whole dynamic system will tend to be stabilized. Therefore, the dynamic equation system is replicated by establishing the three-party game model through , the , and The equilibrium point of the three-party evolutionary game is calculated.

$$F(x) = -x*(x - 1)*(H - Ce + W1 - W2 + F*z + S*z + Pg*p*y) = 0$$

$$F(y) = -y*(y - 1)*(K - Cp + R*z) = 0$$

$$F(z) = z*(z - 1)*(C2 - F + F*x + R*y + S*x) = 0$$

There are eight special equilibria $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, $E_8(1,1,1)$, all stakeholders adopt pure strategies at each equilibrium.

Based on the replicated dynamic equations of the three-party subjects, the Jacobian matrix of the three-party evolutionary game system can be obtained as:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix}$$

$$J_{11} = -x*(H - C_e + W_1 - W_2 + F*z + S*z + P_g*p*y) - (x - 1)*(H - C_e + W_1 - W2 + F*z + S*z + P_g*p*y)$$

$$J_{12} = -P_g*p*x*(x - 1)$$

$$J_{13} = -x*(x - 1)*(F + S)$$

$$J_{21} = 0$$

$$J_{22} = -y*(K - C_P + R*z) - (y - 1)*(K - C_P + R*z)$$

$$J_{23} = -R*y*(y - 1)$$

$$J_{31} = z*(z - 1)*(F + S)$$

$$J_{32} = R*z*(z - 1)$$

$$J_{33} = z*(C_2 - F + F*x + R*y + S*x) + (z - 1)*(C_2 - F + F*x + R*y + S*x)$$

Based on the Lyapunov method, it is known that in the stability analysis of differential systems, stability can be determined by the sign of the eigenvalues of equilibrium points. When all eigenvalues (roots) of an equilibrium point are negative, the point is identified as an evolutionarily stable strategy (asymptotically stable point). By substituting the eight pure strategy points into the Jacobian matrix successively, and calculating the eigenvalues of the equilibrium points, as shown in Table 3, it can be observed that there might exist one evolutionarily stable equilibrium point $E_5(1,1,0)$ within the evolutionary game system.

Numerical Simulation

Evolutionary Stable Strategies

In the evolutionary game of tripartite collaborative governance for the ecological environment of the Pearl River Basin in China, the equilibrium point for the three gaming parties is $E_5(1,1,0)$, implying that enterprises adopt clean production strategies, the public participates in environmental governance, and the government adopts a lenient regulatory strategy. The formation of this optimal strategy is based on a comprehensive consideration of multiple factors.

Firstly, the government's lenient regulatory strategy stems from the fact that relaxed regulation can reduce stringent penalties on enterprises, thereby lowering the enterprises' cost (C_2). In this scenario, the government is more inclined to encourage enterprises to adopt clean production strategies by providing environmental protection subsidies (S) to achieve the goal of environmental protection. Secondly, enterprises choose clean production strategies because the economic benefits (H) from clean production outweigh the revenue (W_1>W_2) from polluting production strategies. Additionally, enterprises need to bear the cost (C_e) of clean production. However, due to the government's lenient regulation and environmental protection subsidy policies, clean production becomes a more attractive choice for enterprises. Lastly, the public's involvement in environmental governance is driven by the environmental improvement benefits (M) received when enterprises adopt clean production strategies. The public is willing to bear the cost (C_P) of participating in environmental governance to encourage enterprises to improve environmental conditions and reduce the impact on environmental pollution ($L_P = 0$), while also promoting better environmental practices through public opinion oversight and social involvement.

Therefore, the formation of the equilibrium point $E_5(1,1,0)$ is based on the collective influence of enterprises pursuing economic benefits, the public seeking environmental improvement, and the government's lenient regulation along with environmental protection subsidy policies. The selection of this optimal strategy aids in achieving the goal of collaborative ecological environmental governance in the Pearl River Basin, balancing the interests of all parties, and promoting sustainable development.

Table 3. System equilibrium points and eigenvalues.

Balancing point	Jacobian matrix eigenvalues			Deterministic conclusions
	λ_1	λ_2	λ_3	
$E_1(0,0,0)$	$H - C_e + W_1 - W_2$	$K - C_P$	$f-C_2$	Instability points
$E_2(1,0,0)$	$C_e - H - W_1 + W_2$	$K - C_P$	$-C_2-S$	Instability points
$E_3(0,1,0)$	$H - C_e + W_1 - W_2 + P_g*P$	$C_P - K$	$f-C_2-R$	Instability points
$E_4(0,0,1)$	$f - C_e + H + S + W_1 - W_2$	$K - C_P + R$	C_2-f	Instability points
$E_5(1,1,0)$	$C_e - H - W_1 + W_2 - P_g*P$	$C_P - K$	$-C_2-R-S$	Ess
$E_6(1,0,1)$	$C_e - f - H - S - W_1 + W_2$	$K - C_P + R$	C_2+S	Instability points
$E_7(0,1,1)$	$f - C_e + H + S + W_1 - W_2 + P_g*P$	$C_P - K - R$	C_2-f+R	Instability points
$E_8(1,1,1)$	$C_e - f - H - S - W_1 + W_2 - P_g*P$	$C_P - K - R$	C_2+R+S	Instability points

However, the real-world scenario may be influenced by various factors, necessitating further research and empirical analysis to validate the effectiveness and applicability of this equilibrium point.

Evolutionary Stability Analysis

To verify the effectiveness of the evolutionary stability analysis, values were assigned to the model in accordance with real-world scenarios, and numerical simulation was conducted using MATLAB 2020b. When $E_5(1,1,0)$ is the stable point, it requires C_e - H - W_1 + W_2 - P_g*P<0 and C_P - K<0 to be satisfied.

Sensitivity Analysis Regarding Relevant Variables in Polluting Enterprises

According to the graphical results of the sensitivity analysis (Fig. 3), as the cost (C_e) of "clean production" or speculative gains (W_2)) for polluting enterprises gradually increases, initially, polluting enterprises may be stimulated to adopt non-clean production strategies. However, as the values continue to rise, this inclination gradually weakens. In this context, governmental regulatory departments might feel increased pressure to promote clean production, possibly intensifying the regulatory scrutiny of polluting enterprises. The public may initially feel the aggravation of environmental pollution issues, but with the strengthening of regulation and the gradual inclination of polluting enterprises towards clean production strategies, environmental quality improves. Meanwhile, with the promotion and implementation of clean production, the public's environmental awareness is enhanced, and they become more willing to support government environmental policies.

With the gradual increase in revenue (W_1) and additional economic gains (H) from adopting "clean production" strategies, polluting enterprises are more inclined towards adopting clean production strategies. Additionally, with the increase in extra economic benefits brought by clean production, the public perceives an improvement in environmental quality, thus being more supportive and appreciative of enterprises engaging in clean production and being more willing to pay for eco-friendly products. At the same time, governmental regulatory departments recognize the positive impact of clean production on environmental protection and socio-economic development, strengthening their confidence in promoting and enforcing environmental policies and making related regulatory strategies and incentive mechanisms clearer and more feasible. In the current environmental protection framework in China, promoting clean production and improving environmental quality have always been core concerns for both the public and the government. Pollution emissions from enterprises often lead to a decline in environmental quality and the public's quality of life. Therefore, increasing W1 and H holds significant strategic relevance for enhancing the efficiency of the environmental protection system and public satisfaction. By optimizing regulatory mechanisms and providing more economic incentives for enterprises engaging in clean production, more polluting enterprises can be encouraged to adopt clean production strategies, thereby promoting overall societal environmental quality enhancement and sustainable economic development. Simultaneously, this can also elevate public environmental awareness and satisfaction, laying a solid foundation for China's green development.

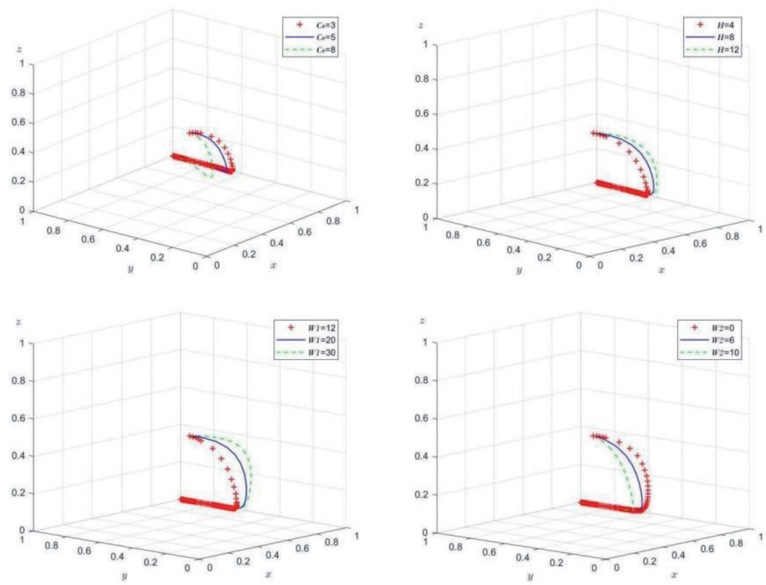

Fig. 3. Sensitivity analyses of variables related to sewage enterprises.

Sensitivity Analysis Regarding Relevant Variables of the Public

Based on the graphical results of the sensitivity analysis (Fig. 4), as the cost (C_p) of public participation in environmental governance continuously decreases and the psychological benefits (K) of such participation continuously increase, the public becomes more inclined to participate in and support environmental protection actions. Furthermore, with the augmentation of psychological benefits, polluting enterprises feel societal pressure and expectations and are thus more likely to adopt clean production and environmental protection measures to enhance their social responsibility image and meet the public's environmental expectations. Simultaneously, governmental regulatory departments perceive the active participation and support of the public for environmental causes, bolstering their confidence in environmental regulation and policy promotion and making the relevant regulatory strategies and public participation mechanisms clearer and more feasible. The polluting behaviors of enterprises affect not only the environmental quality but also the public's quality of life and the sustainable development of society. Therefore, reducing C_p and increasing K hold significant strategic relevance for promoting public participation and corporate responsibility in the environmental protection system. By optimizing regulatory mechanisms, promoting public participation, and fostering corporate environmental responsibility, more polluting enterprises can be incentivized to adopt clean production strategies, thereby enhancing the overall societal environmental quality and increasing public satisfaction. At the same time, this can also elevate the efficiency and confidence of governmental regulatory departments.

Sensitivity Analysis Regarding Relevant Variables in Government Regulatory Departments

Based on the graphical results of the sensitivity analysis (Fig. 5), in the initial stages, with the continuous increase in government regulatory costs (C2) and reward-based expenditures (S) for enterprises, polluting businesses are more likely to adopt environmental measures to obtain government rewards and support, while simultaneously avoiding stringent oversight and penalties. Moreover, as reward-based expenditures rise, the public can perceive an improvement in environmental quality, thus more readily supporting and endorsing businesses that adopt clean production strategies. However, over time, the government might gradually reduce both regulatory costs and reward-based expenditures. Given the heightened environmental awareness among businesses and the widespread adoption of clean production technologies, polluting enterprises should be capable of independently maintaining high environmental standards.

Furthermore, after witnessing the initial success of investments in improving environmental quality and enhancing corporate environmental responsibility, government regulatory departments may shift their focus towards enhancing regulatory efficiency. They might promote education-based and voluntary cooperation environmental models to decrease regulatory costs and reward-based expenditures, emphasizing more corporate self-management and public participation. In China's current environmental governance framework, finding an appropriate balance that both incentivizes businesses to adopt clean production and maintains public satisfaction and government regulatory efficiency is an ongoing, long-term endeavor.

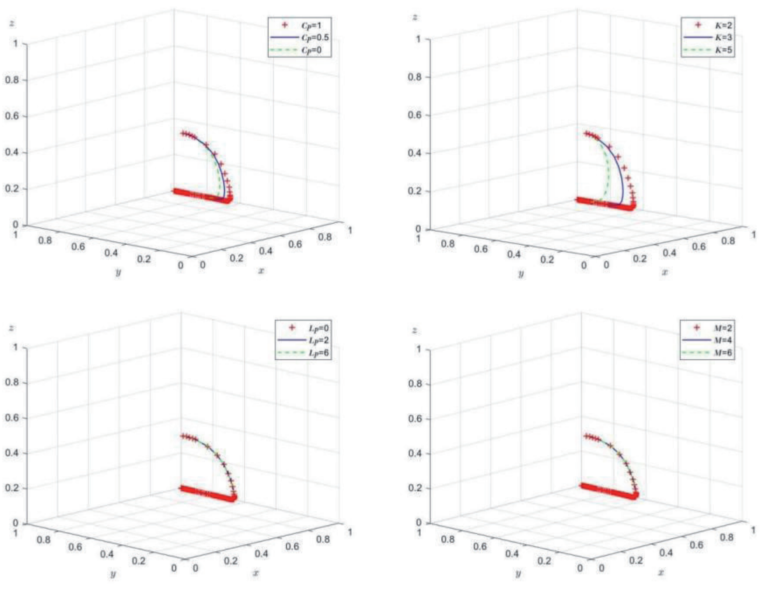

Fig. 4. Sensitivity analysis of variables of interest to the public.

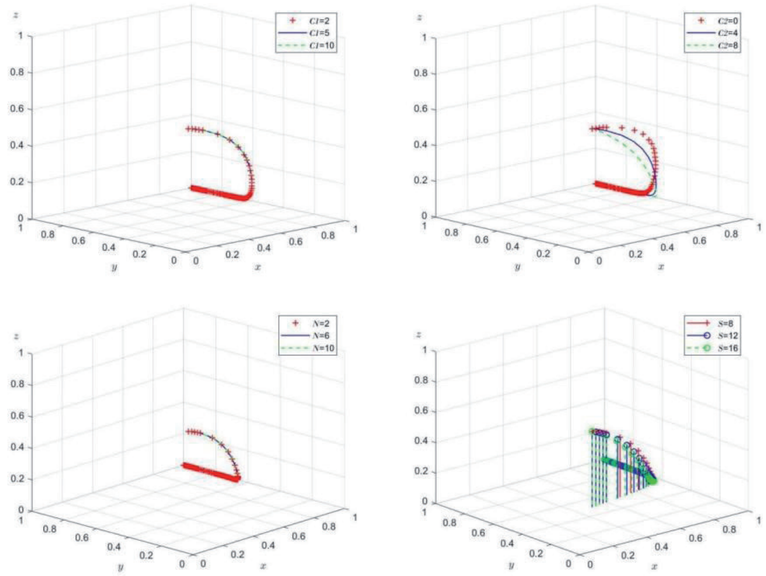

Fig. 5. Sensitivity analysis of variables related to government regulators.

Therefore, exploring and optimizing government regulatory costs (C2) and reward-based expenditures (S) holds significant strategic importance for promoting environmentally responsible behaviors in enterprises, elevating public satisfaction, and ensuring the sustainability and efficiency of government oversight. By adjusting and enhancing regulatory and reward mechanisms, we can further motivate polluting enterprises to adopt clean production strategies, boost the overall societal environmental quality, and lay a solid foundation for China's green development and environmental conservation endeavors.

Results and Discussion

In the recent round of healthcare reform in China, a game mechanism has emerged with polluting enterprises, the public, and government regulatory bodies as the primary stakeholders. This paper, grounded in the perspective of bounded rationality, establishes an evolutionary game model for coordinated governance among government regulatory bodies, polluting enterprises, and the public. It delves into the strategic evolutionary equilibrium of different stakeholders and examines the impact of various factors on the strategic evolution among these three parties. The analysis explores the inherent logic and conditions for coordinated governance through economic incentives or penalties imposed by government regulatory bodies on the unclean production behaviors of polluting enterprises, thereby leveraging the dominant advantage of governmental regulation to compel these enterprises towards clean production initiatives. Under this theoretical framework, further empirical verification of the theoretical findings with real-world data is identified as the subsequent direction of research.

From the vantage point of enhancing overall social welfare, $E_5(1,1,0)$ represents the current optimal strategy selection, where this equilibrium point maximizes the interests of all game participants. The clean production strategy of polluting enterprises has garnered acknowledgment and support from the public, who opt to partake in environmental governance and are willing to bear the corresponding medical expenses. The lenient regulatory strategy of government regulatory bodies effectively curtails regulatory costs, ensuring the stable operation of the health insurance fund. This strategic amalgamation enables the maximization of interests among polluting enterprises, the public, and government regulatory bodies. Overall, the equilibrium point, manifested as "clean production by polluting enterprises," "public engagement in environmental governance," and "lenient regulation by government regulatory bodies" in the game's evolutionary outcomes, underscores that under the new healthcare reform policies, the interest game can attain balance through orchestrating the actions and strategies of all stakeholders. Polluting enterprises provide high-quality clean production services; the public chooses to engage in environmental governance and bears the costs, while government regulatory bodies adopt a lenient regulatory strategy to support and incentivize clean production by polluting enterprises. Such game outcomes contribute to elevating the quality of healthcare services, optimizing resource allocation, and fostering the sustainable development of the entire healthcare system.

Based on the sensitivity analysis graph, it is apparent that with the reduction in the cost of public participation in environmental governance (C_p) and the enhancement of psychological benefits (K), the public is more inclined to engage in and support environmental actions. This proactive participation not only exerts pressure on enterprises, encouraging them to adopt clean production and environmental measures, but also bolsters the confidence of government regulatory bodies in promoting and enforcing environmental policies. This reciprocal stimulation serves as a significant force in advancing environmental awareness and practices, offering strategic guidance for corporate environmental responsibility and public engagement. Meanwhile, from the perspective of government regulatory bodies, as regulatory costs (C_2) and reward-based expenditure (S) towards enterprises increase, enterprises are more willing to adopt environmental measures to secure government rewards and support. This not only has a positive impact on both enterprises and the public but also lays the groundwork for improving environmental quality and elevating corporate environmental responsibility in the initial stages. Over time, and with the elevation of environmental consciousness within enterprises, the government can gradually reduce regulatory costs and reward-based expenditure by enhancing regulatory efficiency, promoting environmental education, and encouraging voluntary cooperation. This gradual adjustment holds strategic significance in maintaining high environmental standards, increasing public satisfaction, and ensuring the sustainability and efficiency of government regulation. By appropriately adjusting and optimizing regulatory and reward mechanisms, further encouragement for autonomous management within enterprises and public engagement can be achieved, thereby solidifying the foundation for China's green development and environmental conservation. This comprehensive analysis affords a multidimensional viewpoint to understand and address complex environmental governance issues.

In addition, our findings on governance coordination underpin the essential role of central oversight, reflecting studies on basin ecological compensation where government intervention aligns stakeholders towards sustainability. Similar to Li M. et al. [46], we identify the need for higher-level mediation for optimal strategies. In corroboration with He Y. et al. [47], our research underscores the importance of spatial ESV analysis for policy efficiency. Furthermore, echoing Wang W. [48], our study recognizes the complexities of transboundary ecological compensation, reinforcing the role of central authorities in environmental management. Achieving tripartite coordinated governance of the ecological environment in China's Pearl River Basin hinges on establishing effective cooperation mechanisms and promoting collaborative actions. For successful reform, active cooperation and collective efforts are required among government regulatory bodies, polluting enterprises, and the public. Firstly, establishing a platform for information sharing is a core step that enables the comprehensive governance information, providing accurate data and communication channels for all parties, and hence fostering coordinated decision-making and actions. Secondly, strengthening government regulation and enforcement is crucial for ensuring law compliance, such as increasing inspection frequency, intensifying penalties for environmental violations, and optimizing emergency response mechanisms to ensure compliant operations of enterprises and public health. For enterprises, government incentives like environmental subsidies, tax benefits, and technical support can reduce the cost of clean production and enhance environmental willingness. Concurrently, the government should bolster the establishment of public participation and public opinion supervision mechanisms, encouraging the public to engage in environmental protection through various channels to improve environmental awareness and social supervision. Moreover, increased support for technological innovation, encouraging the development of new technologies, materials, and methods, can enhance the efficiency and cost-effectiveness of environmental governance. Technological innovation will provide technical support for the ecological environmental governance of the Pearl River Basin, propelling sustainable development in the region. Through the implementation of the aforementioned comprehensive measures, a multi-party involvement, coordinated cooperation governance system for the ecological environment of the Pearl River Basin can be constructed, realizing the continuous improvement and sustainable development of the regional environment.

Conclusion

China's healthcare reform over the past decade has not only marked notable achievements but also provided "Chinese wisdom" to the global healthcare narrative. Despite these advancements, the challenges of healthcare disparities, institutional constraints, the burden of medical expenses, and the fragility of medical supervision persist. They call for a fundamental reform, an urgent call that this paper responds to by constructing an evolutionary game model involving polluting enterprises, the public, and government regulatory bodies. This model, with its novel integration of tripartite interactions within the Pearl River Basin's ecological context, offers a unique perspective on achieving equilibrium in environmental governance. Our identification of the pivotal equilibrium point $E5(1,1,0)$ delineates a scenario where clean production strategies are economically incentivized, governmental regulations are optimally stringent, and public engagement effectively fosters environmental improvement. The model's insights extend beyond theoretical constructs; they provide a concrete, simulation-verified roadmap for ecological environment governance.

In proposing a systematic approach for tripartite coordination, this paper underscores the necessity of multi-faceted reforms that span from enhanced information sharing platforms to bolstered support for technological innovation. These strategies are not just theoretical propositions but actionable pathways that cater to the Pearl River Basin's unique ecological challenges.The implications of this research are manifold, offering theoretical frameworks and practical directives for environmental governance. While the findings are promising, they are not without the need for empirical scrutiny and practical validation, acknowledging the complexity of real-world applications.Thus, while this paper contributes to the ongoing discourse on healthcare reform, it also paves the way for future research endeavors. The evolutionary game model posited here invites further exploration into its applicability across diverse environmental and regulatory landscapes, potentially influencing healthcare reforms in various global contexts.

Conflict of Interest

The authors declare no conflict of interest.

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