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The Role of Environmental Organizations and Chemical Companies in the Fluoride Legislation: the Analysis and Development of Fluoride Emission Limit Regulations

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ABSTRACT

Background: Fluoride, a cornerstone of modern industrial civilization, faces unprecedented global governance challenges. According to 2024 data from the International Fluoride Research Alliance (IFFA), annual global fluoride emissions exceed 5.2 million tonnes, with Asia accounting for 68%. This paradox of strategic resource attributes and environmental risks has spawned a continuous tug-of-war between environmental organizations and chemical companies at the legislative level.

Purpose: This study assesses the role of environmental protection organizations and chemical companies in fluoride legislation to reduce emissions and balance economic development with ecological protection.

Significance: In the global context of the European Union's Fluorine Gas Regulation and the U.S. Clean Water Act amendments, China, as the world's most extensive production base of fluorine chemical industry (holding 42% of the global production capacity in 2024), has a typical significance of its legislative game. The findings of this paper can provide valuable insights for advancing the improvement of fluoride emission regulations in China.

Implications: This paper adopts game theory to model how environmental protection organizations and chemical enterprises interact. Using a hypothesis-testing approach, it analyzes their influence on the development of fluoride emission regulations within fluoride legislation.

Conclusion: The study results showed that the willingness of the enterprises actively linked to the responsibility of fluoride emission reduction is related to the environmental protection organizations to fluoride emission legislation, and the willingness of environmental protection organizations to the legislation of fluoride emission is related to the enterprise's responsibility of fluoride emission reduction.

Keywords: *Environmental organizations; Chemical companies; Fluoride; Legislation; Game theory model.*

INTRODUCTION

Fluoride, an indispensable element in modern industry, is vital across strategic fields, such as semiconductors, photovoltaics, and pharmaceuticals, driving technological progress and industrial upgrading. However, the fierce collision between the dual attributes of this element - environmental toxicity and economic value- sets off a war without smoke on the chessboard of global environmental governance. The game between environmental protection organizations and chemical enterprises around the fluoride emission limitation regulations is not only about the choice of technology paths and sharing of economic costs but also profoundly affects the competition pattern and sustainable development path of the global fluorine chemical industry in the coming decades.

In the study of fluoride pollution, the concentration levels of PFASs in Lake Tana, Ethiopia, were monitored, and the levels of ∑PFASs ranged from 0.073 to 5.6 ng/L (mean 2.9 ng/L).[1] Studied 66 surface water samples from Liaoning, Hubei and Tianjin provinces in 2017. The results showed that the levels of ∑PFASs in water bodies ranged from 13.1 - 69,238 ng/L, with PFBA and PFOA being the main detected substances.[2] Monitored the concentration of PFAAs (Perfluoroalkyl acids) in the river water around a manufacturing plant in Hubei province in 2019, and the results showed that the concentration of ∑PFAAs in the river water ranged from 11.8 to 59.7 ng/L, of which PFBA was the main detected monomer, with an average concentration of 16.2 ng/L.[3]

In the study of environmental regulations, mandatory environmental liability insurance is an effective way to fill this demand gap by exploring the strategic elements that influence the implementation of environmental liability insurance in developing countries.[4] Explores the incentives for accident prevention and cleanup when firms assume environmental liability and find that prior environmental disasters exacerbate the impact of subsequent environmental accidents and that stringent regulation does not trigger optimal incentives for accident prevention and cleanup when the likelihood of a firm's closure can be foreseen.[5] Using banks in Indonesia, The environmental pollution risk can be mitigated by increasing the minimum environmental liability insurance coverage.[6]

The factors influencing the environmental regulation formulation applied the entropy value method to fit the indicators of environmental protection acceptance projects completed in the current year, the number of environmental protection administrative authorities, inspectorates, and administrative penalties to obtain a comprehensive index of government-led environmental regulation.[7] The number of administrative penalties for environmental pollution to measure governmental environmental regulation from the perspective of enforcing environmental protection laws.[8] The proportion of sewage fee revenue to industrial added value as a measurement index.[9] By combing and analyzing the existing studies, this paper finds that the indicators of sewage fee collection and investment in environmental pollution control adopted by the above studies are, in fact, the use of tax and investment tools of economic instruments to control environmental pollution.

Through the above summary of the relevant literature as a whole, it can be seen that for foreign academics on the environmental regulations of the research earlier, the theory and practice are more complete, while most scholars at home focus on environmental protection regulations and system construction in two aspects, emphasizing the theoretical value of the research.[10-12] However, research specifically addressing the impact of environmental protection organizations and chemical enterprises on pollution emission regulations remains limited. Studies on *fluoride* emission regulations are remarkably scant. To address this gap, this paper employs game theory to analyze the roles of environmental protection organizations and chemical enterprises within fluoride emission limitation regulations.

RESEARCH METHODOLOGY

Evolutionary game model between environmental organizations and chemical companies

Basic assumptions

The environment, as a public good, is non-rivalrous and non-exclusive. Enterprises emit fluoride from their production activities into the atmosphere under the principle of cost-utility, i.e., they externalize environmental costs. Therefore, enterprises must regulate fluoride emissions to internalize their externalized environmental costs.[13] The public has the right to existence, development and environment, and fluoride treatment is strongly demanded. Based on the principal-agent theory, environmental protection organizations and enterprises can be regarded as a principal-agent relationship in fluoride governance. As a principal, environmental protection organizations regulate fluoride emissions from enterprises.

In fluoride emission management, environmental protection organizations and enterprises are the decision-making subjects in the game process. Enterprises carry out production activities and manage their non-desired output, fluoride emissions.[14,15] The regulation of fluoride emissions by environmental organizations directly drives technological innovation and the adoption of end-of-pipe equipment to reduce fluoride emissions, and the inputs to fluoride management directly affect the output and profitability of the enterprise's products. This means there is a contradiction between environmental organisations' regulation of fluoride emissions and production by enterprises, which constitute the main factors involved in fluoride governance.

Hypothesis 1: Environmental protection organizations are the enforcers of fluoride emission regulation, and there is information asymmetry between environmental protection organizations and enterprises, pursuing public interest and self-interest maximization. Enterprises are the implementers of fluoride control and pursue profit maximization. Under limited rationality, environmental protection organizations and enterprises understand each other's strategy space and revenue payment and, through repeated games, finally find the optimal strategy.

Assumption 2: In the evolutionary game system of fluoride governance, each subject is randomly paired each time the game is played, and there is no sequential order. The combination of strategies for enterprises is (positive compliance x, negative compliance 1-x), and the combination of strategies for environmental organizations is (positive regulation y, negative regulation 1-y).

Hypothesis 3: When the enterprise is negatively complying with its responsibility, its effort to reduce fluoride emissions is V1. In this case, the enterprise causes an environmental loss S1 and faces a penalty F from the environmental organization.

Hypothesis 4: For the environmental protection organization, the regulatory cost of the environmental protection organization's active regulation is C21, the environmental protection organization faces only promotion incentives, and the political gain of the environmental protection organization's active regulation is θV2 when considering the weight of the fluoride emission indicator in the performance appraisal, at the same time, the environmental protection organization gives fluoride treatment subsidy B and tax relief δ to the enterprise that actively complies with its responsibility, and the penalty for the enterprise that negatively complies with its responsibility is F. The game tree between the environmental protection organization. The game tree of environmental organizations and enterprises is shown in Figure 1. The parameters are defined in Table 1.

Table 1. Parameter definitions

Parametric	Define	Value range
x	The probability that a firm chooses to fulfill its responsibilities actively	[0,1]
y	The probability that an environmental organization chooses active regulation	[0,1]
V1	Economic gains from negative performance by enterprises	>0
S1	Environmental losses arising from negative corporate performance	>0
F	Environmental organizations face penalties when businesses are negatively compliant	>0
C6	The cost of 'greenwashing' in the case of negative corporate compliance	>0
S2	Loss of social reputation in the event of negative performance by the enterprise	>0
C1	Costs of Reducing Fluoride Emissions when Enterprises Actively Comply	>0
t	Combined tax rate for businesses	[0,1]
ΔV1	Economic losses due to resource allocation when enterprises are active in fulfilling their responsibilities	>0
B1	Subsidies for environmental organizations when companies are proactive in fulfilling their responsibilities	>0
δ	Eco-organization rate relief when businesses are proactive in their responsibilities	[0,1]
V2	Environmental benefits when businesses are proactive in fulfilling their responsibilities	>0
α	Degree of effort by enterprises to reduce fluoride emissions	[0,1]
V3	Social reputational benefits when firms are proactive in fulfilling their responsibilities	>0
C21	Environmental organizations actively regulate the regulatory costs of businesses	>0
θ	The extent of promotion incentives for environmental organizations from environmental gains (damages) in performance appraisals	[0,1]
β	Level of effort by environmental organizations to negatively regulate businesses	[0,1]

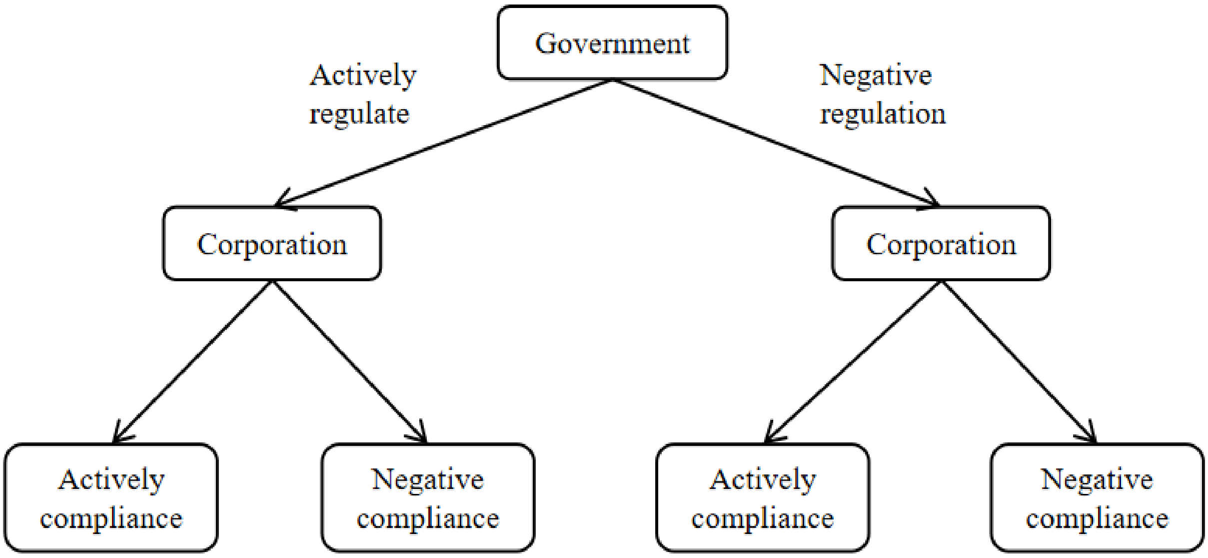

Figure 1. Game tree of environmental organizations and businesses

RESULT AND DISCUSSION

Construct an evolutionary game model

For the enterprise, when the enterprise is negatively complying with its responsibility, its effort to reduce fluoride emissions is α, and the economic gain is V_1. At this time, the enterprise causes an environmental loss S_1 and faces a penalty from the environmental protection organization F.[16-18] When the enterprise is positively complying with its responsibility, the cost of reducing fluoride emissions is C_1, and the comprehensive tax rate is t. Due to the constraints of resources and technology, the enterprise's positive efforts to reduce fluoride emissions attract a greater allocation of limited resources, which causes an economic loss ΔV_1 to the enterprise. More allocations, which causes an economic loss to the enterprise ΔV_1. At the same time, due to the enterprise's efforts to reduce fluoride emissions, the enterprise can additionally receive the environmental organization subsidy B and tax rate reduction δ, and generates an environmental benefit V_2.

For environmental organizations, the regulatory cost of positive regulation by environmental organizations is C_{21}, environmental organizations face only promotion incentives, and the political gain of positive regulation by environmental organizations is ϑV_2 when considering green performance. In contrast, environmental organizations subsidise fluoride treatment and tax breaks δ to positively performing firms and impose fines on negatively performing firms, F. In the case of negative regulation by environmental organizations, the effort to regulate fluoride emission. The game model of the environmental organization and enterprises is shown in Table 2.

Table 2. Game model for environmental organizations and businesses

Corporations environmental organization	Active regulation y	Negative regulation 1-y
Proactively performance 1-x	$(1-t\delta)(V_1-\Delta V_1)-C_1+B$	$(1-t)(V_1-\Delta V_1)-C_1$
	$t\delta(V_1-\Delta V_1)-C_{21}+\theta V_2-B$	$t(V_1-\Delta V_1)-\beta C_{21}+\theta V_2$
Negative performance 1-x	$(1-t)V_1-\alpha C_1-F$	$(1-t)V_1-\alpha C_1-\beta F$
	$tV_1-C_{21}-\theta S_1+F$	$tV_1-\beta C_{21}-\theta S_1+\beta F$

(1) Corporate stabilization strategy

The expected benefits of adopting an 'active responsibility' strategy are:

$$U_{11} = y[(1-t\delta)(V_1-\Delta V_1)-C_1+B]+(1-y)[(1-t)(V_1-\Delta V_1)-C_1]$$

The expected benefit of a firm adopting a 'passive compliance' strategy is:

$$U_{12} = y[(1-t)V_1-\partial C_1-F]+(1-y)[(1-t)(V_1-\partial C_1-\beta F]$$

The average expected return for firms adopting a mixed strategy is:

$$\bar{U}_1 = xU_{11}+(1-x)U_{12}$$

The replication dynamics of a firm's adoption of a 'proactive compliance' strategy is given by the following equation:

$$F_1(x,y)=\frac{dx}{dt}=x(U_{11}-\bar{U}_1)=x(1-x)(U_{11}-U_{12})$$

When, 0<y=y_0<1, $F_1(x,y)=0$at this point, any point in the range of x∈[0,1] is a steady state, and the firm's strategy choice does not change over time. When, $y \neq y_0$, x=0 and x=1 are the two stable points $F_1(x,y)=0$, the analysis of evolutionary stable points is shown in Table 3A.

Table 3A. Analysis of the evolutionary stability point of the enterprise

Conditions			Evolutionary stability point
1	2	3	
y<y0	$F_1^{'}(x,y)\|_{=0}<0$	$F_1^{'}(x,y)\|_{x=1}>0$	x=0
y>y0	$F_1^{'}(x,y)\|_{=0}>0$	$F_1^{'}(x,y)\|_{x=1}<0$	x=1

It can be found that the willingness of enterprises to fulfill their responsibility to reduce fluoride emissions is actively related to the willingness of environmental protection organizations to regulate fluoride emissions.[19] When the willingness of environmental protection organizations to actively regulate fluoride emissions exceeds a certain threshold, enterprises will choose to actively perform their fluoride emission reduction responsibilities to avoid penalties and obtain subsidies to alleviate the pressure to reduce emissions because environmental protection organizations regulate them.[20] On the contrary, when there is a lack of regulation by environmental protection organizations, enterprises will choose to negatively fulfill their responsibility to reduce fluoride emissions to obtain economic benefits, which makes their negative environmental externalities borne by society and ultimately leads to environmental degradation.

(2) Stabilization Strategies for Environmental Organizations

The expected benefits to environmental organizations of adopting an 'active regulation' strategy are:

$$U_{21} = x[t\delta(V_1-\Delta V_1)-C_{21}+\theta V_2-B]+(1-x)[tV_1-C_{21}-\theta S_1+F]$$

The expected benefits to environmental organizations of adopting a 'negative regulation' strategy are:

$$U_{22} = x[t(V_1-\Delta V_1)-\beta C_{21}+\theta V_2]+(1-x)[tV_1-\beta C_{21}-\theta S_1+\beta F]$$

The average expected return for environmental organizations adopting a mixed strategy is:

$$\bar{U}_2 = yU_{21}+(1-y)U_{22}$$

The dynamic equation for the replication of the 'active regulation' strategy adopted by environmental organizations is:

$$F_2(x,y)=\frac{dy}{dt}=y(U_{21}-\bar{U}_2)=y(1-y)(U_{21}-U_{22})$$

$F_2(x,y)=0$ When, 0<x=x0 <1, when any point in the range of x∈[0,1] is a steady state, and the strategic choices of environmental organizations do not change over time.[21-23] When, x ≠ x0, y=0 and y=1 are the two stable points $F_2(x,y)=0$, the analysis of evolutionary stable points is shown in Table 3B.

Table 3B. Analysis of the evolutionary stability point of the enterprise

Conditions			Evolutionary stability point
1	2	3	
y<y0	$F_2^{'}(x,y)\|_{y=0}>0$	$F_2^{'}(x,y)\|_{y=1}<0$	y=1
y>y0	$F_2^{'}(x,y)\|_{y=0}<0$	$F_2^{'}(x,y)\|_{y=1}>0$	y=0

It can be found that the willingness of environmental organizations to regulate fluoride emissions actively is related to the willingness of enterprises to fulfill their responsibility to reduce fluoride emissions.[24] When the willingness of enterprises to fulfill their responsibility to reduce fluoride emissions is higher than a certain threshold, environmental organizations have less income to impose fines on enterprises, and they choose to regulate negatively reduce regulatory costs. In contrast, when enterprises' willingness to reduce fluoride emissions is below a certain threshold, environmental protection organizations will choose to actively regulate fluoride emissions because fines imposed on enterprises' emissions can increase their revenues. The game flow of the fluoride control subjects is shown in Figure 2.

Evolutionary game analysis

Based on the above analysis, environmental protection organizations and enterprise strategies influence each other. According to dynamic equations of environmental protection organizations and enterprises, develop the evolutionary game dynamics system of fluoride emission restrictions of environmental protection organizations and enterprises, and discuss the stability of evolutionary strategy combinations and equilibrium points under the interactive role of environmental protection organizations and enterprises.

Environmental organizations and enterprises dynamically adjust their strategy to reduce fluoride emissions until a Nash equilibrium is reached. Let $F_F = (x, y) = 0$ $F_G = (x, y) = 0$ the four pure strategy equilibrium points of the evolution of the two parties be obtained. According to Lyapunov stability theory, the stability of the equilibrium points can be determined by the eigenvalues of the Jacobian matrix, and the evolutionary stable strategies (ESS) can be determined. The evolutionary stable point is when the eigenvalues of the Jacobian matrix corresponding to the strategy combinations all have negative parts.[25,26] The stability analysis results of the evolutionary features are shown in Table 4.

Table 4. Stability analysis of the evolutionary game

Balance point	Eigenvalue λ_1	Eigenvalue λ_2	Stability
E1(0,0)	-E1+βF	-C21+(1-β)F	Deny
E2(0,)	-E1+G+F	C21-(1-β)F	Case 1
E3(1,0)	E1-βF	-C21-G	Deny
E4(1,1)	E1-G-F	C21+G	Case 2

For case 1, E2(0,1) is the system stability point. At this point, the comprehensive cost of enterprises' active emission reduction is higher than the environmental protection organizations' regulation. In this case, enterprises are negatively fulfilling their responsibilities and environmental protection organizations are negatively regulating, which is an undesirable state, which implies the effectiveness of fluoride emission limitation regulations is insufficient and should be avoided in managing fluoride.[27] For case 2, E4(1,1) is the system stability point; at this time, enterprises actively reduce emissions and explore the potential for emission reduction, and environmental protection organizations actively regulate the significance rather than negative regulation, which is a desirable state.

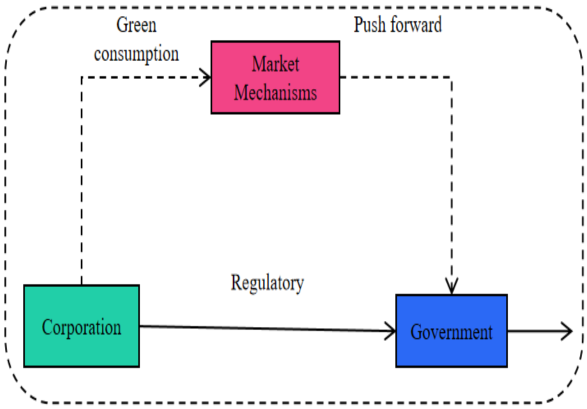

Figure 2. Game analyses of fluoride emission limitation subjects.

Under the pressure of environmental protection organizations to regulate, enterprises actively perform fluoride emission reduction responsibilities. In this case, environmental protection organizations and enterprises work together; the production side reduces direct fluoride emissions, and the formation of environmental protection organizations and enterprises participate in the governance mechanism.[28] This is conducive to enhancing the enterprise's innovation ability, greening products, maximization of social welfare and economic growth.

Based on the analysis of the evolutionary stability of environmental protection organizations and enterprises, it can be found that the enterprises' active implementation of fluoride emission reduction responsibilities is determined by the expected costs and benefits, and the environmental protection organizations, will affect the expected costs and benefits of enterprises. Environmental protection organizations actively regulate enterprises' fluoride emissions and are affected by the combined costs of their regulation, incentives for public participation, incentives for green consumption, and tax incentives; in some cases, environmental protection organizations regulate and positively influence enterprises' fulfillment of their responsibility to reduce fluoride emissions, driving them to reduce emissions and provide green products.[29] Therefore, it is necessary to build a fluoride governance system in environmental organizations and enterprises working together from the production and consumption sides so that the fluoride governance system can evolve towards a desirable equilibrium state.

Driving Paths for Environmental Organizations and Businesses to Work Together to Govern Fluoride Emission Limit Regulations

For environmental organizations, from a purely strategic equilibrium point of view, it is the firms or environmental organizations alone that are the unstable point of the evolutionary gaming system. The

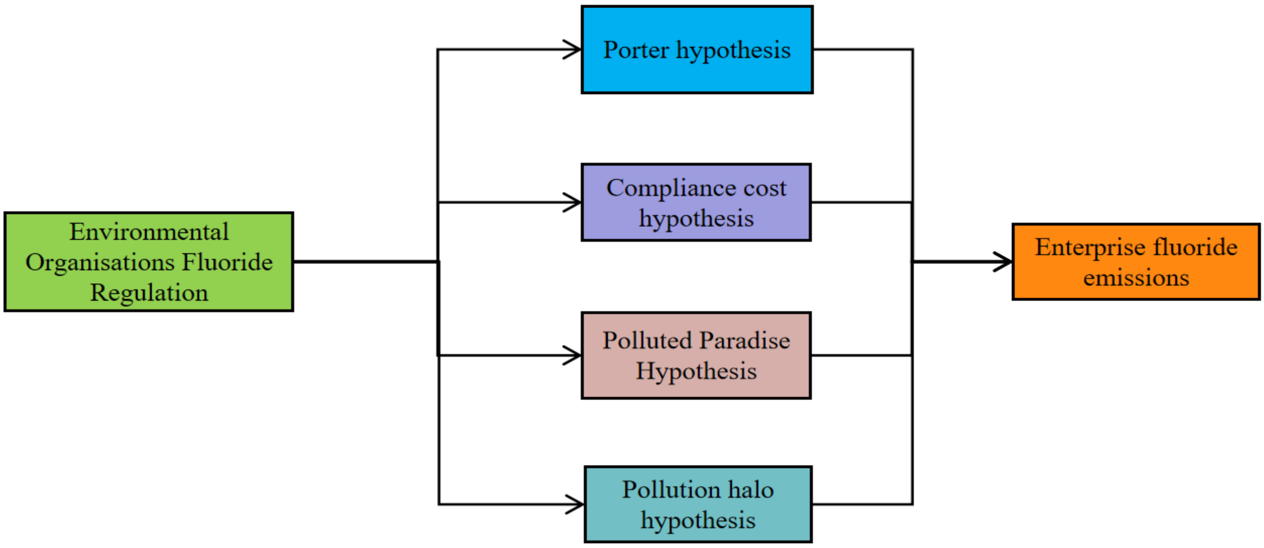

Figure 3. Schematic diagram of the regulation of fluoride emissions from enterprises by environmental organizations.

whole society ultimately bears the negative environmental externalities caused by the production activities of enterprises. Therefore, to make up for the insufficiency of the market mechanism and solve the negative externalities of fluoride emissions from enterprises, environmental protection organizations must constrain and guide the behavior of enterprises through the formulation of emission limitation laws and regulations, and the enforcement of regulations.

Currently, the relationship between environmental pollution and economic development remains controversial, and scholars have put forward a variety of hypotheses.[30] For the impact of regulation by environmental protection organizations, scholars have put forward the follow-the-cost hypothesis and Porter's hypothesis. For fluoride control, based on the compliance cost hypothesis, under the principle of profit maximization, environmental protection organizations regulate the fluoride emissions of enterprises and internalize the externalized environmental costs of enterprises, which directly raises the compliance costs of enterprises and then inhibits technological innovation and reproduction activities of enterprises. The process of environmental organizations regulating fluoride emissions is shown in Figure 3.

For enterprises, the evolutionary gaming system is unstable under the regulation of environmental organizations. This means that fluoride management requires enterprises to fulfill their responsibility to reduce fluoride emissions actively. However, enterprises are profit-driven, which means they are incentivised to fulfill their responsibilities when they can obtain higher benefits when they fulfill their fluoride emission reductions. In the specific reduction of fluoride emissions, the cost of enterprises includes direct investment in reducing fluoride emissions, tax subsidy incentives from environmental organizations, and the social reputation gained from the performance of fluoride emission reduction, etc.

Under the pressure of environmental organizations to regulate, enterprises not only consider the cost of the investment in reducing fluoride emissions but also how to enhance the fulfillment of the responsibility to reduce fluoride through refined management and measures, which aim to the purpose is to enhance corporate value, obtain reproduction resources, improve green innovation output, and achieve sustainable development that takes into account both economic and environmental objectives. Based on this, this study examines why and how enterprises fulfill their responsibility to reduce fluoride emissions under pressure by verifying the impact of corporate responsibility on corporate value and innovation output and how corporate practices can enhance the fulfillment of their responsibility to reduce fluoride emissions. The process of corporate fulfillment of the responsibility to reduce emissions is shown in Figure 4.

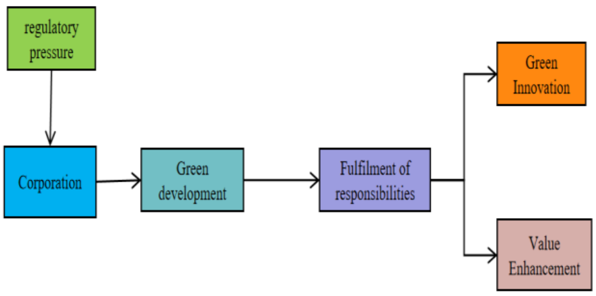

Figure 4. Schematic diagram of enterprises' fulfillment of their responsibility to reduce emissions.

For environmental organizations and enterprise market participation through the consumption of final products to drive enterprise production activities and the accompanying non-desired output fluoride emissions. When environmental protection organizations, and enterprises act as consumers under environmental protection organizations' regulation and consumers' green consumption, the evolutionary gaming system is unstable if the comprehensive cost of enterprises‘ active emission reduction is higher than the fines of the environmental protection organizations’ active regulation, as well as the financial and tax incentives obtained by enterprises' active emission reduction. This means that in fluoride management, even if the enterprise actively fulfils its responsibility to reduce fluoride emissions, if the enterprise actively reduces emissions and provides consumers with green products that cannot obtain higher economic benefits from consumers due to the green attributes of the products, the enterprise may ultimately choose to reduce emissions negatively due to the high cost of emission reduction or because of concerns about the risk of market competition that leads to the enterprise's withdrawal from the market. Based on this, consumers should play a role in the consumption side, actively adjusting the total demand and consumption structure, choosing green consumption, and forcing enterprises to green their production by greening consumption through market participation. The market participation process of environmental organizations, the public and enterprises (Figure 5).

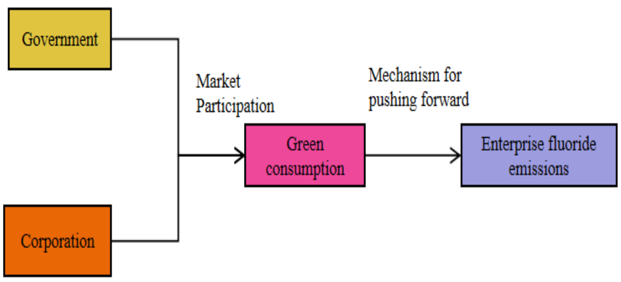

Figure 5. Schematic diagram of market participation by environmental organizations, the public and businesses.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The analysis based on the evolutionary game model shows that the willingness of enterprises to fulfill their fluoride emission reduction responsibilities actively is related to the willingness of environmental protection organizations to legislate on fluoride emissions actively. When the willingness of environmental protection organizations to actively regulate fluoride emissions exceeds a certain threshold, enterprises will choose to actively perform their fluoride emission reduction responsibilities because environmental protection organizations regulate them to avoid penalties and obtain subsidies to alleviate the emission reduction pressure. On the contrary, when environmental protection organisations lack regulation, enterprises will choose to perform their fluoride emission reduction responsibilities negatively to obtain economic benefits, which makes their negative environmental externalities borne by society and ultimately leads to environmental degradation.

The willingness of environmental organizations to actively legislate on fluoride emissions is related to the willingness of enterprises to fulfill their fluoride emission reduction responsibilities. When the willingness of enterprises to fulfill their fluoride emission reduction responsibilities is higher than a certain threshold, environmental protection organizations have less revenue to impose fines on enterprises, and they choose to regulate negatively to reduce regulatory costs. In contrast, when the willingness of enterprises to fulfill their responsibility to reduce fluoride emissions is below a certain threshold, environmental organizations will choose to actively regulate fluoride emissions because of the increased revenue from imposing fines on enterprises for their emissions.

Compare the development and stringency of fluoride emission regulations across different countries/regions (e.g., EU vs US vs China vs India). Research the development, adoption, and cost-effectiveness of Best Available Techniques (BAT) for fluoride emission control.

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None

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