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Seeds of Cross-Sector Collaboration: A Multi-Agent Evolutionary Game Theoretical Framework Illustrated by the Breeding of Salt-Tolerant Rice

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Abstract: In the context of global food security and the pursuit of sustainable agricultural development, fostering synergistic innovation in the seed industry is of strategic importance. However, the collaborative innovation process between seed companies, research institutions, and governments is fraught with challenges due to information asymmetry and bounded rationality within the research and development phase. This paper establishes a multi-agent evolutionary game framework, taking the breeding of salt-tolerant rice as a case study. This study, grounded in the theories of information asymmetry and bounded rationality, constructs a two-party evolutionary game model for the interaction between enterprises and research institutions under market mechanisms. It further extends this model to include government participation, forming a three-party evolutionary game model. The aim is to uncover the evolutionary trends in collaborative behavior under various policy interventions and to understand how governments can foster collaborative innovation in salt-tolerant rice breeding through policy measures. To integrate the impact of historical decisions on the evolution of collaborative innovation, this research employs a delay differential equation (DDE) algorithm that takes historical lags into account within the numerical simulation. The stability analysis and numerical simulation using the DDE algorithm reveal the risk of market failure within the collaborative innovation system for salt-tolerant rice breeding operating under market mechanisms. Government involvement can mitigate this risk by adjusting incentive and restraint mechanisms to promote the system's stability and efficiency. Simulation results further identify that the initial willingness to participate, the coefficient for the distribution of benefits, the coefficient for cost sharing, and the government's punitive and incentivizing intensities are crucial factors affecting the stability of collaborative innovation. Based on these findings, the study suggests a series of policy recommendations including enhancing the initial motivation for participation in collaborative innovation, refining mechanisms for benefit distribution and cost sharing, strengthening regulatory compliance systems, constructing incentive frameworks, and encouraging information sharing and technology exchange. These strategies aim to establish a healthy and effective ecosystem for collaborative innovation in salt-tolerant rice breeding. While this research uses salt-tolerant rice breeding as a case study, the proposed cooperative mechanisms and policy suggestions have universal applicability in various agricultural science and technology innovation scenarios, especially when research meets widespread social needs but lacks commercial profit drivers, underscoring the essential role of government incentives and support. Consequently, this research not only contributes a new perspective to the application of evolutionary game theory in agricultural science and technology innovation but also offers empirical backing for policymakers in advancing similar collaborative innovation endeavors.

Keywords: salt-tolerant rice; breeding; collaborative innovation; evolutionary game; delay differential equation (DDE)

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1. Introduction

In the face of constant climate change and the increasingly severe global food security situation, cooperative innovation in the seed industry is of critical strategic importance for driving sustainable agricultural development. However, collaborative innovation in the seed industry is fraught with difficulties, such as dispersed research resources, unfair benefit distribution, inadequate motivation for collaboration, and isolated efforts among different research groups. Additionally, collaborative innovation in the seed industry is not limited to the improvement and optimization of seed traits; it also involves how companies, research institutions, and governments can integrate resources to establish a new cooperative model, closely connecting various stakeholders in the seed industry to synergize the transformation of scientific research into practical outcomes. Therefore, it is particularly important to coordinate breeding innovation forces, integrate research resources, and establish a government-driven framework for collaborative innovation in the seed industry. This is especially important in the utilization of saline-alkali land, which is widely distributed globally but characterized by high levels of soluble salts in the soil that inhibit or even prevent the growth of most plants [1]; breeding innovation offers significant advantages over traditional methods for improving saline-alkali land. In fact, according to incomplete statistics from UNESCO and FAO, there are about 950 million hectares of saline-alkali land worldwide, with 20–50% of irrigated soils on each continent suffering from excessive salinity. This suggests that nearly 1.5 billion people globally are facing significant food security challenges due to soil salinization, positioning it as an international issue restricting sustainable agricultural development worldwide.

Since the Green Revolution, breeding innovations such as hybrid rice have greatly ensured global food security [2,3]. However, with climate change and environmental crises, traditional breeding techniques can no longer meet the demands of modern agriculture, intensifying calls for a second Green Revolution [4]. The rising global population and urbanization rates pose a dual challenge of food shortages and inadequate farmland. Saline-alkaline soils, with their high potential for food production and minimal environmental impact, have become a focal point for research. In China, the development of saline-alkaline tolerant rice is a highly anticipated research initiative, regarded as a significant and strategic solution to this international challenge. With China's vast saline-alkali lands and rice being a staple food source, breeding saline-alkaline tolerant rice is a national priority research project. This breeding requires long-term R&D, characterized by uncertain outcomes and delayed timelines, which deter purely market-driven investments. Additionally, the development of saline-alkaline tolerant rice has positive externalities such as improving land use and ensuring food security, fostering sustainable agricultural development without immediate economic benefits, thus highlighting the importance of government involvement. Consequently, in 2021, the Chinese government spearheaded the establishment of the National Saline-Alkaline Tolerant Rice Technology Innovation Center. This center, a collaborative effort by the Hunan Hybrid Rice Research Center, Hainan University, Qingdao Seawater Rice Research and Development Center Co., Ltd., and other related enterprises, research institutions, and academic bodies, has formed a diversified and synergistic innovation system. This system strengthens deep cooperation between stakeholders, thereby advancing the research, development, and application of seawater rice technology. In recent years, scholars have conducted extensive research on breeding technologies for saline-alkaline tolerant rice, showing that a combination of multiple breeding techniques is more efficient [5–10]. However, the absence of a collaborative innovation mechanism for breeding saline-alkaline tolerant rice has significantly hindered its development. Therefore, this paper intends to establish a framework of a cooperative innovation enterprise for the seed industry involving research institutions and government agencies, based on the theories of information asymmetry and bounded rationality. This framework will analyze the dynamic interactions between various stakeholders and predict potential evolutionary paths to provide theoretical support for policy making.

Although research on collaborative innovation in salt-tolerant rice breeding is just beginning, traditional studies on collaborative innovation provide a solid theoretical foundation in three main areas: First, research on collaborative innovation examines the operating principles of national systems and various innovation entities from the perspectives of national collaborative innovation systems [11–13]. Second, the "triple helix" framework involves government, industry, and universities [14–16]. Third, open innovation networks led by enterprises integrate global innovation resources and enhance corporate innovation capabilities [17–19]. While these perspectives differ, the industry–academia–research collaborative innovation system is widely recognized as the cornerstone of national innovation system theory. Government subsidies are a pivotal instrument in propelling collaborative innovation among industry, academia, and research institutions. By providing financial support and policy guidance, these subsidies reduce the risks and costs associated with research and development, thereby stimulating the active participation of various innovators. More importantly, they facilitate the construction of platforms and provision of shared resources, which enhances the frequency and depth of interaction among the innovators, thus advancing the overall efficacy of the collaborative innovation system [20–23]. Similarly, public–private partnerships (PPPs) are pivotal in advancing agricultural research. Scholars note that the public and private sectors play complementary roles in U.S. agricultural research, with the private sector's role in research and development growing increasingly prominent. Specifically, the public sector plays a critical role in selecting research themes and rapidly disseminating new knowledge widely [24]. However, others argue that while PPPs have potential in agricultural research within developing countries, successful cases within the international agricultural research community are sparse. Collaborations between public institutions and private enterprises are constrained by divergent incentive structures, costs and risks, mutual negative perceptions, organizational mechanisms, and limited access to information on successful models [25]. Further research into Africa suggests that the sustainability of its agriculture has been impacted by long-term underinvestment. Nevertheless, public and private sectors can collaborate to improve agricultural sustainability. The public sector provides a favorable institutional environment and financial support, while the private sector contributes through product development and the deployment of technical expertise [26]. The commercialization of scientific research is a key phase in the R&D process. Even if the outcomes possess significant technological advantages, the commercialization process is influenced by factors such as the policy environment and investment levels [27–29], necessitating the formulation of appropriate commercialization strategies. Commercialization directly concerns the economic interests of the involved parties and thus is a critical factor affecting their willingness to participate.

Building on previous research, some scholars have constructed two-party evolutionary game models involving universities and enterprises as the main players in collaborative innovation, further analyzing these through numerical simulations [30–33]. However, these studies have not involved the government, which is a crucial participant in collaborative innovation. Thus, some researchers have introduced government incentives as exogenous variables into the two-party evolutionary game model to explore their effects on industry–academia–research collaborative innovation [34]. Other researchers have constructed a three-party dynamic evolutionary game model involving government, enterprise, and universities [35–37] to investigate the impact of mechanisms and pathways of government participation on collaborative innovation.

In summary, although current research has made considerable progress and laid a solid foundation for this topic, there is still room for further investigation and breakthroughs. First, current research on salt-tolerant rice breeding innovation largely focuses on the natural science aspect, emphasizing breeding engineering technology and lacking in-depth economic management studies. Second, most existing collaborative innovation research centers in the industrial sector have few studies specifically addressing breeding collaborative innovation mechanisms; those that do are generally limited to qualitative studies on difficulties and top-level design, lacking discussions on the internal logic of the crop breeding collaborative innovation system and failing to elucidate the mechanisms for collaborative innovation in salt-tolerant rice breeding. Lastly, the numerical simulation algorithms currently used in dynamic evolutionary game studies are based on ordinary differential equations (ODE) solutions, employing 4th and 5th order Runge–Kutta methods. This means the solutions do not change abruptly over time and are suitable for short-term initial value problems. However, dynamic evolutionary game simulations are inherently long-term processes. In economic terms, agents' decisions do not consider decisions from the previous period. This paper uses delay differential equation (DDE) solutions in numerical simulations, based on 2nd and 3rd order Runge–Kutta methods, allowing for adaptive time step selection to accurately simulate dynamics with delays. In economic terms, this is akin to introducing memory and learning mechanisms, requiring agents to consider previous period decisions. In fact, given the high risks associated with seed industry innovation and the growth cycle of crops, which can be several months to a year, the various actors within the collaborative innovation system for salt-tolerant rice breeding often need to base their decisions for the current year on the growth conditions of crops from the previous year's seed innovation. Models considering historical decisions are usually more consistent with many physical, biological, or economic systems in the real world and can more accurately simulate complex dynamic processes.

2. Materials and Methods

2.1. The Two-Party Evolutionary Game Model of "Enterprise–Scientific Research Institution"

2.1.1. Basic Model Assumptions

This paper first establishes a two-party evolutionary game model for the collaborative innovation of salt-tolerant rice breeding under market mechanisms, without government intervention, to explore the necessity of government involvement in such an innovation system.

Assumption 1: In the two-party evolutionary game model of collaborative innovation for salt-tolerant rice breeding without considering government participation, the two types of participating entities are salt-tolerant rice breeding enterprises (E) and scientific research institutions (S). In this model, the enterprises are responsible for providing resources and transforming the outcomes of collaborative innovation, while the scientific research institutions supply knowledge, technology, and research talent. Both parties are boundedly rational and aim to find optimal strategies through repeated games.

Assumption 2: both the breeding enterprises and scientific research institutions can choose whether to engage in collaborative innovation, with their initial willingness to participate denoted by X and Y, respectively.

Assumption 3: As participants in collaborative innovation, both entities will inevitably incur certain innovation costs, including human, material, and financial resources. The paper defines the total cost incurred in collaborative innovation as C, with t representing the proportion of the innovation cost borne by the breeding enterprise and $1 - t$ representing the proportion borne by the scientific research institution.

Assumption 4: We first define the inherent benefits received by the breeding enterprises and scientific research institutions when they do not participate or are passive toward collaborative innovation as R_1 and R_2, respectively. Furthermore, as participants may act opportunistically to seek personal gain and potentially betray the collaboration for speculative benefits, the paper sets S_1 and S_2 as the speculative benefits for the breeding enterprises and scientific research institutions, respectively. Finally, the total benefit derived from the collaborative innovation is defined as R, with a representing the coefficient of the total collaborative innovation revenue allocated to the breeding enterprises, and $1 - a$ representing the coefficient allocated to the scientific research institutions.

Based on these assumptions, the paper constructs the evolutionary game parameters and payoff matrix as shown in Tables 1 and 2, respectively.

Table 1. Parameter Table for Two-Party Evolutionary Game Model.

Variables	Meaning of the Variables	Notes
X	Willingness of Enterprises to Participate	$0 \leq X \leq 1$
Y	Willingness of Research Institutions to Participate	$0 \leq Y \leq 1$
R	Overall Benefits of Collaborative Innovation	——
a	Coefficient of Benefit Distribution	$0 \leq a \leq 1$
R_1	The Benefits of a Company's Negative Treatment	——
R_2	Negative Treatment Benefits for Research Institutions	——
C	Overall Costs of Collaborative Innovation	$C > 0$
t	Coefficient of Cost Sharing	$0 \leq t \leq 1$
S_1	Gains from Corporate Betrayal	——
S_2	Gains from Corporate Betrayal	——

Table 2. Payoff Matrix for Two-Party Evolutionary Game Model.

		Research Institutions	
		Participation	**Betrayal**
Enterprises	Participation	$R_1 + aR - tC$ $R_2 + (1 - a)R - (1 - t)C$	$R_1 - tC$ $R_2 - S_2$
	Betrayal	$R_1 + S_1$ $R_2 - (1 - t)C$	R_1 R_2

2.1.2. Solutions for Evolutionary Stable Strategies

The expected benefits of the breeding enterprises actively participating in collaborative innovation are defined as F_{x11}, with the expected benefits of passive participation defined as F_{x12}, and the average expected benefits as $\overline{F_x}$. The specific settings are given in Equation (1):

$$\begin{aligned} &F_{x11=y}(R_1 + aR - tC) + (1-y)(R_1 - tC) \\ &F_{x12=y}(R_1 + S_1) + (1-y)(R_1) \\ &\overline{F_x} = xF_{x11} + (1-x)F_{x12} \end{aligned} \quad (1)$$

The replicator dynamics equation for the strategy choice of the breeding enterprises is given in Equation (2):

$$F(\mathrm{x}) = \frac{dx}{dt} = x(F_{x11} - \overline{F_x}) = x(1-x)((aR - S_1)y - tC) \quad (2)$$

Similarly, the expected benefits of the scientific research institutions actively participating in collaborative innovation are defined as F_{y11}, with the expected benefits of passive participation defined as F_{y12}, and the average expected benefits as $\overline{F_y}$. The specific settings are given in Equation (3):

$$\begin{aligned} &F_{y11} = x(R_2 + (1-a)R - (1-t)C) + (1-x)(R_2 - (1-t)C) \\ &F_{y12} = x(R_2 + S_2) + (1-x)(R_2) \\ &\overline{F_{\mathrm{y}}} = yF_{y11} + (1-y)F_{y12} \end{aligned} \quad (3)$$

The replicator dynamics equation for the strategy choice of the scientific research institutions is given in Equation (4):

$$F(\mathrm{y}) = \frac{dy}{dt} = y(F_{y11} - \overline{F_{\mathrm{y}}}) = y(1-y)(((1-a)R - S_2)x - (1-t)C) \quad (4)$$

By combining Equations (2) and (4), the replicator dynamics equations of the two-party evolutionary game system for the breeding enterprises and scientific research institutions can be established, and a local stability analysis using the Jacobian matrix J can be performed, ultimately leading to the Jacobian matrix of the system as defined in Equation (5):

$$J = \begin{bmatrix} (1-2x)((aR-S_1)y-tC), x(1-x)(aR-S_1) \\ y(1-y)((1-a)R-S_2), (1-2y)(((1-a)R-S_2)x-(1-t)C) \end{bmatrix} \quad (5)$$

To find the conditions that lead to collaborative innovation between industry, academia, and research, we use the Jacobian matrix to explore the factors that cause the system to converge to the Pareto-optimal state (1,1). By substituting the equilibrium point (1,1) into Equation (5), a new Jacobian matrix J1 is obtained as follows:

$$J_1 = \begin{bmatrix} S_1 - aR + tC, 0 \\ 0, (1-t)C + S_2 - (1-a)R \end{bmatrix} \quad (6)$$

Following Friedman (1991), if all eigenvalues of the Jacobian matrix are less than zero, the equilibrium point is stable within the dynamic evolutionary system. From Equation (6), it is clear that when both $aR > tC + S_1$ and $(1-a)R > (1-t)C + S_2$ are satisfied, the point (1,1) is a stable point of the dynamic evolutionary system. With the parameters set to $t = 0.5$; $C = 15$; $S_1 = 5$; $S_2 = 5$; $a = 0.5$; and $R = 26$, the phase diagrams are depicted in Figure 1. The left side of Figure 1 shows the phase diagram of the dynamic system evolution without considering historical decisions using the ODE method; the right side shows the phase diagram of the dynamic system evolution considering historical decisions using the DDE method.

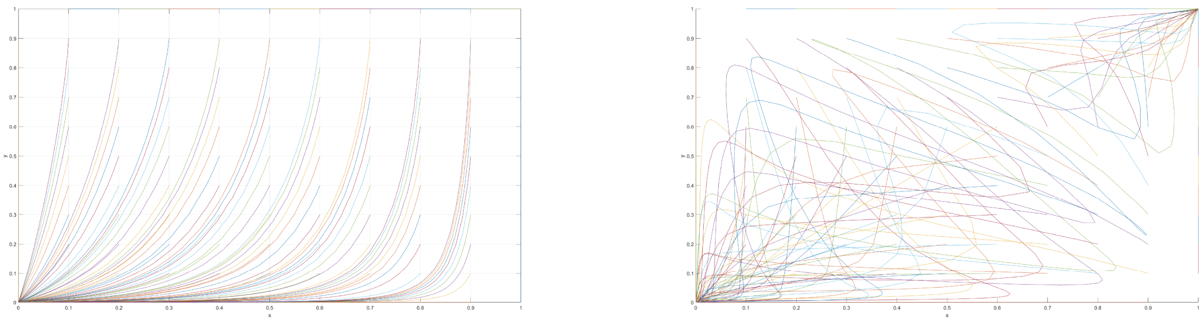

Figure 1. Phase Diagrams of the Two-Party Dynamic Evolutionary Game System.

Observing Figure 1, it is evident that, even when parameters satisfy the equilibrium point (1,1), if historical decisions are not considered, the system's stable equilibrium point remains at (0,0). This is due to the eigenvalues being $-tC$ and $(t-1)C$ when introducing (0,0) into the Jacobian matrix J. Clearly, in this case, the eigenvalues are always less than zero, and (0,0) is the system's equilibrium point. This occurs because, without considering historical decisions, participants tend to be myopic, leading to passive participation or betrayal. However, when historical decisions are taken into account, it is possible for the dynamic evolutionary system to be stable at both (0,0) and (1,1), as memory and learning mechanisms lead individuals to make more complex strategic choices based on historical information, which can result in decisions to engage in collaborative innovation. Nonetheless, without government intervention and considering only the breeding enterprises and scientific research institutions, decision makers may tend toward passive participation or betrayal, underscoring the importance of government involvement.

2.2. The Three-Party Evolutionary Game Model of "Enterprise–Scientific Research Institution–Government"

2.2.1. Basic Model Assumptions

The paper establishes a three-party evolutionary game model for collaborative innovation in salt-tolerant rice breeding with government participation to explore the mechanisms and pathways of such innovation.

Assumption 5: In the three-party evolutionary game model considering government involvement, there are three types of participants, including the breeding enterprises (E), the scientific research institutions (S), and the government (G). In this model, the enterprises are responsible for providing resources and results for collaborative innovation; the scientific research institutions supply the necessary knowledge, technology, and research talent, while the government's role is to offer financial support and subsidies, reducing the cost of collaborative innovation and penalizing any passive involvement or betrayal by the enterprises and institutions. Each entity is boundedly rational and seeks to find the optimal strategy through repeated games.

Assumption 6: the breeding enterprises and scientific research institutions can choose whether to participate in collaborative innovation, with their initial willingness denoted by X and Y, respectively.

Assumption 7: Both the breeding enterprises and scientific research institutions, as participants in collaborative innovation, will inevitably incur certain innovation costs, including human, material, and financial resources. The paper defines the total cost incurred in collaborative innovation as C, with t representing the proportion of the innovation cost borne by the breeding enterprise and $1 - t$ representing the proportion borne by the scientific research institution. Although the government does not directly partake in the collaborative innovation process, it incurs supervisory costs C_3. Moreover, the government provides policy incentives and financial subsidies to reduce the cost of collaborative innovation, which are defined as M.

Assumption 8: The paper initially sets the benefits of the breeding enterprises and scientific research institutions when they are passive toward collaborative innovation as R_1 and R_2, respectively. Furthermore, since participants may act opportunistically, the paper sets S_1 and S_2 as the speculative benefits for the breeding enterprises and scientific research institutions, respectively, if they betray the collaboration. The total benefit derived from the collaborative innovation process is defined as R, with a representing the coefficient of the total collaborative innovation revenue allocated to the breeding enterprises and $1 - a$ representing the coefficient allocated to the scientific research institutions. When the government chooses to participate in the collaborative innovation process, it defines the benefits as R_3; if the government does not participate, there are neither benefits nor costs.

Assumption 9: In the case of government supervision, if the breeding enterprise and scientific research institution show passive involvement or breach their contract, the government will fine both parties to offset the subsidy cost and supervisory cost. The paper defines the penalty amounts as K_1 and K_2, respectively.

Based on these assumptions, the paper constructs the parameters and payoff matrix for the three-party evolutionary game as shown in Tables 3 and 4.

Table 3. Parameter Table for Three-Party Evolutionary Game Model.

Variables	Meaning of the Variables	Notes
X	Willingness of Enterprises to Participate	$0 \leq X \leq 1$
Y	Willingness of Research Institutions to Participate	$0 \leq Y \leq 1$
Z	Willingness of Government to Participate in Regulation	$0 \leq Z \leq 1$
R	Overall Benefits of Collaborative Innovation	——
a	Coefficient of Benefit Distribution	$0 \leq a \leq 1$
R_1	The Benefits of a Company's Negative Treatment	——
R_2	Negative Treatment Benefits for Research Institutions	——
R_3	Benefits Obtained from Government Participation	——
C	Overall Costs of Collaborative Innovation	$C > 0$
t	Coefficient of Cost Sharing	$0 \leq t \leq 1$
C_3	Government Supervision Costs	$C_3 > 0$
M	Government Support for Collaborative Innovation	$M > 0$
S_1	Gains from Corporate Betrayal	——

Table 3. *Cont.*

Variables	Meaning of the Variables	Notes
S_2	Gains from Research Institutions' Speculative Betrayal	——
K_1	Government Penalties for Corporate Betrayal	$K_1 > 0$
K_2	Government Penalties for Research Institutions' Betrayal	$K_2 > 0$

Table 4. Payoff Matrix for Three-Party Evolutionary Game Model.

		Research Institutions	
		Participation	Betrayal
Government Regulation	Enterprises Participation	$R_1 + aR - t(C - M)$ $R_2 + (1 - a)R - (1 - t)(C - M)$ $R_3 - C_3$	$R_1 - t(C - M)$ $R_2 + S_2 - K_2$ $R_3 - C_3 + K_2$
	Enterprises Betrayal	$R_1 + S_1 - K_1$ $R_2 - (1 - t)(C - M)$ $R_3 - C_3 + K_1$	$R_1 - K_1$ $R_2 - K_2$ $R_3 - C_3 + K_1 + K_2$
Government Deregulation	Enterprises Participation	$R_1 + aR - tC$ $R_2 + (1 - a)R - (1 - t)C$ 0	$R_1 - tC$ $R_2 + S_2$ 0
	Enterprises Betrayal	$R_1 + S_1$ $R_2 - (1 - t)C$ 0	R_1 R_2 0

2.2.2. Solutions for the Three-Party Evolutionary Stable Strategy

The paper defines the expected profit for a salt-tolerant rice breeding enterprise actively participating in collaborative innovation as U_{x11}, the expected profit for passive participation as U_{x12}, and the average expected profit as $\overline{U_x}$, which are concretely set in Equation (7):

$$\begin{aligned}
&U_{x11} = yz(R_1 + aR - t(C - M)) + (1 - y)z(R_1 - t(C - M)) + y(1 - z)(R_1 + aR - tC) + (1 - y)(1 - z)(R_1 - tC)\\
&U_{x12} = yz(R_1 + S_1 - K_1) + (1 - y)z(R_1 - K_1) + y(1 - z)(R_1 + S_1) + (1 - y)(1 - z)(R_1)\\
&\overline{U}_x = xU_{x11} + (1 - x)U_{x12}
\end{aligned} \tag{7}$$

The replicator dynamic equation for the strategy selection of the breeding enterprise is defined in Equation (8):

$$U(\mathrm{x}) = \frac{dx}{dt} = x(U_{x11} - \overline{U}_x) = x(1 - x)((aR - S_1)y + (K_1 + tM)z - tC) \tag{8}$$

The expected profit for a scientific research institution actively participating in collaborative innovation is defined as U_{y11}, the expected profit for passive participation as U_{y12}, and the average expected profit as $\overline{U_y}$, which are concretely set in Equation (9):

$$\begin{aligned}
&U_{y11} = xz(R_2 + (1 - a)R - (1 - t)(C - M)) + (1 - x)z(R_2 - (1 - t)(C - M)) +\\
&x(1 - z)(R_2 + (1 - a)R - (1 - t)C) + (1 - x)(1 - z)(R_2 - (1 - t)C)\\
&U_{y12} = xz(R_2 + S_2 - K_2) + (1 - x)z(R_2 - K_2) + x(1 - z)(R_2 + S_2) + (1 - x)(1 - z)(R_2)\\
&\overline{U}_{\mathrm{y}} = yU_{y11} + (1 - y)U_{y12}
\end{aligned} \tag{9}$$

The replicator dynamic equation for the strategy selection of the scientific research institution is defined in Equation (10):

$$U(\mathrm{y}) = \frac{dy}{dt} = y(U_{y11} - \overline{U}_{\mathrm{y}}) = y(1 - y)(((1 - a)R - S_2)x + (K_2 + (1 - t)M)z - (1 - t)C) \tag{10}$$

The expected profit for government supervision of collaborative innovation in salt-tolerant rice breeding is defined as U_{z11}, the expected profit for not supervising as U_{z12}, and the average expected profit as $\overline{U_z}$, which are concretely set in Equation (11):

$$\begin{aligned}&U_{z11} = xy(R_3 - C_3) + (1-x)y(R_3 + K_1 - C_3) + \\ &x(1-y)(R_3 + K_2 - C_3) + (1-x)(1-y)(R_3 + K_1 + K_2 - C_3) \\ &U_{z12} = 0 \\ &\overline{U_z} = zU_{z11} + (1-z)U_{z12}\end{aligned} \tag{11}$$

The government's replicator dynamic equation is defined in Equation (12):

$$U(\mathrm{z}) = \frac{dz}{dt} = z(U_{z11} - \overline{U_z}) = z(1-z)((1-x)K_1 + (1-y)K_2 + R_3 - C_3) \tag{12}$$

By combining Equations (8), (10), and (12), the replicator dynamic equations for the three-party evolutionary game system can be established, and a local stability analysis using the Jacobian matrix J_2 can be performed, ultimately leading to the system's Jacobian matrix as defined in Equation (13):

$$J_2 = \begin{bmatrix} (1-2x)((aR - S_1)y + (K_1 + tM)z - tC), x(1-x)(aR - S_1), x(1-x)(K_1 + tM) \\ y(1-y)((1-a)R - S_2), (1-2y)(((1-a)R - S_2)x + (K_2 + (1-t)M)z - (1-t)C), y(1-y)(K_2 + (1-t)M) \\ z(1-z)K_{1,z}(1-z)K_2, (1-2z)((1-x)K_1 + (1-y)K_2 + R_3 - C_3) \end{bmatrix} \tag{13}$$

According to Lyapunov's [38] study, the equilibrium points in a three-party evolutionary game system should be asymptotically stable, and an equilibrium point can be considered an evolutionarily stable strategy (ESS) if and only if it satisfies strict Nash equilibrium and pure strategy equilibrium. By setting the dynamics of the three-party evolutionary game system to zero, the paper determines 8 local stable equilibrium points: E1(0,0,0), E2(1,0,0), E3(0,1,0), E4(0,0,1), E5(1,1,0), E6(1,0,1), E7(0,1,1), and E8(1,1,1). These 8 points constitute the boundaries of the evolutionary game domain, with all internal equilibrium points being mixed strategy Nash equilibria and not stable points. Therefore, the paper primarily studies the asymptotic stability of the aforementioned 8 equilibrium points. According to Friedman [39], the stability of the asymptotic equilibrium points depends on the sign characteristics of the Jacobian matrix; an equilibrium point is considered ESS when all eigenvalues of the Jacobian matrix are negative. After substituting the 8 equilibrium points into the Jacobian matrix, the eigenvalues are obtained as shown in Table 5.

Table 5. Jacobian Matrix Eigenvalues.

Equilibrium Point	λ_1	λ_2	λ_3
E1(0,0,0)	$-$tC	(t − 1)C	$K_1 + K_2 + R_3 - C_3$
E2(1,0,0)	tC	$(1-a)R - (1-t)C - S_2$	$K_2 + R_3 - C_3$
E3(0,1,0)	$aR - S_1 - tC$	(1 − t)C	$K_1 + R_3 - C_3$
E4(0,0,1)	$K_1 - t(C - M)$	$K_2 - (1-t)(C - M)$	$C_3 - K_1 - K_2 - R_3$
E5(1,1,0)	$S_1 + tC - aR$	$(1-t)C + S_2 - (1-a)R$	$R_3 - C_3$
E6(1,0,1)	$t(C - M) - K_1$	$(1-a)R + K_2 - S_2 - (1-t)(C - M)$	$C_3 - K_2 - R_3$
E7(0,1,1)	$K_1 + t(M - C) + aR - S_1$	$(1-t)(C - M) - K_2$	$C_3 - K_1 - R_3$
E8(1,1,1)	$t(C - M) + S_1 - aR - K_1$	$S_2 + (1-t)(C - M) - (1-a)R - K_2$	$C_3 - R_3$

Due to the complex and numerous parameters in the model, to better analyze the stability, the paper assumes that the benefits of collaborative innovation for the salt-tolerant rice breeding enterprise, the scientific research institution, and the government are greater than the benefits of not engaging in collaborative innovation. This necessitates meeting the three conditions $aR + K_1 > t(C - M) + S_1$; $(1-a)R + K_2 > S_2 + (1-t)(C - M)$; and $R_3 > C_3$, to analyze the sign of the eigenvalues corresponding to different equilibrium points. The paper discusses the equilibrium points under three scenarios as shown in Table 6.

Table 6. Signs of Eigenvalues for Local Equilibrium Points.

Equilibrium Point	Scenario1				Scenario2			
	λ_1	λ_2	λ_3	Stability	λ_1	λ_2	λ_3	Stability
E1(0,0,0)	−	−	+	NESS	−	−	+	NESS
E2(1,0,0)	+	+,−	+	NESS	+	+,−	+	NESS
E3(0,1,0)	+,−	+	−	NESS	+,−	+	−	NESS
E4(0,0,1)	−	−	−	ESS	+	+	−	NESS
E5(1,1,0)	+,−	+,−	+	NESS	+,−	+,−	+	NESS
E6(1,0,1)	+	+	−	NESS	−	+	−	NESS
E7(0,1,1)	+	+	−	NESS	+	−	−	NESS
E8(1,1,1)	−	−	−	ESS	−	−	−	ESS

Note: ESS refers to a stable point, while NESS refers to an unstable point.

Scenario 1: Parameters satisfy $t(C - M) > K_1$; $(1 - t)(C - M) > K_2$, meaning the government's penalty for passive participation or betrayal by the breeding enterprise and scientific research institution is less than the cost shared after government subsidy incentives. In this scenario, as seen in Table 6, the two points E4(0,0,1) and E8(1,1,1) satisfy the condition of all three negative eigenvalues and are thus ESS. The system's evolutionary strategy should be (non-participation, non-participation, participation) or (participation, participation, participation). With parameters set to R = 50; R_3 = 10; t = 0.5; a = 0.5; S_1 = 12; S_2 = 10; K_1 = 3; K_2 = 3; M = 15; C_3 = 8; and C = 20, Figure 2 is drawn, showing the phase diagrams of the collaborative innovation dynamic system evolution both without historical decisions using ODE methodology on the left and with historical decisions using DDE methodology on the right. It is observed that without considering historical decisions, the decisions of the three parties still largely converge to E8(1,1,1), indicating that even if the cost of collaborative innovation is greater than the punishment, the participants still tend to engage in collaborative innovation when profit can be made. When historical decisions are considered, although the decisions are also largely concentrated on E8(1,1,1), there are many instances of choices at E4(0,0,1), suggesting that with memory and learning mechanisms introduced, and under weak regulatory forces, the breeding enterprise and research institution may still betray or passively participate.

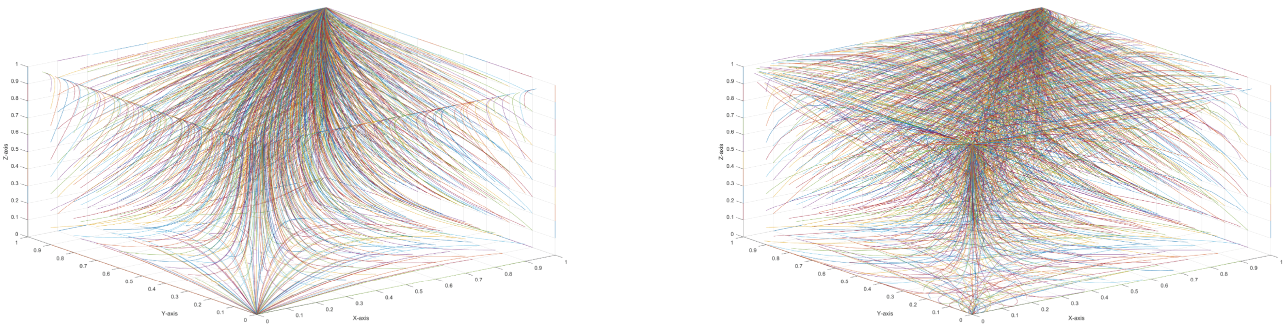

Figure 2. Phase Diagram of Three-Party Game Dynamic System Evolution in Scenario 1.

Scenario 2: Parameters satisfy $t(C - M) < K_1$; $(1 - t)(C - M) < K_2$, meaning the government's penalty for passive participation or betrayal by the breeding enterprise and scientific research institution is greater than the cost shared after government subsidy incentives. In this scenario, as seen in Table 6, only E8(1,1,1) satisfies the condition of all three negative eigenvalues and is thus ESS. The system's evolutionary strategy should be (participation, participation, participation). With parameters set to R = 50; R_3 = 10; t = 0.5; a = 0.5; S_1 = 12; S_2 = 10; K_1 = 15; K_2 = 15; M = 15; C_3 = 8; and C = 30, Figure 3 is drawn, showing the phase diagrams of the collaborative innovation dynamic system evolution both without considering historical decisions using ODE methodology on the left and with historical decisions using DDE methodology on the right. It is observed that, after numerical simulation with the set parameters, regardless of whether or not historical decisions are considered, the decisions of the three parties are largely concentrated on E8(1,1,1). This indicates that with sufficiently strong regulatory forces, the breeding enterprise and scientific research institution are more likely to actively participate in collaborative innovation for salt-tolerant rice breeding.

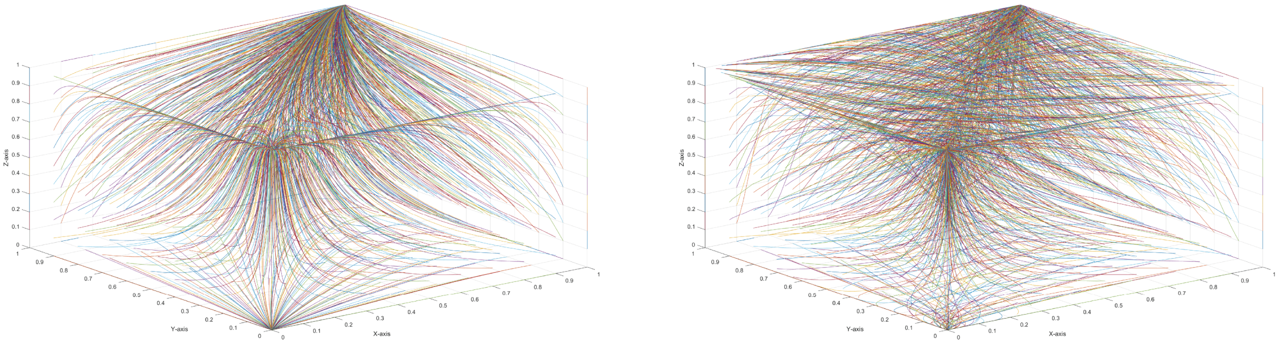

Figure 3. Phase Diagram of Three-Party Game Dynamic System Evolution in Scenario 2.

3. Results

This study conducts simulation analyses of the collaborative innovation system for salt-tolerant rice breeding using MATLAB 2020b software. The purpose is to provide a more intuitive exploration of the strategic changes of the three-party game participants. In this section, we specifically explore the impact of different factors on the behavioral strategies of the game participants. When the system's stable point is E8(1,1,1), the decisions of the multiple parties are considered to be in an optimal state (participation, participation, participation). The parameter values satisfy the constraints: $aR + K_1 > t(C - M) + S_1$; $(1 - a)R + K_2 > S_2 + (1 - t)(C - M)$; and $R_3 > C_3$, indicating that the total benefits of participating in the collaborative innovation of salt-tolerant rice breeding exceed the total cost. The parameters are set as follows: $X = Y = Z = 0.5$; $R = 50$; $R_3 = 10$; $t = 0.5$; $a = 0.5$; $S_1 = 12$; $S_2 = 10$; $K_1 = 5$; $K_2 = 5$; $M = 15$; $C_3 = 8$; and $C = 30$. The algorithm used for numerical simulations in this paper is a delay differential equation (DDE) with a lag period of one year, aiming to incorporate memory and learning mechanisms into the numerical simulation. This allows decision makers to fully consider the previous year's decisions, better simulating real-world decision making behaviors.

3.1. Sensitivity Analysis of Initial Participation Willingness

Figure 4 depicts the sensitivity analysis of the initial willingness to participate for the salt-tolerant rice breeding enterprise (E), scientific research institution (S), and government (G), while keeping other parameters constant. From top to bottom, Figure 4 shows the sensitivity analysis graphs for changes in the initial willingness to participate for the breeding enterprise, scientific research institution, and government, respectively.

Observing Figure 4, we find that the critical value of the initial willingness to participate for both the breeding enterprise and scientific research institution lies between 0.4 and 0.5, while for the government it is between 0 and 0.1. When all parties' initial willingness to participate is below these critical values, their collaborative innovation strategies converge to zero, and the final equilibrium point converges to (0,0,0), indicating a tendency toward passive participation or betrayal of collaborative innovation, with no government involvement. When the initial willingness exceeds the critical values, the collaborative innovation strategies of the breeding enterprise, scientific research institution, and government all converge to one, and the final equilibrium point converges to E8(1,1,1), indicating a tendency for all entities to participate in collaborative innovation. Given that China's basic national condition of having a large population and limited land area has not changed, and the issues of "non-agriculturalization" and "non-grain" use of arable land are prominent, strengthening the protection and improvement of arable land has always been a priority in

China's local government agricultural work. Breeding innovation of salt-tolerant rice can fully tap into the potential of comprehensive utilization of saline-alkali land, serving as an important pathway for the effective use of non-traditional arable land resources. Therefore, local governments in China are generally willing to participate in collaborative innovation for salt-tolerant rice breeding. However, when the breeding enterprise and scientific research institution have a low initial willingness to participate, even with government guidance and supervision, they are still reluctant to engage in collaborative innovation. Thus, increasing the initial expectations of the breeding enterprise and scientific research institution for salt-tolerant rice is a powerful way to promote collaborative innovation in breeding.

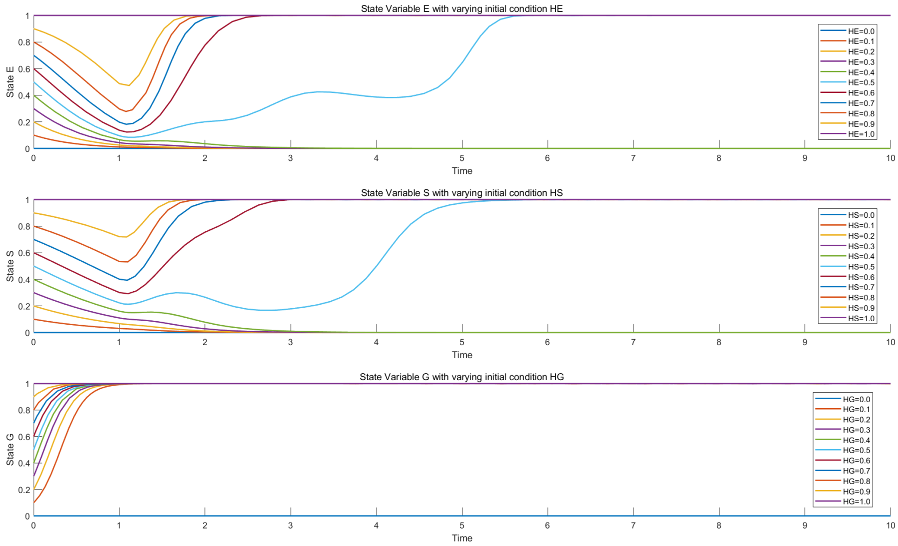

Figure 4. Sensitivity Analysis of Initial Participation Willingness.

3.2. *Sensitivity Analysis of Benefit Distribution and Cost Sharing*

On the premise of keeping other parameters constant, the paper analyzes the sensitivity of collaborative innovation strategies to different benefit distribution coefficients (a) and cost-sharing coefficients (t) for the breeding enterprise (E) and scientific research institution (S); Figure 5 is drawn accordingly.

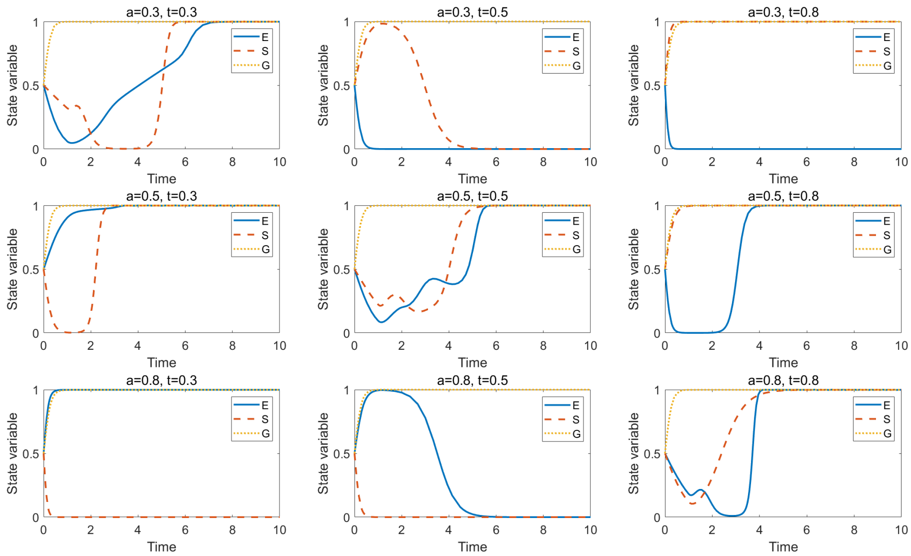

Figure 5. Sensitivity Analysis of Benefit Distribution and Cost Sharing.

Observing Figure 5, we see that when the benefit distribution coefficient (a) and cost-sharing coefficient (t) are equal, as well as when a = 0.5, t = 0.3, and a = 0.5, t = 0.8, the equilibrium point of the salt-tolerant rice breeding collaborative innovation system converges to E8(1,1,1), with all parties choosing to participate in collaborative innovation. When a = 0.3, t = 0.5, and a = 0.8, t = 0.5, the equilibrium point converges to E4(0,0,1), with the breeding enterprise and scientific research institution tending toward passive participation or betrayal of collaborative innovation. When a = 0.3, t = 0.8, the equilibrium point converges to E7(0,1,1), with the breeding enterprise tending toward passive participation or betrayal. When a = 0.8, t = 0.3, the equilibrium point converges to E6(1,0,1), with the scientific research institution tending toward passive participation or betrayal. Overall, the larger the gap between the cost-sharing coefficient and benefit distribution coefficient, the harder it is to reach the optimal equilibrium point E8(1,1,1).

Additionally, observing the three subfigures where the benefit distribution coefficient and cost-sharing coefficient are equal (a = t), we notice that the larger the a and t values for the breeding enterprise, the sooner the equilibrium point of the system converges to E8(1,1,1). For example, at a = t = 0.3, it takes until around the seventh year to converge to E8(1,1,1), while at a = t = 0.8, it takes until only the fifth year. This indicates that, when benefit distribution and cost sharing are equal, it is preferable to allow the breeding enterprise to receive more benefits and share more costs. This is primarily because the breeding enterprise and scientific research institution have different sensitivities to benefits. The primary goal of enterprises is to create shareholder value, and their performance, management bonuses, and employee incentives are often closely related to financial gains, making them more sensitive to benefits. In contrast, while scientific research institutions also care about funding, resources, and benefit acquisition, they tend to focus on long-term knowledge innovation and scientific discovery. Their goal is to drive the advancement of salt-tolerant rice breeding techniques, promote the comprehensive development and utilization of saline-alkali land, and ensure food security, making them less sensitive to benefits.

Finally, when the benefits of collaborative innovation are equally distributed (a = 0.5), whether the breeding enterprise bears higher costs (t = 0.8) or the scientific research institution bears higher costs (t = 0.3), as long as the benefits are equally distributed, they will eventually participate in collaborative innovation. Conversely, when the costs of collaborative innovation are equally shared (t = 0.5), whether the breeding enterprise allocates more benefits (a = 0.8) or the scientific research institution allocates more benefits (a = 0.3), they tend to passively participate or betray collaborative innovation. The main reason is that the early R&D investment in the field of collaborative innovation is seen as a necessary long-term investment, rather than just a cost. Additionally, if the success of collaborative innovation leads to the commercialization and widespread promotion of salt-tolerant rice, it will bring significant economic and social benefits, such as fulfilling corporate social responsibility (CSR) and achieving enough scientific performance to realize social value. Most importantly, there is external support from the government, such as subsidies and related incentive policies, which reduces the sensitivity of both parties to the visible costs of collaborative innovation and focuses more on potential long-term benefits.

3.3. Sensitivity Analysis of Government Supervision Intensity

Under the condition of holding other parameters constant, this study assigns the ratio of different penalty intensities to speculative benefits for the salt-tolerant rice breeding enterprise (E) as P1, and for the scientific research institution (S) as P2. Sensitivity analysis of P1 and P2 on collaborative innovation strategy is conducted, as shown in Figure 6.

Observation of Figure 6 reveals that when P1 = 0.40 and P2 = 0.40 or P1 = 0.40 and P2 = 0.50, the equilibrium point of the salt-tolerant rice breeding collaborative innovation system converges to E4(0,0,1). At this point, both the breeding enterprise and the scientific research institution tend to passively participate or betray the collaborative innovation. In other cases, the equilibrium point converges to E8(1,1,1), indicating that all parties opt to participate in collaborative innovation. This indicates that when P1 and P2 are low, meaning that the penalties are relatively minor compared to the speculative gains, the penalties faced for betraying the collaborative innovation agreement midway are insufficient to outweigh the potential speculative benefits, leading enterprises and institutions to prefer speculative behavior. Conversely, when P1 and P2 are higher, the penalties for betrayal or passive participation exceed the benefits of active collaboration, hence enterprises and institutions are inclined to fully engage in the innovation process. Separate observation of the subgraphs with P1 = 0.40 and P2 = 0.50 as well as P1 = 0.50 and P2 = 0.40, shows that when the penalty intensity for the enterprise is higher (P1 = 0.50 and P2 = 0.40), the equilibrium point tends to converge to E8(1,1,1), indicating a tendency to participate in collaborative innovation. In contrast, when the penalty intensity for the enterprise is lower (P1 = 0.40 and P2 = 0.50), the equilibrium point tends to converge to E4(0,0,1), suggesting a tendency toward passive participation or betrayal. This suggests that, compared to scientific institutions, enterprises are more sensitive to penalty intensity due to their inherent profit-oriented nature, whereas institutions, driven by the pursuit of scientific advancement and technological innovation, tend to participate in collaborative innovation even under lower penalties. Therefore, in the salt-tolerant rice breeding collaborative innovation system, greater focus should be placed on the penalties and constraints for enterprises, in order to explore more reasonable regulatory measures.

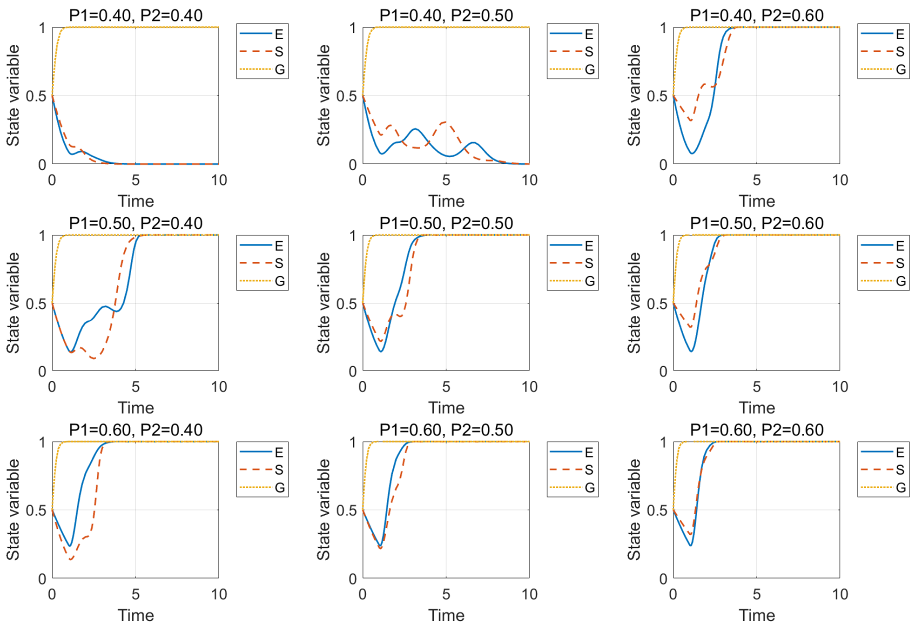

Figure 6. Sensitivity Analysis of Government Penalty Intensity.

3.4. Sensitivity Analysis of Government Subsidy Intensity

With other parameters held constant, the study conducts a sensitivity analysis of the subsidy and incentive measures M provided by the government during the collaborative innovation process, establishing the following indicators:

SCR (Subsidy–Cost Ratio) M/C: This measures the proportion of government subsidies in the total cost of collaborative innovation. An increase in SCR indicates more substantial financial support from the government, reducing the cost burden for enterprises and institutions participating in collaborative innovation.

CBR (Cost–Benefit Ratio) (C-M)/R: This reflects the ratio of the actual cost borne by enterprises and institutions after considering government subsidies to the total benefits gained from collaborative innovation. A lower CBR indicates greater economic attractiveness of collaborative innovation after subsidies.

The specific simulation results are illustrated in Figure 7.

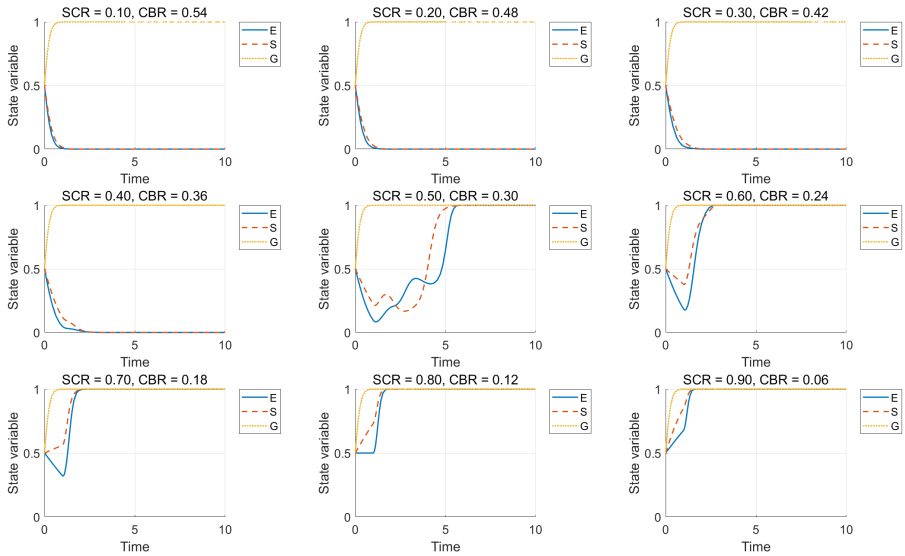

Figure 7. Sensitivity Analysis of Government Subsidy Intensity.

From Figure 7, it is apparent that the critical point for SCR lies between 0.4 and 0.5, and for CBR, the critical point lies between 0.3 and 0.36. When SCR is below the critical point and CBR is above it, the collaborative innovation system converges to E4(0,0,1), with enterprises and institutions tending toward passive participation or betrayal. When SCR is above and CBR below their respective critical points, the system converges to E8(1,1,1), and all parties choose to participate in collaborative innovation. The ratio of government subsidies to the cost of collaborative innovation (SCR) is a significant indicator of the economic attractiveness of collaborative innovation. Government subsidies can alleviate economic burdens, especially during the initial, high-cost, high-risk R&D phase. For salt-tolerant rice breeding, R&D activities may require expensive equipment, advanced technology, and expertise. A higher SCR value implies sufficient government financial support, reducing the financial barriers for enterprises and institutions and encouraging their participation in R&D and innovation. Such policies can help cover mistakes and failures during the development process, bolstering the long-term confidence of collaborative innovation participants, allowing research institutions and enterprises to focus on long-term goals rather than short-term financial pressures. The ratio of actual costs to total benefits from innovation after government subsidies (CBR) is another key indicator of the economic attractiveness of collaborative innovation. A low CBR means that the net cost of collaborative innovation is low and the return on investment is high, which is a strong motivator for enterprises and institutions. In collaborative innovation projects for salt-tolerant rice breeding, a low CBR value might encourage more enterprises to invest in the research of improved rice varieties or to support R&D aimed at increasing crop yields and resilience, thereby helping to ensure food security and agricultural sustainability. Therefore, the government should increase its support for collaborative innovation in salt-tolerant rice breeding, and in addition to direct cash subsidies, explore more effective government incentive measures.

4. Conclusions

Drawing on the theory of information asymmetry and bounded rationality, this paper first establishes a two-party evolutionary game model for "Enterprise–Scientific Research Institution" under market mechanisms and conducts a stability analysis. Subsequently, it establishes a three-party evolutionary game model "Enterprise–Scientific Research Institution–Government" with government participation, discusses the strategic evolution outcomes of the game process under different conditions, and performs numerical simulations and sensitivity analyses using delay differential equations (DDE) that consider historical delays, providing a theoretical basis for constructing mechanisms and pathways for collaborative innovation in salt-tolerant rice breeding. The main conclusions are as follows:

In the "Enterprise–Scientific Research Institution" system for collaborative innovation in salt-tolerant rice breeding established under market mechanisms, the point E1(0,0) is always a stable point (ESS) within the system. Therefore, under market mechanisms, collaborative innovation in salt-tolerant rice breeding faces "market failure" and cannot converge to a Pareto-optimal state. After the introduction of government participation, targeted penalties and regulatory measures by the government reduce negative participation and betrayal by enterprises and institutions; incentive government policies and financial support reduce the total cost of collaborative innovation, internalizing externalities and promoting the rational use of innovation resources.

The initial willingness to participate has different threshold values among enterprises, institutions, and the government. The critical value of initial participation willingness for enterprises and institutions lies between 0.4 and 0.5, while for the government, it is between 0 and 0.1. When their initial willingness to participate is above these threshold values, the final decisions of all parties converge to one, otherwise, they converge to zero. When enterprises and institutions have a low initial willingness to participate, even with government guidance and supervision, they still tend toward passive participation or betrayal of collaborative innovation. Therefore, enhancing the initial expectations of enterprises and institutions for collaborative innovation in salt-tolerant rice breeding is a powerful way to promote such innovation.

First, the benefit distribution coefficient (a) and the cost-sharing coefficient (t) are key to influencing the decision making of the collaborative innovation parties in salt-tolerant rice breeding. When a = t, that is, when the enterprise and institution share benefits and costs, the system is more likely to reach the optimal equilibrium point E8(1,1,1), with all parties actively participating in collaborative innovation. Additionally, the higher the benefit distribution coefficient (a) and cost-sharing coefficient (t) for the enterprise, the faster the parties reach the optimal decision. Second, enterprises and institutions are more sensitive to benefit distribution than to controllable cost sharing, thus the collaborative innovation system requires a fair benefit distribution and cost-sharing mechanism.

In the collaborative innovation system for salt-tolerant rice breeding, when enterprises and institutions face low penalty intensity (low P1 and P2 values), they are more inclined to engage in passive or speculative behavior. Also, when the penalty intensity for enterprises is increased (even if the penalty intensity for institutions is relatively low), the system is more likely to achieve the optimal equilibrium point E8(1,1,1), where all parties actively participate. This suggests that enterprises are less sensitive to government penalties, so when designing incentive and constraint mechanisms, special attention should be paid to increasing the regulatory intensity for enterprises to promote the effective conduct of collaborative innovation.

The government can effectively increase participation in collaborative innovation for salt-tolerant rice breeding by increasing the proportion of subsidies in the cost of collaborative innovation (SCR) and by reducing the ratio of actual costs to total benefits after subsidies (CBR). When the government's financial support reaches a certain threshold, causing SCR to exceed the critical point and CBR to fall below the critical point, enterprises and institutions are more inclined to actively participate in collaborative innovation. Hence, policymakers should focus on increasing government support for collaborative innovation by providing appropriate subsidies and incentive measures to promote cooperation between enterprises and research institutions, further advancing the breeding and development of salt-tolerant rice.

This study's findings offer substantial theoretical and practical insights for directing the strategic deployment of salt-tolerant rice breeding in our country. The research provides an in-depth analysis of the stability of the collaborative innovation system for salt-tolerant rice breeding and scientifically quantifies its evolutionary strategies, presenting new methods for evaluating the efficiency of various cooperation models. Particularly in the context of limited breeding resources, modulating the relationship between benefit distribution and cost assumption can effectively incentivize enterprises and research institutions to participate in collaborative innovation. This is vital for improving the efficiency of resource allocation in breeding. Furthermore, the study accentuates the crucial role of government involvement. Timely and targeted policy support from the government, such as financial subsidies and technical guidance, can powerfully drive the transformation and application of research findings in salt-tolerant rice breeding. This support is not only crucial for the short-term success of breeding projects but also provides strategic security for achieving long-term breeding goals. Through comprehensive policy implementation and optimized planning, we can elevate the overall efficiency of breeding efforts and expedite the development of new varieties. This, in turn, will enhance the market competitiveness and commercial quality of salt-tolerant rice, contributing to sustainable agricultural development. The specific policy recommendations are as follows:

1. Enhancing Initial Participation in Collaborative Innovation for Salt-Tolerant Rice Breeding. The research and application of salt-tolerant rice breeding have substantial social and economic benefits, playing a strategic role in improving the utilization of saline-alkali lands and securing food safety. Therefore, it is crucial to increase the initial motivation for research institutions and enterprises to participate. The government should first create a multi-tiered and open platform for technological exchange and an innovation incubation system, providing researchers with access to a wealth of academic resources and market information, thus lowering the barriers to initiating research and development (R&D). Additionally, initial assessments and risk analysis services provided by professional agencies should offer decision support to potential R&D participants, guiding the scientific allocation of R&D resources. Finally, the government should lead the establishment of a platform for the transformation of salt-tolerant rice breeding outcomes, fostering the commercialization of research findings and encouraging more research institutions and enterprises to engage in the research and development of salt-tolerant rice.
2. Improving the Mechanism for Benefit Distribution and Cost Sharing in Salt-Tolerant Rice Breeding Collaborative Innovation. The development of salt-tolerant rice is a long-term, complex, and high-risk scientific endeavor. Fair and reasonable distribution of benefits and cost sharing is key to stimulating innovation and safeguarding the interests of all partners. The mechanism should take into account the unique aspects of salt-tolerant rice variety development, such as the lengthy breeding process and the unpredictability of outcomes; it should also be detailed to specific stages of salt-tolerant rice development, ensuring that the distribution of benefits and sharing of costs reflect the technical contributions and financial investments of all parties. Since enterprises and institutions are more sensitive to the long-term distribution of benefits than to controllable R&D costs, benefit distribution should account for the investments made during the entire R&D cycle; this includes human, material, and intellectual property investments. Cost-sharing mechanisms, on the other hand, should focus on the fair distribution of uncertainties and risks associated with the R&D process. For example, the government could establish a risk fund to provide a safety net for any additional costs, ensuring that any losses due to risks are reasonably compensated.
3. Establishing and Strengthening the Regulatory Mechanism and Compliance System for Collaborative Innovation in Salt-Tolerant Rice Breeding. An effective regulatory mechanism is essential for the healthy development of salt-tolerant rice breeding R&D. Comprehensive regulatory rules and compliance guidelines should be formulated, specifically targeting the R&D characteristics of the salt-tolerant rice breeding field. The regulatory and compliance system should encompass the entire process, including R&D, review, approval, supervision, incentives, and penalties. A scientific monitoring and evaluation system should be established to quantify the costs of noncompliance, with appropriate levels and frequencies of oversight set to reduce regulatory costs and enhance efficiency. Furthermore, strict regulations should be imposed on the ownership and transfer of intellectual property rights. Regulatory bodies must possess professional judgment and execution abilities to promptly identify and address

violations, such as the misuse of intellectual property or plagiarism. Penalties for noncompliance must be sufficiently severe to deter potential misconduct effectively.

4. Constructing a Theoretical Framework and Practical Pathway for Incentive Mechanisms in Salt-Tolerant Rice Breeding Innovation. In the field of salt-tolerant rice breeding, the government should formulate a systematic set of financial subsidy policies and tax reduction strategies. Special funds should focus on the specific R&D stages and pain points of these crops, considering their uniqueness and long-term contribution to ecological improvement. Specifically, specialized funding should support critical technical stages in the collaborative innovation process, such as the collection, screening, and functional analysis of salt-tolerant rice germplasm. Tax incentives should include corporate income tax deductions for businesses engaged in salt-tolerant rice R&D activities, additional deductions for R&D expenses, and value-added tax benefits for key biotechnological materials and equipment. Incentive mechanisms should be specific to each stage of the development of salt-tolerant rice varieties to reduce the R&D costs of collaborative innovation and thereby attract and encourage more enterprises and research institutions to participate in this research and development field.
5. Promoting the Construction of Information Sharing and Technology Exchange Platforms for Collaborative Innovation in Salt-Tolerant Rice Breeding. Information asymmetry is a significant factor affecting collaborative innovation, and interdisciplinary information sharing is crucial for innovation in salt-tolerant rice breeding. A dedicated information sharing platform should be built to cater to the specific information needs of salt-tolerant rice breeding, integrating data storage, processing, analysis, and communication. The platform should focus on the cutting-edge research and industry dynamics of salt-tolerant rice breeding, providing comprehensive information services that include genomic data, breeding techniques, cultivation management, and market demands. Efficient information management and intelligent analysis tools should offer scientific decision support for researchers, cultivators, and policymakers, promoting the deep integration of production, education, research, and application, and accelerating the transformation and industrial development of salt-tolerant rice research findings.

This paper proposes a collaborative innovation model for salt-tolerant rice breeding based on an evolutionary game framework informed by theories of information asymmetry and bounded rationality. This model distinguishes itself from those in the existing literature in several key ways:

Innovation in Model Design: This study takes into account the role of government in collaborative innovation, incorporating it into the traditional bilateral game between enterprises and research institutions to form a tripartite evolutionary game model. This innovative approach significantly enhances the existing literature by addressing a gap regarding the direct involvement of government, a critical player often overlooked in most current models which focus solely on the cooperation between businesses and research entities.

Integration of Theory and Practice: The model goes beyond theoretical derivation of evolutionarily stable strategies for collaborative innovation by employing delay differential equations (DDE) for numerical simulations. It grounds these in the context of China's distinctive agricultural practices, from which it draws policy recommendations. This integration is instrumental in heightening the practical application of the model.

Feasibility of Policy Implementation: In discussing the model's relevance to the real world, it emphasizes the positive regulatory role of the government in collaborative innovation, including incentives and regulations. The suggested policies are practical, as they are based on a profound understanding of the actual market conditions and governmental functions.

Applicability of the Model: While the study is conducted within the context of salt-tolerant rice breeding, the model's fundamental framework is versatile and can be extended to collaborative innovation research in other agricultural sectors and industries. The model parameters can be adjusted according to the specifics of different scenarios to reflect the uniqueness of various fields.

Complexity of the Real World: A crucial assumption of the model is the bounded rationality of the agents involved. In the real world, the behavior of decision makers can be more complex and influenced by multiple factors. This implies that the model's predictions may be subject to various uncertainties and external shocks. Therefore, discussing the model's sensitivity to parameter changes and resilience to uncertainty is essential.

Practical Application: In real-world scenarios, this model can serve as a theoretical foundation for government and industry decision makers to formulate collaborative innovation policies for salt-tolerant rice breeding. The model can aid governments in understanding how to facilitate cooperation between enterprises and research institutions through financial subsidies, regulatory measures, and mechanisms for sharing benefits and costs.

Limitations: The paper's model offers a novel perspective to understand and promote collaborative innovation, especially in contexts involving government participation. However, applying this model to the complexities and uncertainties of the real world necessitates further research and empirical analysis to validate the assumptions and conclusions of the model. Future research could also consider the model's applicability across different cultural and socioeconomic backgrounds and how it could be tailored to specific industries or regions' needs.

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List of Abbreviations

E	Enterprises
S	Research Institutions
G	Government
X	Willingness of Enterprises to Participate
Y	Willingness of Research Institutions to Participate
Z	Willingness of Government to Participate in Regulation
R	Overall Benefits of Collaborative Innovation
a	Coefficient of Benefit Distribution
R_1	The Benefits Accrued to Enterprises from Negative Treatments
R_2	The Benefits Accrued to Research Institutions from Negative Treatments
R_3	Benefits Obtained from Government Participation
C	Overall Costs of Collaborative Innovation
t	Coefficient of Cost Sharing
C_3	Costs of Government Supervision
M	Government Support for Collaborative Innovation
S_1	Gains from Corporate Betrayal
S_2	Gains from Research Institutions' Speculative Betrayal
K_1	Government Penalties for Corporate Betrayal

K_2	Government Penalties for Research Institutions' Betrayal
λ_1	The First Eigenvalue
λ_2	The Second Eigenvalue
λ_3	The Third Eigenvalue
P1	Ratio of Penalty Intensity to Speculative Benefits for the Salt-Tolerant Rice Breeding Enterprise (E)
P2	Ratio of Penalty Intensity to Speculative Benefits for the Scientific Research Institution (S)
SCR	Subsidy–Cost Ratio (M/C), which measures the proportion of government subsidies in the total cost of collaborative innovation. An increase in SCR is indicative of more substantial financial support from the government, mitigating the cost burden for enterprises and institutions engaged in collaborative innovation.
CBR	Cost–Benefit Ratio (C-M)/R, reflecting the ratio of the actual cost borne by enterprises and institutions after accounting for government subsidies to the total benefits derived from collaborative innovation. A lower CBR denotes a greater economic allure of collaborative innovation subsequent to subsidies.

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