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Research Article

Cooperation Behavior of Opinion Leaders and Official Media on the Governance of Negative Public Opinion in the Context of the Epidemic: An Evolutionary Game Analysis in the Perspective of Prospect Theory

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The reach of online information transmission has expanded due to the rapid growth of social software and Internet technology, and the negative information generated during the COVID-19 outbreak can confuse the public. Therefore, a new challenge in the prevention and control of epidemics is how to supervise negative public perceptions. This study differentiates negative public opinion communication stages through practical cases and is based on the life cycle hypothesis. In order to examine the evolution and stability tactics of each game subject in each stage of the evolution of public opinion, a three-way evolution game model comprising social platform operators, official media, and opinion leaders is created on the basis of prospect theory. Finally, the advanced epidemic model is used to verify the important impact of cooperation between official media and opinion leaders on curbing the transmission of negative public opinion. It is found that the perceived value of game players on income and loss will significantly affect the trend of the tripartite game strategy, and the cooperative behavior of official media and opinion leaders can effectively promote the benign development of online public opinion.

1. Introduction

Numerous social media platforms, including Weibo, Zhihu, and WeChat, have substantially improved the ease of gathering and disseminating information to the general public in the context of the burgeoning Internet [1]. The Internet has been flooded with worries and conversations about the issue among various groups of people from different places ever since COVID-19 broke out in late 2019. Also, vaccination, as an important initiative for the prevention and control of the epidemic, has become one of the topics hotly debated by Internet users [2]. Online social networks are unavoidably a breeding ground for false information because of their openness and anonymity, which has resulted in a low threshold for information diffusion. False claims like "the Delta variant of COVID-19 appears, so the vaccination is ineffective" and "mass vaccination can accelerate virus mutation and render the vaccine ineffective" are frequently used to incite public fear. The broad dissemination of such negative information readily distorts public perceptions and shapes public opinion, impacting the entire situation of epidemic prevention and control and putting the capacity of government agencies for social governance and crisis response to the test.

Online public opinion on social platforms is constantly evolving under the influence of multiple participants. Opinion leaders and Internet vloggers frequently play the roles of communication subjects with interest-seeking characteristics [3], while others, including government agencies and the mainstream media, take on the roles of regulating and guiding public opinion. Based on this, many researchers develop a game model to examine the mechanism of each subject's strategic behavior on the spread of negative online public opinion, propose effective governance countermeasures, and use evolutionary game theory to investigate the influence of interested subjects' strategic choices on public opinion spreading and control [4–6].

This paper builds a tripartite evolutionary game model based on the aforementioned analysis and employs the Lyapunov approach to examine the stability of the mixed strategy equilibrium point of the replicating dynamic system. Two propagation dynamics models are built according to distinct contexts based on the stable evolutionary strategy combination that was acquired, and the parameter sensitivity analysis of each influencing element is carried out using Matlab on the basis of verifying the correctness of the model. Finally, strategies for managing negative public perception are suggested in light of the experimental findings.

This study answers these four key questions:

(1) Based on the bounded rationality hypothesis, what is the result of the evolutionary stable strategy of the tripartite game?

(2) How do the elements affect the strategy choice of the game players?

(3) What are the characteristics of negative information dissemination in each stage of public opinion evolution?

(4) How can official media and opinion leaders better guide public opinion?

2. Related Work

With the development of Internet technology and the widespread use of new media platforms, experts and academics have begun to study social network public opinion in great detail. Combining the findings of the existing research, we discover that academics have conducted research on the connotation, causes, dissemination mechanism, and governance of online public opinion using a variety of methods, including text mining, modeling, and classification prediction, with impressive outcomes.

Lin et al. took the COVID-19 incident as the background, used the 5W communication model to text-mine the relevant public opinion on WeChat in terms of public opinion evolution, text content, communication media, audience, and public opinion influence, used the rooting theory to construct a model of network opinion generation and development, and conducted a study on new media social opinion [7]. Based on the BA scale-free network, Chen et al. introduced social preference theory and analyzed the effects of different social preferences and personal income on the polarization effect of public opinion through simulation experiments [8]. Lan et al. explored the effects of raising the upper growth limit for Internet rumors on user sentiment and optimized the logistic population growth model to investigate changes in network public opinion, which offers a theoretical framework for online public opinion prediction [9]. Based on Langevin's equation, Cheng et al. studied the phenomenon and law of resonance of online public opinion triggered by the frequency of public health emergencies [10]. Xie et al. used text mining techniques, such as latent Dirichlet allocation (LDA), topic modeling, and sentiment analysis, to examine the data in order to comprehend the public reaction to COVID-19 on Weibo [11]. In order to study the structure of public opinion dissemination nodes and the characteristics of mobile Internet dissemination paths, Wang chose "cyberattack" as the research topic and extracted 23567 related items from Sina Weibo [12].

There are some scholars who have also conducted in-depth studies on the dissemination of negative information. Liu proposed a new susceptible-infected-vaccinated-susceptible negative opinion information propagation model with preventive vaccination by constructing double-layer network topology to provide the scientific method and research approach for the study of negative public opinion information propagation in complex networks [13]. In order to analyze the key points of enterprise strategy adjustment in different stages of the dissemination of negative network public opinion, Peng used the negative network public opinion of a Chinese enterprise as the research object and modeled the decision-making behaviors of stakeholders in different stages [14]. To experimentally evaluate the dynamic influence of unfavorable public sentiment on agricultural commodity prices during the COVID-19 pandemic in China, Liu quantified online unfavorable sentiment using microblog text mining and a time-varying parameter vector autoregressive model (TVP-VAR) [15].

In its original form, evolutionary game theory was a game theory application to the evolution of biological populations. Nowadays, it has been widely used in a variety of research areas, such as information dissemination, user interaction, and behavioral research [16]. Xu formulated a tripartite evolutionary game model involving the local government, enterprises, and the public that provided theoretical support for the local government and related participants in making proper decisions in public health emergencies [17]. In order to maintain the sustainable development of network ecology, an evolutionary game model is used to investigate the interaction mechanisms of complex behaviors between Weibo rumor makers, Weibo users, and governments in accordance with mental accounts and prospect theory [18]. In order to examine the coupling evolution of group behavior and viewpoint, Zhao established a collaborative evolution model of public opinion information and views based on dynamic evolutionary social network games connection [19].

Based on the foregoing discussion, this study holds that official media and opinion leaders, as the core of the official public opinion field and the civil public opinion field, respectively, play a crucial role in directing and controlling the trend of public opinion in the process of disseminating negative public opinion information on social platforms. Because of this, this study builds a tripartite game model comprising operators, official media, and opinion leaders and presents the prospect theory to examine how the evolution of public opinion events is influenced by the perceived worth of each subject. Finally, the SIR model is used to verify the important role of collaborative behavior between official media and opinion leaders in curbing the spread of negative public opinion.

3. Basic Assumptions and Model Construction

3.1. Major Participants. Among the subjects involved in the evolution of negative public opinion, there is a game relationship among social platform operators, opinion leaders, and official media. Based on the doctrine of limited rationality and the premise of information asymmetry among subjects, game players will adjust their strategies to maximize their interests in response to changes in the strategic choices of other subjects [20]. Among them, operators, as commercial organizations with a profit motive, will strictly or loosely monitor and regulate the behavior of opinion leaders and media in the balance of profit and loss. The official media often have the responsibility of guiding public opinion and issuing authoritative information on behalf of government departments. However, in reality, official media often "lose their voices" and try to shift the focus of events through negative reporting. Opinion leaders refer to officially certified subjects with extensive influence on social media platforms, such as sports and cultural stars and self-publishers in various fields. When opinion leaders express their views on a hot topic, their followers tend to join the discussion under the intergroup identification effect, thus triggering the phenomenon of network clustering [21, 22]. On the one hand, opinion leaders can reach cooperation with official media and use their influence to actively play a role in guiding public opinion; on the other hand, some opinion leaders stand in opposition to official media based on their profit-seeking attributes, take the lead in questioning the lack of in-depth coverage of official media, etc., and gain gains such as topic heat and popularity using maliciously provoking negative emotions among netizens.

In summary, the tripartite logical relationship between operators, opinion leaders, and official media is shown in Figure 1.

3.2. Model Notation and Basic Assumptions. Based on the above multi-subject analysis, this study proposes the following basic hypotheses.

Assumption 1. Suppose that the probability of the operator choosing the "rigorous regulation" strategy is x $(0 \le x \le 1)$. At this time, cyberspace is clean and upright, and at the same time, the social recognition and credibility of the operator have improved, so the operator will gain at the same time, and the social recognition and credibility of the operator have improved, so the operator will gain the benefits R_1, but it also needs to pay the regulatory costs C_1 $(C_1 < R_1)$ while bearing certain popularity and traffic loss S. Internet users can freely post and share information on the social platform when the operator adopts a lenient regulation strategy with a likelihood of $1 - x$. As a result, the operator can harvest a sizable user base at this time, increasing traffic and generating revenue R_2 $(R_2 < R_1)$. The operator will be subjected to punishment (F) by higher authorities as a result of the situation's bad public opinion fermentation, while the cost of risk (C_2) must be borne by the lenient regulation behavior.

Assumption 2. Suppose that the probability of positive reports by the official media is y $(0 \le y \le 1)$. The official media will be motivated by the government's profit-driven nature G to choose positive reporting, which requires labor cost C_3, when opinion leaders purposefully incite negative emotions in the "civil opinion field." However, the official media can gain benefits R_3 such as influence and credibility by speaking out in a timely and positive manner to stabilize public sentiment. On the contrary, if the official media choose to negative reporting, although they can gain R_4 $(R_4 < R_3)$, they will cause dissatisfaction among netizens and loss of media credibility d, and they also need to pay the cost of reporting C_4.

Assumption 3. Suppose that the probability of opinion leaders cooperating with official media to jointly guide public opinion is z $(0 \le z \le 1)$. At this time, opinion leaders can obtain immaterial incentives (kG) from the official media and will also gain popularity and influence (M), but they will also need to pay the cost of guidance (C_5). If the likelihood that the opinion leader will choose to incite someone maliciously is assumed to be $1 - z$, then that opinion leader must pay the incitement cost C_6 $(C_6 < C_5)$ and could face consequences like blocking under the careful supervision of the operator (f). The opinion leader can get additional incitement gains ΔM on top of obtaining M when they publish an opinion that garners followers' attention and participates in conversations, which can then be translated into financial rewards.

According to the above assumptions, the basic parameters in the evolutionary game model are described in Table 1.

Assumption 4. In reality, C_1, C_2, C_3, C_4, C_5, C_6, and R_2 can be quantified, and the penalties f and F are based on clear penalty regulations, which are deterministic losses and therefore do not suffer from perception bias. However, the parameters R_1, S, R_3, R_4, G, d, kG, M, and ΔM cannot be quantified with objective and accurate values. Therefore, this study introduces prospect theory to measure the gains and losses of the game players and refine the parameters of the game payment matrix. Tversky et al. [23] integrated psychology with economics and improved the expected utility theory by considering irrational psychological factors that influence choice behavior and proposed the prospect theory, and the value function model is expressed as shown in equation (1). In reality, operators, official media, and opinion leaders are finite and rational, and there is a deviation between perceived value and actual utility when gains and losses are uncertain. Decision makers still follow the utility maximization principle when making strategy choices [24].

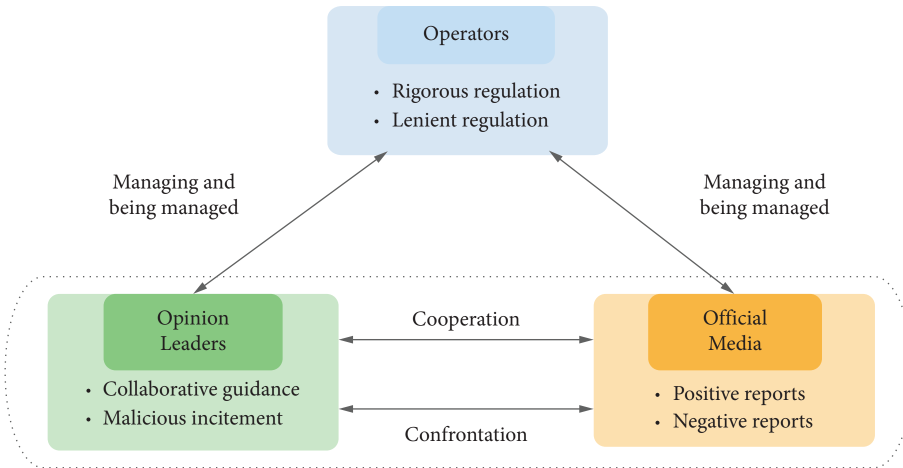


Figure 1: The tripartite logic relationship of operator, official media, and opinion leader.

Table 1: Description of parameter symbols.

Players	Parameter	Meaning
Operators	x	Probability that operators choose the rigorous regulation strategy
	C_1	The cost of operators choosing the rigorous regulation strategy
	R_1	The benefit for the operator of their social recognition and the credibility
	S	The popularity and traffic loss when the operators adopt the lenient regulation strategy
	F	Fines for operators by higher authorities as a result of bad public opinion fermentation
	C_2	The cost of operators choosing the lenient regulation strategy
	R_2	The benefit of traffic when the operators choose the lenient regulation strategy
Official media	y	Probability that official media choose the positive report strategy
	G	The reward that the government grants to the official media for their positive reporting behavior
	C_3	The cost incurred by active official media coverage
	R_3	The benefit for the official media of their influence and credibility
	R_4	The benefit that official media obtain from negative reporting
	d	Fines for official media when they cause dissatisfaction among netizens
	C_4	The cost of the official media's negative report strategy
Opinion leaders	z	Probability that opinion leaders choose the collaborative guidance strategy
	kG	Immaterial incentives that the official media grant to opinion leaders for their collaborative guidance behavior
	M	The benefit for the opinion leaders of their popularity and influence
	C_5	The cost of the opinion leader's collaborative guidance strategy
	C_6	The cost of the opinion leader's malicious incitement strategy
	f	Fines for opinion leaders under the careful supervision of the operator
	ΔM	The benefit for the opinion leader of the additional incitement

$$V(\Delta U)\begin{cases}\Delta U^{\alpha}, & \Delta U \geq 0,\\ -\lambda(-\Delta U)^{\beta}, & \Delta U < 0.\end{cases} \tag{1}$$

In equation (1), $\Delta U \geq 0$ means that the game subject perceives a gain, and vice versa, and the loss perception is used as the basis for decision making. The parameter λ ($\lambda > 1$) indicates the loss aversion coefficient of the stakeholder; the larger value indicates that the stakeholder is more sensitive to loss compared to gain. The parameters α and $\beta \in (0, 1)$ denote the risk attitude coefficients of the gain and loss value functions, respectively, with larger values representing a lower sensitivity to value and a greater preference for risk-taking by the game players [25]. According to prospect theory, people are risk-averse in the face of gains and prefer risk in the face of losses, and they are more sensitive to losses than to gains [26].

Based on the above parameter assumptions, the game payoff matrix can be obtained as shown in Table 2.

Table 2: The payoff matrix of the model.

Tripartite game strategies	Operators	Official media	Opinion leaders
(Rigorous regulation, positive reports, collaborative guidance)	$-C_1 + V(R_1) - V(-S)$	$-C_3$	$V(kG) - C_5 + V(M)$
(Rigorous regulation, positive reports, malicious incitement)	$-C_1 + V(R_1) - V(-S)$	$V(G) - C_3 + V(R_3)$	$-f - C_6 + V(\Delta M)$
(Rigorous regulation, negative reports, collaborative guidance)	$-C_1 + V(R_1)$	$-C_4 + V(R_4)$	0
(Rigorous regulation, negative reports, malicious incitement)	$-C_1 + V(R_1) - V(-S)$	$-C_4 - V(-d) + V(R_4)$	$-f - C_6 + V(\Delta M)$
(Lenient regulation, positive reports, collaborative guidance)	$-C_2 + R_2$	$-C_3$	$V(kG) - C_5 + V(M)$
(Lenient regulation, positive reports, malicious incitement)	$-C_2 + R_2 - F$	$V(G) - C_3 + V(R_3)$	$-C_6 + V(\Delta M)$
(Lenient regulation, negative reports, collaborative guidance)	$-C_2 + R_2 - F$	$-C_4 + V(R_4)$	0
(Lenient regulation, negative reports, malicious incitement)	$-C_2 + R_2 - F$	$-C_4 - V(-d) + V(R_4)$	$-C_6 + V(\Delta M)$

3.3. Model Construction. According to the payoff matrix, the expected earnings U_{x1}, U_x and the average expected earnings $\overline{U}_x$ for operators choosing rigorous or lenient regulation can be calculated as follows:

$$\begin{cases} U_{x1} = V(R_1) - C_1 - V(-S) + zV(-S) - yzV(-S)), \\ U_{x2} = R_2 - F - C_2 + yzF, \\ \overline{U}_x = xU_{x1} + (1-x)U_{x2}. \end{cases} \tag{2}$$

The expected earnings U_{y1}, U_{y1} and the average expected earnings $\overline{U}_y$ of choosing positive or negative reports by official media are

$$\begin{cases} U_{y1} = V(G) - C_3 + V(R_3) - zV(G) - zV(R_3), \\ U_{y2} = V(R_4) - C_4 - V(-d) + zV(-d), \\ \overline{U}_y = yU_{y1} + (1-y)U_{y2}. \end{cases} \tag{3}$$

The expected earnings U_{z1}, U_{z2} and the average expected earnings $\overline{U}_z$ for opinion leaders who choose to cooperate in leading or malignantly inciting are

$$\begin{cases} U_{z1} = y(V(M) - C_5 + V(kG)), \\ U_{z2} = V(\Delta M) - C_6 - fx, \\ \overline{U}_z = zU_{z1} + (1-z)U_{z2}. \end{cases} \tag{4}$$

According to equations (2)–(4), the evolutionary game replication dynamic process consisting of operators, official media, and opinion leaders can be expressed as a three-dimensional dynamical system (I) as shown in the following equation:

$$\begin{cases} \dfrac{dx}{dt} = x(1-x)(C_2 + F + zV(-S) + V(R_1) - C_1 - R_2 - V(-S) - yzF - yzV(-S), \\ \dfrac{dy}{dt} = y(1-y)(C_4 + V(G) + V(R_3) + V(-d) - C_3 - V(R_4) - zV(G) - zV(R_3) - zV(-d)), \\ \dfrac{dz}{dt} = z(1-z)(C_6 - V(\Delta M) - C_5 y + fx + yV(M) + yV(kG)). \end{cases} \tag{5}$$

3.4. Stability Analysis of the Equilibrium Point in the Tripartite Game. Evolutionary equilibria can be obtained by solving equation (5):

(1) Equilibrium points for pure strategy solutions of the three populations:

$E_1(0,0,0)$, $E_2(0,1,0)$, $E_3(0,0,1)$, $E_4(0,1,1)$, $E_5(1,0,0)$, $E_6(1,1,0)$, $E_7(1,0,1)$, and $E_8(1,1,1)$.

(2) Equilibrium points for pure strategy solutions of each single population:

$E_9(V(\Delta M) - C_6/f,\ 0,\ C_1 - C_2 - F + R_2 + V(R_1) + V(-S)/V(-S))$

$E_{10}(0,\ C_6 - V(\Delta M)/C_5 - V(M) - V(kG), V(-d) + C_4 + V(G) + V(R_3) - V(R_4) - C_3/V(G) + V(R_3) + V(-d))$

$E_{11}(1,\ V(\Delta M) - C_6 - f/V(M) - C_5 + V(kG),\ C_4 - C_3 + V(G) + V(R_3) - V(R_4) + V(-d)/V(G) + V(R_3) + V(-d))$

$E_{12}(C_5 + V(\Delta M) - C_6 - V(kG) - V(M)/f,\ 1,\ C_2 + F - C_1 - R_2 - V(R_1) - V(-S)/F)$

(3) When condition (6) is satisfied, there also exists an equilibrium point $E_{13} = (x^*, y^*, z^*)$ of the mixed strategy in the equilibrium solution domain.

$$\begin{cases} C_2 + F + zV(-S) - V(R_1) - C_1 - R_2 - V(-S) - yzF - yzV(-S) = 0, \\ C_4 + V(G) + V(R_3) + V(-d) - C_3 - V(R_4) - zV(G) - zV(R_3) - zV(-d) = 0, \\ C_6 - V(\Delta M) - C_5 y + fx + yV(M) + yV(kG) = 0, \end{cases} \tag{6}$$

where E_1 to E_8 form the boundary of the evolutionary game solution domain $\{(x, y, z)|x = 0, 1; y = 0, 1; z = 0, 1\}$, E_9 to E_{12} are conditional equilibria, and since $C_2 + F - C_1 - R_2 - V(R_1) - V(-S) < 0$, E_{12} is meaningless. When E_9 satisfies $|C_6 - V(\Delta M)| < f$, $(V(\Delta M) - C_6)f > 0$, $C_1 + R_2 + V(R_1) < C_2 + F$, $(C_1 - C_2 - F + R_2 + V(R_1) + V(-S))V(-S) > 0$, E_{10} satisfies $|C_6 - V(\Delta M)| < |C_5 - V(M) - V(kG)|$, $(C_6 - V(\Delta M))(C_5 - V(M) - V(kG)) > 0$, $C_4 < C_3 + V(R_4)$, $(C_4 + V(G) + V(R_3) + V(-d) - V(R_4) - C_3)(V(G) + V(R_3) + V(-d)) > 0$ and E_{11} satisfies $(C_5 + V(\Delta M) - C_6 - V(kG) - V(M))f > 0$, $|C_5 + V(\Delta M) - C_6 - V(kG) - V(M)| < f$, $(C_2 + F - C_1 - R_2 - V(R_1) - V(-S))F > 0$, $C_2 + F - C_1 - R_2 - V(R_1) - V(-S) < F$, $x, y, z \in [0, 1]$, then E_9 to E_{11} are meaningful. According to Hirshleifer's theory, the Jacobi matrix is obtained by solving for the partial derivatives of $F(x)$, $F(y)$, and $F(z)$ independently, which is shown in equation (7).

According to the Lyapunov stability theory, system stability can be measured by the Jacobian matrix. When all eigenvalues in the Jacobi matrix (J) are less than 0, the equilibrium point can be considered an asymptotically stable point of the dynamical system; when at least one eigenvalue in (J) is greater than 0, the equilibrium point is unstable. The equilibrium point is in a critical state and the stability cannot be predicted by the eigenvalue symbol if the eigenvalue of the matrix (J) has zero real part features and the other eigenvalues have negative real parts [27–30]. The solved Jacobian eigenvalues of the resulting equilibrium points are shown in Table 3.

$$J = \begin{bmatrix} \frac{\mathrm{d}x/dt}{dx} & \frac{\mathrm{d}x/dt}{dy} & \frac{\mathrm{d}x/dt}{dz} \\ \frac{\mathrm{d}y/dt}{dx} & \frac{\mathrm{d}y/dt}{dy} & \frac{\mathrm{d}y/dt}{dz} \\ \frac{\mathrm{d}z/dt}{dx} & \frac{\mathrm{d}z/dt}{dy} & \frac{\mathrm{d}z/dt}{dz} \end{bmatrix}$$

$$= \begin{bmatrix} (1-2x)(C_2 + F + zV(-S) + V(R_1) - C_1 - R_2 - V(-S) - yzF - yzV(-S)), x(x-1)z(F + V(-S)), x(x-1)(Fy - V(-S) + yV(-S)) \\ 0, (2y-1)(C_3 - C_4 - V(G) - V(R_3) + V(R_4) - V(-d) + zV(G) + zV(R_3) + zV(-d)), y(y-1)(V(G) + V(R_3) + V(-d)) \\ -fz(z-1), -z(z-1)(V(M) - C_5 + V(kG)), -(2z-1)(C_6 - V(\Delta M) - C_5 y + fx + yV(M) + yV(kG)) \end{bmatrix}. \tag{7}$$

Proposition 5. *When $C_2 + F + V(R_1) - C_1 < R_2$, $C_4 + V(G) + V(R_3) + V(-d) < C_3 + V(R_4)$, and $C_6 - V(\Delta M) + f < 0$ are satisfied, $E_1(0, 0, 0)$ is the evolutionary stability strategy of the system. The eigenvalues of each equilibrium point are shown in Table 4.*

Proof. Under the condition of satisfying Proposition 5, based on the definition of all parameters as positive in this paper, it can be seen from Table 4 that there is a pair of conjugate complex numbers in the eigenvalues of both equilibria E_{10} and E_{11}, and the positivity and negativity of the other eigenvalue cannot be determined, so its stability cannot be determined by the Lyapunov discriminant. The eigenvalues of $E_1(0, 0, 0)$ all have negative real parts, so this point is the evolutionary stability point in the Proposition 5 scenario. At this point, whatever the starting probability of the tripartite strategy choice is, it eventually converges to (0, 0, 0), i.e., lenient regulation by operators, negative reports by official media, and malicious incitement by opinion leaders.

In the proposal 1 scenario, social platform operators obtain higher gains by choosing a lenient regulation strategy compared to a rigorous regulation strategy. As finite rational subject, the operators reduce their sensitivity to the perception of credibility benefits $\alpha_1 < \ln(R_2 C_1 / C_2 F)) / \ln R_1$ and will tend to choose lenient regulation strategies under the principle of profit maximization. At this point, opinion leaders are more sensitive to the perception of additional incitement gains $\alpha_3 > \ln f C_6 / \ln \Delta M$ due to the greater freedom of expression of Internet users, which can drive their choice of incitement strategies. The gradual fermentation of negative public opinion raises the cost of public opinion guidance by official media, which reduces the sensitivity to perceived losses $\beta_2 < (\ln(C_3/C_4) + \ln(R_4^{\alpha 2}/G^{\alpha 2} R_3^{\alpha 2})) / \ln \lambda d$ and increases the

Table 3: Eigenvalues of the Jacobian matrix.

Equilibrium points	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3
$E_1\,(0, 0, 0)$	$C_2 - C_1 + F - R_2 + V(R_1) - V(-S)$	$C_4 - C_3 - V(R_4) + V(G) + V(R_3) + V(-d)$	$C_6 - V(\Delta M)$
$E_2\,(0, 1, 0)$	$C_2 - C_1 + F - R_2 + V(R_1) - V(-S)$	$-(C_4 - C_3 - V(R_4) + V(G) + V(R_3) + V(-d))$	$C_6 - V(\Delta M) - C_5 + V(M) + V(kG)$
$E_3\,(0, 0, 1)$	$C_2 - C_1 + F - R_2 + V(R_1)$	$C_4 - C_3 - V(R_4)$	$-(C_6 - V(\Delta M))$
$E_4\,(0, 1, 1)$	$C_2 - C_1 - R_2 + V(R_1) - V(-S)$	$-(C_4 - C_3 - V(R_4))$	$-(C_6 - V(\Delta M) - C_5 + V(M) + V(kG))$
$E_5\,(1, 0, 0)$	$-(C_2 - C_1 + F - R_2 + V(R_1) - V(-S))$	$C_4 - C_3 - V(R_4) + V(G) + V(R_3) + V(-d)$	$C_6 - V(\Delta M) + f$
$E_6\,(1, 1, 0)$	$-(C_2 - C_1 + F - R_2 + V(R_1) - V(-S))$	$-(C_4 - C_3 - V(R_4) + V(G) + V(R_3) + V(-d))$	$C_6 - V(\Delta M) - C_5 + V(M) + V(kG) + f$
$E_7\,(1, 0, 1)$	$-(C_2 - C_1 + F - R_2 + V(R_1))$	$C_4 - C_3 - V(R_4)$	$-(C_6 - V(\Delta M) + f)$
$E_8\,(1, 1, 1)$	$-(C_2 - C_1 - R_2 + V(R_1) - V(-S))$	$-(C_4 - C_3 - V(R_4))$	$-(C_6 - V(\Delta M) - C_5 + V(M) + V(kG) + f)$
$E_9\,(x_1, 0, z_1)$		$\lambda_1 = \lambda_3 = a_1/2 \pm \sqrt{a_1^2 + 4a_3a_4}/2 \cdot i,\ \lambda_2 = a_2$	
$E_{10}\,(0, y_1, z_2)$		$\lambda_1 = a_5,\ \lambda_2 = \lambda_3 = \pm\sqrt{\lvert a_6a_7\rvert} \cdot i$	
$E_{11}\,(1, y_2, z_3)$		$\lambda_1 = a_8,\ \lambda_2 = \lambda_3 = \pm\sqrt{\lvert a_9a_{10}\rvert} \cdot i$	

Note. To simplify the expression, the equilibrium point coordinates are denoted by x_1, y_1, z_1, and z_2 where $a_1 = 2V(R_1)\,(f + 2C_6 - 2V(\Delta M))/f$; $a_3 = -(C_1 - C_2 - F + R_2 + V(R_1))\,(C_1 - C_2 - F + R_2 + V(R_1) + V(-S))f/V(-S)^2$; $a_{13} = -V(-S)\,(C_6 - V(\Delta M))\,(C_6 - V(\Delta M) + f)/f^2$; $a_2 = (f_1V(R_3) + (F - V(R_1) - C_1 + C_2 - R_2)V(G) + f_1V(-d) - V(-S)\,(V(R_4) + C_3 - C_4))/V(-S)$; $a_4 = -(V(G) + V(R_3) + V(-d))\,(-V(M) + V(\Delta M) - V(kG) + C_5 - C_6)\,(C_6 - V(\Delta M))/(C_5 - V(M) - V(kG))^2$; $a_6 = (C_5 - V(M) - V(kG))\,(V(R_4) + C_3 - C_4)\,(C_3 - C_4) - V(G) - V(R_3) + V(R_4) - V(-d))/(V(G) + V(R_3) + V(-d))^2$; $a_5 = (((-V(\Delta M) + C_6)V(R_3) + (-V(\Delta M) + C_6)V(G) + (-V(\Delta M) + C_6)V(-d) - (V(R_4) + C_3 - C_4)\,(V(M) - V(\Delta M) + V(kG) - V(kG) + C_6))V(-S) + ((V(M) - V(\Delta M) + V(kG) - V(kG) + C_6)V(R_3) + (V(M) - V(\Delta M) + V(kG) - V(kG) + C_6)V(G) + (V(M) - V(\Delta M) + V(kG) - V(kG) + C_6)V(-d) + (V(R_4) + C_3 - C_4)\,(V(\Delta M) - C_6))F + (V(R_1) - C_1 + C_2 - R_2)\,(V(G) + V(R_3) + V(-d))\,(-V(kG) + V(M) + V(kG)))/((V(G) + V(R_3) + V(-d))\,(-V(kG) + V(M) + V(kG)))$; $a_7 = -(V(G) + V(R_3) + V(-d))\,(-V(M) + V(\Delta M) - V(kG) + C_5 - C_6)\,(C_6 - V(\Delta M))/(C_5 - V(M) - V(kG))^2$; $a_8 = (((-C_6 + V(\Delta M) - f)V(R_3) + (-C_6 + V(\Delta M) - f)V(G) + (-C_6 + V(\Delta M) - f)V(-d) + (V(R_4) + C_3 - C_4)\,(V(M) - V(\Delta M) + V(kG) + f - C_5 + C_6))V(-S) + ((-V(M) + V(\Delta M) - V(kG) - f + C_5 - C_6)V(R_3) + (-V(M) + V(\Delta M) - V(kG) - f + C_5 - C6)V(G) + (-V(M) + V(\Delta M) - V(kG) - f + C_5 - C_6)V(-d) - (V(R_4) + C_3 - C_4)\,(-C_6 + V(\Delta M) - f))F - (V(R_1) - C_1 + C_2 - R_2)\,(V(M) - C_5 + V(kG))\,(V(G) + V(R_3) + V(-d)))/((V(G) + V(R_3) + V(-d))\,(V(M) - C_5 + V(kG)))$; $a_9 = (-V(M) + C_5 - V(kG))\,(V(R_4) + C_3 - C_4)\,(C_3 - C_4 - V(G) - V(R_3) + V(R_4) - V(-d))/(V(G) + V(R_3) + V(-d))^2$; $a_{10} = (V(G) + V(R_3) + V(-d))\,(V(M) - V(\Delta M) + V(kG) + f - C_5 + C_6)\,(C_6 - V(\Delta M) + f)/(-V(M) + C_5 - V(kG))^2$.

Table 4: Stability analysis of evolutionary equilibrium points under conclusion 1 conditions.

Equilibrium points	Symbol	Stability
$E_1\,(0, 0, 0)$	$(-, -, -)$	ESS
$E_2\,(0, 1, 0)$	$(-, +, +/-)$	Unstable point
$E_3\,(0, 0, 1)$	$(-, -, +)$	Saddle point
$E_4\,(0, 1, 1)$	$(-, +, +/-)$	Unstable point
$E_5\,(1, 0, 0)$	$(+, -, -)$	Saddle point
$E_6\,(1, 1, 0)$	$(+, +, +/-)$	Unstable point
$E_7\,(1, 0, 1)$	$(+, -, +)$	Unstable point
$E_8\,(1, 1, 1)$	$(+, +, +/-)$	Unstable point
$E_9\,(x_1, 0, z_1)$	$\exists \lambda_2 > 0$	Unstable point
$E_{10}\,(0, y_1, z_2)$	∃ a pair of conjugate complex numbers	Unsure
$E_{11}\,(1, y_2, z_3)$	∃ a pair of conjugate complex numbers	Unsure

sensitivity to perceived gains $\alpha_2 > (\ln C_4/C_3 + \ln\lambda d^{\beta 2})\ln(R_4/R_3G)$, thus tending to choose negative reporting strategies.

Since opinion leaders hold the dominant power of discourse, their followers are easily infected by negative emotions and become negative information disseminators. Negative public opinion will continue to brew and develop into a public opinion crisis since operators and official media are not currently performing their obligations of oversight and public opinion guidance. Government oversight of social platform operators should be improved, the accountability system should be strengthened, and the penalties for malicious incitement by opinion leaders should be increased to enhance the cost of incitement. □

Proposition 6. *The ESS of this system is (0, 1, 1) when the parameters satisfy* $C_2 + F + V(R_1) < R_2 + C_1$, $C_4 > V(R_4) + C_3$, *and* $C_6 + V(M) + V(kG) > V(\Delta M) + C_5$.

Proposition 7. *The ESS of this system is (0, 1, 0) when the parameters satisfy* $C_2 + F + V(R_1) - C_1 < R_2$, $C_4 > V(R_4) + C_3$, *and* $C_6 - V(\Delta M) + f < 0$.

Proposition 8. *The ESS of this system is (0, 0, 1) when the parameters satisfy* $C_2 + F + V(R_1) - C_1 < R_2$, $C_4 + V(G) + V(R_3) + V(-d) < C_3 + V(R_4)$, *and* $C_6 + V(M) + V(kG) > V(\Delta M) + C_5$.

Proposition 9. *The ESS of this system is (1, 0, 0) when the parameters satisfy* $C_2 - C_1 - R_2 + V(R_1) > V(-S)$, $C_4 + V(G) + V(R_3) + V(-d) < C_3 + V(R_4)$, *and* $C_6 - V(\Delta M) + f < 0$.

Proposition 10. *The ESS of this system is (1, 1, 0) when the parameters satisfy* $C_2 - C_1 + F - R_2 + V(R_1) > V(-S)$, $C_4 > V(R_4) + C_3$, *and* $C_6 - V(\Delta M) + f < 0$.

Proposition 11. *The ESS of this system is (1, 0, 1) when the parameters satisfy* $C_2 - C_1 - R_2 + V(R_1) > V(-S)$, $C_4 + V(G) + V(R_3) + V(-d) < C_3 + V(R_4)$, *and* $C_6 + V(M) + V(kG) > V(\Delta M) + C_5$.

Proposition 12. *The ESS of this system is (1, 1, 1) when the parameters satisfy* $C_2 - C_1 - R_2 + V(R_1) > V(-S)$, $C_4 > V(R_4) + C_3$, *and* $C_6 + V(M) + V(kG) > V(\Delta M) + C_5$.

4. Numerical Simulation Analysis

Based on the above theoretical analysis, this study conducts simulation experiments with the use of Matlab to verify the correctness and validity of the model.

4.1. Case Description. The evolution of the event "A medical professional in Xi'an was infected even after being vaccinated" is shown in Figure 2 after monitoring public opinion on the microblogging platform with the use of Python.

The PMI algorithm (pointwise mutual information) proposed by Turney and Littman [31] can be used in the field of text mining to measure the similarity between words. For word1 and word2 in the corpus, when the probability of co-occurrence of the two words in the text is higher, i.e., if the value of pointwise mutual information is higher, it indicates that the semantic relevance of these two words is stronger, as shown in the following equation:

$$\mathrm{PMI}(\mathrm{word1}, \mathrm{word2}) = \log_2\left(\frac{P(\mathrm{word1}, \mathrm{word2})}{P(\mathrm{word1})P(\mathrm{word2})}\right). \quad (8)$$

In the data collection process, a total of 13,731 comment data were obtained, which were manually cleaned, and then the word separation operation was completed with the help of the Jieba word separation tool and en_stopwords, and finally PMI was calculated based on the obtained co-occurrence matrix. The analysis was carried out for the word frequency and weight of these kinds of information, and the visualization results can be obtained using Gephi as shown in Figure 3.

Sentiment analysis of the above data shows that the percentage of negative public opinion is 8.38%, the percentage of positive public opinion is 0.84%, and the rest is neutral. Based on this, the life cycle of this negative public opinion event is abstracted into four stages: the fermentation period, the outbreak period, the decline period, and the calm period, as shown in Figure 4.

4.2. Simulation Analysis

4.2.1. The Evolution of Public Opinion during the Fermentation Period. Public opinion enters the fermentation phase as a result of the blog post "A medical professional in Xi'an was infected even after being vaccinated" spreading on Weibo on a modest scale. The current relationship of the game is consistent with Proposition 5 in Section 3.4, which meets the requirement of $C_2 + F + V(R_1) - C_1 < R_2$, $C_4 + V(G) + V(R_3) + V(-d) < C_3 + V(R_4)$, and $C_6 + f < V(\Delta M)$.

Parameter assumption: $C_1 = 15$, $R_1 = 11$, $S = 5$, $C_2 = 4.4$, $R_2 = 10$, $F = 5$, $C_3 = 18$, $G = 5$, $R_3 = 12$, $C_4 = 8$, $R_4 = 10$, $d = 1$, $kG = 5$, $M = 10$, $\Delta M = 20$, $C_6 = 8$, $f = 2$, and $C_5 = 10$. Based on Tversky [32], the risk attitude coefficient is set to $\alpha_1 = \alpha_2 = \alpha_3 = \beta_1 = \beta_2 = \beta_3 = 0.88$, and the loss aversion coefficient is set to $\lambda = 2.25$. When the initial values of $(x, y, z) = (0.2, 0.2, 0.2), (0.5, 0.5, 0.5)$, and $(0.7, 0.7, 0.7)$ are set for the three cases of strategy combination, the simulation results are shown in Figure 5. The probability of players choosing the second strategy increases with time, and the 3D dynamical system will eventually converge to (0, 0, 0). That is, the operators will choose the strategy of lenient regulation, the official media will choose the strategy of negative reports, and opinion leaders will choose the strategy of malicious incitement.

Assuming that the initial proportion of behavioral decisions taken by the game players is 0.5, a sensitivity analysis of the risk attitude coefficients of the operators, official media, and opinion leaders was carried out without changing other variables. From Figure 6(a), it can be seen that the perceived value of gain is an important influencing factor for operators' strategy choices. A lower α_1 suggests that the operator perceives credibility gains $V(R_1)$ as having less value [24], which lessens the incentive to practice rigorous regulation and causes the operator to be more likely to pick a lenient regulation strategy. For opinion leaders, the incitement cost C_6 is low at this time, and with the increase of α_3, the perceived benefit of incitement gain $V(\Delta M)$ will be higher (Figure 6(b)), and the convergence result of z changes from 1 to 0. Therefore, opinion leaders will express negative views to gain benefits such as traffic and attention, i.e., to achieve the goal of profit maximization through a malicious incitement strategy.

For the official media, the expense of C_3 rises as negative public opinion grows. However, the lower the α_2 and β_2, the lower the perceived value of credibility loss $V(-d)$ and positive reporting gain $V(R_3)$, and as a result, y converges to 0 at a faster rate, meaning that the official media tend to opt for the strategy of negative reports (Figure 6(c)). Due to a number of factors, including negligent regulation by operators, tardy guidance by official media, and a lack of information discernment on the part of Internet users, the public blindly identifies with and spreads negative information on social media, and an increasing number of voices questioning the efficacy of vaccines appear on these platforms (Figure 6).

4.2.2. The Evolution of Public Opinion under the Official Media-Opinion Leader Rivalry during the Outbreak Period. The current relationship of the game is consistent with Proposition 7 in Section 3.4, which meets the requirement of $C_2 + F + V(R_1) - C_1 < R_2$, $C_4 > V(R_4) + C_3$, and $C_6 + f < V(\Delta M)$.

Change the following parameters based on Section 4.2.1: $C_3 = 7$, $C_4 = 9$, $R_4 = 1$, and $d = 3$. In the three cases of $x = y = z = 0.2$, $x = y = z = 0.5$ and $x = y = z = 0.7$, the simulation results are shown in Figure 7(a), and the unique ESS is (0, 1, 0).

At that stage, as a result of operators' lenient regulation, the penalties imposed on opinion leaders were relatively

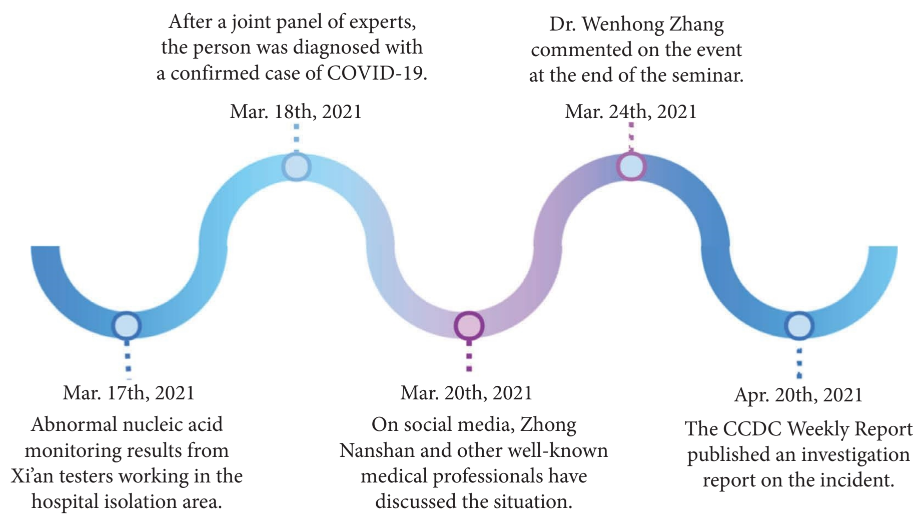


Figure 2: Event development lineage.

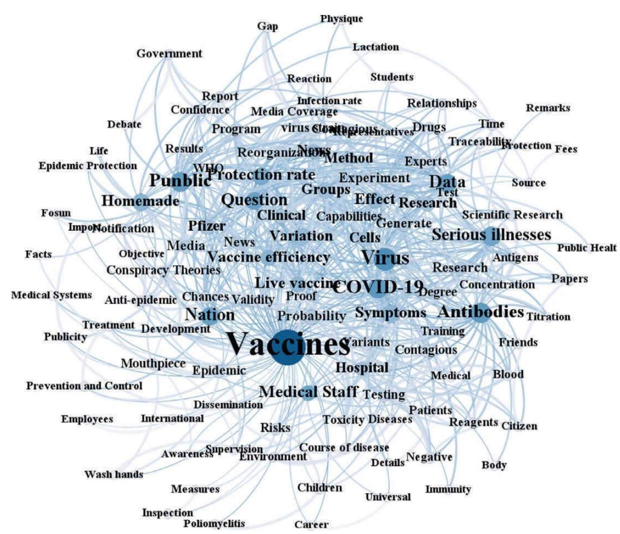


Figure 3: Text co-occurrence network diagram.

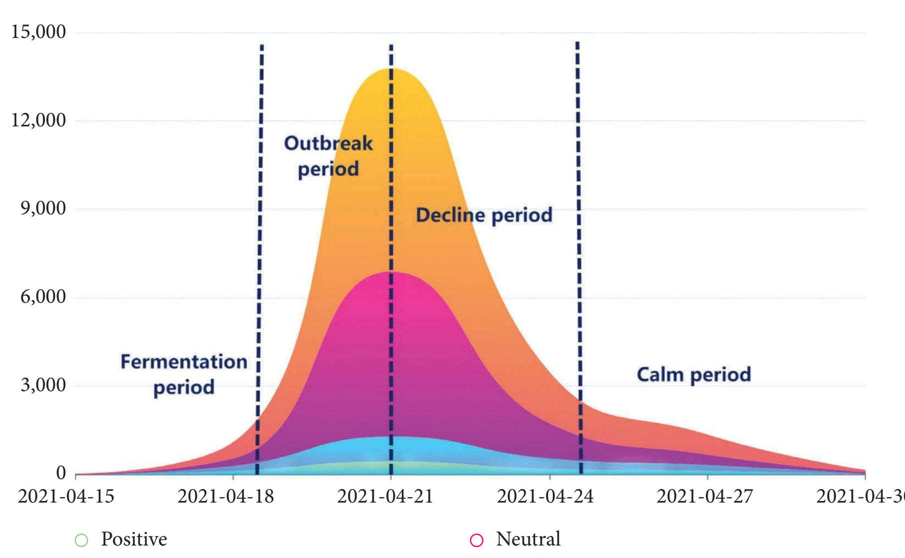


Figure 4: Sentiment analysis.

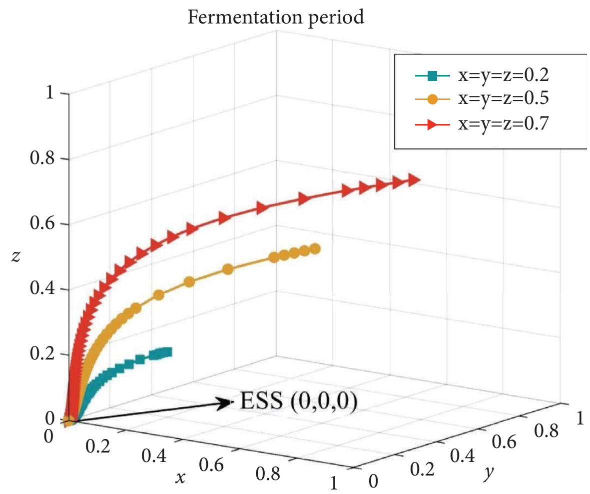


Figure 5: The evolutionary results of the fermentation period.

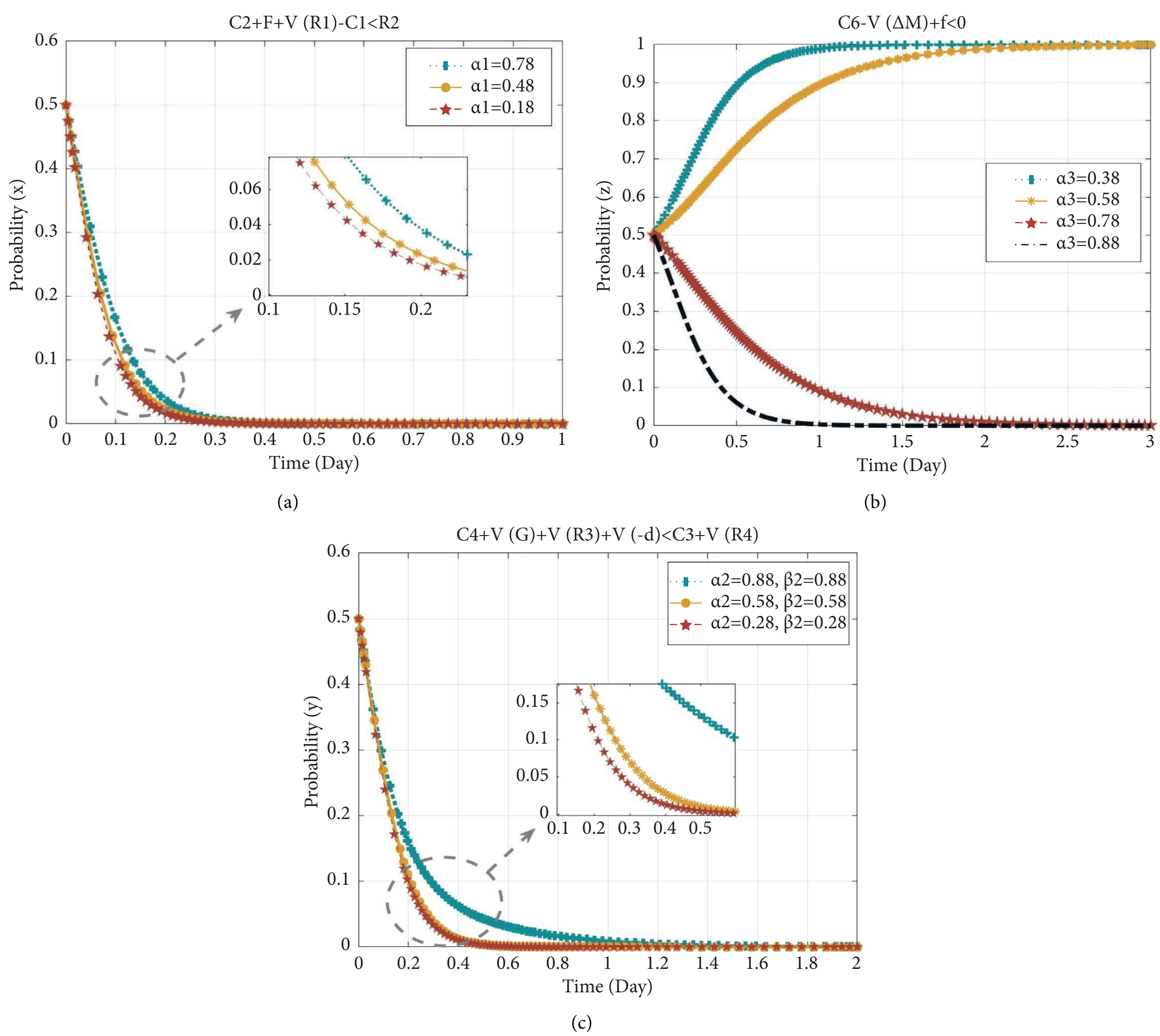


Figure 6: Tripartite evolutionary strategy under different risk attitude coefficients during the fermentation period.

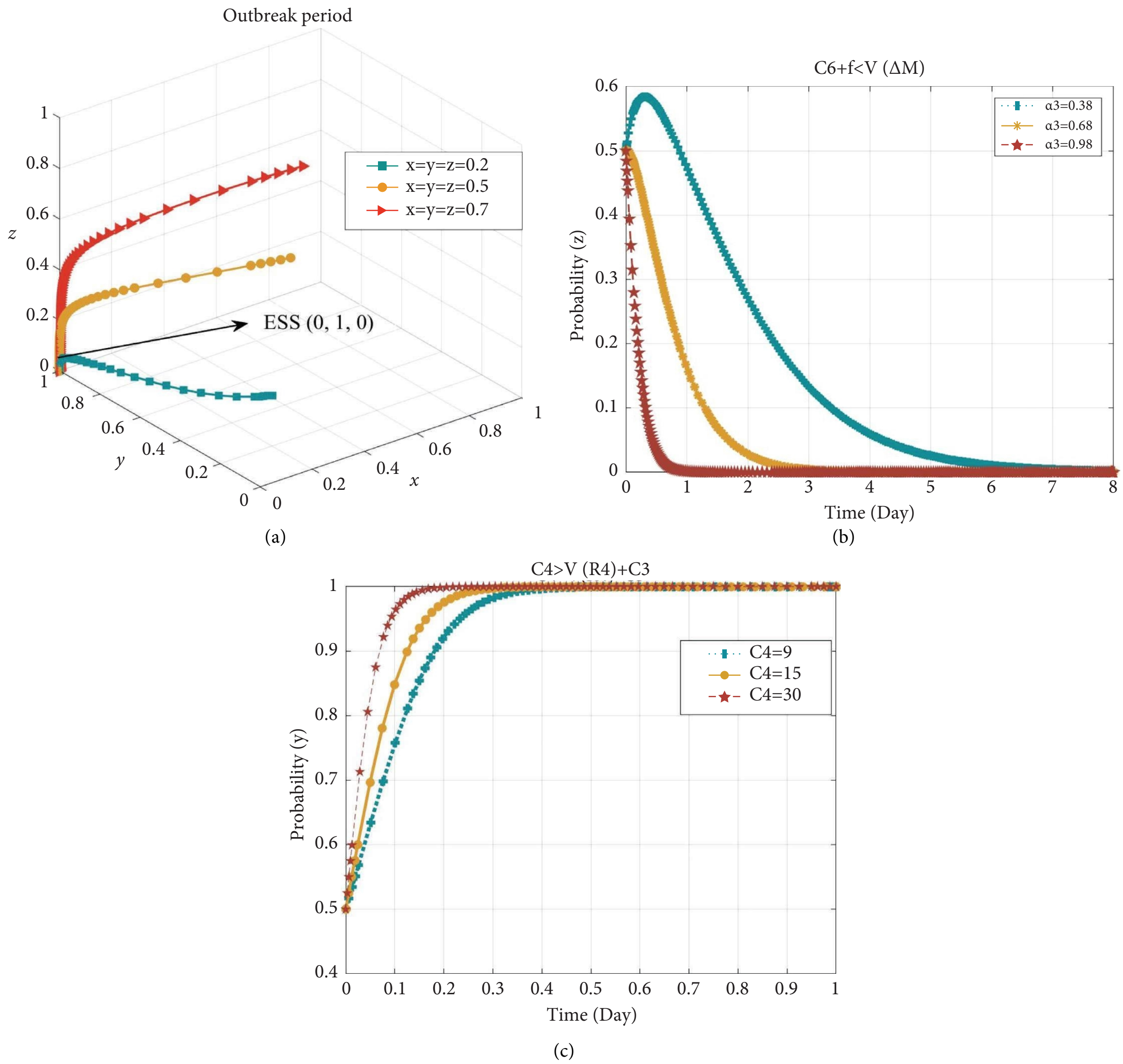


Figure 7: Simulation experimental results of the outbreak period.

lenient. And the extensive discussions among netizens significantly amplified the perceived value of additional benefits $V(\Delta M)$ for these opinion leaders. Consequently, driven by their vested interests, they persistently engaged in malicious incitements (Figure 7(b)). The experimental results in Figure 7(c) show that for the official media, the high cost of negative reporting positively influences the evolution of their behavioral strategies toward positive reporting. When C_4 is higher, y converges faster to 1 under the same condition. This suggests that increasing the cost of negative reporting by official media can effectively inhibit their negative reporting behavior. The official media make positive reports on vaccines to alleviate the public's worries to a certain extent, but it still cannot completely resolve the public opinion crisis. When public opinion evolves to the outbreak period, operators will lose some traffic revenue if they intervene at this time. In addition, if they take regulatory measures such as blocking user accounts and deleting comments, it will not only consume a lot of manpower but also provoke the discontent of netizens, which may lead to secondary public opinion, so operators choose a lenient regulation strategy during this period (Figure 7).

4.2.3. The Evolution of Public Opinion under the Official Media-Opinion Leader Partnership during the Decline Period. The decline period enters with the transmission of negative public opinion under the supervision and guidance of multiple subjects, and the game scenario at this point is consistent with Proposition 12 in Section 3.4 and meets the requirement of $C_2 - C_1 - R_2 + V(R_1) > V(-S)$, $C_4 > V(R_4) + C_3$, and $C_6 + V(M) + V(kG) > V(\Delta M) + C_5$.

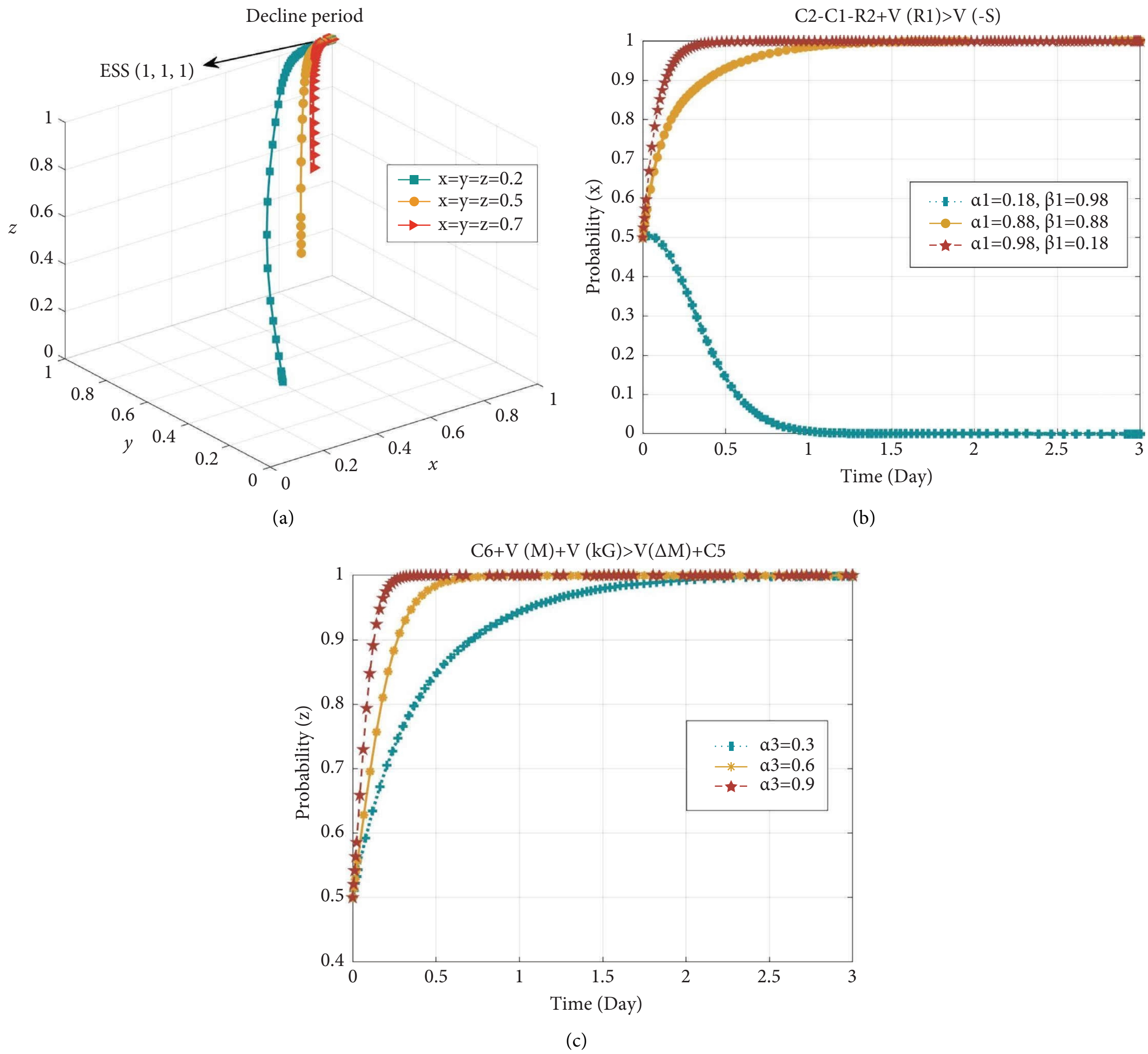


Figure 8: Simulation experimental results of the decline period.

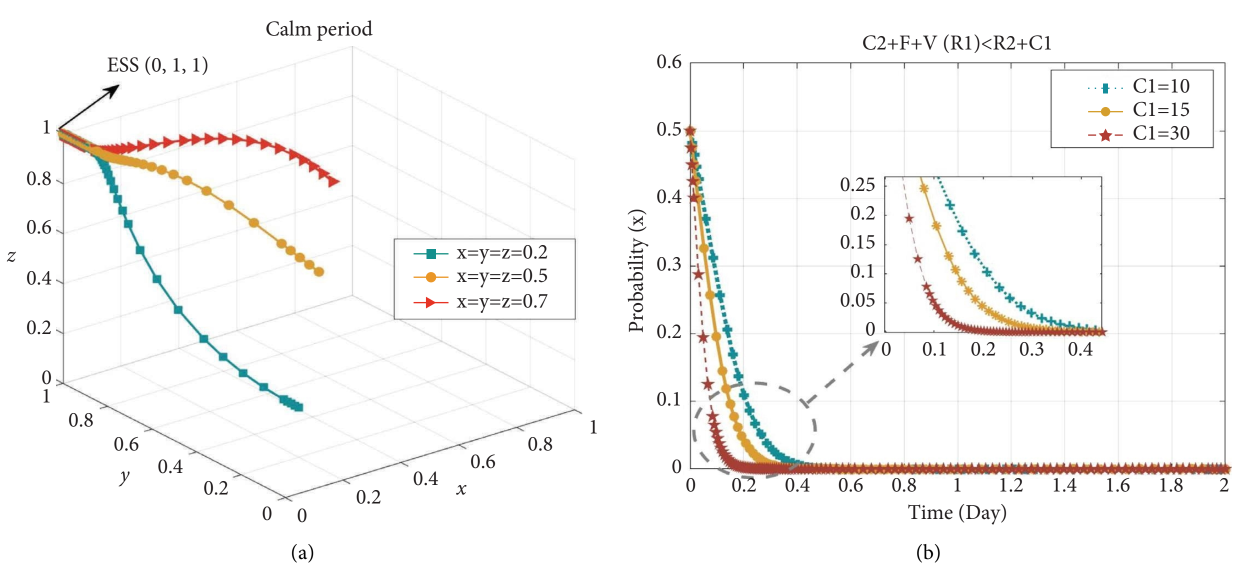
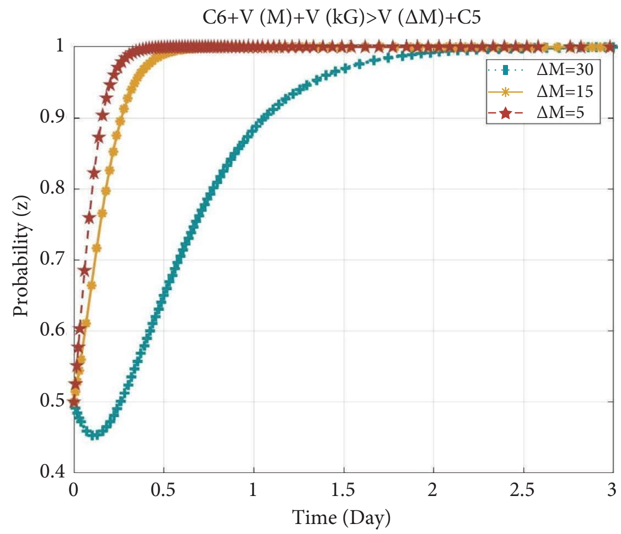


Figure 9: Continued.



(c)

Figure 9: Simulation experimental results of the calm period.

Change the following parameters based on Section 4.2.1: $S = 1$, $C_2 = 9$, $R_2 = 2$, $F = 12$, $C_3 = 7$, $C_4 = 15$, $R_4 = 1$, $d = 3$, $kG = 15$, $M = 20$, $\Delta M = 5$, and $C_5 = 9$. The simulation results under three initial conditions assigned to (x, y, z) as 0.2, 0.5, and 0.7, respectively, are shown in Figure 8(a). In this scenario, the behavioral strategies of the operator, the official media, and the opinion leader can gradually converge and eventually stabilize at the ideal situation of (1, 1, 1).

Due to the lenient early regulation, a public opinion crisis develops, and the operator is punished (F). According to equation (5), finding the first-order partial derivative of the penalty F regarding the behavior of lenient regulation results in $\partial F(x)/F = x(1-x)\ (yz-1) < 0$, i.e., $F(x)$ gradually decreases as F increases, so increasing the penalty for lenient regulation by the operator helps urge it to practice rigorous regulation. In addition, the game subject's perception of non-quantitative gains also affects its decision-making behavior. When operators have higher perceived credibility gains $V(R_1)$ and weaker perceived loss values $V(-S)$, they will tend to choose a rigorous regulation strategy (Figure 8(b)). The cost of negative reporting (C_4) is higher at this point because of the damage done to media credibility during the outbreak period. If they choose to report negatively again, they will fully lose their credibility. The official media decided to adopt a positive reporting stance while being double-monitored by operators and Internet users.

In this case, to motivate opinion leaders to participate in public opinion guidance, the official media will give certain immaterial incentives (kG). Figure 8(c) demonstrates that with the increase of α_3, opinion leaders will choose collaborative guidance strategies at a faster rate because of the greater perceived value of the incentives $V(kG)$. At this point, opinion leaders work with the official media and actively play the role of influencing public opinion in the "civil opinion field," which successfully reduces or even reverses the negative public mood and prevents the spread of bad public opinion (Figure 8).

4.2.4. The Evolution of Public Opinion during the Calm Period. The game scenario at this point is consistent with Proposition 6 in Section 3.4 and meets the requirement of $C_2 + F + V(R_1) < R_2 + C_1$, $C_4 > V(R_4) + C_3$, and $C_6 + V(M) + V(kG) > V(\Delta M) + C_5$.

Change the following parameters based on Section 4.2.2: $C_1 = 10$, $R_1 = 14$, $C_2 = 4$, $kG = 15$, $M = 20$, and $\Delta M = 5$. The simulation results under three initial conditions assigned to (x, y, z) as 0.2, 0.5, and 0.7, respectively, are shown in Figure 9(a), which finally converge to (0, 1, 1).

At this stage, as the enthusiasm and interest of Internet users in participating in discussions diminish, the impact of opinion leaders' incitement, represented by ΔM, is significantly reduced. After carefully considering the potential benefits and drawbacks, they are more inclined to adopt a collaborative guidance strategy (Figure 9(c)). At present, the operators' regulatory costs are higher. As depicted in Figure 9(b), the rate of convergence for x accelerates as C_1 increases. This suggests that operators may tend to favor adopting a more lenient regulatory approach when making decisions based on the Pareto-optimal mindset.

On the basis of satisfying Proposition 6 and the above parameter settings, the effects of parameters kG and G on the game process and outcome are analyzed. Figure 10(a) demonstrates that increasing the immaterial incentive kG increases both the likelihood that opinion leaders will choose collaborative guidance and the likelihood that official media would choose positive reports. Therefore, by providing a variety of incentives, opinion leaders can be drawn to take part in guiding public opinion. Figure 10(b) shows that raising the profit-driven G can raise the likelihood that official media will select active reporting while lowering the likelihood that opinion leaders will select collaborative guidance. Therefore, only increasing incentives to push official media to guide public opinion is not feasible. It should be to improve the incentive system and create "official opinion leaders" who can control discourse in the web public opinion environment and influence public opinion more (Figure 10).

5. Analysis of Negative Public Opinion Dissemination Patterns considering the Cooperative Behavior of Official Media and Opinion Leaders

This study builds an evolutionary game model to analyze the strategic decisions made by each subject based on the various perceived sensitivities of profit and loss during the fermentation, outbreak, decline, and calm periods of public opinion. It has been discovered that media and opinion leaders are more influential and can sway the attitudes and behaviors of Internet users to a certain extent. Therefore, the negative public opinion communication models under the two cases of cooperation and non-cooperation between official media and opinion leaders, respectively, were constructed to further explore the influence of these two on the communication behaviors of Internet users, as shown in Figure 11.

5.1. The SIR Model without the Collaborative Guidance of Official Media and Opinion Leaders

5.1.1. Model Assumptions. From evolutionary game theory, it is clear that each participant, as a finite rational subject, chooses strategies based on the principle of maximizing interests. As a result, during the fermentation and outbreak stages of online public opinion, opinion leaders do not reach a cooperative agreement with the official media, instead opting for the malicious incitement strategy. In this section, we study the evolution of negative public opinion propagation in the (0, 0, 0) and (0, 1, 0) states of the game system.

Assumption 13. Based on the modeling ideas of Kumar [33] and Yu et al. [1], Internet users are classified into the following three categories: S indicates susceptible Internet users who are initially exposed to public opinion and may change their status under the influence of negative remarks; I indicates infected Internet users who spread negative information on social platforms after being exposed to public opinion information; R indicates immune Internet users who are not interested in the topic or no longer participate in its spread due to positive guidance from official media.

Assumption 14. $S(t)$, $I(t)$, and $R(t)$ are used to denote the proportion of the number of Internet users in each type of state to the total number of Internet users at moment t, respectively. Assume that $S(t)$, $I(t)$, and $R(t)$ are continuously differentiable functions concerning time t, and $S(t)+I(t)+R(t)=1$. Therefore, the specific conversion of each type of Internet user is shown in Figure 12.

The interpretation of each parameter in Figure 12 is shown in Table 5.

Based on the above assumptions, the following differential equation is obtained according to the propagation dynamics theory [27]:

$$\begin{cases} \dfrac{dS}{dt} = A - a\gamma z_2 SI - a\beta y_1 S + a(\alpha x_2 + \beta y_2)R, \\[2ex] \dfrac{dI}{dt} = a\gamma z_2 SI - a(\alpha x_1 + \gamma z_1)I, \\[2ex] \dfrac{dR}{dt} = a\beta y_1 S + a(\alpha x_1 + \gamma z_1)I - a(\alpha x_2 + \beta y_2)R. \end{cases} \tag{9}$$

5.1.2. Propagation Equilibrium Point and Stability Analysis. There are two basic propositions of system (9) as follows.

Proposition 15. *When $R_0 \le 1$, the zero propagation equilibrium $(A/(a\beta y_1), 0, 0)$ is locally asymptotically stable, and there is no propagator in the system. This proposition shows that public sentiment is developing in a rational and objective direction under the active guidance of official media. There is no spread of negative information in the multi-expressed public opinion discourse space, and the social platform network environment is clear.*

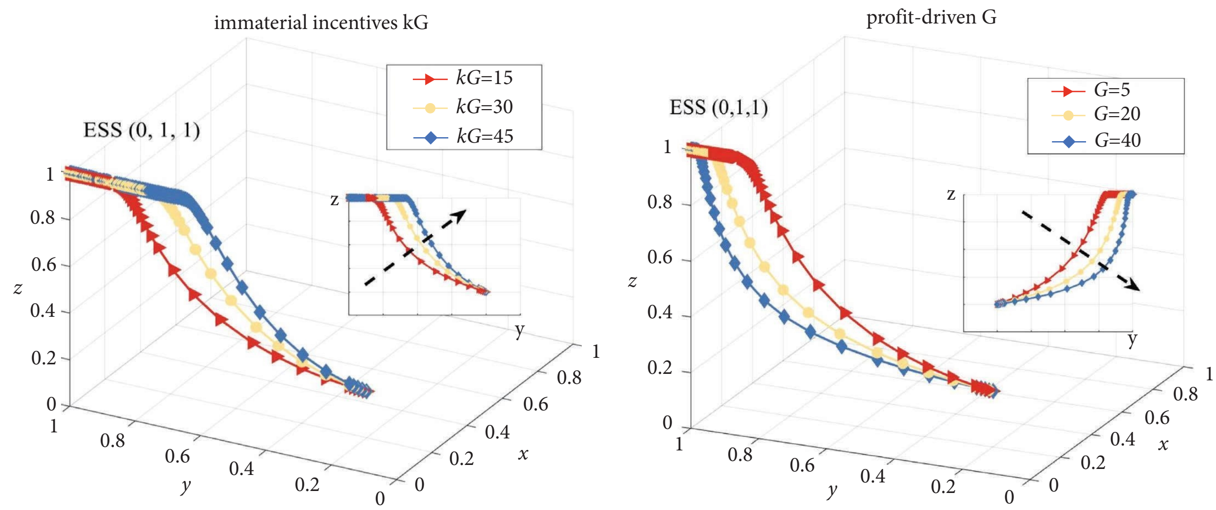
Proposition 16. *When $R_0 > 1$, the non-zero propagation equilibrium (S^*, I^*, R^*) is locally asymptotically stable, and the propagation of negative public opinion information occurs in the system.*

$$\begin{cases} S^* = \dfrac{(\alpha x_1 + \gamma z_1)}{(\gamma z_2)}, \\[2ex] I^* = \dfrac{A}{(a(\alpha x_1 + \gamma z_1))} - \dfrac{(\beta y_1(\alpha x_1 + \gamma z_1))}{(\alpha \gamma z_2)}, \\[2ex] R^* = \dfrac{(\alpha x_1 + \gamma z_1)}{(\alpha x_2 + \beta y_2)}. \end{cases} \tag{10}$$

The proposition shows that under the influence of opinion leaders' inflammatory remarks, some netizens actively or passively become negative information disseminators based on emotional resonance. In this case, the scope of negative public opinion will continue to expand, and the public opinion ecology will be destroyed.

5.1.3. Analysis of Propagation Threshold and Simulation Experiment. Based on the study of the improved infectious disease model in the literature [28–30], it can be seen that the propagation threshold R_0 can roughly determine the spread and trend of online public opinion, and the size of R0 is affected by multiple parameter factors in the model. The smaller the propagation threshold is, the more beneficial it is to control the spread of public opinion. The propagation threshold $R_0 = Aa\gamma z_2 / a(\alpha x_1 + \gamma z_1)\beta y_1(\alpha x_1 + \gamma z_1)$ can be obtained from equation (10).

Proposition 17. *In the fermentation period and the outbreak period, if the official media seizes the dominance of public*



(a) (b)

Figure 10: The effect of kG and G on the evolutionary strategies.

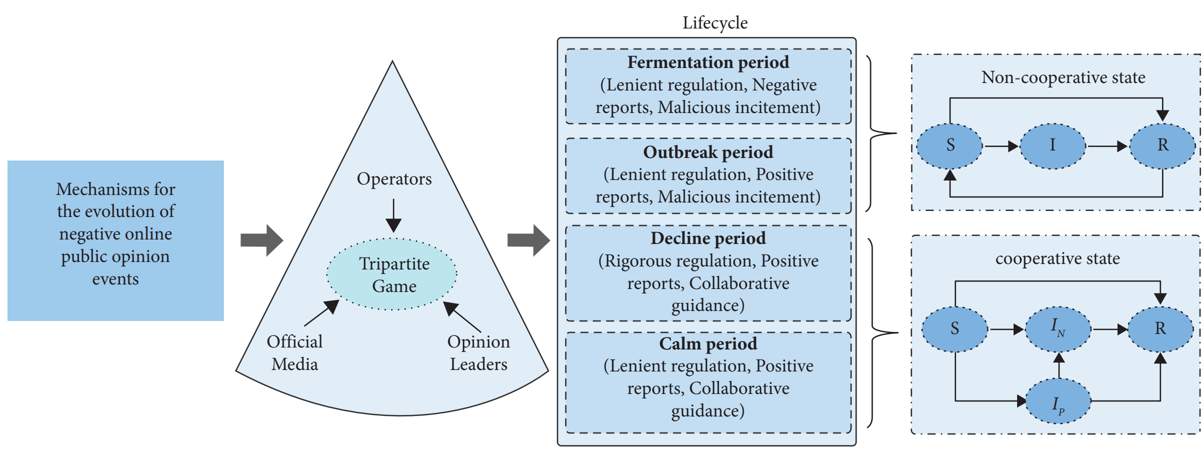


Figure 11: Evolutionary mechanism of negative public opinion dissemination.

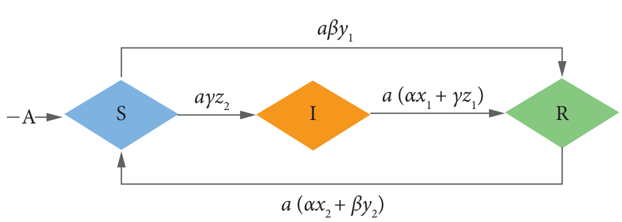


Figure 12: The evolution process of different state nodes.

opinion, choosing a positive reporting strategy will help block the spread of public opinion; opinion leaders choosing a malicious incitement strategy will not be conducive to public opinion control.

Proof. Let R_0 take partial derivatives of y_1 and z_2, and we can get: $\partial R_0/\partial y_1 = -A\gamma z_2/(\beta y_1^2(\alpha x_1+\gamma z_1)^2) < 0$, which means the positive report strategy has a negative effect on R_0, and the higher probability of positive reporting by official media helps to control public opinion. From $\partial R_0/\partial z_2 = A\gamma/(\beta y_1(\alpha x_1 + \gamma z_1)^2) > 0$, it can be seen that the malicious incitement strategy plays a positive role on R_0, i.e., as the incitement probability of opinion leaders increases, the spread of negative opinion expands.

To verify the rationality of the model, Matlab is used to simulate the propagation law of the SIR model without the collaborative guidance of official media and opinion leaders. Assuming $A = 0.000001$, $a = 0.8$, and $\alpha = \beta = \gamma = 0.5$, we get the changing trend of $I(t)$ under different stable strategies of operators, official media, and opinion leaders, as shown in Figure 13.

It can be seen from Figure 13 that when the tripartite evolutionary stability strategy is (rigorous regulation, active reports, collaborative guidance), public opinion will be most effectively controlled. Opinion leaders have a significant network influence, which makes it simple for Internet users to blindly follow their negative opinions and cause group polarization. When the strategy evolved to (lenient regulation, negative reports, malicious incitement), the spread of negative public opinion quickly broke out, and the number

Table 5: Parameter description of the SIR model.

Parameters	Interpretation
A	The increase rate of Internet users over time
a	The decision weight
A, β, and γ	The trust degree of Internet users in operators, official media, and opinion leaders, respectively
$a\gamma z_2$	The likelihood of S spreading negative opinion information based on trust and identification with it, as instigated by opinion leaders
$a\beta y_1$	The probability of Internet users transforming into R under the active reports of official media
$a(\alpha x_1 + \gamma z_1)$	The probability of no longer spreading public opinion under rigorous regulation by operators and guidance by opinion leaders
$a(\alpha x_2 + \gamma y_2)$	The probability of R transforming into S due to the forgetting mechanism under the operators' lenient regulation and the official media's negative reports

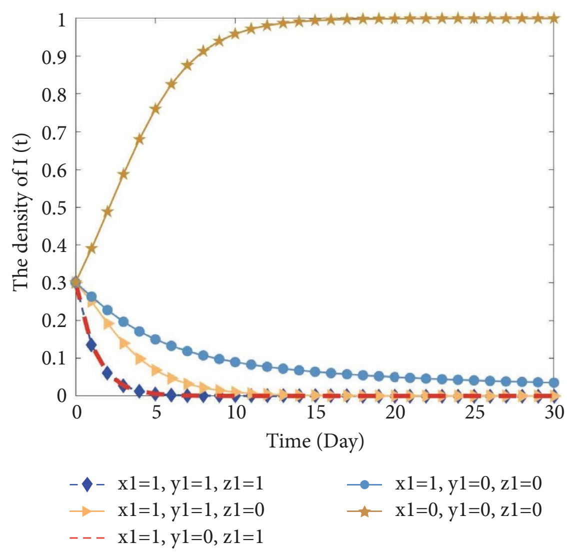


Figure 13: The density of $I(t)$ under different stable strategies.

of communicators increased rapidly, easy to develop into a situation difficult to control.

Taking the outbreak period as an example, the effect of trust degree on the spread of negative public opinion is investigated by varying the values of α, β, and γ while leaving other parameters constant. Assuming that the initial value of netizens' trust in operators, official media, and opinion leaders is 0.5, the simulation results are shown in Figure 14.

Figure 14(a) shows that under lenient operator regulation, Internet users' incitement behavior will be exempt from punishment, and when a is higher, Internet users will spread negative information more scrupulously; Figure 14(b) shows that if official media actively disclose and interpret public opinion information to the public and meet the information needs of Internet users, it will help enhance media trust, reducing Internet users' motivation to troll; Figure 14(c) demonstrates that as netizens' trust in opinion leaders grows, so does their willingness to support and spread their ideas. As a result, an increasing number of netizens start spreading false information, which exacerbates the ongoing superposition of negative public opinions in a vicious cycle. □

5.2. The SI_NI_PR Model under the Collaborative Guidance of Official Media and Opinion Leaders

5.2.1. Model Assumptions. As the public opinion environment deteriorates, operators intervene in supervision, and at the same time, thanks to the collaborative guidance of opinion leaders and official media, public opinion has entered a period of decline and calm. This section investigates the evolution of negative public opinion propagation in the (1, 1, 1) and (0, 1, 1) states of the game system.

Proposition 18. *Official media and opinion leaders' actions have a significant impact on public opinion and have a direct impact on how netizens' status changes: S(t) stands for observers on the Internet who interact with information about public opinion without acting; $I_N(t)$ for infected users who spread negative information; $I_P(t)$ for infected users who spread positive information with the active guidance of official media; and R(t) for immune users who lose interest in transmission and leave the transmission system.*

Proposition 19. *The specific conversion of various types of Internet users is shown in Figure 15.*

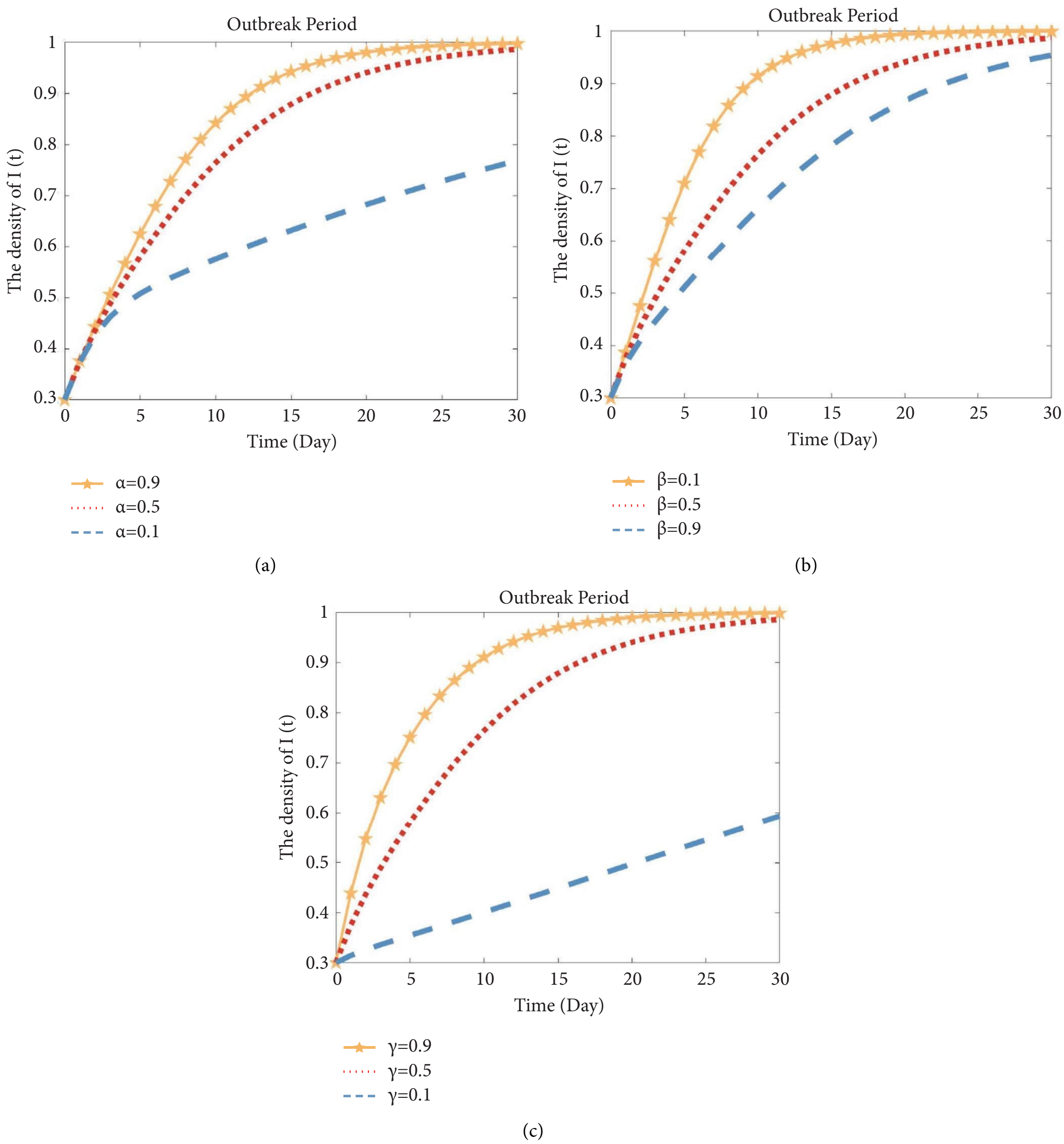


Figure 14: The density of $I(t)$ under different trust degrees during the outbreak period.

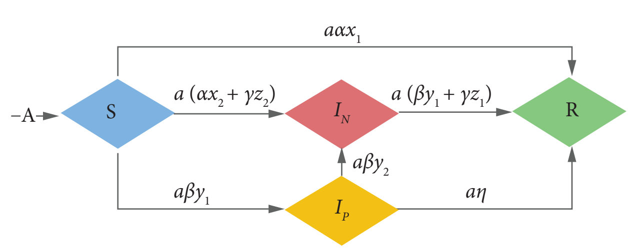


Figure 15: The evolution process of different state nodes.

Table 6: Parameter description of the SI_NI_PR model.

Parameters	Interpretation
$a\alpha x_1$	The probability that S stops paying attention to public opinion under rigorous regulation by operators
$a(\alpha x_2 + \gamma z_2)$	The probability of S becoming I_N under the lenient regulation of operators and the malicious instigation of opinion leaders
$a(\beta y_1 + \gamma z_1)$	The probability of I_N becoming I_P under the positive report of official media
$a\beta y_2$	The probability of I_P to I_N
$a(\beta y_1 + \gamma z_1)$	The probability of I_N no longer spreading public opinion under the joint guidance of official media and opinion leaders
$a\eta$	The probability of I_P to R

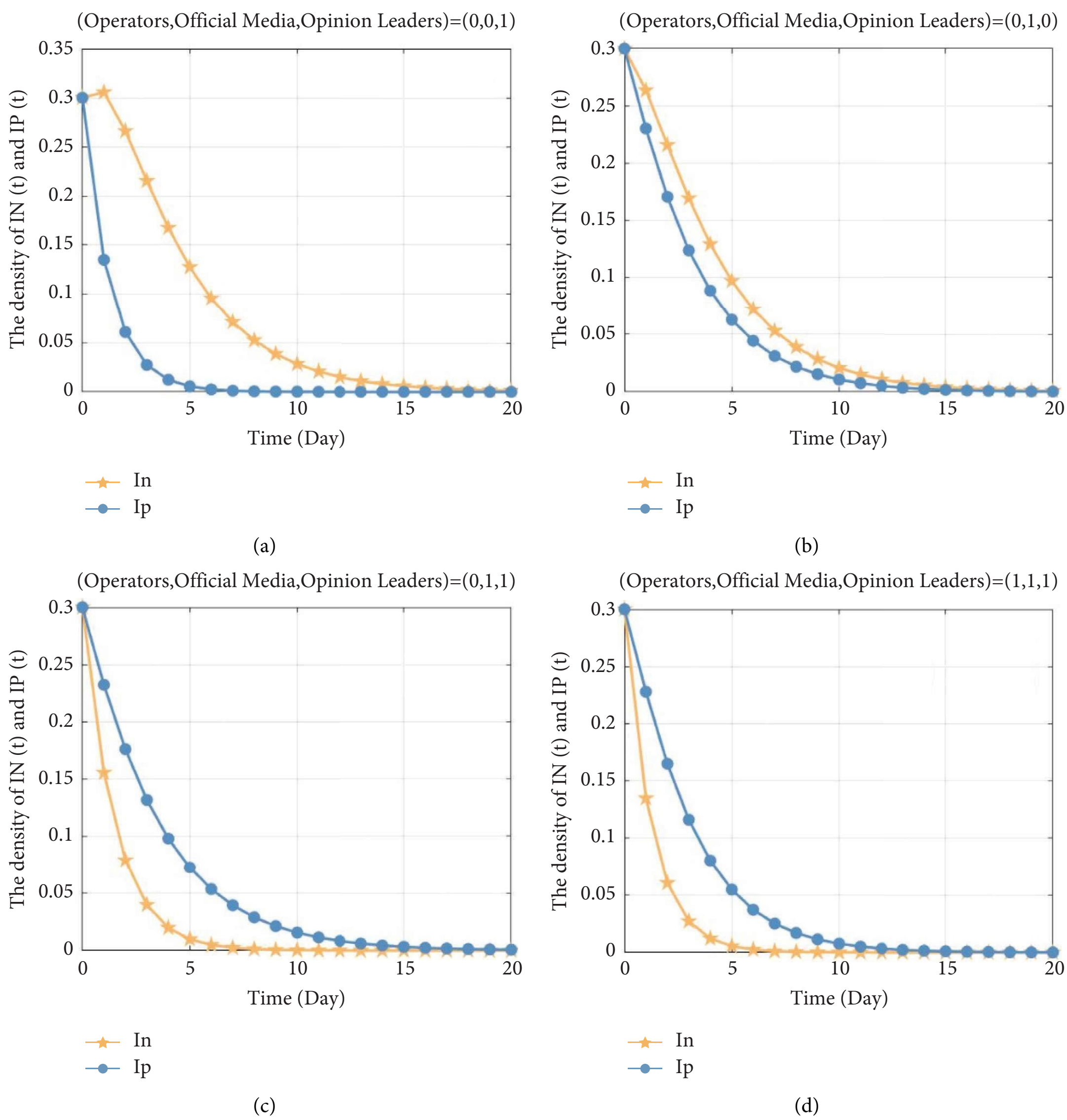


Figure 16: The density of $I_P(t)$ and $I_N(t)$ under different stable strategies.

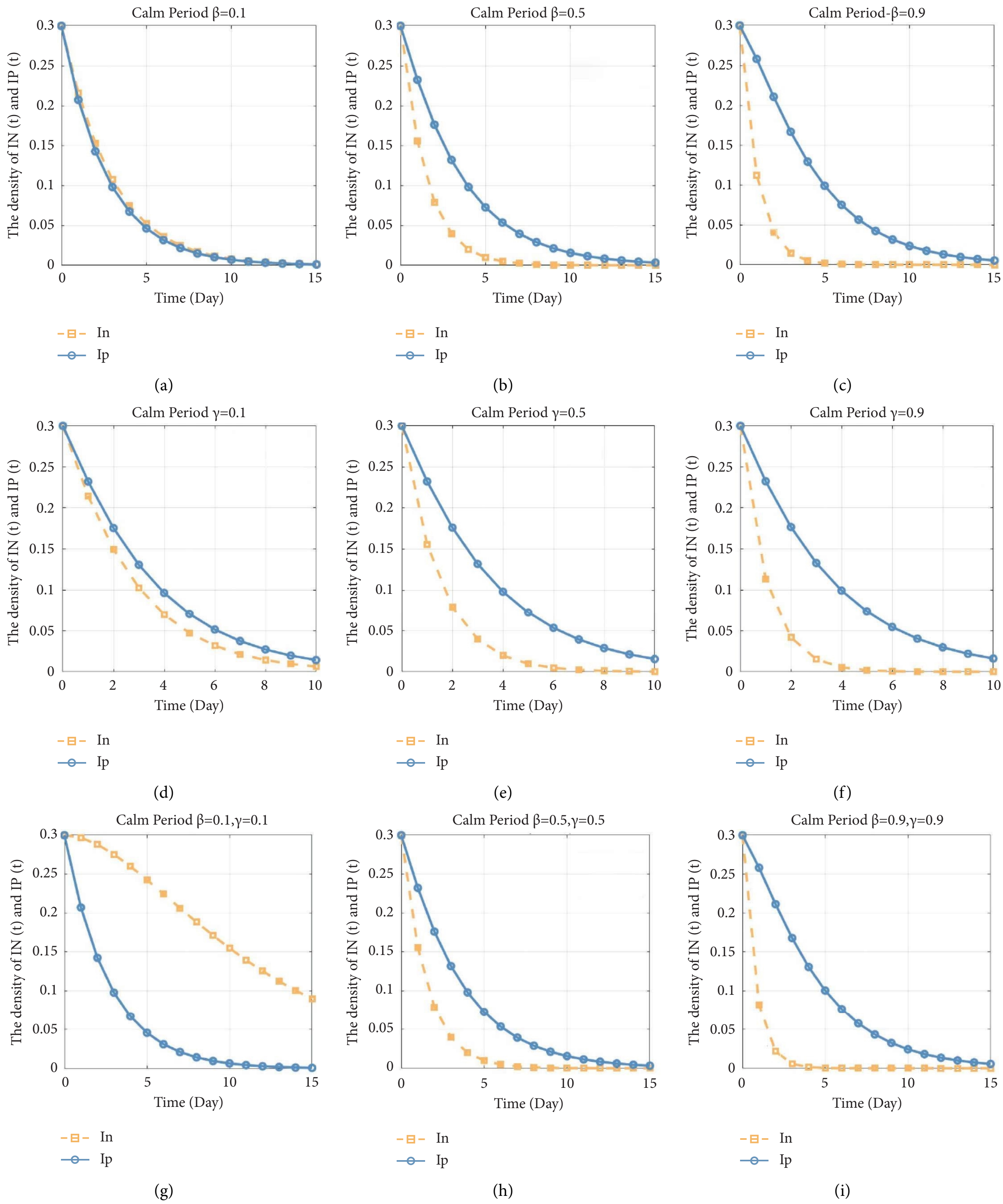


FIGURE 17: The density of $I_P(t)$ and $I_N(t)$ under different trust degrees during the calm period.

The interpretation of each parameter in Figure 15 is shown in Table 6.

Based on the above assumptions, the following differential equation is obtained:

$$\begin{cases} \dfrac{dS}{dt} = A - a(\alpha x_2 + \gamma z_2)SI_N - a\beta y_1 SI_P - a\alpha x_1 S, \\ \dfrac{dI_N}{dt} = a(\alpha x_2 + \gamma z_2)SI_N - a(\beta y_1 + \gamma z_1)I_N + a\beta y_2 I_P, \\ \dfrac{dI_P}{dt} = a\beta y_1 SI_P - a\beta y_2 I_P - a\eta I_P, \\ \dfrac{dR}{dt} = a\alpha x_1 S + a(\beta y_1 + \gamma z_1)I_N + a\eta I_P, \\ S(t) + I_N(t) + I_P(t) + R(t) = 1. \end{cases} \quad (11)$$

5.2.2. Propagation Equilibrium Point and Stability Analysis. First, let $I = I_N + I_P$, $\rho = a(\alpha x_2 + \gamma z_2) + a\beta y_1$ and $\theta = a(\beta y_1 + \gamma z_1) + a\eta$, and let each equation be zero; then:

$$\begin{cases} \dfrac{dS}{dt} = A - \rho SI - a\alpha x_1 S \,(1), \\ \dfrac{dS}{dt} = \rho SI - \theta I \,(2). \end{cases} \quad (12)$$

According to (2), we can find $I^* = 0$ or $S^* = \theta/\rho$. When $I^* = 0$, we can get $S^* = A/(a\alpha x_1)$ by substituting into equation (12), that is, $(A\rho/(a\alpha x_1), 0)$; when $S^* = \theta/\rho$, $I^* = A/\theta - a\alpha x_1/\rho$, then we get $(\theta/\rho, A/\theta - a\alpha x_1/\rho)$.

Based on (12), the equilibrium point of negative public opinion propagation is solved, and Propositions 20 and 21 are obtained.

Proposition 20. *When $R_0 \leq 1$, the zero propagation equilibrium $(A/(a\alpha x_1), 0)$ is locally asymptotically stable.*

Proposition 21. *When $R_0 > 1$, the non-zero propagation equilibrium $(\theta/\rho, A/\theta - a\alpha x_1/\rho)$ is locally asymptotically stable.*

5.2.3. Analysis of Propagation Threshold and Simulation Experiment. The propagation threshold $R_0 = A\rho/a\alpha x_1\theta$ can be obtained from $I^* = A/\theta - a\varphi/\rho$, that is, $R_0 = Aa(\alpha x_2 + \gamma z_{2+}\beta y_1)/a\alpha x_1(a(\beta y_1 + \gamma z_1) + a\eta)$.

Proposition 23. *Operators that follow rigorous regulation procedures can halt the propagation of negative public opinion to a certain extent; the strategic choice of opinion leaders has a significant impact on public opinion trends. While choosing incitement may hasten the fermentation of negative public opinion, cooperating with the official media to guide public opinion will promote its dissipation.*

Proof. Let R_0 take partial derivatives of x_1, x_2, z_1, and z_2, and we can get: $\partial R_0/\partial x_1 = -(A(\alpha x_2 + \beta y_1 + \gamma z_2))/(a\alpha x_1^2(\eta + \beta y_1 + \gamma z_1)) < 0$ and $\partial R_0/\partial x_2 = A/(ax_1(\eta + \beta y_1 + \gamma z_1)) > 0$. For operators, the likelihood of rigorous regulation increases with the likelihood that public opinion will be successfully managed. Instead, the lax regulatory approach will affect its credibility and further expand the impact of negative public opinion. It can be seen from $\partial R_0/\partial z_1 = -(A\gamma(\alpha x_2 + \beta y_1 + \gamma z_2))/(a\alpha x_1(\eta + \beta y_1 + \gamma z_1)^2) < 0$ and $\partial R_0/\partial z_2 = (A\gamma)/(a\alpha x_1(\eta + \beta y_1 + \gamma z_1)) > 0$ that the choice of opinion leaders to collaborate with official media to guide public opinion will be conducive to public opinion control, and z_2 will positively affect R_0, that is, with the increase in the probability of opinion leaders choosing malicious incitement, it will be more unfavorable to the control of public opinion.

Assuming $A = 0.000001$, $a = 0.8$, $\alpha = \beta = \gamma = 0.5$, and $\eta = 0.5$, the numerical simulation of model (9) can be obtained. Figure 16 depicts the evolution of $I_P(t)$ and $I_N(t)$.

Figures 16(a) and 16(b) show that when operators practice lenient regulation, it is frequently hard to quell public opinion by relying entirely on a single force of official media or opinion leaders. However, when opinion leaders and the official media work together to influence public opinion, regardless of the operators' chosen strategy, good governance results can be achieved, as demonstrated in Figures 16(c) and 16(d).

Taking the calm period as an example, the effect of trust degree on the spread of negative public opinion is investigated by varying the values of α, β, and γ while leaving other parameters constant, as illustrated in Figure 17.

Figures 17(a)–17(c) demonstrate that when netizens' faith in the official media is low, the official media's reports cannot win the netizens' recognition, which will eventually result in a recovery in negative public opinion. As β increases, netizens are more likely to shift to I_P. In order to increase their credibility in the age of new media, the official media should therefore keep developing their reporting methods and actively respond to audience concerns.

In Figure 17(d), when netizens have low faith in the guidance of opinion leaders, negative information tends to spread widely in the public opinion field, resulting in the coexistence of positive and negative information. Figures 17(e) and 17(f) illustrate that as γ increases, the number of negative information disseminators (I_N) gradually decreases while I_P gradually occupies the public opinion field.

Figures 17(g)–17(i) demonstrate that β and γ have a strong impact on the spread of negative public opinion. The outcome of public opinion governance is extremely unsatisfactory when Internet users have little confidence in both official media and opinion leaders. In order to mutually foster the positive growth of online public opinion, media and opinion leaders should be encouraged to actively improve their own quality and raise the quality of information distribution. □

6. Conclusion

In the age of new media, social platforms are an important channel for the public to obtain news and information and a major vehicle for the proliferation of negative information. For instance, when disseminated, a lot of negative information concerning vaccines is covered with scientific "veneer," making it more challenging for audiences to tell facts from fiction. It is simple to create a "spiral of silence" under the group's psychological mechanism and entice an increasing number of netizens to take part in public opinion activities.

This study analyzes the equilibrium strategy combinations used by operators, official media, and opinion leaders in the game system and determines the stable strategies in four stages: fermentation, outbreak, decline period, and calm. Finally, a Matlab numerical simulation is used to examine the various implications of each game subject's participation roles under various perceived values of loss and gain on the development of the entire public opinion event. The following key findings are attained as a result of studying the influence of the two different scenarios on the trend of public opinion and improving the contagion model in light of the evolution results that include two scenarios of cooperation or non-cooperation between opinion leaders and official media:

(1) This study finds that the higher the probability of operators choosing a strict management strategy is, the more likely the negative public opinion will be effectively controlled; on the contrary, if they choose lax management, they will not be able to control the first signs of a public opinion crisis at the source. Therefore, operators should strengthen the supervision of negative public opinions and increase the traceability of negative information creators and disseminators. Operators should use artificial intelligence technology to continuously optimize the accuracy of identifying false negative information and stop false information at the source. On the other hand, they should increase the supervision of false information, improve the traceability mechanism, promptly block bad accounts, and successfully stop the spread of false public opinion. Furthermore, it is important to continually open up and improve the user-reporting system, collaborate with self-media and opinion leaders, and enhance the ability to debunk rumors. This is crucial in creating a clean and clear online space.

(2) According to this study, it is conducive to receding public opinion when the official media opt to actively report. However, if the official media chooses to report negatively, it will prompt speculative queries from netizens, which will then be more likely to fall into the "Tacitus trap" and ultimately cause the intensification of negative public opinion. Since the public has cognitive limits and frequently relies on the media to quench their informational thirst during public health emergencies like COVID-19, the official media should take on the social duty. For instance, in response to unfavorable public discussions about vaccines, the official media should frame the situation as quickly and rationally as possible, provide prompt clarification of inaccurate information based on reliable experimental findings and other data, arouse the audience's rational emotions, and lessen online users' misconceptions about vaccines. However, the official media, based on their "official" features, are more stereotypical in their reporting than Internet opinion leaders, and the guidance impact is frequently poor in the contemporary public opinion environment.

(3) This study finds that opinion leaders, as the center of discourse power in the civil opinion field, play the role of "weathervane" in the direction of negative public opinion. If opinion leaders choose to collaborate with official media, netizens will tend to become positive information disseminators under the guidance of both. In contrast, when opinion leaders choose a malicious incitement strategy, Internet users will continue to expand the influence of negative information under the interaction of negative emotions, which will eventually lead to a public opinion crisis. Opinion leaders are more likely to win the public's recognition and trust than the official media. In order for them to transmit positive energy in numerous public opinion venues, the government should deliberately create "official opinion leaders" in a variety of sectors. Since opinion leaders are limited rational subjects whose strategic choices depend on interest relations, the government should innovate incentive mechanisms and increase non-material incentives to boost the likelihood of cooperation between opinion leaders and official media, to firmly grasp the right to speak in the "public opinion field" of the government and the public, and thereby promote the healthy development of the public opinion ecological environment.

This study only selects one case to abstract the life cycle of public opinion, which lacks universality. This paper solely takes into account the classification of infected Internet users (I) into two categories: positive transmitters (I_P) and negative transmitters (I_N), in the section on communication model construction. Internet users may actually exhibit a more complicated evolutionary dynamic process based on various emotional and psychological elements; therefore, the communication model in this study needs to be continuously adjusted. In reality, some Internet users have a neutral attitude and promote eclectic viewpoints. The next step can be to study the influence of cooperative behaviors of official media and opinion leaders on the evolution of negative public opinion based on the two-layer coupled network model since Internet users' communication behaviors in offline social networks may not be consistent with those in online social networks.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

LW was responsible for conceptualization. HZ was responsible for methodology. WH was responsible for formal analysis. JW was responsible for original draft preparation. All authors have read and agreed to the published version of the manuscript.

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