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A FOUR-DIMENSIONAL EVOLUTIONARY GAME ANALYSIS OF QUALITY CHEATING BEHAVIOR IN TRADITIONAL CHINESE MEDICINE SUPPLY CHAIN

Abstract. *A sustainable supply chain of Traditional Chinese Medicine (TCM) is vital for public health. However, for many years, TCM manufacturers have suffered from the quality cheating behaviours of their suppliers (Chinese herbal medicine providers). Aiming at managing those quality cheating behaviours and improving the potency of TCM effectively, a four-dimensional evolutionary game model composed of Chinese herbal medicine suppliers and TCM manufacturers was established, and two quality inspection methods were introduced: chemical inspection and biological assay inspection were introduced to screen unqualified and low-potency Chinese herbal medicines (CHM), respectively. The model results are obtained through the analysis of stable strategy and evolution paths, and the influence of some parameters such as the percentage of suppliers selected, rewards, and punishments on the evolutionary stable state was analysed by numerical simulation experiments in the MATLAB software. The results showed that TCM manufacturers can reach an optimal state: purchasing high-potency CHM at the lowest possible inspection costs. The government regulators and manufacturers can improve the quality of CHM by changing the above parameters.*

Keywords*: Traditional Chinese Medicine Supply Chain Quality, Supply Chain Quality Management, Evolutionary Game, Multi-Behavioural Strategy, Numerical Simulation, Quality Inspection*

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1. Introduction

Traditional Chinese medicine (TCM) plays an important role in health care in many countries and has been widely used in mainland China to prevent and control COVID-19. Therefore, it is very important and necessary to increase the sustainability of the TCM supply chain. As the cornerstone of improving sustainability, quality must be guaranteed. However, unlike Western medicine, TCM is made up of plants rather than chemicals. As a result, quality management of TCM is much more difficult than Western medicine. Many factors, such as the natural conditions, the picking timing, or the processing methods (Zhou, Li, Chang, & Bensoussan, 2019), affect the potency of the main raw materials of TCM, Chinese herbal medicines (CHM). It increases information asymmetry between TCM manufacturers and their CHM suppliers, which lead to the suppliers' quality cheating behaviours to increase profit. There are many ways to cheat on quality. For example, the supplier may adulterate CHM with some unqualified substances, such as undeclared drugs/chemical substances, non-drug components (M. Xu et al., 2019), or low-potency CHM components. According to the Annual Report on Unqualified Drug Quality Data of China Yaozhi.com: from 2017 to 2019, Chinese herbal medicines accounted for 64%, 73%, and 76% of all unqualified medicines, respectively, and the proportions increase year by year. How to prevent the quality cheating behaviours in TCM supply chains, such as suppliers providing unqualified or low-potency CHM, is essential to improve the sustainability of TCM supply chains. In addition, the unqualified and low-potency CHM should belong to two different levels (Zhou et al., 2019). Providing unqualified CHM, which is not listed in the pharmacopoeia, is an illegal behaviour of the supplier to attain high profits and may cause harm to users, but most of the reasons for the low-potency are due to improper practices in the planting or preservation process, such as inappropriate picking time.

The existing research related to TCM quality management focused on supply chain quality management, and the TCM supply chain quality management mainly includes the supervision and traceability of the supply chain. Some scholars use the Internet of Things and other technologies to plan and implement a detailed information inspection and traceability system for the Chinese herbal medicine supply chain, and to number, process, and trade Chinese herbal medicines, it is possible to realise a high-supervision model from cultivation to sales of Chinese herbal medicines (Hu, Sun, Zhou, & Ruan, 2020). The circulation traceability system of the Chinese herbal medicine supply chain can control the quality of Chinese herbal medicine throughout the process. He and Shi use the agricultural sensors on the Internet of Things technology platform to realise the high-supervision model of CHM from planting to sales (He & Shi, 2021). Combined with the Internet of Things technology to automatically collect information, blockchain technology ensures the

security of information circulation, which can form a closed loop of information in the circulation of CHM, and realise the supervision of the circulation process of CHM (Ming-Yi, Chong-Yu, Chuan-Biao, Xiong, & Sheng-Nan, 2020). Additionally, the medicinal regulatory system and related laws and regulations also play an important role (M. Wang, Yao, Sun, Liang, & Chen, 2022), the government strengthens the surveillance of TCM production and strictly enforces GACP and GMP standards to minimise the risk of problems such as adulteration and contamination of TCM materials (J. Zhang, Wider, Shang, Li, & Ernst, 2012). And the regulation of CHM at the national level is to protect public health and consumers from potentially harmful herbal materials (Chau & Wu, 2006; Ssempijja et al., 2020). Different countries have different regulatory focuses on Chinese herbal medicines, but the one commonality between every county is that the primary focus is the safety of the consumer (Thakkar et al., 2020). Regulators must contribute to the communication with the scientific community and industry to adapt regulatory requirements to changes in the CHM market.

When reviewing the literature, we can find some research on agricultural food artificial quality problems. The TCM supply chain has certain similarities to the agricultural food supply chain (He & Shi, 2021). Therefore, artificial quality problem research in the field of agricultural and food supply chain can provide a reference for the research of the TCM supply chain. Relevant scholars have conducted research on the quality of the agricultural product supply chain from different perspectives, including incentives, punishment supervision, and food safety traceability of agricultural product quality control. As an increasingly popular way to coordinate food quality improvements, quality incentive contracts can effectively improve food quality in agricultural supply chains (Goodhue, 2011). As a way to improve product quality, many scholars have carried out research on the quality supervision of agricultural product supply chain, effective quality supervision can enable producers to produce higher quality products (Z. Liu, Mutukumira, & Chen, 2019). However, some market participants (producers or sellers) speculate on how regulators will investigate future violations by observing the results of regulatory agencies' investigations on past violations, to reduce punishments for quality cheating (Ma & Hu, 2021).

Apart from all of the above, the fundamental purpose of quality control is to control the potency of herbal medicines, and other scholars have conducted special research on the potency of Chinese herbal medicines. Such as metabolomics has been used as the key technique to differentiate the potency and toxicity of herbs when their components are examined separately or in combination (Han, Sun, Zhang, Yan, & Wang, 2020). By discussing the establishment of a Q-marker system for Chinese herbal medicines, Kang et al. found that the ecological environment will have an impact on the potency of Chinese herbal medicines (Kang, Dou, & Xu, 2019). The current quality control methods of CHM mainly based on chemical composition indicators generally cannot fully reflect the potency of CHM and are hard to correlate with clinical effectiveness and safety. The biological assay inspection of CHM can

better compensate for the shortcomings of current quality control methods (Hui et al., 2021).

In summary, it can be seen that current scholars have carried out relevant research on quality issues in the traditional Chinese medicine industry from multiple perspectives. However, some quality problems of CHM, such as adulteration, low-potency caused by improper preservation, etc., are caused by human factors. By combing the relevant literature, we found that there is a lack of research on this. There are many behavioural game studies in the field of the agricultural supply chain, such as Su et al. established a three-party evolutionary game model composed of farmers, marketers, and consumers to discuss how to ensure the quality of agricultural products under the direct-purchase mode of agricultural merchants and supermarkets (Su, Liu, & Hou, 2018). Therefore, we try to use game thinking to deal with these problems of CHM, a four-dimensional evolutionary game model was established composed of CHM suppliers and TCM manufacturers, and two quality inspection methods: chemical inspection and biological assay inspection, were introduced to solve the problems of unqualified and low potency of CHM, respectively. Based on the two strategies of the original evolutionary game participants, three strategies are respectively added, which is more in line with reality. A four-dimensional hypercube coordinate axis is established to intuitively represent the evolution paths. Furthermore, the existing literature lacks a distinction between unqualified and low-potency CHM in one study. Therefore, we decided to carry out targeted research on this. In this paper, the unqualified phenomenon and low-potency of CHM are taken as research objects at the same time. The chemical inspection and biological assay inspection are applied, respectively, to control the two quality problems. To reduce the inspection costs of TCM manufacturers, a random quality inspection was introduced into the model (Starbird, 2005). We hope to be able to provide a reference for TCM manufacturers to reduce quality inspection costs while ensuring the quality of CHM.

2. Methods

2.1. Model Establishment

2.1.1. Problem Description and Model Assumptions

In the current industry of CHM, when suppliers provide CHM to manufacturers, they must show quality inspection reports of CHM from third-party inspection institutions. When the quality inspection reports indicate that their CHM is qualified, the suppliers are permitted to provide CHM to manufacturers. However, to avoid suppliers providing false quality inspection reports, manufacturers will selectively conduct quality inspections of CHM.

In this paper, multiple behavioural strategies are introduced to establish a four-dimensional evolutionary game model composed of CHM suppliers and TCM manufacturers. The strategies of suppliers are (provide qualified and high-potency CHM, provide qualified but low-potency CHM, provide unqualified CHM), denoted

as (AB, $\bar{A}$B, $\bar{B}$), when the CHM is unqualified, the potency is no longer considered, where A means the strategy of suppliers to provide high-potency CHM, B means the strategy of suppliers to provide qualified CHM, $\bar{A}$ is the supplement of A, and $\bar{B}$ is the supplement of B.

The manufacturers use two quality inspection methods to inspect the CHM: chemical inspection and biological assay inspection. Chemical inspection refers to the use of chemical methods to inspect the corresponding element content to identify whether the CMH has adulteration, staining, illegal weight gain, etc. This method is widely used, and is simple to operate compared to the biological assay inspection method, and the inspection cost is set as C_1. The biological assay inspection is a method that uses the specific experimental design to reflect the potency and safety of medicines by using the biological effects of medicines on the experimental system, to achieve the purpose of evaluating and controlling the potency of CHM. The cost of the biological assay inspection is set as C_2 , and according to *Interpretation of Guidance on Biological Assay of Traditional Chinese Medicine* from *China Food & Drug Administration Magazine* (Hui et al., 2021), we have $(C_1 < C_2)$.

The possible strategies set of manufacturers are (using two inspection methods to inspect all suppliers' CHM, using random inspection of two inspection methods, using chemical random inspection and all the biological assay inspection, using all the chemical inspection and biological assay random inspection), denoted as(MN, $\bar{M}$ $\bar{N}$, $\bar{M}$N, M $\bar{N}$). The randomly selected object in the strategies is suppliers, and the object of quality inspections is the CHM of the suppliers selected. Where M means the strategy of manufacturers to carry out the chemical inspection on all suppliers' CHM. N means the strategy of manufacturers to carry out the biological assay inspection on all suppliers' CHM. $\bar{M}$ means manufacturers will select the suppliers' percentage of β to carry out the chemical inspection on their CHM, $\beta \in [0,1)$. $\bar{N}$ means manufacturers will select the suppliers' percentage of γ to carry the biological assay inspection on their CHM, $\gamma \in [0,1)$, β and γ are independent. However, because of the particularity of CHM, the chemical inspection is difficult to fully reflect the potency of CHM, and the biological assay inspection can not only identify whether CHM is qualified, but also determine whether CHM is high-potency. Therefore, in the actual situation, when manufacturers conduct the biological assay inspection on the CHM provided by all suppliers, they will not conduct the chemical inspection again, that is, strategy MN does not exist, and strategy $\bar{M}$N is equivalent to strategy N. Therefore, the final strategies set of manufacturers are ($\bar{M}$ $\bar{N}$, M $\bar{N}$, N).

The following assumptions were made:

(1) The income of suppliers selling high-potency CHM is D, and the income of manufacturers producing medicines is Q. The medicines produced by using different potency CHM will bring potential benefits and losses to manufacturers (regardless of potency, manufacturers will purchase the CHM for subsequent production activities, so the potential benefits and losses are no longer considered in

the model), so under the same payment, manufacturers will give priority to selecting high-potency CHM.

(2) Manufacturers purchase CHM by bidding, suppliers need to pay a certain security deposit F_1 before bidding (refer to the bidding documents of company Tongrentang Chinese Medicine in China). If some suppliers win the bid, they can provide CHM to manufacturers with qualified inspection reports. In the process of receiving and selectively inspecting the CHM, if the CHM provided by the suppliers is found to be unqualified, that is, the suppliers provide false quality inspection reports, the deposit will be deducted, and the manufacturers refuse to purchase the CHM. If the CHM is qualified or the manufacturers do not perform quality inspections on the CHM, the manufacturers must return the deposit to the suppliers.

(3) In the process of purchasing CHM, the purchasers will first conduct a traits inspection of the CHM. The traits inspection means that the purchasers rely on their experience and relevant theories to identify whether the CHM meets requirements; we have not considered the cost of traits inspection. The CHM with obvious quality problems will be directly returned by the purchasing personnel, so the situation of suppliers providing CHM with obvious quality problems was not considered, and the unqualified CHM mentioned in the model cannot be found by the trait inspection.

(4) The quality assurance Agreement of Guangdong Yifang Pharmaceutical Co., LTD was referred, and based on the reward and punishment mechanism (P. Xu, Li, Yang, & Li, 2022; X. Zhang, Su, & Yuan, 2018), if the CHM is inspected as high-potency, the suppliers can obtain rewards L from manufacturers (such as increasing procurement volume and establishing a long-term cooperative relationship, etc., without additional payment by manufacturers), and if the low-potency CHM is inspected, the price of F_2 will be deducted as punishments. To ensure the motivation of the biological assay inspection behaviour of manufacturers, there is $F_2 > C_2$.

(5) When the chemical inspection and the biological assay inspection exist at the same time, the chemical inspection is performed first, followed by the biological assay inspection. If the unqualified CHM of a supplier is found by the chemical inspection, the biological assay inspection for this supplier's CHM will not be performed.

(6) When a supplier provides unqualified CHM and false quality inspection reports are not found, the additional income is b. When the supplier provides qualified but low-potency CHM is not inspected, the additional income is a. It can be known from the actual situation that $b > a$.

(7) If manufacturers purchase unqualified CMH such as adulteration, staining, illegal weight gain, etc., it will lead to the production of substandard and even harmful to public health of medicines. And the expected punishments for manufacturers from the government is F_3. There are some notations used in the model as shown in Table 1:

Table 1. Notations

Notations	Significance
D	The income of suppliers selling high-potency CHM
b	The additional income of suppliers when the unqualified CHM is not found
a	The additional income of suppliers when the low-potency CHM is not found
Q	The income of manufacturers from the production of medicines
C_1	The cost of the chemical inspection
C_2	The cost of the biological assay inspection
β	The percentage of suppliers that are selected to carry out the chemical inspection on their CHM
γ	The percentage of suppliers are selected to carry out the biological assay inspection on their CHM
F_1	The security deposit is paid by the suppliers before bidding
F_2	The punishments for suppliers if the low-potency CHM is inspected
F_3	The punishments that manufacturers receive from the government
L	The rewards that the suppliers receive from the manufacturers if the high-potency CHM is inspected

2.1.2. Evolutionary game model for the CHM supply chain

In our model, x $(x \in (0,1))$ means the proportion of suppliers who provide qualified CHM B, y $(y \in (0,1))$ means the proportion of suppliers who provide high-potency CHM A, this means that the proportion of suppliers who choose the strategy of AB is xy, the proportion of suppliers who choose the strategy of $\bar{A}B$ is $x\ (1-y)$, and the proportion of suppliers who choose the strategy of $\bar{B}$ is $(1-x)$. And z $(z \in (0,1))$ means the proportion of manufacturers who choose the strategy of M $\bar{N}$, w $(w \in (0,1))$ means the proportion of manufacturers who choose the strategy of N, this means that the proportion of the manufacturers who choose the strategy of $\bar{M}$ $\bar{N}$ is $(1-z-w)$.

The payoff matrix of the model was established as Table 2:

Table 2. The payoff matrix of the model

		Manufacturers		
		$\bar{M}\ \bar{N}\quad 1-z-w$	$M\ \bar{N}\ z$	$N\quad w$
Suppliers	$AB\quad xy$	$D+\gamma L;$ $Q-\beta C_1-\gamma C_2$	$D+\gamma L;$ $Q-C_1-\gamma C_2$	$D+L;$ $Q-C_2$
	$AB\quad x\ (1-y)$	$D+(1-\gamma)a-\gamma F_2;$ $Q-\beta C_1-\gamma C_2+\gamma F_2$	$D+(1-\gamma)a-\gamma F_2;$ $Q-C_1-\gamma C_2+\gamma F_2$	$D-F_2;$ $Q-C_2+F_2$
	$\bar{B}\quad 1-x$	$(D+b)\big(1-(\beta+\gamma(1-\beta))\big)-(\beta+\gamma(1-\beta))F_1;$ $\big(\beta+\gamma(1-\beta)\big)F_1-\beta C_1-\gamma(1-\beta)C_2+(1-(\beta+\gamma(1-\beta)))(Q-F_3)$	$-F_1;$ F_1-C_1	$-F_1;$ F_1-C_2

For a more intuitive analysis of the model, the binary group is introduced to represent the strategies of the two gamers as shown in Table 3. The binary group of manufacturers is recorded as (x,y), and the binary group of suppliers is recorded as (z,w).

Table 3. The payoff matrix of the model

Behavioural strategy	Quaternary group	Suppliers	TCM manufacturers
High potency, The biological assay inspection	(1,1,0,1)	$D+L$	$Q-C_2$
High potency, The chemical inspection	(1,1,1,0)	$D+\gamma L$	$Q-C_1-\gamma C_2$
High potency, Random inspection	(1,1,0,0)	$D+\gamma L$	$Q-\beta C_1-\gamma C_2$
Qualified but low potency, The biological assay inspection	(1,0,0,1)	$D-F_2$	$Q-C_2+F_2$

Behavioural strategy	Quaternary group	Suppliers	TCM manufacturers
Qualified but low potency, The chemical inspection	(1,0,1,0)	$D+(1-\gamma)a-\gamma F_2$	$Q-C_1-\gamma C_2+\gamma F_2$
Qualified but low potency, Random inspection	(1,0,0,0)	$D+(1-\gamma)a-\gamma F_2$	$Q-\beta C_1-\gamma C_2+\gamma F_2$
Adulterated, The biological assay inspection	(0,0,1,1)	$-F_1$	F_1-C_2
Adulterated, The chemical inspection	(0,0,1,0)	$-F_1$	F_1-C_1
Adulterated, Random inspection	(0,0,0,0)	$(D+b)\big(1-(\beta+\gamma(1-\beta))\big)-(\beta+\gamma(1-\beta))F_1$	$\big(\beta+\gamma(1-\beta)\big)F_1-\beta C_1-\gamma(1-\beta)C_2+(1-(\beta+\gamma(1-\beta)))(Q-F_3)$

2.1.3. Equilibrium solution

Calculate the expected benefit of the suppliers based on the payoff matrix.

When suppliers choose the strategy of AB, their benefit is:

$$u_1=(1-z-w)(D+\gamma L)+z(D+\gamma L)+w(D+L) \tag{1}$$

The benefit for suppliers who choose the strategy of $\bar{A}B$ is:

$$u_2=(1-z-w)(D+(1-\gamma)a-\gamma F_2)+z(D+(1-\gamma)a-\gamma F_2)+w(D-F_2) \tag{2}$$

The benefit for suppliers who choose the strategy of $\bar{B}$ is:

$$u_3=(1-z-w)\Big((D+b)\big(1-(\beta+\gamma(1-\beta))\big)-(\beta+\gamma(1-\beta))F_1\Big)+z(-F_1)+w(-F_1) \tag{3}$$

The expected benefit for the suppliers is the following.

$$u=xyu_1+x(1-y)u_2+(1-x)u_3 \tag{4}$$

Since the growth rate of the suppliers' proportion of providing qualified CHM is proportional to the difference between the expected return and the average expected return when the suppliers provide qualified, but low-potency CHM and high-potency CHM. So, from Equation 4, the replication dynamic equation for suppliers to choose B is:

$$\frac{dx}{dt}=\big(xy+x(1-y)\big)\Big(\frac{xy}{xy+x(1-y)}u_1+\frac{x(1-y)}{xy+x(1-y)}u_2-u\Big)=-x(x-1)(((g\beta-g-hy+a+F_2)w+(1-z)(1-\beta)g+yh-F_2-a)\gamma+((g-\beta g+yh-F_2-a)w-(z-1)\beta g+zb+zg-a(y-1)) \tag{5}$$

where, $g = D + b + F_1$, $h = F_2 + L + a$.

The replication dynamic equation for suppliers to choose A is:

$$\frac{dy}{dt} = xy(u_1 - u) = xy((1-xy)(L(\gamma(1-w)+w)+D) - x(1-y)((w-1)(a+F_2)\gamma + a(1-w) - wF_2 + D - (1-x)(1-z-w)\Big((D+b)\big(1-\beta-\gamma(1-\beta)\big) - \big(\beta+\gamma(1-\beta)\big)F_1 - (z+w)F_1\Big) \quad (6)$$

Calculate the expected benefit of the manufacturers based on the payoff matrix.

When manufacturers choose the strategy of $\bar{M}$ $\bar{N}$, their benefit is:

$$v_1 = xy(Q+e-\beta C_1-\gamma C_2) + x(1-y)(Q-e-\beta C_1-\gamma C_2+\gamma F_2) + (1-x)\big(\big(\beta+\gamma(1-\beta)\big)F_1 - \beta C_1 - \gamma(1-\beta)C_2 + (1-(\beta+\gamma(1-\beta)))(Q-F_3)\big) \quad (7)$$

The benefit for manufacturers who choose the strategy of M $\bar{N}$ is:

$$v_2 = xy(Q+e-C_1-\gamma C_2) + x(1-y)(Q-e-C_1-\gamma C_2+\gamma F_2) + (1-x)(F_1-C_1) \quad (8)$$

The benefit for manufacturers who choose the strategy of N is:

$$v_3 = xy(Q+e-C_2) + x(1-y)(Q-e-C_2+F_2) + (1-x)(F_1-C_2) \quad (9)$$

The expected benefit for the manufacturers is:

$$v = (1-z-w)v_1 + zv_2 + wv_3 \quad (10)$$

The replication dynamic equation for the manufacturers to choose M is:

$$\frac{dz}{dt} = z(v_2 - v) = -z(\gamma\Big(x\big(\beta m(w+z-1) + w\big((y-1)F_2 - n\big) + (1-z) + (2-2y)F_2\big)\Big) + (1-\beta)m(w+z-1)) + x(\beta n(1-z-w) + (z-1)n + w(m+(1-y)F_2)) + (\beta m(w+z-1)-w) + (1-z)m) \quad (11)$$

The replication dynamic equation for the manufacturers to choose N is:

$$\frac{dw}{dt} = w(v_3 - v) = -w(\gamma\left(x\begin{pmatrix}\beta(w+z-1)m + & w+1\big((y-1)F_2-n\big)\\ +z\big((2y-2)F_2-n\big) - n + (1-y)F_2\end{pmatrix} + (1-\beta)(w+z-1)m\right) + x\begin{pmatrix}\beta(1-z-w)n\\ +\ w\big((1-y)F_2-n\big) + zn + (y-1)F_2 - n\end{pmatrix} + (\beta(w+z-1)-w)m + (1-z)(n+C_1)\Big) - m + C_2 - F_1 - F_3) \quad (12)$$

where $m = Q + C_2 - F_1 - F_3$, $n = Q - F_1 - F_3$.

Let $\frac{dz}{dt} = 0$, $\frac{dw}{dt} = 0$, $\frac{dx}{dt} = 0$, $\frac{dy}{dt} = 0$, we got the 10 equilibrium points:

$N_1(1,0,0,0)$, $N_2(1,1,0,0)$, $N_3(1,0,1,1)$, $N_4(1,0,0,1)$, $N_5(1,1,0,1)$, $N_6(1,1,1,0)$,

$N_7(x=1, y=\frac{(1-\gamma)F_2+\beta C_1+\gamma C_2-C_2}{(1-\gamma)F_2}, z=0, w=\frac{a-\gamma(L+a+F_2)}{(1-\gamma)(L+a+F_2)})$,

$N_8(x=1, y=\frac{\gamma(Q+C_2-F_1-F_3)-(Q+C_1-F_1-F_3)}{\gamma(Q+C_2-F_1-F_3)-Q+F_1+F_3}, z=\frac{(\gamma-1)(\beta(D+b+F_1)-b)-\gamma(D+L+F_1)}{(1-\gamma)(1-\beta)(D+b+F_1)}, w=0)$,

$N_9(x=\frac{\gamma(\beta-1)(Q+C_2-F_1-F_3)-(Q+C_1-F_1-F_3)+Q+C_2-F_1-F_3}{\gamma(\beta(Q+C_2-F_1-F_3)-Q+F_1+F_3)+(1-\beta)(Q-F_1-F_3)}, y=1, z=0, w=\frac{(1-\gamma)(\beta(D+b+F_1)+\gamma(D+L+B+F_1)-b)}{(1-\gamma)(\beta(D+b+F_1)-D-L-b-F_1)})$,

$N_{10}(x=1, y=\frac{(1+\gamma)F_2+C_1+\gamma C_2-C_2}{(1+\gamma)F_2}, z=\frac{L+F_2}{(1-\gamma)(L+a+F_2)}, w=\frac{a-\gamma(L+a+F_2)}{(1-\gamma)(L+a+F_2)})$.

The Jacobian matrix can be calculated from the above replicated dynamic equations (Huang, He, Chen, & Yang, 2017):

$$\begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} \\ k_{21} & k_{22} & k_{23} & k_{24} \\ k_{31} & k_{32} & k_{33} & k_{34} \\ k_{41} & k_{42} & k_{43} & k_{44} \end{bmatrix} \quad (13)$$

2.2. Analysis of stable strategy and evolution paths

The stable state of each equilibrium point was solved as in Table 4. From the results of the equilibrium points, Proposition 1 was drawn:

Table 4. Local Stability Analysis of Equilibrium Points

Equilibrium Points	Eigenvalues of Jacobian Matrix	conditions of stable equilibrium points
$N_1(1,0,0,0)$	$(\beta-1)C_1-2F_2\gamma$, $(\gamma-1)C_2+(1-\gamma)F_2+\beta C_1$, $\gamma(L+a+F_2)-a$, $(\gamma(\beta(D+b+F_1)-D-b-F_1+a+F_2)-\beta(D+b+F_1)-a+b$	Case 1
$N_2(1,1,0,0)$	$(\beta-1)C_1$, $(\gamma-1)C_2+\beta C_1$, $a-\gamma(L+a+F_2)$, $(\gamma(\beta(D+b+F_1)-D-b-F_1-L)-\beta(D+b+F_1)+b$	Case 2
$N_3(1,0,1,0)$	$(\gamma-1)C_2+(1+\gamma)F_2+C_1$, $2\gamma F_2-(\beta-1)C_1$, $\gamma(L+a+F_2)-a$, $\gamma(a+F_2)-D-F_1-a$	No
$N_4(1,0,0,1)$	$(1-\gamma)C_2-(1+\gamma)F_2-C_1$, $(1-\gamma)C_2-(\gamma-1)F_2-\beta C_1$, $L+F_2$, F_2-D-F_1	No
$N_5(1,1,0,1)$	$(1-\gamma)C_2-C_1$,	No

Equilibrium Points	Eigenvalues of Jacobian Matrix	conditions of stable equilibrium points
	$(1-\gamma)C_2-\beta C_1$, $-L-F_2$, $-L-D-F_1$	
$N_6(1,1,1,0)$	$(1-\beta)C_1$, $(\gamma-1)C_2+C_1$, $a-\gamma(L+a+F_2)$, $-\gamma L-D-F_1$	No
$N_7 \sim N_{10}$	There are positive and negative eigenvalues	Saddle point

Proposition 1: The points $N_1(1,0,0,0)$ and $N_2(1,1,0,0)$ can be stable equilibrium points. In the evolutionary stable state, the evolutionary stable strategy of manufacturers is $\bar{M}$ $\bar{N}$, and strategy B for suppliers cannot become the evolutionary stable strategy.

This Proposition is consistent with the actual situation, when manufacturers adopt any quality inspection, speculators of suppliers will be found. For manufacturers, regardless of the strategy of M $\bar{N}$ or N, they need to pay high inspection costs. So, $\bar{M}$ $\bar{N}$ is undoubtedly the best strategy, which can effectively avoid unqualified CHM, identify the potency of CHM, and control the costs of inspections.

Case 1: $C_2 > \beta C_1 + \gamma C_2$, $\gamma < \frac{a}{L+F_2+a}$, $\beta > \frac{b}{D+F_1+b}$. The local stability analysis of equilibrium points can be obtained (see Table 5), the equilibrium point $N_1(1,0,0,0)$ is the only stable equilibrium point, and the dynamic evolution phase diagram of the system is drawn as Figure 1. In this evolutionary stable state, the evolutionary stable strategy of suppliers is $\bar{A}B$, and the evolutionary stable strategy of manufacturers is $\bar{M}$ $\bar{N}$. The reason for this state may be that manufacturers not only make $\beta > \frac{b}{D+F_1+b}$ by controlling β and F_1, but $\gamma < \frac{a}{L+F_2+a}$ by unadjusted γ, F_2 and L. The percentage of suppliers selected to carry out the biological assay inspection is too low on their CHM to suppliers tend to provide CHM with low-potency. For manufacturers, medicines produced using low-potency CHM may have negative effects, so the evolutionary stable state may be satisfactory, but not optimal.

Case 2: $C_2 > \beta C_1 + \gamma C_2$, $\beta > \frac{b}{D+F_1+b}$, $\gamma > \frac{a}{L+F_2+a}$. The local stability analysis of equilibrium points can be obtained (see Table 6), the equilibrium point $N_2(1,1,0,0)$ is the only stable equilibrium point, and the dynamic evolution phase diagram of the system is drawn as Figure 2. In this evolutionary stable state, the evolutionary stable strategy of suppliers is AB, and the evolutionary stable strategy of manufacturers is $\bar{M}$ $\bar{N}$. This evolutionary stable state is the optimal state, suppliers will provide high-potency CHM, and high inspection costs from manufacturers can be avoided.

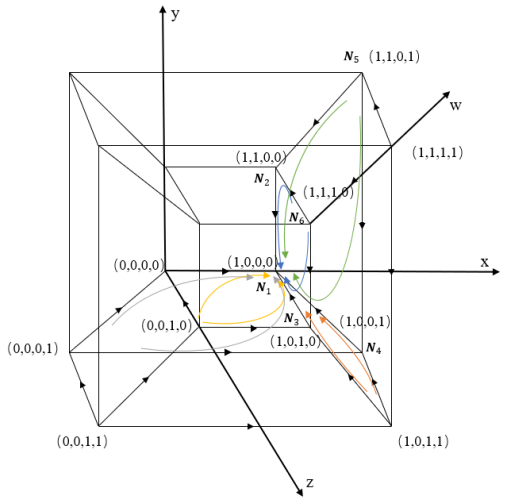

Figure 1. The dynamic evolution phase diagram of Case 1

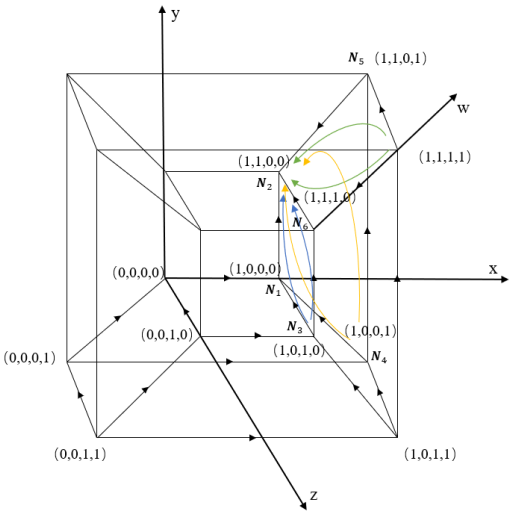

Figure 2. The dynamic evolution phase diagram of Case 2

Proposition 2: When the cost of the $\bar{M}$ $\bar{N}$ strategy of manufacturers is less than the cost of the N strategy, that is, $C_2 > \beta C_1 + \gamma C_2$, $\beta > \frac{b}{D+F_1+b}$, if $\gamma < \frac{a}{L+F_2+a}$, the evolutionary stable strategy is [$\bar{A}$B, $\bar{M}$ $\bar{N}$]; if $\gamma < \frac{a}{L+F_2+a}$, the evolutionary stable strategy is [AB, $\bar{M}$ $\bar{N}$], and the latter is the optimal stable strategy.

Case 3: When $C_2 < \beta C_1 + \gamma C_2$, The local stability analysis of equilibrium points can be obtained. There is no stable equilibrium point and there is no practical significance in management, so no analysis was done.

3. Numerical Simulation

To determine how to make the system evolve to the ideal state under different conditions, and explore the relevant dynamic evolution paths, we used the numerical simulation experiment to analyse the system evolution paths of Case 2. We run the numerical simulation for two reasons: first, numerical simulations provide a quantitative analysis of iteration and interactions of game players' strategies in a more intuitive manner to demonstrate how their strategies evolve in each stage of the quality of CHM under different parameter conditions (Jiang, Wei, Jia, & Ma, 2022). Second, this method can effectively reflect the internal regularity of dynamic changes in the game's strategy when lacking data for empirical analysis (Y. Liu et al., 2022; Yuan et al., 2022). In addition, Wang et al. (2021) proposed that the advantage of the simulation model lies not in how real it is, but in its usefulness in depicting the internal regularity of the changes. Therefore, to make the parameter setting consistent with reality, we refer to market data of Ligusticum chuanxiong in 2019 from China. To facilitate the analysis, the real data is reduced by a factor of ten, such as the parameter D is the income of suppliers selling high-potency CHM, the total cost of planting per mu is 2400 yuan, the income per mu is 3000, so the actual D should be 600, but in the model, $D = 60$. From Case 2 and other parameters, we assumed $\beta = 0.5$, $\gamma = 0.3$, and the assignment results of parameters are shown in Table 5:

Table 5. The assignment of parameters

parameters	value	parameters	value
D	60	F_1	5
b	30	F_2	15
a	6	F_3	50
Q	100	L	10
β	0.5	C_1	5
γ	0.3	C_2	10

Due to the high cost of the biological assay inspection, in reality, manufacturers may not carry out the biological assay inspection on all suppliers' CHM. It means that we assumed that manufacturers choose the initial value of the biological assay inspection $w = 0$ is reasonable in this experiment. The following numerical simulation experiment is carried out by taking the initial value $x = 0.5$, $y = 0.2$, $z = 0.5$, $w = 0$ as an example.

3.1. The influence of γ on the evolutionary stable state

According to Case 2 and Table 5, $\gamma > \frac{a}{L+F_2+a} = 0.19$. First, we took $\gamma = 0.1$, $\gamma = 0.5$, $\gamma = 0.7$ to perform numerical simulation shown as Figure 3, when $\gamma = 0.1$, Case 2 becomes Case 1, the equilibrium point $N_1(1,0,0,0)$ is the stable equilibrium point, which is completely consistent with the model results. When $=$

0.5, $\gamma = 0.7$, the evolutionary result reaches a satisfactory state { $\bar{M}$ $\bar{N}$, AB} for Case 2, which means that TCM manufacturers conduct random inspection of two inspection methods on suppliers selected, excessive quality inspection costs will be avoided. In addition, suppliers tend to provide high potency CHM, to avoid punishments and losses from cheating behaviours.

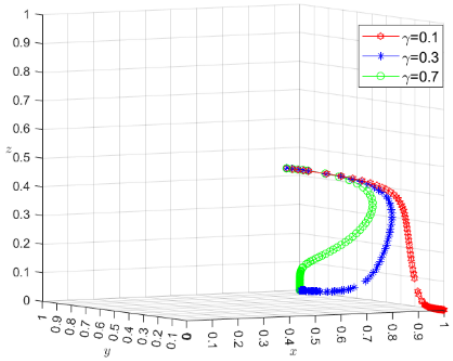

Figure 3. The Evolution paths with different γ

3.2. The influence of β on the evolutionary stable state

According to Case 2 and Table 5, $\beta > \frac{b}{D+F_1+b} = 0.32$, so we took $\beta = 0.4$, $\beta = 0.6$, $\beta = 0.9$, and $\gamma = 0.3$, $x = 0.3$, $y = 0.2$, $z = 0.5$. The evolution paths shown in Figure 4 are consistent with the result of Case 2, with the increase of β, the suppliers evolve faster toward $x = 1$. This means that TCM manufacturers that improve the intensity of chemical inspections can make suppliers more inclined to supply qualified CHM.

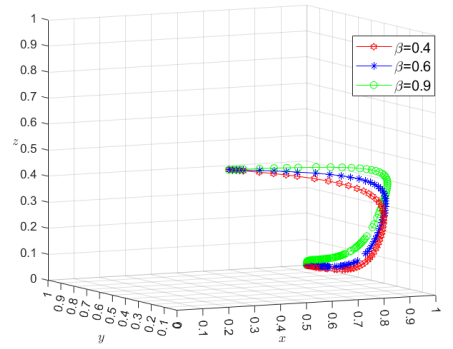

Figure 4. The Evolution paths with different β

Based on the above analysis, we drew Proposition 3.

Proposition 3: Improving the intensity of the chemical inspection is an effective way to reduce the unqualified phenomena of CHM such as adulteration, staining, illegal weight gain, etc., and improving the intensity of the biological assay inspection is an effective way to ensure the potency of CHM.

3.3. The influence of F_1 on the evolutionary stable state

According to Case 2 and Table 5, we took $F_1 = 5$, $F_1 = 15$, and $F_1 = 25$. From Figure 5, we can find that F_1will change the evolution paths of the system, and with the increase of F_1, the suppliers evolve faster toward $x = 1$. It means that increasing F_1 will make suppliers more inclined to provide qualified CHM. So, increasing F_1 is an effective way to ensure the quality of CHM. When the problem of quality cheating behaviours is serious, manufacturers can avoid excessive inspection costs by increasing the security deposit F_1 is paid by the suppliers before bidding, it is an effective way to improve the quality of CHM.

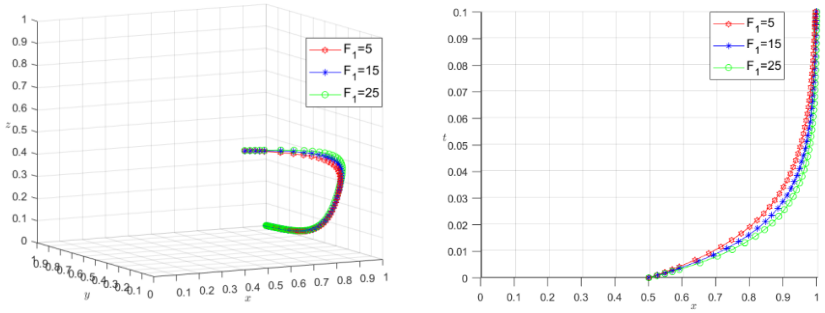

Figure 5. The influence of F_1 on the evolution paths

3.4. The influence of L and F_2 on the evolutionary stable state

To analyse the influence of F_2 on the evolution speed of the strategy of suppliers in Case 2, we took $F_2 = 15, 25$ and 35. From Figure 6, with the increase of F_2, the suppliers evolve faster toward $y = 1$ obviously, it means that TCM manufacturers improve F_2 can make suppliers more inclined to supply high potency CHM. So, increasing F_1 is an effective way to ensure the potency of CHM.

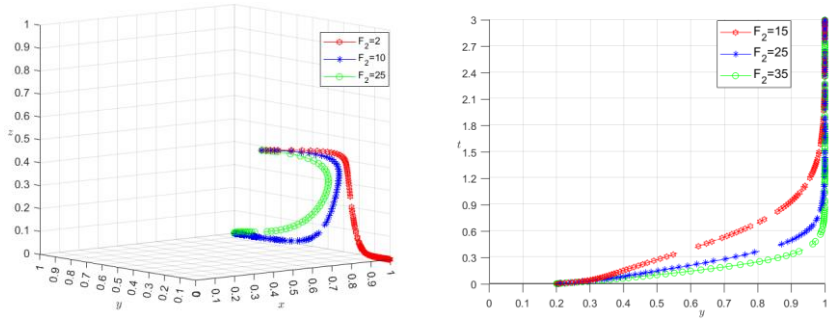

Figure 6. The influence of F_2 on the evolution paths

By analysing the simulation results of parameters F_1, L, F_2, the following Proposition can be drawn.

Proposition 4: With the increase of F_1, L, F_2, the speed of the evolution of the system to the evolutionary stable state will increase, and suppliers will be more inclined to provide qualified and high-potency CHM. Therefore, increasing the rewards and punishments is one of the effective ways to ensure the quality of CHM.

3.5. The influence of F_3 on the evolutionary stable state

According to Case 2 and Table 5, let $F_3 = 50$, 100, and 500. From Figure 7, we can find that F_1 will change the evolution paths of the system, and when F_3 becomes large, the supplier will increase the intensity of chemical inspection. With the increase of F_3, the manufacturer evolves slower toward $z = 0$. When F_3 increases to a certain value such as $F_3 = 500$, the manufacturer evolves toward
$z = 1$ firstly, and then toward $z = 0$. It means that with the increase of the punishments that manufacturers receive from the government, to avoid punishments from the government, manufacturers must increase the intensity of chemical inspection at the beginning of the evolution, and suppliers have to increase the proportion of qualified CHM provided As time goes by, when z reaches its peak, fewer suppliers provide unqualified CHM, manufacturers will reduce the intensity of chemical inspection to control the cost of it.

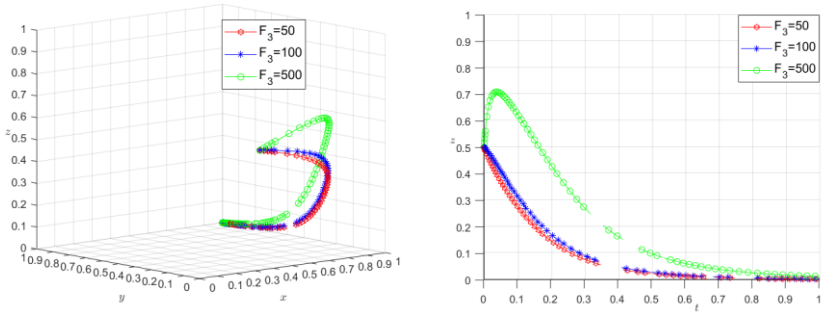

Figure 7. The Evolution paths with different F_3

From Figure 8, we can find that the evolution speed of the supplier to $x = 1$ increases as F_3 increases, it means that the punishments F_3 that manufacturers receive from the government will indirectly affect the evolution speed of suppliers to $x = 1$. Because with the increase of F_3, unqualified CHM may make manufacturers face punishments will increase, on they will improve quality inspection intensity to avoid the punishments. Therefore, manufacturers will evolve slower toward $z = 0$, and suppliers must have a faster evolution speed to $x = 1$.

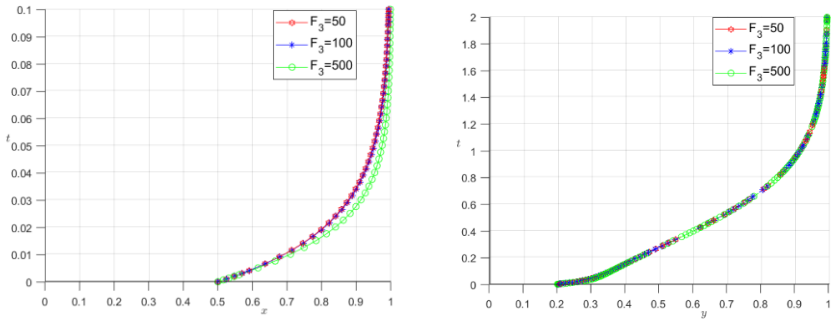

Figure 8. The influence of F_3 on the evolution speed of manufacturers' strategy

Proposition 5: If the government regulators increase the punishments on the manufacturers who produce unqualified medicines, it will force the manufacturer to pay more attention to the quality of CHM. Then, we can observe the increasing proportion of suppliers who provide qualified CHM. However, this cannot motivate suppliers to provide high-potency CHM. Therefore, when the problems of unqualified CHM are serious, the government regulators can deal with the problems by increasing the punishments.

4. Conclusions

To improve the sustainability of the TCM supply chain, we considered the quality cheating behaviours such as providing unqualified or low-potency CHM of CHM suppliers and established a four-dimensional evolutionary game model composed of CHM suppliers and TCM manufacturers. In this model, the influence of chemical inspection and biological assay inspection on the quality of CHM were first analysed. On the basis of ensuring qualified CHM, the potency of CHM was discussed. Then, through numerical simulation, we researched the influence on the evolutionary stable state of γ, β, L, F_1, F_2. Finally, by analysing the influence of exogenous variables on the evolutionary stable state, we think this model has good stability.

Firstly, based on the analysis of this research, the main conclusions are as follows:

(1) When the manufacturers' cost of inspections in the random inspection strategy is less than the cost of inspections in the biological assay inspection strategy, the percentage of suppliers selected to carry out the chemical inspection and biological assay inspection in their CHM is greater than the critical value, suppliers will tend to provide high-potency CHM.

(2) To purchase high-potency CHM, the biological assay inspection is a necessary choice, but to control the cost of inspections, manufacturers should select suppliers randomly and conduct the chemical inspection and biological assay inspection on their CHM at the same time. TCM manufacturers will reach an optimal state: purchasing high-potency CHM at the lowest possible inspection costs.

(3) γ, β, L, F_1, F_2, and F_3 will affect the quality of CHM provided by suppliers, the government regulators and manufacturers can improve the quality of CHM by changing the above parameters.

Secondly, to improve the quality of CHM and the sustainability of the TCM supply chain, the following managerial implications for manufacturers and government regulators can be obtained:

(1) As an internal member of the TCM supply chain, TCM manufacturers can make efforts to improve the sustainability of the TCM supply chain. First, it is an effective quality inspection method to randomly select suppliers and conduct the chemical inspection and biological assay inspection on their CHM at the same time. Second, increasing the intensity of inspection, rewards, and punishments may avoid quality cheating behaviours.

(2) A sustainable TCM supply chain is vital for public health, and as a manager, government regulators should take some measures to ensure its sustainability. Government regulators can increase the punishments for unqualified pharmaceutical manufacturers directly, and indirectly increase the proportion of suppliers who provide qualified CHM, but in this study, they cannot influence whether suppliers provide high-potency CHM.

Finally, this study considers the game between CHM suppliers and TCM manufacturers, and it may be helpful for TCM manufacturers and government regulators to make decisions to deal with the cheating behaviours of CHM suppliers to ensure the quality of CHM. However, this research still has the following limitations and room for further research:

(1) For the government regulators, we only introduced a parameter of the punishments that manufacturers receive from the government as a research object, but changes in government policy may have a significant impact on the system in this study. Therefore, future studies could try to make the government a party to the game to investigate the influence of the government on the quality of CHM in additional detail.

(2) This study does not consider the potential gains from high-potency CHM and the potential losses from low-potency CHM, but these are essential for manufacturers. Therefore, future research can consider the potential gains and losses as new parameters.

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