Jointing quality effort and contract decision in green agri-food supply chain based on differential game

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Abstract

Purpose – The managerial questions of this paper are as follows, and the authors are trying to solve them: How revenue sharing contract (CSR) degree and government subsidy affect the agri-food quality? What kind of model (WPC, revenue-sharing contract [RSC] and cooperative) would be more effective in motivating manufacturers and retailer to increase effort and improve agri-food quality? What kind of model (WPC, RSC and cooperative) would make manufacturer and retailer better off?

Design/methodology/approach – Considering the jointing quality effort and contract decision in green agri-food supply chain, this paper proposes six models that consider CSR of manufacturer and retailer, and then the obtained optimal solutions are compared and analyzed. At the same time, the impact of government subsidies is analyzed, and corresponding conclusions are drawn.

Findings – The results show that, first of all, whether the increasing CSR of the manufacturer or the retailer can motivate both parties to improve the agri-food quality effort investment. Second, the WPC and RSC contract may play different role in different cases. Finally, under the model with government subsidies, regarding positive influence of government subsidies on efforts of manufacturer and retailer, quality and profits of members is investigated. Based on these conclusions, this study puts forward the following policy suggestions. Firstly, governments should formulate reasonable subsidy policies to support manufacturer and retailer to improve the agri-food quality, thereby promoting green industries' development. Secondly, manufacturer and retailer should actively improve CSR and strengthen the effort of agri-food so as to advance quality. Finally, manufacturer and retailer can choose cooperative model or WPC contract.

Research limitations/implications – In this paper, one manufacturer and one retailer are considered. Since the agri-food supply chain structure in reality is more complicated, the future research direction can consider the supply chain structure with one manufacturer and multiple retailers. In addition, this paper only considers the subsidy, and future research can classify the subsidy into different types.

Originality/value – The study makes two substantive contributions to the body of knowledge in the field of sustainable operations:(1) incorporating quality-based demand function in supply chain and dynamic process of agri-food quality; (2) exploring the impact of CSR awareness of members and subsidy of government on agri-food quality, and comparing the influence in different models.

Keywords CSR, Supply chain, Subsidy, Differential game, Agri-food quality

Paper type Research paper

1. Introduction
The increasing demand for high-quality organic food and the requirement for environmental conservation have promoted the development of green agri-food. Green and sustainable development has become critical for the agri-food industry (Mangla *et al.*, 2018). Green agri-food refers to the safe, high-quality agricultural food and the related food produced in a way without any damage to the ecological environment, processed according to the green food standards implemented by the government (He *et al.*, 2018). For example, green agri-food such as corn, organic vegetables and fruits has gradually permeated our lives. Hence, the consumers' perceptions of agri-food quality will affect the price of agri-food and consumers' purchasing decisions (Rana and Paul, 2017).

The quality of agri-food depends on the joint efforts of the entire chain. Generally, the agri-food supply chain consists of one agricultural producer, processing manufacturer, retailer and consumers. In the supply chain operation, every member is engaged in keeping quality activities. The current research mainly focuses on the two echelons in the agri-food supply chain: the manufacturer's decisions in green production and the retailer's decision in keeping fresh and green marketing. On the one hand, manufacturers actively conduct R&D to develop green and high-quality agri-food. On the other hand, the retailers store agri-food in cold storage to keep it fresh. Thus, manufacturers adopt some technologies to design and produce green agri-foods, and retailers make effort to maintain green agri-food.

The agri-food quality is related not only to members' efforts, but also to the corporate social responsibility (CSR) awareness of every member (Li, 2020). With the increasingly serious problems of agri-food quality, all sectors of society are paying more and more attention to CSR. Therefore, members should recognize the importance of CSR awareness in quality improvement. In China, the government encourages firms to ensure green food quality by implementing subsidy policies. Hence, it is necessary to study the issue of green agri-food quality in the supply chain when considering CSR awareness and government subsidy.

Members in a supply chain are primarily interested in maximizing individual profit rather than maximizing the profit of the integrated supply chain. The contracts are commonly used to mitigate such opportunistic behavior and to coordinate the total supply chain more efficiently. Supply chains are often governed by whole price contract (WPC), revenue-sharing contract (RSC) and two-part tariff contract. This paper studies the WPC, RSC and cooperative model to investigate the supply chain coordination. Since the agri-food quality in supply chain demonstrates long-term and dynamic characteristics, we introduce a differential game model, which can describe the dynamic process. The purpose of this paper is to study how supply chain members improve or maintain quality when considering CSR awareness and government subsidy in the long run. We attempt to develop a differential game model composed of one manufacturer and one retailer. By comparing the equilibrium results and performing a numerical simulation in different situations, we obtained relevant research results and provided some practical suggestions for quality in supply chain management from a dynamic perspective.

Based on this discussion, the managerial questions of this paper are as follows: How CSR degree and government subsidy affect the agri-food quality? Which kind of model (WPC, RSC and cooperative) would be more effective in motivating manufacturers and retailers to increase effort and improve agri-food quality? Which kind of model (WPC, RSC and cooperative) would make manufacturer and retailer better off?

Our work makes two substantive contributions to the body of knowledge in the field of sustainable operations: (1) incorporating quality-based demand function in supply chain and dynamic process of agri-food quality, and (2) exploring the impact of CSR awareness of members and subsidy of government on agri-food quality and comparing the influence in different models.

2. Literature review

2.1 Green food supply chain

The first stream of the research is related to the operation of green food supply chain management. The green food supply chain includes the raw material producer, a processor, a distributor, a retailer and consumers (Yadav et al., 2022). Some researches mainly focus on the two echelons: green supply chains, which discusses the manufacturer's decisions in green production, and retailer's promotion of green decisions in sales. Zhu et al. (2018) studied that product demand is affected by green production and green promotion. Hong and Guo (2019) investigated a two-echelon supply chain that consists of a manufacturer and retailer, in which the manufacturer designs and produces a green product, whereas the retailer promotes the green product in their market through green marketing. Giri et al. (2018) indicated that the greenness level hinges on a manufacturer's effort in a green supply chain. Furthermore, several studies have found that retailer's green behavior can motivate consumers' actual purchasing behavior. Andic et al. (2012) investigated the green marketing tools of retailers, such as environmental advertising and consumer environmental education, which can promote the green input and purchase of consumers. These studies have laid the foundation for our study. However, few studies have addressed the dynamics of green foods quality in the process, which is one of the main features in our model.

2.2 CSR and subsidy in supply chain

There are many scholars who have studied the social responsibility management in supply chain. With pressure from society, an increasing number of firms realize to fulfill CSR. The CSR is a corporate behavior in which firms demonstrate their social and moral responsibilities to their stakeholders, realizing corporate social values. Servaes and Tamayo (2013) found that firms actively undertaking social responsibility can obtain greater value. Some researchers further examine the effects of CSR on the benefits of the supply chain. Panda (2014) established a manufacturer-retailer supply chain coordination model and studied the effects of CSR on the profits of the channel members. Liu et al. (2019) discussed a dominant manufacturer with CSR behavior consciousness and a retailer with CSR investment in closed-loop supply chain. The result indicated that both the CSR behavior consciousness of the manufacturer and CSR investment of the retailer can enhance the recycling rate of waste products and improve the performance of members. The research of Liu et al. (2021) shows that the operation mode of two retailers considers CSR investment is the best. And their conclusion indicates that the retailers with CSR investment gain more profits than those without CSR investment. He et al. (2023) design the framework of an omnichannel supply chain system. Their conclusion proves that CSR can reduce emissions and improve the overall supply chain profits.

In order to promote firms to actively fulfill their social responsibility, the government implements subsidy policies. Tang and Chen (2016) used the data of 2010–2014 A-share agricultural listed companies in Shanghai stock market as a sample to empirically examine the impacts of fiscal and tax subsidy on the fulfillment of social responsibility. The paper of Li (2020) investigated the impact of government subsidy on CSR. The results showed that government subsidy can simultaneously increase the enthusiasm of the manufacturer and the retailer to fulfill their social responsibility. The aforementioned literature mainly studies the influencing factors of CSR in supply chain management.

Besides the influence of subsidy on CSR, the impact of subsidy on efforts and profits of members has been investigated. Yang and Xiao (2017) studied how government intervention affects green levels of green products and expected profits. The results showed this can improve the profits of manufacturer and retailer. Lou et al. (2020) studied government green subsidies of the two echelon supply chains and the optimal strategies and problems of manufacturers and retailers. Different from the previous papers, in this paper the impact of CSR on the quality of green food in supply chain is investigated.

2.3 Contract mechanism
The third stream of relevant literature investigates contract types in the supply chain. WPC, revenue-sharing contract (RSC) cost-sharing contract, two-part tariff contract, buy back contract and so on are adopted in the supply chain coordination. Bhaskaran and Krishnan (2009) conceptualized and modeled the revenue, cost and effort-sharing collaborative arrangements between two firms for the optimal joint-development approach when considering various technological and market parameters. Tsao and Sheen (2012) found that the cost-sharing ratio can achieve channel coordination within a certain range and ensure increased profit distribution. A two-part tariff can achieve perfect supply chain coordination (Pfeiffer, 2016). Dai et al. (2017) also showed that cost-sharing contracts can improve the profit of supply chain members and the total profit of supply chain compared with non-cooperative models. Zhang and Yousaf (2020) analyzed green supply chain coordination and further proved that green improvement benefits from the implementation of the two-part tariff contract. The aforementioned studies have proven that the improvement of greenness of supply chain is strongly linked to the cooperation among supply chain members overall.

The revenue-sharing contract is also widely used by firms to mitigate or eliminate the double marginalization problem due to asymmetric information of members. In product greenness and government subsidy area, the revenue-sharing contract also has been adopted. Liu et al. (2019) investigated that a manufacturer and a retailer cooperate to improve product greenness by revenue-sharing and cost-sharing contracts. They found that when a manufacturer acts as the leader of the Stackelberg game, the revenue-sharing contract brings higher product greenness, which makes the manufacturer and the retailer better off. Shao and Liu (2022) examined a complementary product supply chain when considering the consumers' environmental awareness and the green subsidies. Their conclusion indicated that compared to wholesale price contracts, revenue-sharing contract motivates manufacturer to improve the greenness of subsidized products and a Pareto improvement for the whole supply chain and its members.

3. Method
3.1 Problem description and assumptions
To fully and quickly promote sales, many manufacturers have launched their own online stores during the last decade – the offline and online channel is becoming increasingly popular. Research on dual-channel supply chain considers that a traditional offline and an online channel coexist. The offline channel is based on the traditional retail purchasing system, while the customers also directly purchase the food online from the manufacturers.

This paper builds a dual-channel supply chain consisting of a manufacturer and a retailer. Manufacturer's decision variables include quality effort level $M(t)$ and wholesale price $w(t)$. The retailer's decision variables are quality effort level $R(t)$ and retail price $p(t)$. The definition of related parameters is shown in Table 1.

To ensure the real solution, we assume λ lie in the intervals $\left(0, \frac{1}{4}\right)$, $\left(\frac{1}{4}, \frac{1}{2}\right)$, $\left(\frac{1}{2}, \frac{2}{3}\right)$

The differential game model is formulated under the following assumptions.

Assumption 1. The efforts of manufacturers and retailers collectively affect the quality, but with the fresh degree deterioration and depreciation of agri-food, a natural decline will occur. Drawing on the research of El Ouardighi (2014), this paper assumes that the higher level of CSR of the manufacturer and the retailer can enhance agri-food quality. Hence, the differential equation for agri-food quality over time:

$$\dot{q(t)} = (1 + \theta_1)M(t) + (1 + \theta_2)R(t) - \varphi q(t), q(0) = q_0 \geq 0 \tag{1}$$

Parameter	Definition
$M(t)$	Quality effort level of manufacturer at time t
$R(t)$	Quality effort level of retailer at time t
$q(t)$	Food quality at time t
$w(t)$	Manufacturer's wholesale price to retailer at time t
$p(t)$	Food retail price at time t
$\varphi > 0$	Natural decay rate of quality
$\theta_1 \in (0,1)$	Level of CSR for manufacturer
$\theta_2 \in (0,1)$	Level of CSR for retailer
$D(t)$	Sales function
a	The potential number of consumers in the market
b	Price sensitivity factor of consumers
λ	Proportion of offline consumers
$\rho > 0$	Discount factor
V_m	Manufacturer's revenue function
V_r	Retailer's revenue function
V_t	Total revenue function of supply chain

Source(s): Authors' own work

Table 1.
Parameter description

Assumption 2. The market demand is determined by the price, the quality and the level of CSR. The demand function in this paper takes the form of separable multiplication. In the demand function, demand (1) decreases linearly with increasing retail price, and increases linearly with increasing agri-food quality; (2) increases linearly with the sum of the CSR levels of manufacturer and retailer; (3) The proportion of offline consumers' potential purchasing power in the market is λ (He *et al.*, 2018). Hence, the demand function of offline and online are:

$$D_{off} = q(\lambda a - bp)(1 + \theta), D_{on} = [(1 - \lambda)a - bp](1 + \theta), \theta = \frac{\theta_1 + \theta_2}{2} \qquad (2)$$

Assumption 3. High-quality agri-food inevitably attracts more customers, but this is also accompanied by better food design and higher production costs for these goods. This article assumes that manufacturer and retailer's quality effort cost is a convex function of the level of quality effort:

$$C_m(t) = \frac{M(t)^2}{2}, C_r(t) = \frac{R(t)^2}{2} \qquad (3)$$

Assumption 4. The manufacturer and the retailer have the same discount factor $\rho(\rho > 0)$.

3.2 Model construction and solution

Since agri-food improvement is a long-term dynamic process, it is useful to introduce a dynamic framework into the research. Therefore, we use the differential game to solve the equilibrium strategy based on the assumption that the manufacturer and the retailer seek to maximize profit in the long run, considering the effects of CSR and subsidy. To better

compare the different decision-making modes in the game, we further compare and analyze the equilibrium strategies of the manufacturer and the retailer under the WPC model without (with) subsidy, RSC model without (with) subsidy and cooperative model without (with) subsidy. Then, the paper analyzes whether the RSC or cooperation can help the optimal decision of the manufacture and the retailer achieve a Pareto improvement. The effect subsidy on the efforts and quality also is investigated. For convenience in writing and understanding, time t is omitted in the next section of analysis.

W superscript is used to indicate the relevant variables in the WPC model without subsidy

R superscript is used to indicate the relevant variables in the RSC model without subsidy

C superscript is used to indicate the relevant variables in the cooperative model without subsidy

WS superscript is used to indicate the relevant variables in the WPC model with subsidy

RS superscript is used to indicate the relevant variables in the RSC model with subsidy

CS superscript is used to indicate the relevant variables in the cooperative model with subsidy

3.2.1 WPC model without subsidy. In the WPC model, the manufacturer sells the agri-food to the retailer at the wholesale price w, and the retailer sells it to the consumer at the price p. The manufacturer also sells online through direct channel at price p. The objective functions of the manufacturer and retailer are as follows:

$$\max_{M,w} V_m^W(q) = \int_0^\infty e^{-\rho t}\left\{wp(\lambda a - bp)(1+\theta) + pq[(1-\lambda)a - bp](1+\theta) - \frac{M^2}{2}\right\}dt \quad (4)$$

$$\max_{R,p} V_r^W(q) = \int_0^\infty e^{-\rho t}\left[(p-w)q(\lambda a - bp)(1+\theta) - \frac{R^2}{2}\right]dt \quad (5)$$

P1. Under the WPC model without subsidy, the optimal feedback equilibrium strategies of the manufacturer and the retail are shown:

(1)   The quality efforts of the two parties and the optimal equilibrium strategies of the wholesale price and retail price are:

$$M^W = \frac{a^2\left(4\lambda - 8\lambda^2 + 1\right)(1+\theta)(1+\theta_1)}{12b(\varphi + \rho)}, w^W = \frac{(1-\lambda)a}{3b} \quad (6)$$

$$R^W = \frac{a^2(4\lambda - 1)^2(1+\theta)(1+\theta_2)}{36b(\varphi + \rho)}, p^W = \frac{(1+2\lambda)a}{6b} \quad (7)$$

The proportion of offline consumers, the potential number of consumers in the market, the price sensitivity factor of consumers and the CSR of the manufacturer or the retailer affect the quality effort of the manufacturer and the retailer.

From proposition 1(i), both the quality efforts of the manufacturer and the retailer increase as the CSR of the manufacturer or the retailer increases. The retail price increases as the proportion of offline consumers increases.

(2)   The optimal trajectory equation of agri-food quality is:

$$q^W(t) = q_{SS}^W + \left(q_0 - q_{SS}^W\right)e^{-\varphi t} \quad (8)$$

Among them, $q_{SS}^W = \frac{a^2(1+\theta)[3(1+\theta_1)^2(4\lambda-8\lambda^2+1)+(1+\theta_2)^2(4\lambda-1)^2]}{36b\varphi(\varphi+\rho)}$ is the stable value of food quality $(t \to \infty)$.

Proposition 1(ii) implies that the agri-food quality converges to the steady-state q_{SS}^W when time t approaches positive infinity. When the initial value of quality is above the steady-state quality, a longer operational horizon leads the members to lower the CSR, causing decrease in quality. When the quality is lower than the steady-state quality, the members tend to increase CSR. Thus, the quality significantly increases.

(3) The profits of manufacturer and retailer can be calculated as follows:

$$V_r^W(q) = \frac{a^2(4\lambda-1)^2(1+\theta)}{36b(\varphi+\rho)}q_0 + a^4(1+\theta)^2 \left\{ \frac{\left[(1+\theta_2)^2(4\lambda-1)^4\right]}{2592b^2(\rho+\varphi)^2\rho} + \frac{6(1+\theta_1)^2(4\lambda-1)^2(4\lambda-8\lambda^2+1)}{2592b^2(\rho+\varphi)^2\rho} \right\} \quad (9)$$

$$V_m^W(q) = \frac{a^2(4\lambda-8\lambda^2+1)(1+\theta)}{12b(\varphi+\rho)}q_0 + a^4(1+\theta)^2 \left\{ \frac{3(1+\theta_1)^2(4\lambda-8\lambda^2+1)^2}{864b^2(\rho+\varphi)^2\rho} + \frac{2(1+\theta_2)^2(4\lambda-1)^2(4\lambda-8\lambda^2+1)}{864b^2(\rho+\varphi)^2\rho} \right\} \quad (10)$$

3.2.2 RSC model without subsidy. Some manufacturers supply their fresh organic agricultural food to retailers at a zero wholesale price and receive compensation in the forms of revenue-sharing payment. Based on the research of El Ouardighi (2014), we set whole price w = 0. In the RSC model, the retailer shares the revenue with the manufacturer in the ratio $\tau(0 < \tau < 1)$, and its revenue is $1 - \tau$.

$$\max_{M,w} V_m^W(q) = \int_0^\infty e^{-\rho t}\left\{ pq[(1-\lambda)a - bp](1+\theta) + (1-\tau)pq(\lambda a - bp)(1+\theta) - \frac{M^2}{2} \right\} dt \quad (11)$$

$$\max_{R,p} V_r^R(q) = \int_0^\infty e^{-\rho t}\left\{ \tau pq(\lambda a - bp)(1+\theta) - \frac{R^2}{2} \right\} dt \quad (12)$$

P2. Under the RSC model without subsidy, the optimal feedback equilibrium strategies of the manufacturer and the retail are shown:

(1) The quality efforts of the two parties and the optimal equilibrium strategies of the retail price are:

$$M^R = \frac{a^2[2\lambda - (2+\tau)\lambda^2](1+\theta)(1+\theta_1)}{4b(\varphi+\rho)} \quad (13)$$

$$R^R = \frac{a^2\lambda^2\tau(1+\theta)(1+\theta_2)}{4b(\varphi+\rho)}, p^R = \frac{\lambda a}{2b} \quad (14)$$

Proposition 2 is similar to proposition 1, which indicates that the quality efforts of both the manufacturer and the retailer increase as the CSR of the manufacturer or the retailer increases. We will compare the difference of impact of CSR on quality in the two models in the section of numerical analysis. Different from the proposition 1, the quality effort of the retailer increases as the ratio τ increases. On the contrary, the quality effort of the manufacturer decreases as the ratio τ increases.

(1) The optimal trajectory equation of agri-food quality is:

$$q^R(t) = q^R_{SS} + \left(q_0 - q^R_{SS}\right)e^{-\varphi t} \tag{15}$$

Among them, $q^R_{SS} = \frac{a^2(1+\theta)\{[2\lambda-(2+\tau)\lambda^2](1+\theta_1)^2+\lambda^2\tau(1+\theta_2)^2\}}{4b\varphi(\varphi+\rho)}$ is the steady state $(t \to \infty)$.

Proposition 2(ii) also implies that the agri-food quality converges to the steady-state q^R_{SS} when time t approaches positive infinity.

(1) The profits of manufacturer and retailer can be calculated as follows:

$$V^R_r(q) = \frac{a^2(1+\theta)\lambda^2\tau}{4b(\varphi+\rho)}q_0 + \frac{a^4(1+\theta)^2\lambda^2\tau\left\{2[2\lambda-(2+\tau)\lambda^2](1+\theta_1)^2+\lambda^2\tau(1+\theta_2)^2\right\}}{32b^2(\varphi+\rho)^2\rho}$$

$$\tag{16}$$

$$V^R_m(q) = \frac{a^2(1+\theta)[2\lambda-(2+\tau)\lambda^2]}{4b(\varphi+\rho)}q_0 + \frac{a^4(1+\theta)^2[2\lambda-(2+\tau)\lambda^2]}{32b^2(\varphi+\rho)^2\rho}.$$

$$\tag{17}$$

$$\frac{\left\{[2\lambda-(2+\tau)\lambda^2](1+\theta_1)^2+2\lambda^2\tau(1+\theta_2)^2\right\}}{32b^2(\varphi+\rho)^2\rho}$$

3.2.3 Cooperative model. Under cooperative strategy, the manufacturer and the retailer aim to maximize the overall benefits of the supply chain. The overall revenue of the supply chain is:

$$\max_{M,R,p}V^C(q) = \int_0^\infty e^{-\rho t}\left\{pq(a-2bp)(1+\theta)-\frac{M^2}{2}-\frac{R^2}{2}\right\}dt \tag{18}$$

P3. Under the cooperative model without subsidy, the optimal feedback equilibrium strategies of the manufacturer and the retail are shown:

(1) The quality efforts of the two parties and the optimal equilibrium strategies of the retail price are:

$$M^C = \frac{a^2(1+\theta)(1+\theta_1)}{8b(\varphi+\rho)}, R^C = \frac{a^2(1+\theta)(1+\theta_2)}{8b(\varphi+\rho)}, P^C = \frac{a}{4b} \tag{19}$$

(2) The optimal trajectory equation of agri-food quality is:

$$q^C(t) = q^C_{SS} + \left(q_0 - q^C_{SS}\right)e^{-\varphi t} \tag{20}$$

Among them, $q^C_{SS} = \frac{a^2(1+\theta)[(1+\theta_1)^2+(1+\theta_2)^2]}{8b(\varphi+\rho)\varphi}$ is the stable value of the quality of agri-food under centralized decision-making $(t \to \infty)$.

In the cooperative model, the conclusion is similar to it in the WPC or RSC model. But the retail price is independent of λ, which means that the proportion of offline consumers has on impact on the retail price in cooperative model. This result implies that the members do not need to consider the proportion of offline consumers when setting the wholesale price.

$$V^C = \left[\frac{a^2(1+\theta)}{8b(\varphi+\rho)}\right]q_0 + \frac{a^4(1+\theta)^2\left[(1+\theta_1)^2 + (1+\theta_2)^2\right]}{128b^2(\varphi+\rho)^2\rho} \tag{21}$$

(1) The profit supply chain can be calculated as follows:

3.2.4 WPC model with government subsidy. The objective function of manufacturer is:

$$\max_{M,w} V_m^{WS}(q) = \int_0^\infty e^{-\rho t}\left[wq(\lambda a - bp)(1+\theta) + pq(1-\lambda)(a-bp)(1+\theta) - \frac{(1-\eta_m^{WS})M^2}{2}\right]dt \tag{22}$$

The objective function of retailer is:

$$\max_{R,p} V_r^{WS}(q) = \int_0^\infty e^{-\rho t}\left[(p-w)q(\lambda a - bp)(1+\theta) - \frac{(1-\eta_r^{WS})R^2}{2}\right]dt \tag{23}$$

In this research, the manufacturer and the retailer are participants, so the revenue of government is total profits minus cost. The objective function of the government is:

$$\max_{\eta_m,\eta_r} V_G^{WS}(q) = \int_0^\infty e^{-\rho t}\left[pq(a-2bp)(1+\theta) - \frac{M^2}{2} - \frac{R^2}{2}\right]dt \tag{24}$$

P4. Under the WPC model with subsidy, the optimal feedback equilibrium strategies of the manufacturer and the retail are shown:

$$M^{WS} = \frac{a^2(4\lambda - 8\lambda^2 + 1)(1+\theta)(1+\theta_1)}{12b(\varphi+\rho)(1-\eta_m^{WS})} \tag{25}$$

$$w^{WS} = \frac{a(1-\lambda)}{3b}, \eta_m^{WS} = 1 - \frac{3(4\lambda - 8\lambda^2 + 1)}{4(\lambda - 2\lambda^2 + 1)} \tag{26}$$

$$R^{WS} = \frac{a^2(4\lambda - 1)^2(1+\theta)(1+\theta_2)}{36b(\varphi+\rho)(1-\eta_r^{WS})} \tag{27}$$

$$p^{WS} = \frac{a(1+2\lambda)}{6b}, \eta_r^{WS} = \frac{3(4\lambda - 8\lambda^2 + 1)}{4(\lambda - 2\lambda^2 + 1)} \tag{28}$$

(1) The quality efforts of the two parties, the optimal equilibrium strategies of the whole price and retail price and the ratios of subsidizing to manufacturer and retailer are:

Proposition 4 indicates that the quality of the manufacture (retailer) increases as the subsidy coefficient of the manufacturer (retailer) increases.

(2) The optimal trajectory equation of agri-food quality is:

$$q^{WS}(t) = q_{SS}^{WS} + (q_0 - q_{SS}^{WS})e^{-\varphi t} \tag{29}$$

$$q_{SS}^{WS} = \frac{a^2(1+\theta)\left[3(1-\eta_r^{WS})(4\lambda-8\lambda^2+1)(1+\theta_1)^2 + (1-\eta_m^{WS})(4\lambda-1)^2(1+\theta_2)^2\right]}{36b\varphi(\varphi+\rho)(1-\eta_m^{WS})(1-\eta_r^{WS})} \tag{30}$$

(3) The profits of manufacturer, retailer and supply chain can be calculated as follows:

$$V_m^{WS}(q) = \frac{(4\lambda-8\lambda^2+1)a^2(1+\theta)}{12b(\varphi+\rho)}q_0 + \frac{1}{\rho}\left[\frac{(1+\theta_1)^2 m_{s1}^2}{2(1-\eta_m^{WS})} + \frac{(1+\theta_2)^2 m_{s1}r_{s1}}{(1-\eta_r^{WS})}\right] \tag{31}$$

$$V_r^{WS}(q) = \frac{(4\lambda-1)^2 a^2(1+\theta)}{36b(\varphi+\rho)}q_0 + \frac{1}{\rho}\left[\frac{(1+\theta_2)^2 r_{s1}^2}{2(1-\eta_r^{WS})} + \frac{(1+\theta_1)^2 m_{s1}r_{s1}}{(1-\eta_m^{WS})}\right] \tag{32}$$

3.2.5 RSC model with government subsidy. In RSC model, the retailer shares the revenue with the manufacturer in the ratio $\tau_s(0 < \tau_s < 1)$, and its revenue is $1 - \tau_s$. Based on the research of El Ouardighi (2014), we set whole price as $\omega = 0$.

The objective function of the manufacturer is:

$$\max_{M,w} V_m^{RS}(q) = \int_0^\infty e^{-\rho t}\left\{\begin{array}{l} pq[(1-\lambda)a - bp](1+\theta) + \\[2mm] (1-\tau_s)pq(\lambda a - bp)(1+\theta) - \dfrac{(1-\eta_m^{RS})M^2}{2}\end{array}\right\}dt \tag{33}$$

$$= \int_0^\infty e^{-\rho t}\left[pq(a-2bp)(1+\theta) - \tau_s pq(\lambda a - bp)(1+\theta) - \frac{(1-\eta_m^{RS})M^2}{2}\right]dt$$

The objective function of the retailer is:

$$\max_{R,p} V_r^{RS}(q) = \int_0^\infty e^{-\rho t}\left[\tau_s pq(\lambda a - bp)(1+\theta) - \frac{(1-\eta_r^{RS})R^2}{2}\right]dt \tag{34}$$

The objective function of the government is:

$$\max_{\eta_m,\eta_r} V_G^{RS}(q) = \int_0^\infty e^{-\rho t}\left[pq(a-2bp)(1+\theta) - \frac{M^2}{2} - \frac{R^2}{2}\right]dt \tag{35}$$

P5. Under the RSC model with subsidy, the optimal feedback equilibrium strategies of the manufacturer and the retail are shown:

(1) The quality efforts of the two parties, the optimal equilibrium strategies of the retail price and the ratios of subsidizing to manufacturer and retailer are:

$$M^{RS} = \frac{a^2\left[2\lambda - (2+\tau_s)\lambda^2\right](1+\theta)(1+\theta_1)}{4b(\varphi+\rho)(1-\eta_m^{RS})}, \eta_m^{RS} = \frac{\tau_s\lambda}{2(1-\lambda)} \tag{36}$$

$$R^{RS} = \frac{a^2\tau_s\lambda^2(1+\theta)(1+\theta_2)}{4b(\varphi+\rho)(1-\eta_r^{RS})}, p^d = \frac{\lambda a}{2b}, \eta_r^{RS} = 1 - \frac{\tau_s\lambda}{2(1-\lambda)} \tag{37}$$

Different from the proposition 4, the ratio τ_s has the influence on the quality effort of the manufacturer and the retailer.

(2) The optimal trajectory equation of agri-food quality is:

$$q^{RS}(t) = q^{RS}_{SS} + \left(q_0 - q^{RS}_{SS}\right)e^{-\varphi t} \tag{38}$$

Among them, $q^{RS}_{SS} = \frac{a^2(1+\theta)\{[2\lambda - (2+\tau_s)\lambda^2](1-\eta_r)(1+\theta_1)^2 + \tau_s\lambda^2(1-\eta_m)(1+\theta_2)^2\}}{4b\varphi(\varphi+\rho)(1-\eta_m)(1-\eta_r)}$ is the steady state $(t \to \infty)$.

(3) The profits of manufacturer, retailer and supply chain can be calculated as follows:

$$V^{RS}_m(q) = \frac{a^2(1+\theta)\left[2\lambda - (2+\tau)\lambda^2\right]}{4b(\varphi+\rho)}q_0 + a^4(1+\theta)^2\left[2\lambda - (2+\tau)\lambda^2\right] \cdot$$

$$\left\{\frac{\left[2\lambda - (2+\tau)\lambda^2\right](1-\eta_r)(1+\theta_1)^2 + 2\lambda^2\tau(1-\eta_m)(1+\theta_2)^2}{32b^2(\varphi+\rho)^2(1-\eta_r)(1-\eta_m)\rho}\right\} \tag{39}$$

$$V^{RS}_r(q) = \frac{a^2(1+\theta)\lambda^2\tau}{4b(\varphi+\rho)}q_0 + a^4(1+\theta)^2\lambda^2\tau \cdot$$

$$\left\{\frac{2\left[2\lambda - (2+\tau)\lambda^2\right](1-\eta_r)(1+\theta_1)^2 + \lambda^2\tau(1-\eta_m)(1+\theta_2)^2}{32b^2(\varphi+\rho)^2(1-\eta_r)(1-\eta_m)\rho}\right\} \tag{40}$$

3.2.6 Cooperative model with government subsidy.

$$\max_{M,R,p} V^{CS}(q) = \int_0^\infty e^{-\rho t}\left[pq(a-2bp)(1+\theta) - \frac{(1-\eta^{CS}_m)M^2}{2} - \frac{(1-\eta^{CS}_r)R^2}{2}\right]dt \tag{41}$$

$$\max_{\eta_m,\eta_r} V^{CS}_G(q) = \int_0^\infty e^{-\rho t}\left[pq(a-2bp)(1+\theta) - \frac{M^2}{2} - \frac{R^2}{2}\right]dt \tag{42}$$

(1) The quality efforts of the two parties, the optimal equilibrium strategies of the retail price and the ratios of subsidizing to manufacturer and retailer are:

$$M^{CS} = \frac{a^2(1+\theta)(1+\theta_1)}{8b(\varphi+\rho)\left(1-\eta^{CS}_m\right)}, R^{CS} = \frac{a^2(1+\theta)(1+\theta_2)}{8b(\varphi+\rho)\left(1-\eta^{CS}_m\right)} \tag{43}$$

$$p^{CS} = \frac{a}{4b}, \eta^{CS}_m = \eta^{CS}_r = 0 \tag{44}$$

In the cooperative model with government subsidy, the optimal subsidy coefficient is zero. In the cooperative model, the profit of the manufacturer or the retailer is the best. The government needs not to subsidize the manufacturer or the retailer.

(2) The optimal trajectory equation of agri-food quality is:

$$q^{CS}(t) = q^{CS}_{SS} + \left(q_0 - q^{CS}_{SS}\right)e^{-\varphi t} \tag{45}$$

$$q_{SS}^{CS} = \frac{a^2(1+\theta)\left[(1+\theta_1)^2(1-\eta_r^C) + (1+\theta_2)^2(1-\eta_m^C)\right]}{8b\varphi(\varphi+\rho)(1-\eta_r^C)(1-\eta_m^C)} \tag{46}$$

(3) The profit of supply chain can be calculated as follows:

$$V^{CS}(q) = \frac{a^2(1+\theta)}{4b(\varphi+\rho)}q_0 + \frac{a^4(1+\theta)^2\left[(1+\theta_1)^2 + (1+\theta_2)^2\right]}{128b^2(\varphi+\rho)^2\rho} \tag{47}$$

3.3 Model comparison and parameter analysis

Corollary 1. The comparison and analysis of the optimal solution of efforts of the manufacturer and the retailer in the three models with and without government subsidies are as follows:

$$M^{WS} > M^W, M^{RS} > M^R, M^{CS} > M^C$$

$$R^{WS} > R^W, R^{RS} > R^R, R^{CS} > R^C$$

$$M^C = R^C, M^{CS} = R^{CS} \text{ when } \eta_m^C = \eta_r^C = \frac{1}{2}$$

From corollary 1, it can be known that, first of all, compared to model without government subsidies, under the model with government subsidies, the efforts of manufacturer and retailer are higher. When $\eta_m^C = \eta_r^C = \frac{1}{2}$, in cooperative model without subsidy or with subsidy, the effort of manufacturer is equal to the effort of the retailer.

Corollary 2. The comparison and analysis of influencing degree of CSR of the manufacturer and the retailer on agri-food quality.

In WPC model, when $\lambda < 1/2$, $\frac{\partial q_{SS}^W}{\partial\theta_1} > \frac{\partial q_{SS}^W}{\partial\theta_2} > 0$, it can be seen that the impacting degree of the manufacturer's CSR on quality is greater than that of the retailer's CSR. In the RSC model, when $\tau = 1/2$, $\lambda < 1/2$, $\frac{\partial q_{SS}^R}{\partial\theta_1} > \frac{\partial q_{SS}^R}{\partial\theta_2} > 0$, it can be seen that the impacting degree of the manufacturer's CSR on quality is greater than that of the retailer's CSR. In cooperative model, $\frac{\partial q_{SS}^C}{\partial\theta_1} = \frac{\partial q_{SS}^C}{\partial\theta_2} > 0$, it is learned that the manufacturer's CSR and retailer's CSR have the same effect on the quality level.

Corollary 3. The influence of CSR of the manufacturer and the retailer on effort in models without subsidy.

In the WPC model, when $\theta_1 = \theta_2$, $\lambda < 5/12$, $\frac{\partial M^W}{\partial\theta_1} > \frac{\partial M^W}{\partial\theta_2}$, $\frac{\partial R^W}{\partial\theta_1} > \frac{\partial R^W}{\partial\theta_2}$, the influencing effect of the manufacturer's CSR on manufacturer's effort is greater than that of retailer's CSR on manufacturer's effort. The influencing effect of the manufacturer's CSR on retailer's effort is greater than that of retailer's CSR on retailer's effort. In the RSC model, when $\theta_1 = \theta_2$, $\lambda < 2/3$, $\tau = 1/2$, $\frac{\partial M^W}{\partial\theta_1} > \frac{\partial M^W}{\partial\theta_2}$, $\frac{\partial R^W}{\partial\theta_1} > \frac{\partial R^W}{\partial\theta_2}$. In the cooperative model, when $\theta_1 = \theta_2$, $\frac{\partial M^C}{\partial\theta_1} = \frac{\partial M^C}{\partial\theta_2}$, $\frac{\partial R^C}{\partial\theta_1} = \frac{\partial R^C}{\partial\theta_2}$, it is learned that the manufacturer's CSR and the retailer's CSR have the same effect on the effort of manufacturer and retailer.

4. Numerical analysis

In the previous paragraphs, the optimal effort and pricing decisions of agri-food with and without government subsidies under three models are studied separately. By comparing and analyzing the optimal solutions of the different models and studying the influence of parameters on decision variables, some important conclusions are drawn. Next, the correctness of relevant conclusions is verified by assigning parameters in the model. With reference to the setting of related parameters in the literature and the data obtained from the survey of China's agri-food industries, each parameter and its assignment are as follows: $a= 100, b= 5, \varphi= 0.1, \rho= 0.2, \tau= 0.5, \tau_s= 0.5$.
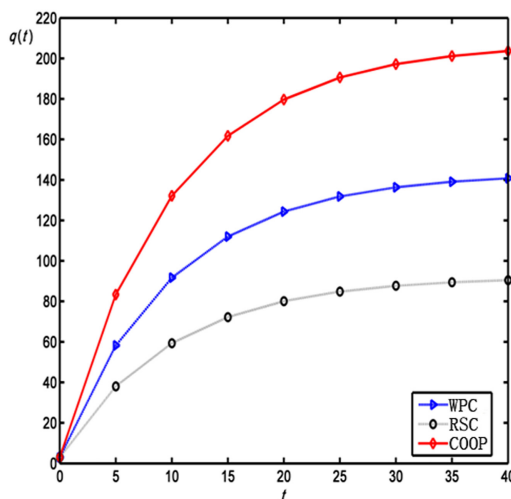
4.1 Numerical comparison of the dynamic trajectory of agri-food quality in different models

Figures 1 and 2 show that agri-food quality tends to reach a steady state when t approaches infinity. From Figures 1 and 2, in three models, whether or not considering the subsidy, the agri-food quality in cooperative model is the highest. The agri-food quality in WPC model is higher than that in RSC model. The result implies that subsidy can enhance the food quality in three models. Furthermore, the members should preferentially choose the WPC.

4.2 Impact of CSR on the effort of manufacturer and retailer

To test the influence of the proportion of offline consumers, $\lambda = 0.4$ and $\lambda = 0.6$ are also considered in the model. Every figure (a) shows the situation when $\lambda = 0.4$, and every figure (b) shows the situation when $\lambda = 0.6$.
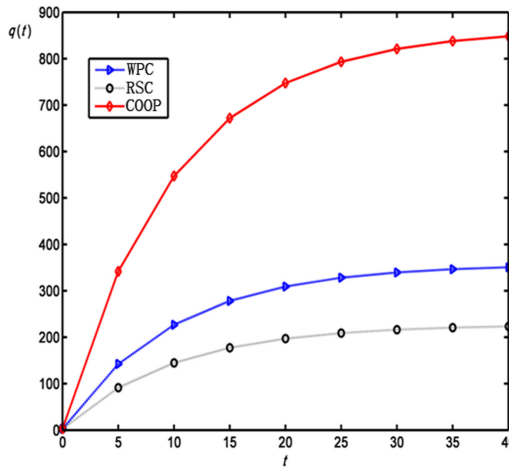
Figures 3(a) and 3(b) show that in WPC model without subsidy, as the CSR of the manufacturer and the retailer increases, the agri-food effort of manufacturer and retailer gradually increases. Figure 3(a) shows that the agri-food effort of the manufacturer is higher than that of the retailer when the λ (proportion of offline consumers) is 0.4. Figure 3(b) shows that when the λ (proportion of offline consumers) is 0.6 (over 50%), considering the most cases of CSR, the agri-food effort of the manufacturer is lower than that of the retailer. In small zones, the agri-food effort of the manufacturer is higher than that of the retailer. As shown in

Source(s): Authors' own work

Source(s): Authors' own work

(a)   (b)

Source(s): Authors' own work

Figures 3(a) and 3(b), when the proportion of offline consumers is lower, namely the proportion of online consumers is higher, the manufacturer has the strong motivation to keep higher level of effort. When the proportion of offline consumers is higher, the retailer has the strong motivation to keep higher level of effort.
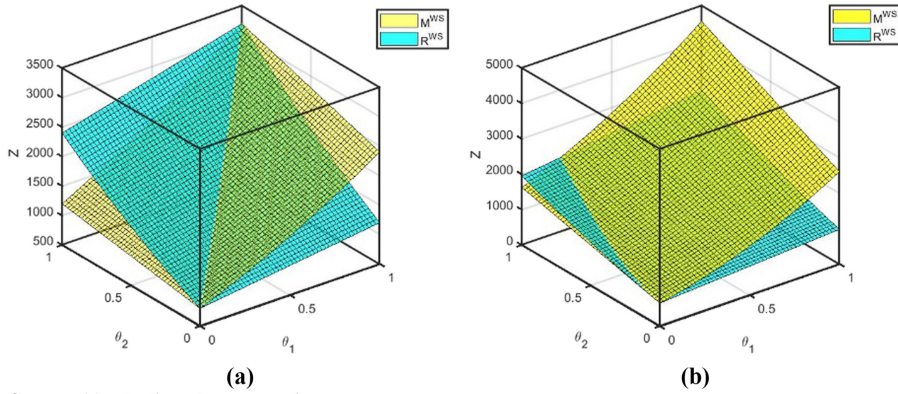
Figures 4(a) and 4(b) show that in the RSC model without subsidy, as the CSR of the manufacturer and the retailer increases, the agri-food efforts of the manufacturer and the retailer gradually increase. Figure 4(a) shows that the agri-food effort of the manufacturer is higher than that of the retailer. Figure 4(b) shows that when the proportion of offline consumers is 0.6 (over 50%), considering most cases of CSR, the agri-food effort of the manufacturer is higher than that of the retailer. Different from the WPC model, the effort of the manufacturer is almost higher than that of the retailer in the RSC model.

Figures 5(a) and 5(b) show that in WPC model with subsidy, as the CSR of the manufacturer and the retailer increases, the agri-food effort of manufacturer and retailer gradually increases. Figure 5(a) shows that when $\theta_1 > \theta_2$, the agri-food effort of the
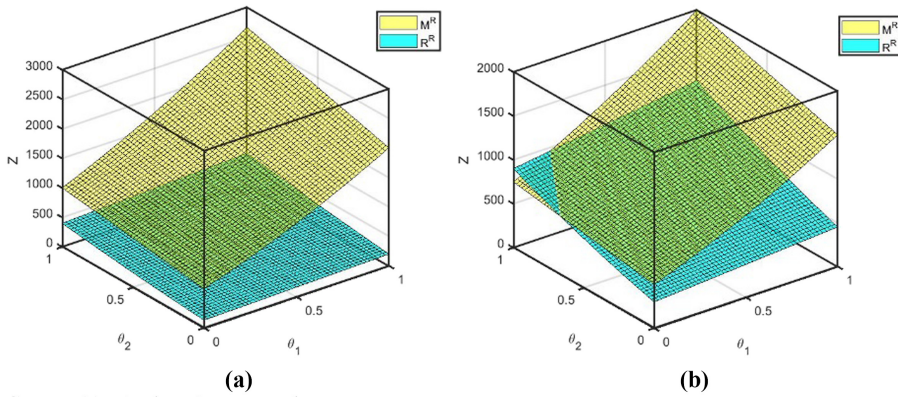
manufacturer is higher than that of the retailer. When $\theta_1 < \theta_2$, the agri-food effort of the retailer is higher than that of the manufacturer. This indicates that when the proportion of offline consumers is 0.4, the effort of both manufacturer and retailer increases with the increasing CSR. Figure 5(b) shows that when the proportion of offline consumers is 0.6 (over 50%), considering most cases of CSR, the agri-food effort of the manufacturer is higher than that of the retailer. Figure 5(b) shows that the effort of the manufacturer is almost higher than that of the retailer in the WPC model with subsidy.

Figures 6(a) and 6(b) show that in RSC model with subsidy, the effort of the manufacturer increases with CSR of the manufacturer and the retailer. The effort of retailer also increases with the increasing CSR of the manufacturer and the retailer. Figure 6(a) shows that when $\theta_1 > \theta_2$, the agri-food effort of the manufacturer is higher than that of the retailer. When $\theta_1 < \theta_2$, the agri-food effort of the retailer is higher than that of the manufacturer. This indicates that the conclusion is similar to the WPC model with subsidy. Figure 6(b) shows that when the proportion of offline consumers is 0.6 (over 50%), considering most cases of CSR, the agri-food effort of the retailer is higher than that of the manufacturer. Figure 5(b) shows that the effort of the retailer is almost higher than that of the manufacturer in the RSC model with subsidy.
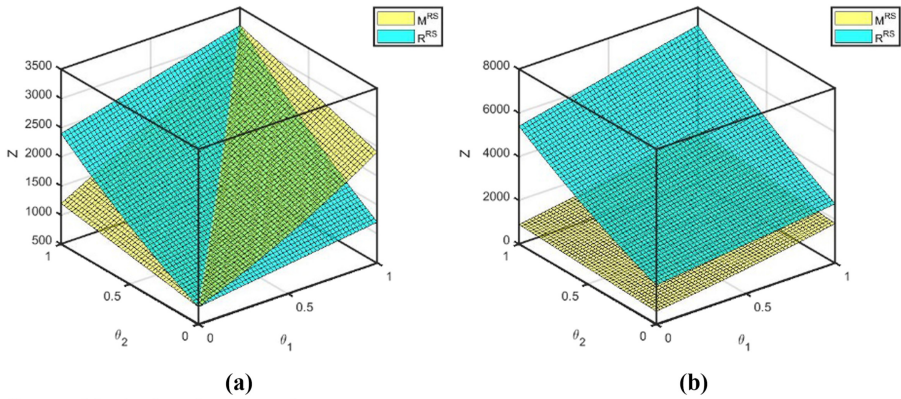
Figure 6.
The quality efforts of
the manufacturer and
the retailer in the RSC
model with subsidy

(a)   (b)

Source(s): Authors' own work

Figure 7(a) shows that when the proportion of offline consumers is 0.4 (under 50%), the effort of manufacturer is nearly equal. Figure 7(b) shows that when the proportion of offline consumers is 0.6 (over 50%), the effort of the manufacturer in RSC model is higher than that in the WPC model.

Figure 8(a) shows that when the proportion of offline consumers is 0.4 (under 50%), the effort of the manufacturer in the RSC model is higher than that in the WPC model. Figure 8(b) shows that when the proportion of offline consumers is 0.6 (over 50%), the effort of the retailer is nearly equal.

4.3 Profits of members under different models without or with subsidy
As can be seen from Table 2, this example has the following characteristics. In every model, profits increase as the CSR levels θ_1 and θ_2 of manufacturers and retailers increase. The profit of the manufacturer, the retailer and supply chain in cooperative model is highest. The profit of the manufacturer, the retailer and supply chain in the WPC model is higher than that in the RSC model. And subsidizing to the manufacturer, the retailer can improve the profits of the manufacturer, the retailer and supply chain.
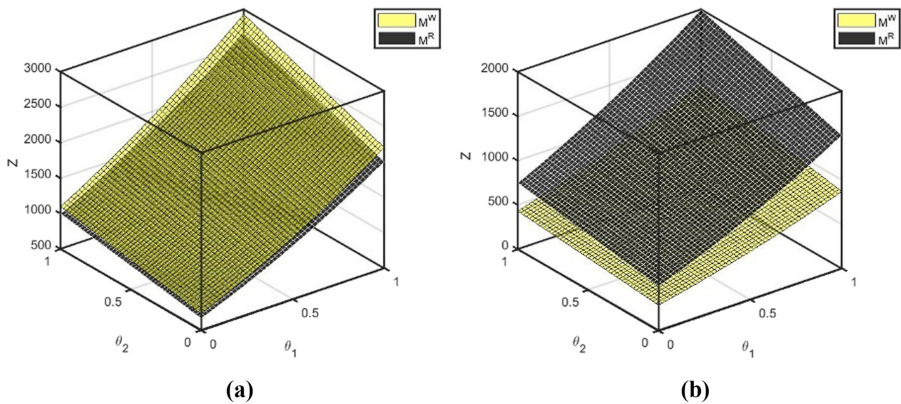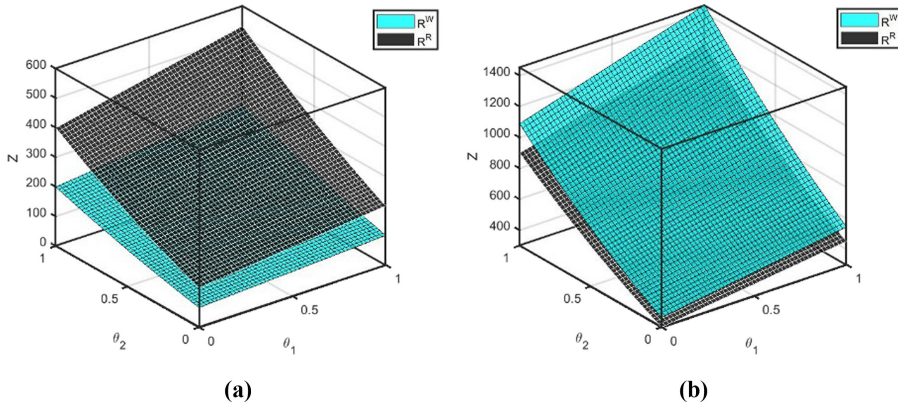

Figure 7.
The comparison of
quality efforts of the
manufacturer in the
WPC and RSC models
without subsidy

(a)   (b)

Source(s): Authors' own work

(a) (b)

Source(s): Authors' own work

Figure 8.
The quality effort of
retailer in the WPC and
RSC models without
subsidy

		V_m	V_r	V
No subsidy				
$\theta_1 = 0.2$	*WP*C	1770.89	19.07	1789.96
$\theta_2 = 0.2$	*RSC*	714.58	32.96	747.73
	Cooperative	2792.77		
$\theta_1 = 0.4$	*WP*C	2310.77	27.07	2337.84
$\theta_2 = 0.2$	*RSC*	934.69	45.90	980.93
	Cooperative		3752.11	
$\theta_1 = 0.6$	*WP*C	3013.08	38.27	3051.36
$\theta_2 = 0.6$	*RSC*	1221.82	63.77	1286.18
	Cooperative	5039.24		
$\theta_1 = 0.8$	*WP*C	3927.37	53.65	3981.02
$\theta_1 = 0.8$	*RSC*	1596.44	88.08	1685.46
	Cooperative	6754.13		
Subsidy				
$\theta_1 = 0.2$	*WP*C	4411.10	45.81	4456.91
$\theta_2 = 0.2$	*RSC*	1759.86	81.56	1841.43
	Cooperative	9356.54		
$\theta_1 = 0.4$	*WP*C	5754.51	64.29	5818.80
$\theta_2 = 0.4$	*RSC*	2299.61	113.65	2413.25
	Cooperative	11409.85		
$\theta_1 = 0.6$	*WP*C	7501.59	89.96	7591.55
$\theta_2 = 0.6$	*RSC*	3002.90	158.00	3160.90
	Cooperative	13790.93		
$\theta_1 = 0.8$	*WP*C	9775.49	125.01	9900.50
$\theta_2 = 0.8$	*RSC*	3919.63	218.38	4138.00
	Cooperative	16599.79		

Table 2.
The profits of members
when CSR in different
levels

Source(s): Authors' own work

4.4 Discussion

In this section, we further summarize and discuss the results obtained in the numerical analysis. First of all, it can be concluded that in section 4.1, in the three models, whether or not considering the subsidy, the agri-food quality in cooperative model is highest. And the agri-food quality in

the WPC model is higher than that in the RSC model. Furthermore, the implementation of government subsidies is good for the agri-food. Secondly, compared to model without government subsidies, under the model with government subsidies, the efforts of manufacturer and retailer are higher. Therefore, in order to motivate the effort of manufacturer and retailer, the government can implement a certain extent of subsidy. This supports the conclusion of Li (2020). Thirdly, we can conclude from Section 4.2 that the continuous improvement of CSR of the manufacturer and the retailer will enhance the quality of agri-food and efforts of the manufacturer and the retailer. Especially, when the proportion of offline consumers and the ratio of revenue sharing meet some conditions, it can be seen that the impacting degree of the manufacturer' CSR on quality is greater than that of the retailer's CSR in the WPC model or the RSC model. And in cooperative model, the impacting degree of the manufacturer's CSR on quality is the same as that of the retailer's CSR. Finally, Section 4.3 shows that the continuous increase of CSR of manufacturer and retailer has led to the continuous increase in the profit of every member. The subsidy policy also can enhance the profit of every member. More specially, the profit of members in the WPC model is higher than that in the RSC model and in the cooperative model, and specially the profit of member is the highest. This conclusion is not consistent with the conclusions obtained in the literature. It further shows that government subsidies are conducive to promoting the development of green agri-food and promoting environmental protection sustainable development.

5. Conclusion
Considering the jointing quality effort and contract decision in green agri-food supply chain, this paper proposes six models that consider the CSR of the manufacturer and the retailer, and then the obtained optimal solutions are compared and analyzed. At the same time, the impact of government subsidies is analyzed, and corresponding conclusions drawn.

The results show that, first of all, whether the increasing CSR of the manufacturer or the retailer can motivate both parties to improve the agri-food quality effort investment. In the WPC model, when CSR of M and R is equal, when the ratio of offline consumer is less than 50%, the effect of CSR of manufacturer on food quality is larger than that of CSR of retailer on food quality. Otherwise, when the ratio of offline consumer is larger than 50%, the effect of CSR of manufacturer on food quality is smaller than that of CSR of retailer on food quality. When the ratio of offline consumer is larger than 50%, the effect of CSR on food quality also depends on the revenue-sharing coefficient. In the RSC model, when revenue-sharing coefficient $\tau = 1/2$ and the ratio of offline consumer is less than 50%, the effect of CSR of manufacturer on food quality is larger than that of CSR of retailer on food quality.

Second, the WPC and RSC may play different roles in different cases. For agri-food quality, when the proportion of offline consumers is 0.4 (under 50%), the effort of manufacturer in the WPC model is higher than that in the RSC model. When the proportion of offline consumers is 0.6 (over 50%), the effort of manufacturer in the WPC model is lower than that in the RSC model. The effort of retailer is contrary. For profit view, profit of each member is higher in the WPC model.

Finally, under the model with government subsidies, regarding positive influence of government subsidies on efforts of manufacturer and retailer, quality and profits of members are investigated. The subsidy can improve the quality effort of the manufacturer and the retailer. And the effect of subsidy on retailer is greater than that on manufacturer. Under the background of subsidy, the quality effort of retailer may be higher than the effort of manufacturer. Whether the subsidy is present or not, the agri-food quality in the cooperation model is highest, while the agri-food quality in the RSC model is lowest.

Based on the conclusions, this study puts forward the following policy suggestions. Firstly, governments should formulate reasonable subsidy policies to support the

manufacturer and the retailer to improve the agri-food quality, thereby promoting development of green industries. Secondly, the manufacturer and the retailer should actively improve CSR and strengthen the effort of agri-food so as to advance quality. Finally, the manufacturer and the retailer can choose cooperative model or WPC contract in supply chain.

In this paper, one manufacturer and one retailer are considered. Since the agri-food supply chain structure in reality is more complicated, the future research direction can consider the supply chain structure with one manufacturer and multiple retailers. In addition, this paper only considers the subsidy, and future research can classify the subsidy into different types.

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