

WHO SHOULD UNDERTAKE CORPORATE SOCIAL RESPONSIBILITY IN FRESHNESS PRESERVATION FOR DUAL-CHANNEL FRESH FOOD PRODUCTS SUPPLY CHAIN?

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This paper examines the impact of corporate social responsibility (CSR) on the fresh food supply chain. Using a Stackelberg game framework, three scenarios are developed: scenario M_1 (No CSR), scenario M_2 (CSR by the retailer), and scenario M_3 (CSR by the supplier), to make efforts on the freshness preservation. The analysis reveals that increased CSR commitment consistently leads to lower retail prices, more significant preservation efforts, and larger consumer surplus. While CSR enhances social utility, it often comes at the expense of supply chain members' profits. In the retailer-led CSR scenario, the supplier's dominant position increases overall supply chain profitability despite reduced retailer profits. Counter-intuitively, in the supplier-led CSR scenario, overall profitability decreases, but consumers benefit from fresher products at lower prices due to higher preservation efforts and lower online channel sales prices. The findings suggest that strategic CSR adoption can improve social welfare and market competitiveness, providing a theoretical basis for real-world business decisions. Future research could explore optimal CSR allocation within the supply chain to balance profitability and social welfare.

Keywords: Dual-Channel Supply Chain System; Freshness Preservation Effort; Corporate Social Responsibility; Stackelberg Game.

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1. INTRODUCTION

As the internet continues to expand, the proportion of products purchased online is increasing significantly, with the fresh produce e-commerce industry experiencing rapid growth. According to iResearch, the size of China's fresh produce e-commerce market reached 458.5 billion yuan in 2020, representing a 64.0% increase over 2019. This growth trend is expected to continue, with the market size projected to exceed one trillion yuan by 2023. Globally, the fresh food e-commerce market also exhibited a robust compound annual growth rate (CAGR) of 13.89% from 2020 to 2023. However, alongside this rapid development, many fresh food companies are prioritizing profit maximization while neglecting their corporate social responsibility (CSR), which has led to several negative societal impacts. For instance, Dingdong, a prominent player in the fresh produce e-commerce market, was investigated for selling dead fish as live fish, failing to meet quality standards. Similarly, Missfresh, another major company in this sector, has faced repeated consumer complaints regarding food quality. These incidents highlight the urgent need for companies to enhance their CSR practices to ensure food safety and consumer satisfaction, fostering sustainable development within the industry.

To address the issue of corporate social responsibility (CSR) deficiency, the State Council elevated CSR to a national strategic priority in 2014 and promulgated the Guide to Social Responsibility 2015. Both initiatives established clear mandates for enterprises to fulfill their social responsibilities. Furthermore, the 2021 amendment to the Food Safety Law of the People's Republic of China explicitly stipulates that food production and operation enterprises must be accountable to consumers and assume social responsibility. In response to these national policies and the pursuit of sustainability, several corporate social responsibility practices have been implemented. For instance, Freshippo introduced a "compensation for bad fruit" service and a "compensation for non-living seafood" policy to enhance consumer trust and ensure product quality. JD Fresh, on the other hand, has increased its investment in preservation technologies by adopting recyclable insulation boxes and reducing disposable packaging and ice bags. These measures not only minimize resource waste and environmental impact but also effectively safeguard the quality of fresh produce. Today, CSR has emerged as

a pivotal concept within supply chain management, with firms increasingly held accountable for their societal and environmental impacts, particularly in food safety (Liu *et al.*, 2022).

Fresh products are not merely essential food items for human consumption but also necessities in daily life. However, given the short life cycle and stringent freshness requirements of fresh produce, companies must invest in preservation efforts to mitigate the decay of freshness. Such investments ensure that consumers receive products with more freshness than prior conditions (He *et al.*, 2022). The safety and freshness of fresh produce are intrinsically linked, thus rendering investment in preservation efforts indispensable. In practice, the effectiveness of efforts to preserve fresh food is closely correlated with the implementation of Corporate Social Responsibility (CSR) by preservation enterprises. By leveraging advanced technologies such as the Internet of Things (IoT) and blockchain, enterprises enhance food freshness through the improvement of cold chain logistics and the establishment of agricultural bases. These efforts not only exemplify the fulfillment of corporate social responsibility (CSR) but also aim to achieve a win–win value creation from farm to table. Evidently, an increasing number of firms are incorporating consumer interests into their decision-making processes, rather than solely pursuing profit maximization.

Against this backdrop, this study seeks to address the following research questions:

- (1) What is the relationship between undertaking CSR and investing in freshness preservation?
- (2) How does CSR affect supply chain members' profits, supply chain efficiency, and social welfare under different responsible parties?
- (3) How can supply chain members balance economic and social benefits through preservation and pricing decisions under different CSR responsibility settings?

To address these questions, this paper investigates the corporate social responsibility (CSR) behavior of fresh food enterprises within a dual-channel supply chain system, examining the preservation efforts and pricing strategies across different scenarios (supply chain without CSR, retailers adopting CSR alone, and suppliers adopting CSR alone). It offers a novel perspective on understanding the impact of CSR on supply chain decision-making. The specific contributions of this research are as follows. Firstly, this paper addresses the gap in the existing literature regarding the role of CSR in fresh food supply chains. By constructing a theoretical model, it analyzes the effects of CSR on preservation efforts, pricing, profits, consumer surplus, and social welfare. The study reveals the positive role of CSR in enhancing product freshness, reducing prices, increasing demand, and improving social welfare. This finding provides a theoretical foundation for fresh food enterprises to implement CSR, demonstrating that CSR not only enhances corporate image but also boosts market competitiveness through improved product quality and lower prices. Secondly, this paper elucidates the impact of CSR stakeholders on supply chain performance by comparing supply chain decisions across three scenarios. The research finds that when suppliers alone assume CSR responsibilities, although their profits may be somewhat affected, consumer surplus and social welfare are significantly enhanced. This conclusion offers important insights for business decision-makers: in a dual-channel supply chain, suppliers can improve overall supply chain efficiency by actively undertaking CSR, enhancing consumer trust and brand loyalty. Lastly, the findings of this paper provide valuable references for policymakers. The study demonstrates that CSR implementation can effectively enhance social welfare, particularly in the fresh food sector. The positive impact of CSR on preservation efforts and pricing can help reduce food waste and improve consumer welfare. Therefore, the government can encourage enterprises to undertake CSR through policy incentives such as tax breaks or subsidies, promoting the sustainable development of the fresh food supply chain. In summary, this paper provides a comprehensive exploration of the role of CSR in the dual-channel supply chain of fresh food through theoretical analysis and model construction. It offers significant theoretical support and practical guidance for enterprise decision-making, policy formulation, and academic research.

The remainder of this paper is organized as follows. Section 2 discusses the related literature, and Section 3 describes the basic scenario and modeling denotations. Then, Section 4 sets up, solves models, and analyzes the equilibrium solution, and Section 5 compares the scenario according to analytical results and numerical analysis. Finally, Section 6 concludes the paper while providing some prospects on future research, and all proofs are included in the Appendix.

2. LITERATURE REVIEW

This study primarily relates to two streams of research: corporate social responsibility (CSR) and the fresh food product supply chain.

2.1 Related literature on CSR

With the sustainable development of the global economy, corporate social responsibility (CSR) has emerged as a prominent research topic in recent years. The concept of CSR was initially introduced by Bowen (1953), who contended that companies should not solely focus on economic benefits but also consider the broader implications of their actions. Following Bowen's seminal work, the definition of CSR has evolved through subsequent scholarly contributions. Manne and Wallich (1972) emphasized that companies should voluntarily fulfill their corporate social responsibility. Johnson (1971) developed four complementary perspectives on CSR: the traditional definition, benefits maximization, utility maximization, and the lexicon view. Carroll (1979) further refined the concept by defining CSR as the economic, legal,

ethical, and philanthropic expectations that society holds for companies. This four-part definition has become a cornerstone in CSR literature. In recent years, the stakeholder perspective has gained prominence in defining CSR. Romani *et al.* (2013) clarified that CSR encompasses moral and ethical considerations, environmental protection, and consumer welfare. An *et al.* (2025) expanded upon this by integrating aspects such as corporate workers and social ethics into the CSR framework, highlighting both complementary and competitive dimensions of CSR implementation. Overall, numerous scholars have elaborated on the meaning of CSR from diverse theoretical perspectives, reflecting its multifaceted nature and evolving significance in contemporary business environments.

From a supply chain system research perspective, scholars have primarily approached theoretical modeling studies of Corporate Social Responsibility (CSR) through two main strands. One strand portrays CSR as an investment behavior aimed at enhancing stakeholder interests, treating CSR as an internal variable, and focusing on corporate input decisions. For instance, Ni *et al.* (2010) examined supply chain decisions when the supplier fulfills social responsibility and the retailer shares socially responsible costs through wholesale price contracts, finding that reasonable cost allocation between upstream and downstream partners can improve supply chain performance. Hsueh (2014) explored equilibrium decision-making and coordination in CSR implementation by manufacturers, assuming CSR as a cost input. The study concluded that CSR can enhance the profitability of the supply chain system and that revenue-sharing contracts can effectively coordinate the supply chain and elevate the level of social responsibility. Raza (2018) developed deterministic and stochastic demand models for a supply chain comprising a manufacturer and a retailer, focusing on price and CSR investment. They derived optimal joint decisions on pricing, inventory, and CSR investment, demonstrating the interplay between these factors in supply chain management. Raj *et al.* (2018) investigated scenarios where a manufacturer makes environmental decisions and a retailer determines the level of social responsibility, finding that the retailer's fulfillment of social responsibility is more beneficial to overall supply chain performance. Ma *et al.* (2017) considered the impact of uncertainty on supply chain profits under asymmetric information regarding social responsibility costs for retailers and manufacturers. They showed that manufacturers' profits are positively related to uncertainty, while retailers' profit changes depend on the range of variations in social responsibility costs. Modak *et al.* (2019b) examined corporate philanthropy as a CSR initiative and investigated the choice of recycling channels and coordination mechanisms in a two-level closed-loop supply chain. Their research highlighted the role of CSR in shaping supply chain sustainability and efficiency through strategic decision-making and coordination mechanisms. Overall, these studies underscore the multifaceted role of CSR in supply chain management, emphasizing its potential to enhance profitability, improve stakeholder welfare, and promote sustainable practices through strategic investment and coordination.

Other scholars have conceptualized CSR as the degree to which a firm prioritizes the interests of its stakeholders, operationalized as external variables within their models. Panda (2014) characterized CSR as a supply chain member's concern for consumer surplus, examining how manufacturers' or retailers' adoption of CSR influences decision-making and profit dynamics within the supply chain. He discovered that when one party assumes CSR responsibilities, its profits may decline, while the profits of the other party increase. Building on this foundation, Panda *et al.* (2016) demonstrated that as CSR is more extensively fulfilled, the net profits of channel members are likely to increase concurrently. However, this outcome depends on how CSR is implemented and how social responsibility is shared among channel members. Panda *et al.* (2017) further explored the impact of manufacturers' heightened concern for social responsibility, finding that it enhances retailer profits and the recycling rate of used products, albeit at the potential expense of manufacturers' economic profits. Modak *et al.* (2014) investigated the influence of manufacturers' CSR initiatives on pricing decisions and profits within a dual-channel supply chain. They identified thresholds for social responsibility concerns necessary for the successful operation of a dual-channel supply chain, demonstrating that CSR fulfillment can enhance overall supply chain profits. They also proposed a Nash bargaining scheme to equitably distribute residual profits among supply chain members. In a subsequent study, Modak *et al.* (2019a) extended their research to a closed-loop supply chain comprising a socially responsible manufacturer, a recycler, and multiple retailers. They found that the extent of product recycling is directly proportional to the manufacturer's degree of CSR fulfillment. Additionally, they established that there exists a threshold for recycling activities, beyond which optimal benefits can be achieved through CSR practices. Collectively, these studies highlight the complex interplay between CSR implementation and supply chain profitability, emphasizing the importance of strategic CSR fulfillment and collaborative responsibility-sharing among supply chain members to achieve economic and social benefits.

2.2 Related literature on the fresh food products' supply chain

In recent years, scholars have conducted extensive research on various aspects of the fresh food supply chain, including inventory management (Muriana *et al.*, 2016; Dan *et al.*, 2012; Li *et al.*, 2019), pricing strategies and coordination (Wang and Zhao, 2021; Ma *et al.*, 2020; Yan *et al.*, 2022; Su *et al.*, 2022), and product freshness preservation (Hsu *et al.*, 2010; Dye, 2013). Cai *et al.* (2010) examined optimal ordering, pricing, and coordination strategies for the fresh produce supply chain under decentralized and centralized decision-making frameworks. Their analysis began with the retailer's efforts to extend the shelf life and maintain the freshness of perishable products, highlighting the importance of these factors in shaping supply chain dynamics. Cao *et al.* (2021) investigated optimal pricing, freshness effort decisions, and coordination mechanisms within a dual-channel fresh produce supply chain. They focused on how freshness, influenced

by supplier efforts and time decay, impacts pricing, freshness effort decisions, and overall coordination within the supply chain. Zhang *et al.* (2024) explored a two-tier fresh food supply chain comprising one supplier and one fresh food e-retailer. In this context, freshness-keeping efforts could be provided by either the supplier or the e-retailer, while the latter also offered value-added services. Ketzenberg *et al.* (2023) employed a simple linear wholesale price contract to investigate the value of data sharing in a two-echelon fresh product supply chain. They found that data sharing helps improve product freshness, reduce waste, and is most valuable when products are moderately perishable and demand is volatile. Fang *et al.* (2024) incorporated time-varying produce freshness to explore the optimal decisions of the supplier and the retailer and further identified a coordination contract that achieves Pareto improvement. Collectively, these studies emphasize the critical role of freshness preservation, inventory management, and strategic pricing in optimizing supply chain performance within the fresh produce sector. They also highlight the importance of coordination mechanisms and their role in enhancing economic and social outcomes.

Based on the preceding discussion and analysis, existing research on Corporate Social Responsibility (CSR) exhibits several notable characteristics. Most prior studies on CSR have been empirical (Wang *et al.*, 2020; Chan *et al.*, 2020; Haroon *et al.*, 2025), with limited attention devoted to mathematical modeling. Moreover, the existing literature predominantly focuses on single-channel or closed-loop supply chains, often neglecting the complexities of dual-channel systems. Furthermore, most of the literature assumes that supply chain members prioritize economic profit maximization as their primary decision-making objective. This assumption overlooks the social welfare responsibilities that firms should fulfill towards stakeholders, despite the increasing trend of large corporations actively engaging in CSR initiatives in recent years.

Additionally, while much of the literature examines the relationship between market demand and sales price, or the degree of CSR implementation, there is a notable gap in research that integrates CSR and preservation efforts within a dual-channel supply chain context. Specifically, few studies have explored the interplay between CSR, preservation efforts, and their combined impact on supply chain dynamics, profitability, and social welfare. This gap highlights the need for further research to address the multifaceted role of CSR and preservation efforts in modern supply chain management. Table 1 shows the gap between this paper and the related literature.

Table 1. The gap between this paper and the related literature.

Article	Dual-channel structure	Fresh food supply chain	Freshness preservation effort	Corporate social responsibility (CSR)
Panda <i>et al.</i> (2017)				√
Modak <i>et al.</i> (2019a)				√
Cao <i>et al.</i> (2021)	√	√	√	
Ketzenberg <i>et al.</i> (2023)		√	√	
Fang <i>et al.</i> (2024)		√	√	
Zhang <i>et al.</i> (2024)		√	√	
This paper	√	√	√	√

Building on these insights, we employ mathematical modeling to investigate a representative dual-channel supply chain, comprising a single retailer and a single supplier. In this context, we incorporate Corporate Social Responsibility (CSR) and preservation efforts into the supply chain framework. Specifically, we integrate social welfare responsibility, with a focus on consumer surplus, into the supply chain and construct three models: (1) a supply chain without CSR (pursuing profit maximization), (2) a scenario where the retailer assumes CSR (pursuing social welfare maximization), and (3) a scenario where the supplier assumes CSR (pursuing social welfare maximization). Utilizing game theory, we analyze these scenarios to examine the effects of CSR compliance on various critical factors, including market demand, wholesale price, and retail price. By comparing the parameters across different models, we assess the impact of CSR and preservation efforts on the decision variables and profits of supply chain members. This analysis provides a robust theoretical foundation and offers practical guidance for operational management in e-commerce platforms within the fresh produce industry.

3. THE BASIC MODEL AND MODELING DONATIONS

This paper examines a dual-channel supply chain system comprising a supplier (denoted as O) and a retailer (denoted as S). The supplier is considering investing in freshness-preserving technology to enhance the quality of its perishable products. These products are sold through two channels: direct online sales to consumers and wholesale distribution to retailer. The supplier sells the products in bulk to the retailer at a wholesale price w . The retailer sells the products to end consumers at a retail price p_2 and $p_2 > w$. Additionally, the supplier sells the products directly to consumers online at a price p_1 . The unit production cost of the perishable product is c . The prices set for online and retail sales significantly

influence the demand in each channel. Figure 1 illustrates the supply chain system, highlighting the business relationship between the supplier (O) and the retailer (S).

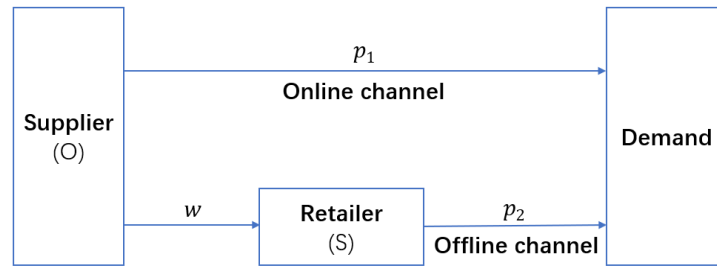


Figure 1. Supply chain system.

The sequence in which the game unfolds is as follows: the supplier first decides the wholesale price w , the online channel sales price p_1 and the preservation effort input y . Subsequently, the retailer decides the retailer's channel sales price p_2 . The timing of events is illustrated in Figure 2.

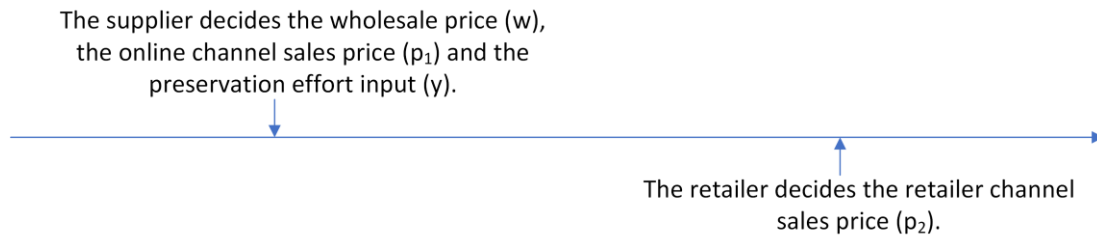


Figure 2. The timing of events.

In alignment with the existing literature, this paper makes the following assumptions:

(1). Geographical Proximity and Delivery Time Consistency: Customers and retailers are typically located within the same city or region. Consequently, products from dual channels (direct online sales and retail distribution) are delivered to customers within the same time frame.

(2). Investment in Freshness-Preserving Technology: To enhance market share and meet consumer demand for freshness, the supplier invests in research and development of fresh produce preservation technology. Let the effort invested in this technology be denoted by y . The freshness of the raw product is represented by θ , which is influenced by the preservation effort y exerted by the supplier. Drawing from reference (Cai *et al.*, 2010; Liu *et al.*, 2021; Zhang *et al.*, 2024), the freshness function is formulated as $\theta_v = y\theta_0$, where θ_0 denotes the initial freshness of the raw product ($0 \leq \theta_0 \leq 1$) and y represents the effort invested in freshness preservation ($0 \leq y \leq 1$). The freshness function indicates that the greater the supplier's preservation effort, the higher the resulting product freshness. For analytical convenience and based on reference (Liu *et al.*, 2021), we further assume $\theta_0 = 1$.

In the context of fresh product research, freshness functions are often modeled as time-dependent. One common form is the exponential decay function, where freshness declines exponentially over time and is represented as $F(t) = e^{-\mu t}$, with $F(t)$ denoting freshness, t representing time, and μ representing the freshness decay rate. Another frequently used form is the linear decay function, in which freshness decreases linearly over time and is given by $F(t) = 1 - kt$, where k is the decay coefficient, t is time, and $F(t) \geq 0$.

(3). Monotonic relationship between freshness and preservation effort: In a simplified analysis, the freshness level, θ_v , exhibits a monotonic relationship with the preservation effort y . Expressly, an increase in y leads to a corresponding increase in θ_v , while a decrease in y results in a decrease in θ_v . Therefore, the analysis of freshness can be equivalently treated as the analysis of preservation effort. Throughout the supply chain cycle, the supplier is solely responsible for the costs associated with maintaining product freshness. The impact of preservation effort on the cost is captured by the factor v_1 , which satisfies the condition $v_1 > \frac{(3+2\beta)\gamma^2}{2(1-\beta)\beta}$. The economic intuition behind the constraint is as follows: when consumers become increasingly sensitive to freshness (γ increases), or when channel substitutability approaches the extremes (β is either very large or very small), the marginal return on preservation effort rises sharply. If preservation remains inexpensive (i.e., v_1 is too low), profit-maximizing firms will be driven to push preservation efforts to their upper limit. Therefore, only when the cost impact factor for preservation effort inputs (v_1) exceeds a certain threshold,

firms will adopt a limited and feasible level of preservation effort to avoid over-preservation. For analytical convenience and based on reference (Zhang *et al.*, 2024; Du and Lu, 2023; Yu and Xiao, 2017) , the freshness cost function is specified as $C(y) = \frac{1}{2} v_1 y^2$.

(4). Market Demand Specification in the Dual-Channel Supply Chain: To streamline the analysis, this paper assumes that the supplier and the retailer offer identical products to the same market within the dual-channel supply chain system. Market demand is primarily influenced by the price and the freshness of the product. Specifically, the demand functions for online channel O and offline channel S are formulated as follows:

$$D_1 = a - p_1 + \beta p_2 + \gamma y \tag{0}$$

and

$$D_2 = a - p_2 + \beta p_1 + \gamma y \tag{0}$$

where a represents the potential market demand for online and offline channels. The parameter β denotes the cross-price elasticity coefficient, which captures the substitutability between the two channels, with $0 < \beta < 1$. The variables p_1 and p_2 represent the selling prices in online channel O and offline channel S, respectively. The parameter γ is the consumer's freshness sensitivity factor, $\gamma > 0$, reflecting the responsiveness of demand to the freshness effort exerted by the supplier. The term γy captures the impact of freshness effort on demand, where a larger γ indicates a more significant increase in demand per unit of preservation effort.

(5). Incorporating CSR Behavior and Consumer Surplus into the Profit Function: This paper introduces Corporate Social Responsibility (CSR) behavior as an external variable, where supply chain members assume social responsibilities and incorporate consumer surplus into their profit functions. Consumer surplus is the difference between the maximum amount consumers are willing to pay and the actual price they pay for the product. According to Panda *et al.* (2017), consumer surplus can be expressed as:

$$CS = \int_p^{p_{max}} D dp = \frac{D^2}{2} \tag{3}$$

In the context of this dual-channel supply chain, the consumer surplus for the supplier's online channel is calculated as:

$$CS_{D_1} = \int_{p_1}^{p_1^{max}} D_1 dp_1 = \int_{p_1}^{p_2\beta + \gamma y + a} (a - p_1 + \beta p_2 + \gamma y) dp_1 = \frac{(a - p_1 + \beta p_2 + \gamma y)^2}{2} \tag{4}$$

Similarly, the consumer surplus for the retailer's offline channel is:

$$CS_{D_2} = \int_{p_2}^{p_2^{max}} D_2 dp_2 = \int_{p_2}^{a + p_1\beta + \gamma y} (a - p_2 + \beta p_1 + \gamma y) dp_2 = \frac{(a - p_2 + \beta p_1 + \gamma y)^2}{2} \tag{5}$$

where p_{max} is determined by setting $D_i=0$. From Equations (4) and (5), it is evident that the magnitude of consumer surplus is influenced by the selling price and the preservation effort.

Let R (where $0 \leq R \leq 1$) denote the proportion of consumer surplus that the supplier incorporates into its utility function. A higher value of R indicates more significant consideration of consumer surplus and, consequently, a stronger assumption of social responsibility. Specifically, when R approaches 0, the supply chain member neglects social responsibility, focusing primarily on profit maximization. Conversely, when R approaches 1, it implies that the supply chain member fully accounts for consumer surplus, prioritizing social welfare in its decision-making process.

In practice, the fulfillment of corporate social responsibility (CSR) is often assessed based on standards such as the Responsible Business Alliance (RBA), Social Accountability 8000 (SA8000), Supplier Ethical Data Exchange (SEDEX), and Business Social Compliance Initiative (BSCI). These standards primarily aim to improve labor rights, occupational health and safety, environmental management, and business ethics, serving as key initiatives in advancing CSR across the supply chain. For analytical tractability in this study, CSR is quantified in terms of the consumer surplus (Panda and Modak, 2016; Panda *et al.*, 2016; Modak *et al.*, 2016a; Modak *et al.*, 2016b; Kopel and Brand, 2012; Ni *et al.*, 2010). Here, R denotes the firm's level of emphasis on CSR. In reality, R can be measured by the ratio of a firm's annual CSR-related expenditures to its operating profits, or determined according to CSR evaluation standards such as RBA, SA8000, SEDEX, or BSCI.

This section commences with the formulation of a Stackelberg game for the three scenarios delineated previously. Within this framework, the fresh produce supplier assumes the role of the leader. Initially, the supplier determines the wholesale price w , the preservation effort level y for the fresh produce, and the online sales price p_1 . Based on the established wholesale price w , preservation effort level y , and online sales price p_1 , the fresh produce e-commerce company (acting as the follower) decides on the retail price p_2 .

The paper investigates the impact of Corporate Social Responsibility (CSR) levels among supply chain members on the equilibrium decision-making and profitability of the supply chain system. It employs comparative analysis to identify the optimal CSR-sharing strategy for supply chain members. The primary variables are presented in Table 2.

Table 2. Main variables and meanings.

Variables	Meanings
a	Potential market demand
D_1	Online channel demand
D_2	Demand from the retail channel
p_1	Online channel sales price
p_2	Retailer channel sales price
w	Supplier wholesale price
c	Unit cost
y	Preservation effort input
v_1	Cost impact factor for preservation effort inputs
β	Inter-channel cross-price elasticity factor
γ	Consumer sensitivity factor for freshness
$C(y)$	Cost of preservation efforts
Π	Profits
U	Social utility welfare function
Π_{OS}	Overall supply chain profit
M_1	No SCR Scenario
M_2	Scenario CSR by the retailer alone
M_3	Scenario CSR by the supplier alone
O	Supplier
S	Retailer
R	Percentage of CSR undertaken
θ_v	The freshness function
θ_0	The initial freshness

4. MODELING AND ANALYSIS OF EQUILIBRIUM RESULTS

Here we will consider three scenarios and provide their equilibrium analysis.

4.1. No CSR undertaken by supply chain - Scenario M₁

In the supply chain system, the supplier acts as a leader. The decision sequence of the model is as follows: first, the supplier decides the wholesale price w , the input y for preservation effort, and price p_1 of the product to maximize his profit; then, the retailer decides the selling price p_2 of the product to maximize his profit based on the supplier's decision. The profit function of the supplier, the retailer, and the whole supply chain under scenario M₁, where no member in the supply chain implements the CSR, is, respectively,

$$\Pi_O^{M_1}=(p_1 - c)D_1+(w - c)D_2 - C(y), \Pi_S^{M_1}=(p_2 - w)D_2 \text{ and } \Pi_{OS}^{M_1} = \Pi_O^{M_1} + \Pi_S^{M_1}.$$

With the optimal method, we can obtain the equilibrium outcome of scenario M₁ in Lemma 1.

Lemma 1: Under Scenario M_1 , the optimal outcomes for pricing are obtained as follows.

$$p_1^{M_1} = \frac{-2v_1(a+c-\beta)+c(3+\beta)\gamma^2}{4v_1(-1+\beta)+(3+\beta)\gamma^2}, p_2^{M_1} = \frac{av_1(-3+\beta)+cv_1(-1+\beta^2)+c(3+\beta)\gamma^2}{4v_1(-1+\beta)+(3+\beta)\gamma^2},$$

$$w^{M_1} = \frac{-2v_1(a+c-\beta)+c(3+\beta)\gamma^2}{4v_1(-1+\beta)+(3+\beta)\gamma^2}, y^{M_1} = -\frac{(a+c(-1+\beta))(3+\beta)\gamma}{4v_1(-1+\beta)+(3+\beta)\gamma^2}.$$

Proof: The proof process is obtained according to the optimal necessary conditions. So, we omit its process. And then, we can get the optimal demands and profits of members as follows.

$$D_1^{M_1} = \frac{v_1(a+c(-1+\beta))(-2+\beta+\beta^2)}{4v_1(-1+\beta)+(3+\beta)\gamma^2}, D_2^{M_1} = \frac{v_1(a+c(-1+\beta))(-1+\beta)}{4v_1(-1+\beta)+(3+\beta)\gamma^2},$$

$$\Pi_O^{M_1} = -\frac{v_1(a+c(-1+\beta))^2(3+\beta)}{8v_1(-1+\beta)+2(3+\beta)\gamma^2}, \Pi_S^{M_1} = \frac{v_1^2(a+c(-1+\beta))^2(-1+\beta)^2}{(4v_1(-1+\beta)+(3+\beta)\gamma^2)^2} \text{ and } \Pi_{OS}^{M_1} = -\frac{v_1(a+c(-1+\beta))^2(2v_1(-1+\beta)(7+\beta)+(3+\beta)^2\gamma^2)}{2(4v_1(-1+\beta)+(3+\beta)\gamma^2)^2}.$$

4.2. CSR undertaken by the retailer alone - Scenario M_2

The supplier also acts as the leading party in the supply chain system. The decision sequence of the model is that the supplier aims to maximize profit and decides the wholesale price w and the preservation effort input y and price p_1 of the product. Then, the retailer will determine the selling price p_2 of the product based on the supplier's decision to maximize its social utility welfare function.

The social utility welfare function of the retailer under scenario M_2 is $U_S^{M_2} = (w - c)D_2 + \frac{R(D_2^2)}{2}$, and the profit of the retailer under Scenario M_2 is $\Pi_S^{M_2} = (p_2 - w)D_2$, the profit function for a supplier is $\Pi_O^{M_2} = (p_1 - c)D_1 + (w - c)D_2 - C(y)$, and the profit of the whole supply chain system is $\Pi_{OS}^{M_2} = \Pi_S^{M_2} + \Pi_O^{M_2}$.

With the optimal method, we can obtain the equilibrium outcome of scenario M_2 in Lemma 2.

Lemma 2: Under scenario M_2 , the optimal outcomes for pricing are obtained as follows.

$$p_1^{M_2} = \frac{-((-2+R)v_1(a+c-\beta))+c(-3+R+(-1+R)\beta)\gamma^2}{2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2}, p_2^{M_2} = \frac{av_1(3+R(-2+\beta)-\beta)+cv_1(-1+\beta)(-1+(-1+R)\beta)+c(-3+R+(-1+R)\beta)\gamma^2}{2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2},$$

$$w^{M_2} = \frac{-((-2+R)v_1(a+c-\beta))+c(-3+R+(-1+R)\beta)\gamma^2}{2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2}, y^{M_2} = -\frac{(a+c(-1+\beta))(-3+R+(-1+R)\beta)\gamma}{2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2},$$

$$CS_{D_2} = \frac{v_1^2(a+c(-1+\beta))^2(-1+\beta)^2}{2(2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2)^2}, U_S^{M_2} = -\frac{(-2+R)v_1^2(a+c(-1+\beta))^2(-1+\beta)^2}{2(2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2)^2}.$$

And then, we can get the optimal demands and profits of members as follows.

$$\Pi_O^{M_2} = \frac{-v_1(a+c(-1+\beta))^2(-3+R+(-1+R)\beta)}{4(-2+R)v_1(-1+\beta)+2(-3+R+(-1+R)\beta)\gamma^2}, \Pi_S^{M_2} = -\frac{(-1+R)v_1^2(a+c(-1+\beta))^2(-1+\beta)^2}{(2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2)^2},$$

$$\Pi_{OS}^{M_2} = -\frac{v_1(a+c(-1+\beta))^2(2v_1(-1+\beta)(7+\beta+R(-6+R+(-2+R)\beta))+(-3+R+(-1+R)\beta)^2\gamma^2)}{2(2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2)^2},$$

$$D_1^{M_2} = \frac{v_1(a+c(-1+\beta))(-1+\beta)(-2+R+(-1+R)\beta)}{2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2} \text{ and } D_2^{M_2} = \frac{-v_1(a+c(-1+\beta))(-1+\beta)}{2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2}.$$

4.3. CSR undertaken by the supplier alone - Scenario M_3

The supplier acts as the leading party in the supply chain system. The decision sequence of the model is that the supplier aims to maximize its social utility welfare function and decides the wholesale price w and the preservation effort input y and price p_1 of the product. Then, the retailer will decide the selling price p_2 of the product based on the supplier's decision to maximize its profit.

The social utility welfare function of the supplier under scenario M_3 is $U_O^{M_3} = (p_1 - c)D_1 + (w - c)D_2 - C(y) + \frac{R(D_1^2)}{2}$, and the profit for a supplier under scenario M_3 is $\Pi_O^{M_3} = (p_1 - c)D_1 + (w - c)D_2 - C(y)$.

The profit for a retailer under scenario M_3 is $\Pi_S^{M_3} = (p_2 - w)D_2$. And the total profit of the supply chain under scenario M_3 is $\Pi_{OS}^{M_3} = \Pi_O^{M_3} + \Pi_S^{M_3}$.

With the optimal method, we can obtain the equilibrium outcome for scenario M_3 in Lemma 3.

Lemma 3: Under scenario M_3 , the optimal outcomes for pricing are obtained as follows.

$$p_1^{M_3} = \frac{-((cv_1(-1+\beta))(-4+R\beta)+av_1(4+R(-4+\beta+2\beta^2))+c(-6+R+(-2+R)\beta)\gamma^2)}{(2v_1(-1+\beta)(4+R(-2+\beta^2))-(-6+R+(-2+R)\beta)\gamma^2)},$$

$$p_2^{M_3} = \frac{(cv_1(-1+\beta)(2-R+2\beta)+av_1(-6+3R+2\beta-2R\beta^2))-c(-6+R+(-2+R)\beta)\gamma^2}{(2v_1(-1+\beta)(4+R(-2+\beta^2))-(-6+R+(-2+R)\beta)\gamma^2)},$$

$$W^{M_3} = \frac{-((v_1(a+c-c\beta)(4+R(-2+\beta^2))+c(-6+R+(-2+R)\beta)\gamma^2))}{(2v_1(-1+\beta)(4+R(-2+\beta^2))-(-6+R+(-2+R)\beta)\gamma^2)}, y^{M_3} = \frac{((a+c(-1+\beta))(-6+R+(-2+R)\beta)\gamma)}{(2v_1(-1+\beta)(4+R(-2+\beta^2))-(-6+R+(-2+R)\beta)\gamma^2)},$$

$$U_O^{M_3} = \frac{v_1(a+c(-1+\beta))^2(-6+R+(-2+R)\beta)}{4v_1(-1+\beta)(4+R(-2+\beta^2))-2(-6+R+(-2+R)\beta)\gamma^2}, CS_{D_1} = \frac{2v_1^2(a+c(-1+\beta))^2(-2+\beta+\beta^2)}{(2v_1(-1+\beta)(4+R(-2+\beta^2))-(-6+R+(-2+R)\beta)\gamma^2)}.$$

And then we can get the optimal demands and profits of members as follows.

$$D_1^{M_3} = \frac{2v_1(a+c(-1+\beta))(-2+\beta+\beta^2)}{2v_1(-1+\beta)(4+R(-2+\beta^2))-(-6+R+(-2+R)\beta)\gamma^2}, D_2^{M_3} = -\frac{v_1(a+c(-1+\beta))(-1+\beta)(-2+R+\beta)}{2v_1(-1+\beta)(4+R(-2+\beta^2))-(-6+R+(-2+R)\beta)\gamma^2},$$

$$\Pi_S^{M_3} = \frac{v_1^2(a+c(-1+\beta))^2(-1+\beta)^2(-2+R+\beta)^2}{(-2v_1(-1+\beta)(4+R(-2+\beta^2))+(-6+R+(-2+R)\beta)\gamma^2)^2},$$

$$\Pi_{OS}^{M_3} = \frac{(v_1(a+c(-1+\beta))^2(2v_1(-1+\beta)(-4(7+\beta)+R(28+R(1+\beta)(-3+2\beta^2)-4\beta(-2+\beta(4+\beta))))-(-6+R+(-2+R)\beta)^2\gamma^2))}{(2(-2v_1(-1+\beta)(4+R(-2+\beta^2))+(-6+R+(-2+R)\beta)\gamma^2)^2)},$$

$$\Pi_O^{M_3} = \frac{(v_1(a+c(-1+\beta))^2(2v_1(-1+\beta)(-8(3+\beta)+R(-12+R+(-4+R)\beta)(-2+\beta^2))-(-6+R+(-2+R)\beta)^2\gamma^2))}{(2(-2v_1(-1+\beta)(4+R(-2+\beta^2))+(-6+R+(-2+R)\beta)\gamma^2)^2)}.$$

4.4. Analysis of equilibrium results

By comparing the optimal outcomes of the above scenarios, we can find the following propositions.

Proposition 1: $\frac{\partial p_1^{M_2}}{\partial R} > 0, \frac{\partial D_2^{M_2}}{\partial R} > 0, \frac{\partial W^{M_2}}{\partial R} > 0, \frac{\partial \Pi_O^{M_2}}{\partial R} > 0, \frac{\partial U_{OS}^{M_2}}{\partial R} > 0, \frac{\partial \Pi_{OS}^{M_2}}{\partial R} > 0, \frac{\partial y^{M_2}}{\partial R} > 0, \frac{\partial p_2^{M_2}}{\partial R} < 0, \frac{\partial D_1^{M_2}}{\partial R} < 0, \frac{\partial \Pi_S^{M_2}}{\partial R} < 0.$

Proposition 1 reveals that within this supply chain system, the supplier holds a dominant position, and the retailer takes corporate social responsibility (CSR) into account. As the retailer's CSR level escalates, several notable changes occur. Specifically, the supplier's selling price and the wholesale price increase. Concurrently, the supplier's investment in preservation efforts rises, leading to an augmentation of the supplier's profit. Additionally, the impact on the social welfare function becomes more pronounced. However, conversely, the retailer's selling price, the market demand for the supplier's products, and the retailer's profit all exhibit a downward trend.

Furthermore, when the retailer's CSR level increases, Proposition 1 elucidates that the supplier's selling price rises with the wholesale price. This phenomenon can be attributed to the supplier's strategic objective of maximizing its profit. As the retailer continues to elevate CSR practices, there is a growing emphasis on product freshness. Consequently, the retailer exerts increasing pressure on the supplier. This impetus prompts the supplier to enhance its investment in preservation measures, resulting in an improved preservation effect compared to the previous situation.

Additionally, when the wholesale price of goods increases, the retailer adopts a strategy of offering lower selling prices to customers as a manifestation of its support. As a result, although the market demand for the retailer's products may increase, the reduction in retail price leads to an overall decline in the retailer's profit. In contrast, while the market demand for the supplier's products decreases, the relatively high online channel sales price enables the supplier's profit to increase. Consequently, the overall profitability of the supply chain system improves.

Proposition 2: $\frac{\partial p_2^{M_3}}{\partial R} < 0, \frac{\partial D_1^{M_3}}{\partial R} > 0, \frac{\partial W^{M_3}}{\partial R} > 0, \frac{\partial y^{M_3}}{\partial R} > 0, \frac{\partial U_{OS}^{M_3}}{\partial R} > 0, \frac{\partial \Pi_O^{M_3}}{\partial R} < 0, \frac{\partial \Pi_{OS}^{M_3}}{\partial R} < 0, \frac{\partial p_1^{M_3}}{\partial R} < 0, \frac{\partial D_2^{M_3}}{\partial R} < 0, \frac{\partial \Pi_S^{M_3}}{\partial R} < 0.$

Proposition 2 posits that within the supply chain system, the supplier holds a dominant position and takes corporate social responsibility (CSR) into consideration, while the retailer focuses on maximizing profit. As the supplier's CSR level elevates, a series of changes transpires. The supplier's selling price decreases, yet its investment in preservation efforts surges. Concurrently, the online channel market demand expands, and the wholesale price increases. Paradoxically, the supplier's profit diminishes. At the same time, the social utility welfare function grows, and the overall profit of the supply chain declines. From the retailer's perspective, the decline in retail price is accompanied by a contraction in market demand within the retail channel, leading to a corresponding reduction in profit.

Specifically, by Proposition 2, with the upward trajectory of the supplier's CSR level, the supplier's investment in preservation efforts escalates, and so does the wholesale price. However, due to the decline in the online channel sales price, the retailer also lowered its retail price to enhance market competitiveness. As the supplier continuously enhances its CSR engagement, it places more significant emphasis on product freshness. Despite expanding the online channel market demand, the supplier's profit keeps dropping. This is primarily due to the augmented investment in preservation efforts, which squeezes profit margins.

Furthermore, when consumers become aware that the supplier is shouldering CSR and acting in their interests, they will gravitate towards supporting the supplier's online channel. This, in turn, leads to a reduction in the demand for the retailers' channel, a decline in the retailer's profit, and a negative impact on the overall profitability of the supply chain.

Collectively, Proposition 1 and Proposition 2 elucidate that the dominant position of the supplier exerts a profound influence on the overall profitability of the supply chain. Moreover, there exists a positive correlation between the investment in preservation efforts and the level of corporate social responsibility (CSR).

Proposition 3: (1) $p_1^{M_2} > p_1^{M_1} > p_1^{M_3}, p_2^{M_1} > p_2^{M_3} > p_2^{M_2};$ (2) $w^{M_3} > w^{M_2} > w^{M_1}, y^{M_3} > y^{M_2} > y^{M_1};$ (3) $D_1^{M_3} > D_1^{M_1} > D_1^{M_2}, D_2^{M_2} > D_2^{M_1} > D_2^{M_3}.$

Proposition 3 posits that upon comparing the three models, under scenario M_3 , the supplier sets the lowest online price and encounters the greatest market demand. Scenario M_3 exhibits the highest wholesale price. As for the retail price, scenario M_1 ranks the highest, followed by scenario M_3 and then M_2 . In terms of the supplier's investment in preservation efforts, scenario M_3 leads, with scenarios M_2 and M_1 trailing behind. Scenario M_2 also witnesses the highest demand in the retailer's retail market. The diverse objectives pursued by the members of the supply chain across different models lead to corresponding fluctuations in the key variables.

As indicated by Propositions 1–3, under the dual-channel structure in this paper, the supplier acts as the leader in the Stackelberg game. It can always transfer the additional costs to the retailer by increasing the wholesale price. When the retailer undertakes CSR, the supplier can still maintain its profit by passing on the associated costs. To enhance consumer surplus, the retailer reduces the retail price, sacrificing part of its profit. This stimulates demand in the retail channel, thereby increasing the supplier's profit and ultimately boosting the total profit of the supply chain. In contrast, when the supplier undertakes CSR, to enhance consumer surplus, the supplier increases investment in freshness preservation and intensifies its preservation efforts, while simultaneously reducing the online selling price. This dual strategy exerts pressure on the supplier's profit, resulting in a decline. To offset the resulting profit loss, the supplier raises the wholesale price accordingly. From the retailer's perspective, it must lower the retail price to maintain competitiveness. However, even with this adjustment, it struggles to match the supplier's advantage. Consequently, demand in the online channel surges rapidly, while demand in the retail channel continues to shrink, leading to a decline in the retailer's profit. When the supplier undertakes CSR, the profits of all supply chain members decline, resulting in a reduction in the overall supply chain profit. In summary, for individual supply chain members, undertaking CSR typically results in a partial loss of their profit. For the supply chain as a whole, total profit increases only when the profit gained from CSR outweighs the associated losses.

Proposition 4: *The supplier prefers the scenario where the retailer implements CSR, and hates the scenario where it implements CSR itself. When $0 \leq R < \bar{R}$, the retailer prefers the scenario in which no member implements CSR, followed by the scenario in which it implements CSR itself, and least prefers the scenario in which the supplier implements CSR. When $\bar{R} < R \leq 1$, the retailer still prefers no CSR implementation, but next prefers the scenario in which the supplier implements CSR, and least prefers implementing CSR itself. That is: $\Pi_0^{M_3} < \Pi_0^{M_1} < \Pi_0^{M_2}$, and $\Pi_S^{M_1} > \Pi_S^{M_2} > \Pi_S^{M_3}$ only if $0 < R < \bar{R}$, otherwise, $\Pi_S^{M_1} > \Pi_S^{M_3} > \Pi_S^{M_2}$, where $\bar{R} = \text{Arg}\{R(\beta, \gamma) | \Pi_S^{M_3} - \Pi_S^{M_2} = 0\}.$*

The proof is shown in the appendix.

Proposition 4 posits that across all three models, the supplier's profit is highest under scenario M_2 , followed by scenario M_1 , and then scenario M_3 . The retailer's profit is contingent upon the level of corporate social responsibility (CSR) commitment. When the CSR-related variable R is within a specific range, the profit under scenario M_1 is the largest, followed by the M_2 mode and then scenario M_3 . Once R exceeds this range, scenario M_1 still yields the highest profit, and the M_3 mode generates more profit than scenario M_2 .

Figure 3 illustrates \bar{R} and the retailer's profit region when $v_1 = \frac{1}{2}$ and $v_1 = 1$ respectively. From Figure 3, we can find that the M_3 dominance increases as v_1 decreases.

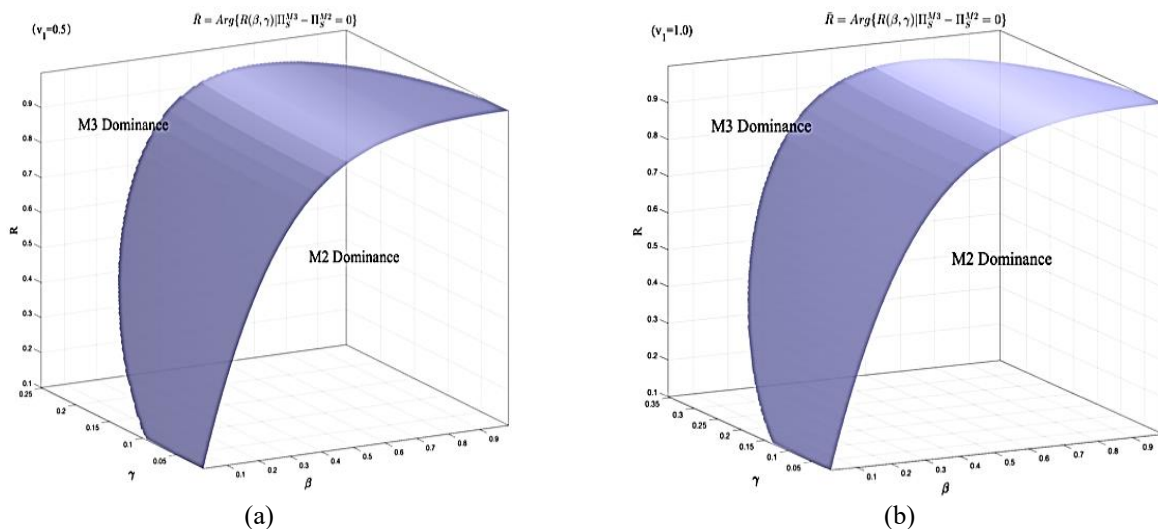


Figure 3. The comparison of Retailer profits between M_2 and M_3 .

For the supplier, when the retailer undertakes CSR—as in scenario M_2 —the retailer aims to maximize a social utility welfare function, while the supplier remains focused on profit maximization. The supplier benefits from an increase in both the wholesale price and demand from the retail channel, as well as a higher price in its direct online channel, all of which contribute to substantial profits. In this scenario, the supplier not only enjoys the benefits brought by CSR but also shifts the increased cost of preservation efforts to the retailer. Hence, the supplier is more inclined to let the retailer undertake CSR responsibilities. In contrast, when the supplier takes on CSR itself, it must simultaneously enhance consumer surplus and bear the cost of preservation, resulting in a dual squeeze on profit, potentially leading to lower profitability than in the scenario without any CSR involvement.

For the retailer, maximum profitability is often achieved when the supply chain does not undertake CSR. In such a case, the retailer neither faces cost pass-through from the supplier nor incurs any CSR-related expenses. When the supply chain undertakes CSR, two situations arise: if the retailer undertakes CSR, it must prioritize maximizing social welfare, which leads to profit losses and additional cost burdens; if the supplier undertakes CSR, the retailer suffers from negative impacts caused by cost pass-through. Specifically, when the level of CSR concern (denoted by R) is low, the profit loss from the retailer undertaking CSR is less than the cost pass-through loss it would bear if the supplier assumes CSR. Thus, a rational retailer would prefer to undertake CSR voluntarily. However, when R is high, the negative impact of undertaking CSR on the retailer's profit becomes substantial. Although cost pass-through from the supplier still imposes a burden, it is less severe than the profit loss from undertaking CSR directly. Hence, the retailer would avoid assuming CSR responsibility.

Moreover, we find that under both M_2 and M_3 scenarios, the retailer's profit increases as the consumer sensitivity factor for freshness rises. This indicates that as consumers place greater emphasis on product freshness, the retailer benefits without incurring any cost related to preservation efforts.

Proposition 5 : $U_0^{M_3} > U_S^{M_2}$

The proof process is shown in the appendix.

Proposition 5 shows that the social welfare utility function under scenario M_3 is more significant than the social welfare utility function under scenario M_2 .

Propositions 1 - 3, along with Proposition 5, suggest that the level of preservation effort and the values of social utility welfare are higher when the supplier undertakes corporate social responsibility (CSR) compared to the non-CSR supply chain scenario (M_1) and the situation where the retailer undertakes CSR (M_2). If one aims to boost social welfare by achieving higher levels of preservation effort, choosing a fresh produce supplier that engages in CSR (M_3) can effectively achieve this objective.

5. NUMERICAL EXAMPLES AND ANALYSIS

To enhance the clarity of the central propositions presented in the article and to conduct a more in-depth exploration of the influence of the supply chain's corporate social responsibility (CSR) level on the equilibrium outcomes under the three modes discussed, this section will build upon the initial analysis. It is assumed that all members within the supply chain are economically rational, adhering to the condition $p \geq w \geq c$. Drawing on the model established in the previous section, data were assigned by referencing the work of Liu *et al.* (2021), and appropriate adjustments were made to align with the actual context of this paper.

Here assumes that $v_1 = 33, \beta = 0.4, c = 20, R = 0.5, a = 100, \gamma = 0.5$ according to the market investigation. When analyzing a specific parameter, the preset value will be adjusted.

5.1. The impact of the level of CSR undertaken on prices

Figures 4 and 5 reveal that the level of CSR undertaken by supply chain members is increasing. Under scenario M_2 (CSR by the retailer), the online channel sales price p_1 rises slightly, aligning with the actual price increase. Conversely, under scenario M_3 (CSR by the supplier), p_1 declines continuously. This trend is associated with the supplier's CSR initiatives, which involve sacrificing profits to enhance social utility welfare.

Figure 6 shows that as CSR levels increase, the retail price p_2 decreases in scenario M_2 and M_3 . Under scenario M_2 , the retailer's selling price falls because it undertakes CSR, prioritizing consumer welfare over its profits. This action enhances the social utility welfare. Under scenario M_3 , the supplier undertakes CSR and lowers the online channel price to enhance consumer surplus. Consequently, the retailer must also reduce its retail price simultaneously to boost its competitiveness.

Figure 7 demonstrates that the wholesale price w increases in scenarios M_2 and M_3 , but the magnitude of the increase varies with the undertaker of CSR. Under scenario M_3 , the rise in w is more pronounced. This is because the supplier's CSR initiative, while benefiting consumers, also increases costs. To offset these costs and maintain profitability, the supplier raises the wholesale price. Under scenario M_2 , the supplier increases the wholesale price to maximize profits,

but the increase is more moderate than in scenario M_3 . This reflects the supplier's consideration to avoid overburdening the retailer, who is already sacrificing profits through CSR initiatives.

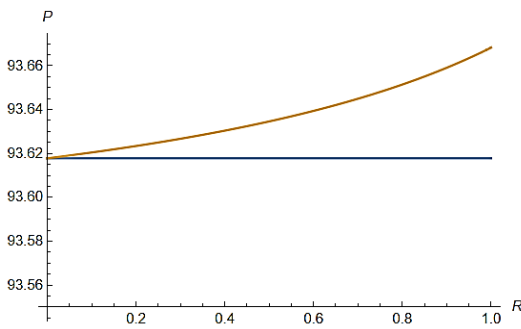


Figure 4. The impact of the proportion of CSR undertaken on $p_1(M_1, M_2)$

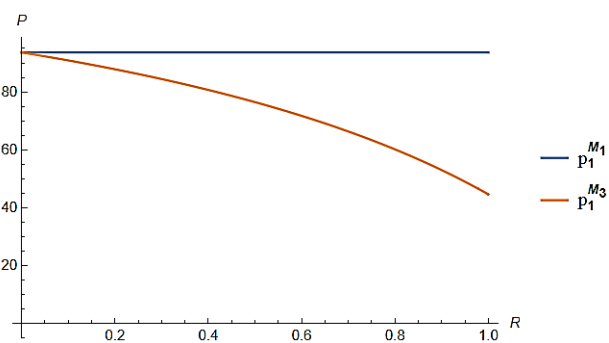


Figure 5. The impact of the proportion of CSR undertaken on $p_1(M_1, M_3)$.

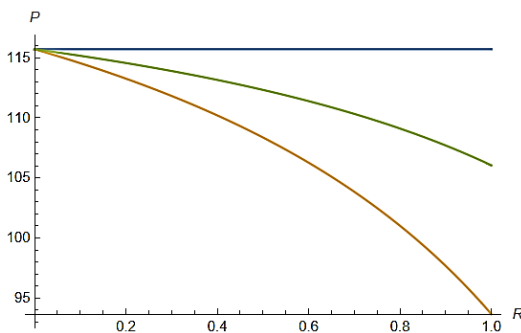


Figure 6. The impact of the proportion of CSR undertaken on p_2 .

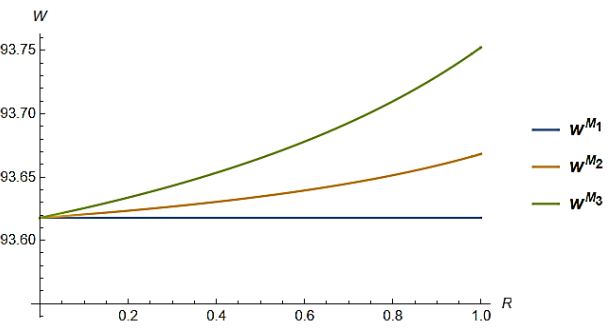


Figure 7. The impact of the proportion of CSR undertaken on w .

5.2. The impact of the level of CSR undertaken on supply chain profitability

Figures 8–10 collectively illustrate the impact of CSR commitment levels on the profits of supply chain members. Firstly, in the case of the supplier, scenario M_2 (CSR undertaken by the retailer) shows that the supplier's profits increase as CSR levels rise. This can be attributed to two primary factors: the supplier's dominant position within the supply chain and the retailer's lack of alternative sourcing options. Motivated by profit maximization, the supplier can effectively compress the retailer's profit margins, increasing its profits.

In contrast, scenario M_3 (CSR undertaken by the supplier) reveals a decline in the supplier's profits. This is primarily due to the CSR initiatives, which require the supplier to sacrifice a portion of its profits to enhance consumer benefits and social welfare. The supplier's profit reduction in this model underscores the trade-offs between corporate profitability and social responsibility.

Secondly, regarding the retailer, Figure 9 demonstrates that retailer profits decline regardless of the CSR adopted. However, the magnitude of the decline and the outcome vary significantly between scenarios. The retailer's profit is always highest under scenario M_1 . When R is low, the profit under scenario M_2 exceeds that of M_3 ; however, when R is high, the profit under scenario M_3 surpasses that of M_2 . Under scenario M_2 , the retailer's profit is squeezed by the supplier's dominant position and CSR cost, leading to a substantial reduction in profitability. Under scenario M_3 , the retailer's profit also declines, which is jointly caused by the supplier's cost shifting and a demand reduction in the retail channel. This highlights the complex interplay between CSR initiatives and profit dynamics within the supply chain, emphasizing the need for strategic decision-making to balance corporate and social objectives.

From Figure 10, when examining the overall supply chain profitability, only scenario M_2 demonstrates an increase in total supply chain profit among the three models. In contrast, scenario M_3 shows a significant reduction in total supply chain profit. Even under scenario M_2 , where the retailer's profit diminishes as CSR commitment increases, the overall supply chain profit still rises, as evidenced by Figures 9 and 10. This underscores the supplier's dominant position in the supply chain and validates the findings of previous studies. Under scenario M_3 , when the supplier undertakes CSR, it sacrifices its profit to maximize social welfare utility. This results in a reduced total supply chain profit. This outcome further highlights the critical role of the supplier's profit in determining the overall supply chain's profitability.

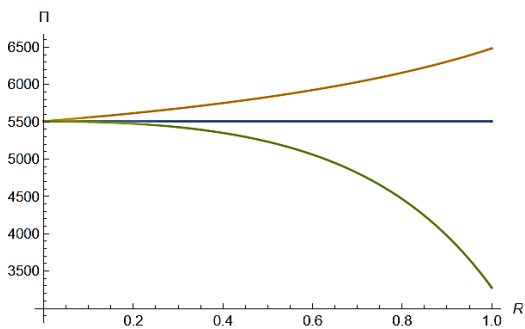


Figure 8. The impact of the proportion of CSR undertaken on supplier profitability.

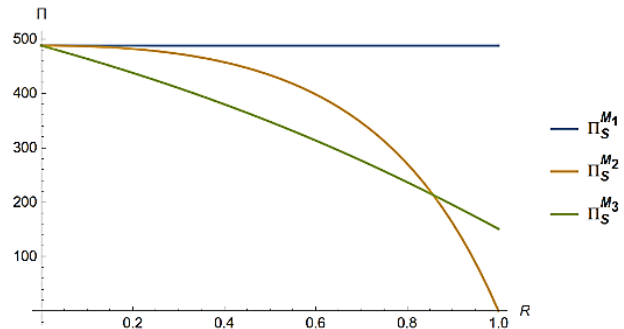


Figure 9. The impact of the proportion of CSR undertaken on retailer profitability.

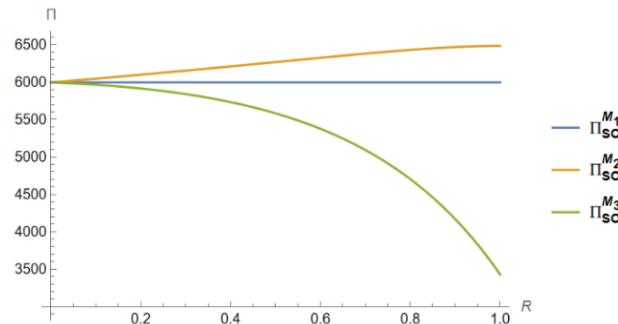


Figure 10. The impact of the proportion of CSR undertaken on the overall profitability of the supply chain.

5.3. The impact of the level of CSR undertaken on preservation efforts, social welfare, and consumer surplus

As depicted in Figure 11, it's obvious that undertaking CSR by the enterprise can improve the consumer surplus, whether the supplier or the retailer is the undertaker. We calculate the consumer surplus in the dual-channel in M_1 , M_2 , and M_3 . Among the three scenarios, consumer surplus is lowest in Scenario M_1 , followed by Scenario M_2 , while Scenario M_3 yields the highest consumer surplus. This outcome arises because, under Scenario M_3 , the supplier holds a dominant position in the channel and can simultaneously enhance preservation efforts and reduce the online channel sales price, thereby increasing consumer surplus. Furthermore, as shown in Figure 12, we apply the social welfare function $SW = \Pi_o + \Pi_s + CS$ to compute the total social welfare in each scenario. The results support our conclusion: corporate engagement in social responsibility significantly enhances social welfare. As the percentage of CSR undertaken increases, the supplier-led CSR scenario initially yields the highest social welfare. However, when R exceeds a certain threshold, the retailer-led CSR scenario results in greater social welfare.

Furthermore, Figure 13 illustrates that the supplier and retailer, when engaging in CSR, contribute significantly to preservation efforts to enhance product freshness. These efforts surpass the level of fresh investment observed in the baseline model (M_1), where no CSR is undertaken. This highlights the positive impact of CSR adoption by supply chain members on overall freshness management and consumer welfare.

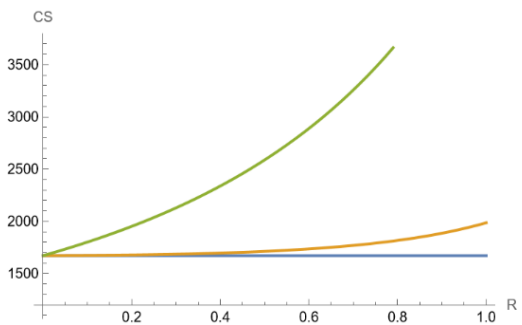


Figure 11. The impact of the proportion of CSR undertaken on the consumer surplus.

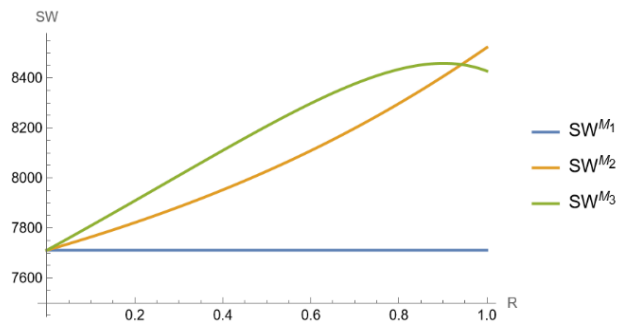


Figure 12. The impact of the proportion of CSR undertaken on the social welfare.

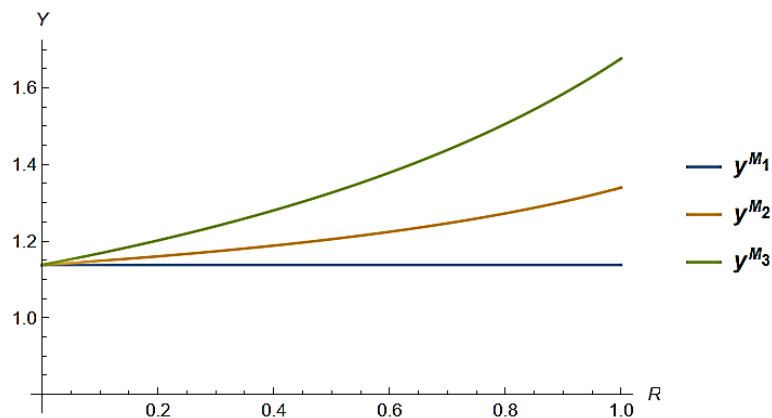


Figure 13. The impact of the proportion of CSR undertaken on preservation efforts

Figures 11 to 13 demonstrate that undertaking CSR has a positive impact on social utility welfare, consumer surplus, and preservation efforts. This highlights the broader benefits of CSR initiatives in enhancing social welfare. However, Figures 8 to 10 indicate that these enhanced outcomes are achieved at the expense of enterprises' profits. This implies that enterprises' ability to transcend short-term gains and proactively assume social responsibility with a long-term perspective is crucial for enhancing social welfare.

6. CONCLUSIONS AND FUTURE RESEARCH

6.1. Conclusions

The rapid development of the social economy and the swift dissemination of information have led to an increasing focus on food safety issues, particularly in the fresh produce sector. Recently, concerns regarding the safety of fresh food have sparked widespread online debates, prompting a critical examination of whether fresh fruit corporations are fulfilling their corporate social responsibility (CSR). As direct stakeholders in food safety, consumers are at the forefront of this discussion.

In this context, this paper employs consumer surplus as a proxy for CSR and constructs three scenarios based on the Stackelberg game framework: Scenario M_1 , where no CSR is undertaken by the supply chain; Scenario M_2 , where CSR is undertaken solely by the retailer; and Scenario M_3 , where CSR is undertaken solely by the supplier. The study analyzes the impact of CSR on preservation efforts, profits, and prices, and through comparative analysis, arrives at the following key conclusions:

- (1) **Impact of CSR Commitment:** When the retailer undertakes CSR, the retail price decreases; when the supplier assumes CSR, the sales price in the online channel is reduced. Both scenarios lead to more significant preservation efforts and an increase in consumer surplus. This suggests that CSR initiatives can enhance overall market efficiency and social welfare.
- (2) **Social Utility and Profit Trade-offs:** Supply chain members often sacrifice their profits to enhance consumer welfare. Given the increasingly fierce competition in the fresh food market, CSR adoption not only improves food quality but also strengthens corporate image and market competitiveness. Therefore, firms must carefully navigate the trade-off between their own profitability and social benefits, striving to achieve a balance that enhances social welfare without incurring excessive profit loss.
- (3) **Retailer-Led CSR scenario (M_2):** In this scenario, the supplier holds a dominant position in the supply chain, leading to increased profits for the supplier and overall supply chain profitability, despite a decline in the retailer's profit. This highlights the significant influence of dominant supply chain members on the behavior and outcomes of other participants.
- (4) **Supplier-Led CSR scenario (M_3):** Although the overall profitability of the supply chain generally decreases under this scenario, higher CSR levels result in fresher finished products and more significant consumer surplus, driven by increased preservation efforts. If the goal is to achieve higher-quality products and higher consumer surplus, the supplier-led CSR scenario (M_3) may be the preferred choice. This finding also provides a theoretical basis for real-world business decision-making.

In summary, this paper underscores the multifaceted impact of CSR on the fresh food supply chain, highlighting the trade-offs between profit maximization and social welfare enhancement. The findings suggest that strategic CSR adoption can improve consumer surplus, enhance social welfare, and contribute to sustainable supply chain management. Future research could explore the optimal allocation of CSR responsibilities within the supply chain to balance profitability and social utility.

In practice, proactive corporate social responsibility (CSR) engagement can generate multiple positive outcomes for both enterprises and society. From the perspective of business development, CSR helps enhance brand image and corporate reputation, foster greater consumer and public recognition, and strengthen supply chain stability through more robust stakeholder relationships. At the societal level, corporate fulfillment of social responsibility plays a vital role in advancing sustainable development and promoting social equity. However, undertaking CSR is not without cost. The implementation process is often accompanied by increased expenses and heightened managerial complexity, thereby imposing financial pressures and administrative challenges on the firm.

Nevertheless, sustained social development still calls for enterprises to shoulder social responsibilities, particularly leading firms in supply chains. These firms should transcend short-term profit considerations and adopt a long-term strategic perspective. Such firms are expected to lead by example, becoming benchmarks for CSR. Their proactive engagement not only benefits their stakeholders but also motivates other supply chain partners to undertake CSR, thereby contributing to broader societal progress. For instance, Freshippo (Hema Fresh) has actively advanced CSR practices across various domains—including sustainable development, rural revitalization, environmental protection, and public welfare—deeply integrating commercial and social value, and establishing itself as a role model for corporate responsibility in the industry. Hema promotes organic farming to reduce chemical usage by establishing "Organic Hema Villages," thereby safeguarding farmers' health while lowering consumer procurement costs. It also advances digital agricultural base construction, supporting farmers in scaling up production and transitioning toward green practices—achieving value co-creation from farm to table. Unilever, meanwhile, has embedded CSR into its corporate DNA by formulating clear policies on key issues such as climate protection, water conservation, sustainable agriculture, food safety, human rights, and consumer rights. In addition to large corporations, small and medium-sized enterprises can also make meaningful contributions to CSR by leveraging their unique capabilities—such as investing in technological innovation, improving energy efficiency, and reducing emissions—to fulfill their social responsibilities through concrete actions.

Ultimately, enterprises must continuously strengthen their sense of responsibility, shifting CSR from a passive obligation to a proactive commitment. The concept of social responsibility should be deeply embedded in corporate strategy and brand development, enabling the synergistic growth of economic performance and social value.

6.2. Future research

This study is not without limitations. First, the study uses consumer surplus as a proxy for CSR performance. However, in practice, CSR encompasses multiple dimensions—such as environmental protection and employee welfare—which may not be fully captured by consumer surplus alone. Future research could incorporate multi-attribute utility theory to evaluate CSR performance more comprehensively. Second, the freshness function adopted in this paper is relatively simple and does not account for time, a key determinant of product freshness. Future studies could model freshness using an exponential function to systematically analyze the dynamic effects of time on product freshness. Finally, the paper employs a standard linear demand function, which may not adequately reflect consumer heterogeneity. In reality, consumer perceptions of CSR can influence purchasing decisions, as many prefer products from firms with strong CSR performance. Future research could adopt the Hotelling model to segment consumers and better capture the characteristics of different demand types.

Besides, this paper focuses solely on a single fresh produce supplier and a single retailer. However, given the highly competitive nature of the market, this assumption is overly idealized. Future research could extend this framework to incorporate multiple suppliers and retailers, more accurately reflecting real-world supply chain dynamics.

With the rapid development of the internet, the e-commerce sector for fresh produce is expanding continuously. Notably, some fresh food e-commerce companies have begun to establish community-based offline stores that integrate online warehousing and distribution functions. Examples include Peapod and Freshippo. The influence of corporate social responsibility (CSR) on decision-making within this "online-to-offline" fresh food supply chain warrants further exploration. Specifically, future research could examine how CSR initiatives impact supply chain efficiency, consumer trust, and overall sustainability.

When companies embrace CSR, they often prioritize maximizing social utility and welfare over maximizing profits. While this may lead to a temporary reduction in profits, it significantly enhances food safety, protecting consumer health and reducing the wastage of social resources. In the long term, such actions can bolster a company's reputation, driving out less responsible competitors and fostering a more sustainable market environment.

Future research could explore innovative contractual mechanisms designed to simultaneously enhance corporate profits and social welfare. Additionally, the role of governments and multinational organizations in incentivizing companies to adopt CSR practices could be examined. These areas hold significant potential for advancing theoretical understanding and practical applications in supply chain management.

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APPENDIX

Proof of Proposition 1

To find out the $p_1^{M_2}$, $D_2^{M_2}$, w^{M_2} , $\Pi_O^{M_2}$, $U_{OS}^{M_2}$, $\Pi_{OS}^{M_2}$, y^{M_2} , $p_2^{M_2}$, $D_1^{M_2}$, $\Pi_S^{M_2}$ -to-R first derivative expression. It can be judged by conditions such as $v_1 > \frac{(3+2\beta)\gamma^2}{2(1-\beta)\beta}$, $1 > \beta > 0$, $0 < \gamma < 1$, $a \gg c > 0$.

Proof of Proposition 2

Proposition 2, whose proof process is the same as Proposition 1.

Proof of Proposition 3

Taking Online Sales Price P_1 as an example, we can get:

$$p_1^{M_1} - p_1^{M_2} = \frac{Rv_1(a+c(-1+\beta))(1-\beta)\gamma^2}{(4v_1(-1+\beta)+(3+\beta)\gamma^2)(2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2)}.$$

Easy-to-know molecules $Rv_1(a+c(-1+\beta))(1-\beta)\gamma^2 > 0$, Then only the denominator needs to be observed.

Since $v_1 > \frac{(3+2\beta)\gamma^2}{2(1-\beta)\beta}$, So $(4v_1(-1+\beta) + (3+\beta)\gamma^2) < 0$, $(2(-2+R)v_1(-1+\beta) + (-3+R+(-1+R)\beta)\gamma^2) > 0$.

We can get $p_1^{M_1} - p_1^{M_2} < 0$.

$$p_1^{M_1} - p_1^{M_3} = \frac{Rv_1(a+c(-1+\beta))(-2+\beta+\beta^2)(4v_1(-1+\beta)+(5+2\beta)\gamma^2)}{(4v_1(-1+\beta)+(3+\beta)\gamma^2)(2v_1(-1+\beta)(4+R(-2+\beta^2))-(-6+R+(-2+R)\beta)\gamma^2)}.$$

Since $(a+c(-1+\beta)) < 0$, $(-2+\beta+\beta^2) < 0$, $Rv_1 > 0$ and $(-1+\beta) < 0$, so $(4v_1(-1+\beta) + (5+2\beta)\gamma^2) < 0$.

So, the numerator is more significant than 0.

About the denominator, since $(4v_1(-1+\beta) + (3+\beta)\gamma^2) < 0$, $(2v_1(-1+\beta)(4+R(-2+\beta^2)) - (-6+R+(-2+R)\beta)\gamma^2) < 0$, So the denominator is more significant than 0.

We can get $p_1^{M_1} - p_1^{M_3} > 0$ and $p_1^{M_2} > p_1^{M_1} > p_1^{M_3}$.

The same can be got for other variables.

Proof of Proposition 4

$$\Pi_O^{M_1} - \Pi_O^{M_2} = \frac{Rv_1^2(a+c(-1+\beta))^2(-1+\beta)^2}{(4v_1(-1+\beta)+(3+\beta)\gamma^2)(2(-2+R)v_1(-1+\beta)+(-3+R+(-1+R)\beta)\gamma^2)}.$$

It is easy to see that the numerator is more significant than 0.

About the denominator, Since $v_1 > \frac{(3+2\beta)\gamma^2}{2(1-\beta)\beta}$, so $(4v_1(-1+\beta) + (3+\beta)\gamma^2) < 0$, $(2(-2+R)v_1(-1+\beta) + (-3+R+(-1+R)\beta)\gamma^2) > 0$. We can get $\Pi_O^{M_1} - \Pi_O^{M_2} < 0$.

$$\Pi_O^{M_1} - \Pi_O^{M_3} = -\frac{R^2v_1^2(a+c(-1+\beta))^2(-2+\beta+\beta^2)^2(2v_1(-1+\beta)(-2+\beta^2)-(-1+\beta)\gamma^2)}{(4v_1(-1+\beta)+(3+\beta)\gamma^2)(-2v_1(-1+\beta)(4+R(-2+\beta^2))+(-6+R+(-2+R)\beta)\gamma^2)^2}.$$

Since $v_1 > \frac{(3+2\beta)\gamma^2}{2(1-\beta)\beta}$, $(2v_1(-1+\beta)(-2+\beta^2) - (-1+\beta)\gamma^2) > 0$, so the numerator is more significant than 0.

Since $v_1 > \frac{(3+2\beta)\gamma^2}{2(1-\beta)\beta}$, $(4v_1(-1+\beta) + (3+\beta)\gamma^2) < 0$, so the denominator is more significant than 0.

We can get $\Pi_0^{M_1} - \Pi_0^{M_3} < 0$.

In summary can be obtained, $\Pi_0^{M_3} < \Pi_0^{M_1} < \Pi_0^{M_2}$.

$$\Pi_S^{M_1} - \Pi_S^{M_2} = v_1^2(a + c(-1 + \beta))^2(-1 + \beta)^2 \left(\frac{1}{(4v_1(-1 + \beta) + (3 + \beta)\gamma^2)^2} + \frac{-1 + R}{(2(-2 + R)v_1(-1 + \beta) + (-3 + R + (-1 + R)\beta)\gamma^2)^2} \right).$$

Because $v_1^2(a + c(-1 + \beta))^2(-1 + \beta)^2 > 0$, we just have to analyze $\left(\frac{1}{(4v_1(-1 + \beta) + (3 + \beta)\gamma^2)^2} + \frac{-1 + R}{(2(-2 + R)v_1(-1 + \beta) + (-3 + R + (-1 + R)\beta)\gamma^2)^2} \right)$ and reduce it. Then, we can get this formula:

$$\frac{R(2v_1(-1 + \beta) + (1 + \beta)\gamma^2)^2 - (-1 + \beta)\gamma^2(4v_1(-1 + \beta) + (3 + \beta)\gamma^2)}{(4v_1(-1 + \beta) + (3 + \beta)\gamma^2)^2(2(-2 + R)v_1(-1 + \beta) + (-3 + R + \beta + R\beta)\gamma^2)^2}.$$

It is easy to learn that the denominator is more significant than 0. We must analyze numerator since $v_1 > \frac{(3 + 2\beta)\gamma^2}{2(1 - \beta)\beta}$, $1 > \beta > 0, 0 < \gamma < 1, a, c > 0$. So, $R(R(2v_1(-1 + \beta) + (1 + \beta)\gamma^2)^2 - (-1 + \beta)\gamma^2(4v_1(-1 + \beta) + (3 + \beta)\gamma^2)) > 0$. We can get $\Pi_S^{M_1} - \Pi_S^{M_2} > 0$.

$$\Pi_S^{M_1} - \Pi_S^{M_3} = v_1^2(a + c(-1 + \beta))^2(-1 + \beta)^2 \left(\frac{1}{(4v_1(-1 + \beta) + (3 + \beta)\gamma^2)^2} - \frac{(-2 + R + R\beta)^2}{(-2v_1(-1 + \beta) + (4 + R(-2 + \beta^2)) + (-6 + R + (-2 + R)\beta)\gamma^2)^2} \right).$$

We just have to analyze $\left(\frac{1}{(4v_1(-1 + \beta) + (3 + \beta)\gamma^2)^2} - \frac{(-2 + R + R\beta)^2}{(-2v_1(-1 + \beta) + (4 + R(-2 + \beta^2)) + (-6 + R + (-2 + R)\beta)\gamma^2)^2} \right)$ and reduce it.

Then, we can get this formula: $\frac{R(2 + \beta)(2v_1(-1 + \beta)\beta + (1 + \beta)\gamma^2)(2v_1(-1 + \beta)(8 + R(-4 - 2\beta + \beta^2)) - (-4(3 + \beta) + R(4 + 5\beta + \beta^2))\gamma^2)}{(4v_1(-1 + \beta) + (3 + \beta)\gamma^2)^2(-2v_1(-1 + \beta) + (4 + R(-2 + \beta^2)) + (-6 + R - 2\beta + R\beta)\gamma^2)^2}$.

It is easy to learn that the denominator is more significant than 0. we just must analyze numerator. Since $(8 + R(-4 - 2\beta + \beta^2)) > 0, 2v_1(-1 + \beta)(8 + R(-4 - 2\beta + \beta^2)) < 0$.

Since $v_1 > \frac{(3 + 2\beta)\gamma^2}{2(1 - \beta)\beta}$, $(2v_1(-1 + \beta)(8 + R(-4 - 2\beta + \beta^2)) - (-4(3 + \beta) + R(4 + 5\beta + \beta^2))\gamma^2) < 0$.

Since $(2v_1(-1 + \beta)\beta + (1 + \beta)\gamma^2) < 0$,

$R(2 + \beta)(2v_1(-1 + \beta)\beta + (1 + \beta)\gamma^2)(2v_1(-1 + \beta)(8 + R(-4 - 2\beta + \beta^2)) - (-4(3 + \beta) + R(4 + 5\beta + \beta^2))\gamma^2) > 0$.

So, the numerator is more significant than 0. We can get $\Pi_S^{M_1} > \Pi_S^{M_3}$.

When $\Pi_S^{M_2} - \Pi_S^{M_3} = 0$, we can get:

$$\bar{R} = \text{Root}[4v_1^2 - 16v_1^2\beta + 24v_1^2\beta^2 - 16v_1^2\beta^3 + 4v_1^2\beta^4 - 8v_1\gamma^2 + 24v_1\beta\gamma^2 - 24v_1\beta^2\gamma^2 + 8v_1\beta^3\gamma^2 + 4\gamma^4 - 8\beta\gamma^4 + 4\beta^2\gamma^4].$$

Where $0 < R < \bar{R}, \Pi_S^{M_2} > \Pi_S^{M_3}$. Where $\bar{R} < R < 1, \Pi_S^{M_3} < \Pi_S^{M_2}$.

In summary can be obtained: $0 < R < \bar{R}, \Pi_S^{M_1} > \Pi_S^{M_2} > \Pi_S^{M_3}, \bar{R} < R < 1, \Pi_S^{M_1} > \Pi_S^{M_3} > \Pi_S^{M_2}$.

Proof of Proposition 5

$$U_0^{M_3} - U_S^{M_2} = \frac{1}{2}v_1(a + c(-1 + \beta))^2 \left(\frac{-6 + R + (-2 + R)\beta}{2v_1(-1 + \beta)(4 + R(-2 + \beta^2)) - (-6 + R + (-2 + R)\beta)\gamma^2} + \frac{(-2 + R)v_1(-1 + \beta)^2}{(2(-2 + R)v_1(-1 + \beta) + (-3 + R + (-1 + R)\beta)\gamma^2)^2} \right).$$

Because $\frac{1}{2}v_1(a + c(-1 + \beta))^2 > 0$, we just have to analyze

$\left(\frac{-6 + R + (-2 + R)\beta}{2v_1(-1 + \beta)(4 + R(-2 + \beta^2)) - (-6 + R + (-2 + R)\beta)\gamma^2} + \frac{(-2 + R)v_1(-1 + \beta)^2}{(2(-2 + R)v_1(-1 + \beta) + (-3 + R + (-1 + R)\beta)\gamma^2)^2} \right)$ and reduce it. we can get this formula:

$$\frac{2v_1^2(-1 + \beta)^2(2R^3(1 + \beta) - 8(5 + 3\beta) + R(48 + 32\beta + 2\beta^2 - 2\beta^3)) + R^2(-18 - 14\beta - \beta^2 + \beta^3)}{((2v_1(-1 + \beta)(4 + R(-2 + \beta^2)) - (-6 + R - 2\beta + R\beta)\gamma^2)(2(-2 + R)v_1(-1 + \beta) + (-3 + R - \beta + R\beta)\gamma^2)^2)}$$

$$\frac{(-2 + R)v_1(-1 + \beta)(66 + 52\beta + 10\beta^2 + 4R^2(1 + \beta)^2 - R(35 + 48\beta + 13\beta^2))\gamma^2 + (-6 + R - 2\beta + R\beta)(-3 + R - \beta + R\beta)^2\gamma^4}{((2v_1(-1 + \beta)(4 + R(-2 + \beta^2)) - (-6 + R - 2\beta + R\beta)\gamma^2)(2(-2 + R)v_1(-1 + \beta) + (-3 + R - \beta + R\beta)\gamma^2)^2)}.$$

About the denominator, Since $R \in [0, 1], \beta \in (0, 1), v_1 > \frac{(3 + 2\beta)\gamma^2}{2(1 - \beta)\beta}$, so $(2v_1(-1 + \beta)(4 + R(-2 + \beta^2)) - (-6 + R - 2\beta + R\beta)\gamma^2) < 0$. It is easy to learn that the denominator is less than 0.

About the numerator, since $R \in [0,1]$, $\beta \in (0,1)$, $v_1 > \frac{(3+2\beta)\gamma^2}{2(1-\beta)\beta}$, we have $(2R^3(1+\beta) - 8(5+3\beta) + R(48 + 32\beta + 2\beta^2 - 2\beta^3)) < 0$. It is easy to learn that the numerator is less than 0.

In summary, we can obtain: $U_O^{M_3} - U_S^{M_2} > 0$.