Optimal Strategies for the Green Supply Chain with Reference Price Effect

Shengju Sang and Zhihui Lu

Abstract—**In this paper, we study the influence of the optimal strategies with the consumer's reference price effect in a green supply chain under decentralized and cooperative policies. The optimal strategies with two Stackelberg game structures and a vertical Nash game are derived. Our results reveal that regardless of bargaining power of the supply chain members, the supplier achieves more profits under the decentralized policy compared to the cooperative one. Meanwhile, both the supply chain members can benefit from integrating the reference price effect into their decision making processes. Additionally, in the absence of reference price considerations, wholesale prices, retail prices, and greening level are all higher than when this effect is accounted for.**

***Index Terms*—reference price effect, channel power structure, optimal strategy, green supply chain,**

I. INTRODUCTION

NOWADAYS, the advent of the green era has caused changes in consumer demand. More and more consumers are inclined to buy energy-efficient, low-polluting, and environmentally friendly products. In response to this trend and to mitigate their environmental footprints, some companies have initiated green practices and are actively promoting eco-friendly products.

Recently, considerable attention on the green supply chains has been given to the examination of pricing strategies. Ghosh and Shah [1] explored how different channel structures influenced wholesale prices, retail prices, greening levels, and profit margins. Qin et al. [2] investigated two environmental cost allocation models using a Nash bargaining game and a Stackelberg game framework, assuming the supplier exhibits fairness concerns. Liu et al.[3] examined the optimal pricing policies and coordination mechanisms with behavioral pricing strategies. Sang [4] investigated the determination of optimal decisions in an uncertain green supply chain, where both market demand and the costs associated with green products were considered as uncertain variables, and the retailer adopted a risk-averse stance. Shen et al.[5] also proposed green supply chain models that incorporate government intervention within an uncertain environment. In a closed-loop supply chain, Yi et al. [6] explored how the supplier's financial constraints and commitment to corporate social responsibility influenced green trade practices. Modak et al. [7] investigated green investment strategies in closed-loop supply chain models under conditions of random pricing. Furthermore, a growing body of research has focused on deriving optimal pricing policies in dual-channel green supply chains. Peng et al. [8] explored competitive and cooperative strategies within dual-channel green supply chains involving two retailers and one supplier. Zhao et al. [9] examined green promotion and pricing decisions with multiple suppliers. Pal et al. [10] investigated the pricing policies, promotional effort and green innovation level, concluding that dual channel structures outperform single-channel ones in terms of efficiency for green product. Barman et al. [11] studied the green supply chain model comprising a retailer, a supplier, and a supplier, employing the Stackelberg game approach to analyze strategic interactions. Yavari et al. [12] analyzed the effects of financial cap-and-trade regulations on pricing decisions under conditions of market disruption. Yan et al. [13] examined optimal pricing and emission reduction policies considering the phenomenon of bidirectional free-riding.

Green supply chain contracts play a crucial role in coordinating profits allocation. Recently, some research has focused on investigating coordination mechanisms in green supply chains to enhance operational efficiency and sustainability performance. To coordinate the green channel, Ghosh and Shah [14] investigated a cost sharing contract. Song and Gao [15] studied a retailer-led revenue sharing contract and a bargaining-based revenue sharing contract, to improve product greening level. Hong and Guo [16] proposed three contract mechanisms to enhance the overall performance of green supply chains. In a green closed loop supply chain, Jia et al. [17] proposed a profit-sharing contract with considering the supplier's fairness concerns. Yang et al. [18] examined three Stackelberg game models incorporating fairness concerns and proposed a cost-sharing contract for coordinating green supply chain operations. Shen et al. [19] proposed a cost-sharing model and a bargaining model to evaluate the impact of contracts on green supply chain performance under uncertainty. In a big data environment, Esmaeeli et al. [20] applied a game theoretic approach to investigate how big data investment influenced decision-making in green supply chains under different power structures.

The consumer usually compares the price of the goods suggested by the retailer with the reference price to determine whether or not to buy green products. Reference price represents the mental price of the consumer, significantly impacts on seller's profit [21], and improves the channel efficiency [22]. In a three-level closed-loop supply chain, Xu and Liu [23] studied the pricing decisions of

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supply chain actors under the influence of reference pricing. Malekian and Rasti-Barzoki [24] analyzed the impact of reference price effects on advertising policies using a game theoretic approach. Colombo and Labrecciosa [25] examined the dynamic pricing strategies in a setting where consumer behavior was influenced by reference price effects. Wang et al. [26] analyzed pricing and inventory policies under a reference price framework with a nonlinear demand function. Sang [27] explored how fairness concerns and reference prices jointly influence greening strategies and pricing decisions. Huang et al. [28] analyzed three government incentive schemes under the influence of consumer reference price effects. They found that the design of subsidy mechanisms was significantly impacted by these reference price effects.

Most existing studies on green supply chains have focused on the greening level decisions made by the supplier, without fully addressing the implications of the reference price effect. This paper examines pricing decisions and greening levels while considering consumer reference price effects. Specifically, we explore scenarios where the supplier alone or in collaboration with the retailer determines the greening level. To underscore the issue of channel conflict, we analyze three primary game-theoretic models involving the interactions between the retailer and the supplier: the Supplier-leader Stackelberg (SS) game, the Retailer-leader Stackelberg (RS) game, and the Vertical Nash (VN) game.

The paper proceeds as follows. Section II presents the problem description and introduces the key notations used in our supply chain models. Section III derives three non-cooperative game scenarios that incorporate the reference price effect, assuming greening level is set by the supplier. Section IV extends the analysis to cooperative settings, presenting three game-theoretic frameworks in which greening level is jointly decided by the supplier and the retailer. Section V offers a comparative evaluation of the results derived in the preceding sections. In Section VI, a numerical example is conducted to illustrate the theoretical findings and offer further insights. Finally, Section VII summarizes the main conclusions and outlines potential areas for further investigation.

II. Model Description

This study focuses on a two-echelon green supply chain consisting of a supplier and a retailer. The supplier provides green products and wholesales them to the retailer, who then sells the products to end consumers. We assume that only one item is provided by the supplier and only single item is sold by the retailer.

Following [1] and [23], the market demand for green products is jointly influenced by several factors, including market potential, retail price, greening level, and consumer reference price. The demand function is formally defined as follows:

$$q = a - bp + \alpha\theta - \beta\left(p - r\right) \quad (1)$$

where $a > 0$ denotes the market scale, $p > 0$ denotes the retail price, $b > 0$ denotes the sensitivity of demand to price, $\theta > 0$ denotes the greening level, $\alpha > 0$ represents the sensitivity of demand to greening level, $r > 0$ represents the reference price, and $\beta > 0$ is the reference price coefficient.

Further, let w represent the supplier's wholesale price, c represent the supplier's marginal cost, m represent the retailer's profit margin. Accordingly, the retail price is $p = w + m$, which reflects the structure that the retail price p consists of the wholesale price w set by supplier plus retailer's profit margin m. As a result, the market demand is

$$q = a - b\left(w+m\right) + \alpha\theta - \beta\left(w+m-r\right) \quad (2)$$

We assume that the supplier's marginal cost is independent of greening level. Furthermore, achieving a certain greening level requires a fixed investment cost, which is expressed as $I\theta^2$. I is the supplier's investment coefficient.

To ensure the existence of optimal solutions in our models, the parameters meet $I > \dfrac{3\alpha^2}{4\left(\beta+b\right)}$.

Based on the problem description, the profits of the supplier and retailer are presented in Equations (3) and (4), respectively.

$$\pi_S = \left(w-c\right)\left[a - b\left(w+m\right) + \alpha\theta - \beta\left(w+m-r\right)\right] - I\theta^2 \quad (3)$$

$$\pi_R = m\left[a - b\left(w+m\right) + \alpha\theta - \beta\left(w+m-r\right)\right] \quad (4)$$

III. Decentralized Channel Policy

Under the decentralized channel policy, the supplier independently determines its own wholesale price and greening level, while the retailer sets its own profit margin.

A. Supplier Stackelberg game

In the Supplier Stackelberg (SS) game, the supplier assumes a dominant role. Accordingly, the supplier is the Stackelberg leader, while the retailer is the follower. Based on the retaile's reaction function, the supplier first determines the wholesale price and greening level. Subsequently, the retailer optimizes its profit margin to maximize its own profit.

Theorem 1. The optimal equilibrium strategies in the SS game are

$$w^{SS*} = \frac{4I\left[a+\beta r-\left(\beta+b\right)c\right]}{8I\left(\beta+b\right)-\alpha^2} + c,$$

$$\theta^{SS*} = \frac{\alpha\left[a+\beta r-\left(\beta+b\right)c\right]}{8I\left(\beta+b\right)-\alpha^2},$$

$$m^{SS*} = \frac{2I\left[a+\beta r-\left(\beta+b\right)c\right]}{8I\left(\beta+b\right)-\alpha^2}.$$

Proof. We obtain the optimal solutions by backward induction. From Equation (4), the reaction function is

$$m\left(w,\theta\right) = \frac{a+\beta r+\alpha\theta-\left(\beta+b\right)w}{2\left(\beta+b\right)}.$$

The supplier's profit function is derived by substituting $m\left(w,\theta\right)$ into (3), which yields:

$$\pi_S = \frac{1}{2}\left(w-c\right)\left[a+\beta r-\left(\beta+b\right)\left(w+m\right)+\alpha\theta\right] - I\theta^2.$$

The Hessian matrix of π_S is

$$\mathrm{H}=\begin{bmatrix}-(b+\beta) & \frac{1}{2}\alpha \\ \frac{1}{2}\alpha & -2I\end{bmatrix}.$$

Since $I>\frac{3\alpha^2}{4(\beta+b)}$, then the H is negative definite matrix. By solving $\partial\pi_{\mathrm{S}}/\partial w=0$ and $\partial\pi_{\mathrm{S}}/\partial\theta=0$, we obtain w^{SS*} and θ^{SS*}. Substituting w^{SS*} and θ^{SS*} into $m(w,\theta)$ yields m^{SS*}.

The proof of Theorem 1 is completed.

From Theorem 1, the optimal retail price, the optimal profits of the supplier and the retailer are as follows:

$$p^{SS*}=m^{SS*}+w^{SS*}=\frac{6I\left[a+\beta r-(\beta+b)c\right]}{8I(\beta+b)-\alpha^2}+c,$$

$$\pi_{\mathrm{S}}{}^{SS*}=\frac{I\left[a+\beta r-(\beta+b)c\right]^2}{8I(\beta+b)-\alpha^2},$$

$$\pi_{\mathrm{R}}{}^{SS*}=\frac{4I^2(\beta+b)\left[a+\beta r-(\beta+b)c\right]^2}{\left[8I(\beta+b)-\alpha^2\right]^2}.$$

Remark 1. If we do not consider the reference price, then the optimal policies in the SS game reduce to

$$w^{SS*}=\frac{4I(a-bc)}{8Ib-\alpha^2}+c,\quad \theta^{SS*}=\frac{\alpha(a-bc)}{8Ib-\alpha^2},$$

$$m^{SS*}=\frac{2I(a-bc)}{8Ib-\alpha^2},\quad p^{SS*}=\frac{6I(a-bc)}{8Ib-\alpha^2}+c,$$

$$\pi_{\mathrm{S}}{}^{SS*}=\frac{I(a-bc)^2}{8Ib-\alpha^2},\quad \pi_{\mathrm{R}}{}^{SS*}=\frac{4I^2b(a-bc)^2}{\left(8Ib-\alpha^2\right)^2}.$$

B. Retailer Stackelberg game

In the Retailer Stackelberg (RS) game, the retailer assumes a dominant role. Based on the supplier's reaction function, the retailer first determines the profit margin. Subsequently, the supplier optimizes its wholesale price and greening level to maximize its own profit.

Theorem 2. The optimal equilibrium strategies in the RS game are

$$w^{RS*}=\frac{I\left[a+\beta r-(\beta+b)c\right]}{4I(\beta+b)-\alpha^2}+c,$$

$$\theta^{RS*}=\frac{\alpha\left[a+\beta r-(\beta+b)c\right]}{2\left[4I(\beta+b)-\alpha^2\right]},$$

$$m^{RS*}=\frac{a+\beta r-(\beta+b)c}{2(\beta+b)}.$$

Proof. We obtain the optimal solutions by backward induction. From Equation (3), by solving $\partial\pi_{\mathrm{S}}/\partial w=0$ and $\partial\pi_{\mathrm{S}}/\partial\theta=0$, the reaction functions are

$$w(m)=\frac{2I\left[a+\beta r-(\beta+b)(m+c)\right]}{4I(\beta+b)-\alpha^2}+c,$$

$$\theta(m)=\frac{\alpha\left[a+\beta r-(\beta+b)(m+c)\right]}{4I(\beta+b)-\alpha^2}.$$

The retailer's profit is derived by substituting $w(m)$ and $\theta(m)$ into (4), which yields:

$$\pi_{\mathrm{R}}=\frac{2I(\beta+b)m\left[a+\beta r-(\beta+b)(m+c)\right]}{4I(\beta+b)-\alpha^2}.$$

By solving $\mathrm{d}\pi_{\mathrm{R}}/\mathrm{d}m=0$, we obtain m^{RS*}. Substituting m^{RS*} into $w(m)$ and $\theta(m)$ yields w^{RS*} and θ^{RS*}.

Theorem 2 is proved.

From Theorem 2, the optimal retail price, the optimal profits of the supplier and the retailer are as follows:

$$p^{RS*}=m^{RS*}+w^{RS*}=\frac{\left[6I(\beta+b)-\alpha^2\right]\left[a+\beta r-(\beta+b)c\right]}{2(\beta+b)\left[4I(\beta+b)-\alpha^2\right]}+c,$$

$$\pi_{\mathrm{S}}{}^{RS*}=\frac{I\left[a+\beta r-(\beta+b)c\right]^2}{4\left[4I(\beta+b)-\alpha^2\right]},$$

$$\pi_{\mathrm{R}}{}^{RS*}=\frac{I\left[a+\beta r-(\beta+b)c\right]^2}{2\left[4I(\beta+b)-\alpha^2\right]}.$$

Remark 2. If we do not consider the reference price, then the optimal policies in the RS game reduce to

$$w^{RS*}=\frac{I(a-bc)}{4Ib-\alpha^2}+c,\quad \theta^{RS*}=\frac{\alpha(a-bc)}{2\left(4Ib-\alpha^2\right)},$$

$$m^{RS*}=\frac{a-bc}{2b},\quad p^{RS*}=\frac{\left(6Ib-\alpha^2\right)(a-bc)}{2b\left(4Ib-\alpha^2\right)}+c,$$

$$\pi_{\mathrm{S}}{}^{RS*}=\frac{I(a-bc)^2}{4\left(4Ib-\alpha^2\right)},\quad \pi_{\mathrm{R}}{}^{RS*}=\frac{I(a-bc)^2}{2\left(4Ib-\alpha^2\right)}.$$

C. Vertical Nash (VN) game

The retailer and the supplier hold symmetric positions in this game. Both players simultaneously and independently determine their respective decision variables to maximize their profits.

Theorem 3. The optimal equilibrium strategies in the VN game are

$$w^{VN*}=\frac{2I\left[a+\beta r-(\beta+b)c\right]}{6I(\beta+b)-\alpha^2}+c,$$

$$\theta^{VN*}=\frac{\alpha\left[a+\beta r-(\beta+b)c\right]}{6I(\beta+b)-\alpha^2},$$

$$m^{VN*}=\frac{2I\left[a+\beta r-(\beta+b)c\right]}{6I(\beta+b)-\alpha^2}.$$

Proof. From Equations (3) and (4), by solving $\partial\pi_{\mathrm{S}}/\partial w=0$, $\partial\pi_{\mathrm{S}}/\partial\theta=0$ and $\mathrm{d}\pi_{\mathrm{R}}/\mathrm{d}m=0$, the optimal solutions w^{VN*}, θ^{VN*} and m^{VN*} can be obtained.

The proof of Theorem 3 is completed.

From Theorem 3, the optimal retail price, the optimal profits of the supplier and the retailer are as follows:

$$p^{VN*}=m^{VN*}+w^{VN*}=\frac{4I\left[a+\beta r-(\beta+b)c\right]}{6I(\beta+b)-\alpha^2}+c,$$

$$\pi_{\mathrm{S}}{}^{VN*}=\frac{I\left[4I(\beta+b)-\alpha^2\right]\left[a+\beta r-(\beta+b)c\right]^2}{\left[6I(\beta+b)-\alpha^2\right]^2},$$

$$\pi_R^{VN*} = \frac{4I^2(\beta+b)[a+\beta r-(\beta+b)c]^2}{[6I(\beta+b)-\alpha^2]^2}.$$

Remark 3. If we do not consider the reference price, then the optimal policies in the VN game reduce to

$$w^{VN*} = \frac{2I(a-bc)}{6Ib-\alpha^2}+c,\quad \theta^{VN*} = \frac{\alpha(a-bc)}{6Ib-\alpha^2},$$

$$m^{VN*} = \frac{2I(a-bc)}{6Ib-\alpha^2},\quad p^{VN*} = \frac{4I(a-bc)}{6Ib-\alpha^2}+c,$$

$$\pi_S^{VN*} = \frac{I(4Ib-\alpha^2)(a-bc)^2}{(6Ib-\alpha^2)^2},\quad \pi_R^{VN*} = \frac{4I^2b(a-bc)^2}{(6Ib-\alpha^2)^2}.$$

IV. COOPERATIVE POLICY

Under this policy, the greening level is set by a bargaining process between the supplier and the retailer. They decide the greening level cooperatively

$$\max\pi = \max\pi_S(\theta)\times\pi_R(\theta) \tag{5}$$

A. Supplier Stackelberg Cooperative Policy

The supplier holds a dominant position in SSCP (Supplier Stackelberg Cooperative Policy). First, the supplier sets its wholesale price by incorporating retailer's reaction function. Subsequently, the retailer sets its profit margin to maximize its own profit. Finally, the greening level is jointly determined through a Nash bargaining scheme.

Theorem 4. The optimal equilibrium strategies in the SSCP are

$$w^{SSCP*} = \frac{A_1[A_2+3I(\beta+b)]}{(\beta+b)A_3}+c,$$

$$m^{SSCP*} = \frac{A_1[A_2+3I(\beta+b)]}{2(\beta+b)A_3},$$

$$\theta^{SSCP*} = \frac{A_1\{2A_2-[2I(\beta+b)-\alpha^2]\}}{\alpha A_3}.$$

where

$$A_1 = a+\beta r-(\beta+b)c,$$

$$A_2 = \sqrt{I(\beta+b)[I(\beta+b)+\alpha^2]},$$

$$A_3 = 8I(\beta+b)-\alpha^2.$$

Proof. We obtain the optimal solutions by backward induction. From Equation (4), the optimal reaction function is

$$m(w,\theta) = \frac{a+\beta r-(\beta+b)w+\alpha\theta}{2(\beta+b)}.$$

The supplier's reaction function is derived by substituting $m(w,\theta)$ into (3), and letting $\partial\pi_S/\partial w = 0$, which yields:

$$w(\theta) = \frac{a+\beta r+(\beta+b)c+\alpha\theta}{2(\beta+b)}.$$

Substituting $w(\theta)$ into $m(w,\theta)$, we can get

$$m(\theta) = \frac{a+\beta r-(\beta+b)c+\alpha\theta}{4(\beta+b)}.$$

Substituting $w(\theta)$ and $m(\theta)$ into Equations (3) and (4), the profit functions are obtained as follows:

$$\pi_S(\theta) = \frac{[a+\beta r-(\beta+b)c+\alpha\theta]^2}{8(\beta+b)} - I\theta^2,$$

$$\pi_R(\theta) = \frac{[a+\beta r-(\beta+b)c+\alpha\theta]^2}{16(\beta+b)}.$$

The supplier and retailer collaboratively determine greening level by solving the following model:

$$\max\pi = \max\pi_S(\theta)\times\pi_R(\theta) = \left\{\frac{[a+\beta r-(\beta+b)c+\alpha\theta]^2}{8(\beta+b)} - I\theta^2\right\}\times\left\{\frac{[a+\beta r-(\beta+b)c+\alpha\theta]^2}{16(\beta+b)}\right\}.$$

By solving $\mathrm{d}\pi/\mathrm{d}\theta = 0$, we have

$$\theta^{SSCP*} = \begin{cases} -\dfrac{A_1}{\alpha} \\ -\dfrac{A_1\{2A_2+[2I(\beta+b)-\alpha^2]\}}{\alpha A_3} \\ \dfrac{A_1\{2A_2-[2I(\beta+b)-\alpha^2]\}}{\alpha A_3} \end{cases}$$

If $I > \dfrac{3\alpha^2}{4(\beta+b)}$, then the third value of θ^{SSCP*} is positive. Substituting θ^{SSCP*} into $w(\theta)$ and $m(\theta)$ yields w^{SSCP*} and m^{SSCP*}.

Theorem 4 is proved.

From Theorem 4, the optimal retail price, the optimal profits of the supplier and the retailer are as follows:

$$p^{SSCP*} = \frac{3A_1[A_2+3I(\beta+b)]}{2(\beta+b)A_3}+c,$$

$$\pi_S^{SSCP*} = \frac{IA_1^2\{2A_2-[2I(\beta+b)-\alpha^2]\}}{2\alpha^2A_3},$$

$$\pi_R^{SSCP*} = \frac{A_1^2[A_2+3I(\beta+b)]^2}{4(\beta+b)A_3^2}.$$

Remark 4. If we do not consider the reference price, then the optimal policies in the SSCP game reduce to

$$w^{SSCP*} = \frac{(\alpha-bc)\left[\sqrt{Ib(Ib+\alpha^2)}+3Ib\right]}{b(8Ib-\alpha^2)}+c,$$

$$m^{SSCP*} = \frac{(\alpha-bc)\left[\sqrt{Ib(Ib+\alpha^2)}+3Ib\right]}{2b(8Ib-\alpha^2)},$$

$$\theta^{SSCP*}=\frac{(\alpha-bc)\left[2\sqrt{Ib\left(Ib+\alpha^2\right)}-\left(2Ib-\alpha^2\right)\right]}{\alpha\left(8Ib-\alpha^2\right)},$$

$$p^{SSCP*}=\frac{3(\alpha-bc)\left[\sqrt{Ib\left(Ib+\alpha^2\right)}+3Ib\right]}{2b\left(8Ib-\alpha^2\right)}+c,$$

$$\pi_S^{SSCP*}=\frac{I(\alpha-bc)^2\left[2\sqrt{Ib\left(Ib+\alpha^2\right)}-\left(2Ib-\alpha^2\right)\right]}{2\alpha^2\left(8Ib-\alpha^2\right)},$$

$$\pi_R^{SSCP*}=\frac{(\alpha-bc)\left[\sqrt{Ib\left(Ib+\alpha^2\right)}+3Ib\right]^2}{4b\left(8Ib-\alpha^2\right)^2}.$$

B. Retailer Stackelberg Cooperative Policy

The retailer holds a dominant position in RSCP (Retailer Stackelberg Cooperative Policy). First, the retailer determines profit margin using the supplier's reaction function. Subsequently, the supplier decides its wholesale price to maximize its own profit. Finally, the greening level is jointly determined through a Nash bargaining scheme.

Theorem 5. The optimal equilibrium strategies in the RSCP are

$$w^{RSCP*}=\frac{B_1\left[B_2+6I(\beta+b)\right]}{2(\beta+b)B_3}+c,$$

$$m^{RSCP*}=\frac{B_1\left[B_2+6I(\beta+b)\right]}{(\beta+b)B_3},$$

$$\theta^{RSCP*}=\frac{B_1\left\{2B_2-\left[4I(\beta+b)-\alpha^2\right]\right\}}{\alpha B_3}.$$

where

$$B_1=a+\beta r-(\beta+b)c,$$

$$B_2=\sqrt{2I(\beta+b)\left[2I(\beta+b)+\alpha^2\right]},$$

$$B_3=16I(\beta+b)-\alpha^2.$$

Proof. We obtain the optimal solutions by backward induction. From Equation (3), the optimal reaction function is

$$w(m,\theta)=\frac{a+\beta r+(\beta+b)c-(\beta+b)m+\alpha\theta}{2(\beta+b)}.$$

Substituting $w(m,\theta)$ into (4), and let $\mathrm{d}\pi_R/\mathrm{d}m=0$, the retailer's reaction function is

$$m(\theta)=\frac{a+\beta r-(\beta+b)c+\alpha\theta}{2(\beta+b)}.$$

Substituting $m(\theta)$ into $w(m,\theta)$, we can get

$$w(\theta)=\frac{a+\beta r+3(\beta+b)c+\alpha\theta}{4(\beta+b)}.$$

Substituting $m(\theta)$ and $w(\theta)$ into Equations (3) and (4), the profit functions are obtained as follows:

$$\pi_S(\theta)=\frac{\left[a+\beta r-(\beta+b)c+\alpha\theta\right]^2}{16(\beta+b)}-I\theta^2,$$

$$\pi_R(\theta)=\frac{\left[a+\beta r-(\beta+b)c+\alpha\theta\right]^2}{8(\beta+b)}.$$

The supplier and retailer collaboratively determine greening level by solving the following model:

$$\max\pi=\max\pi_S(\theta)\times\pi_R(\theta)=\left\{\frac{\left[a+\beta r-(\beta+b)c+\alpha\theta\right]^2}{16(\beta+b)}-I\theta^2\right\}\times\left\{\frac{\left[a+\beta r-(\beta+b)c+\alpha\theta\right]^2}{8(\beta+b)}\right\}.$$

By solving $\mathrm{d}\pi/\mathrm{d}\theta=0$, we have

$$\theta^{RSCP*}=\begin{cases}-\dfrac{B_1}{\alpha}\\ -\dfrac{B_1\left\{2B_2+\left[4I(\beta+b)-\alpha^2\right]\right\}}{\alpha B_3}\\ \dfrac{B_1\left\{2B_2-\left[4I(\beta+b)-\alpha^2\right]\right\}}{\alpha B_3}\end{cases}.$$

If $I>\frac{3\alpha^2}{4(\beta+b)}$, then the third value of θ^{RSCP*} is positive. Substituting θ^{RSCP*} into $w(\theta)$ and $m(\theta)$ yields w^{RSCP*} and m^{RSCP*}.

The proof of Theorem 5 is completed.

From Theorem 5, the optimal retail price, the optimal profits of the supplier and the retailer are as follows:

$$p^{RSCP*}=\frac{3B_1\left[B_2+6I(\beta+b)\right]}{2(\beta+b)B_3}+c,$$

$$\pi_S^{RSCP*}=\frac{IB_1^2\left\{2B_2-\left[4I(\beta+b)-\alpha^2\right]\right\}}{2\alpha^2B_3},$$

$$\pi_R^{RSCP*}=\frac{B_1^2\left[B_2+6I(\beta+b)\right]^2}{2(\beta+b)B_3^2}.$$

Remark 5. If we do not consider the reference price, then the optimal policies in the RSCP game reduce to

$$w^{RSCP*}=\frac{(\alpha-bc)\left[\sqrt{2Ib\left(2Ib+\alpha^2\right)}+6Ib\right]}{2b\left(16Ib-\alpha^2\right)}+c,$$

$$m^{RSCP*}=\frac{(\alpha-bc)\left[\sqrt{2Ib\left(2Ib+\alpha^2\right)}+6Ib\right]}{b\left(16Ib-\alpha^2\right)},$$

$$\theta^{RSCP*}=\frac{(\alpha-bc)\left[2\sqrt{2Ib\left(2Ib+\alpha^2\right)}-\left(4Ib-\alpha^2\right)\right]}{\alpha\left(16Ib-\alpha^2\right)},$$

$$p^{RSCP*}=\frac{3(\alpha-bc)\left[\sqrt{Ib\left(Ib+\alpha^2\right)}+6Ib\right]}{2b\left(16Ib-\alpha^2\right)}+c,$$

$$\pi_S^{RSCP*}=\frac{I(\alpha-bc)^2\left[2\sqrt{2Ib\left(2Ib+\alpha^2\right)}-\left(4Ib-\alpha^2\right)\right]}{2\alpha^2\left(16Ib-\alpha^2\right)},$$

$$\pi_{\mathrm{R}}{}^{RSCP*}=\frac{(\alpha-bc)^2\left[\sqrt{2Ib\left(2Ib+\alpha^2\right)}+6Ib\right]^2}{2b\left(16Ib-\alpha^2\right)^2}.$$

C. Vertical Nash Cooperative Policy

The supplier and the retailer are the same position in the VNCP (Vertical Nash Cooperative Policy). The retailer decides profit margin, while the supplier sets its wholesale price. These decisions are made simultaneously and independently, with each party aiming to maximize its own profit. Then, they determine greening level cooperatively by the Nash bargaining scheme.

Theorem 6. The optimal equilibrium strategies in the VNCP are

$$w^{VNCP*}=\frac{C_1\left[C_2+9I(\beta+b)\right]}{4(\beta+b)C_3}+c,$$

$$m^{VNCP*}=\frac{C_1\left[C_2+9I(\beta+b)\right]}{4(\beta+b)C_3},$$

$$\theta^{VNCP*}=\frac{C_1\left\{3C_2-\left[9I(\beta+b)-4\alpha^2\right]\right\}}{4\alpha C_3}.$$

where

$$C_1=a+\beta r-(\beta+b)c,$$

$$C_2=\sqrt{I(\beta+b)\left[9I(\beta+b)+8\alpha^2\right]},$$

$$C_3=9I(\beta+b)-\alpha^2.$$

Proof. From Equations (3) and (4), by solving $\partial\pi_{\mathrm{S}}/\partial w=0$ and $\partial\pi_{\mathrm{R}}/\partial m=0$, the optimal reaction functions are

$$w(\theta)=\frac{a+\beta r+2(\beta+b)c+\alpha\theta}{3(\beta+b)},$$

$$m(\theta)=\frac{a+\beta r-(\beta+b)c+\alpha\theta}{3(\beta+b)}.$$

Substituting $w(\theta)$ and $m(\theta)$ into Equations (3) and (4), the profits functions are obtained as follows:

$$\pi_{\mathrm{S}}(\theta)=\frac{\left[a+\beta r-(\beta+b)c+\alpha\theta\right]^2}{9(\beta+b)}-I\theta^2,$$

$$\pi_{\mathrm{R}}(\theta)=\frac{\left[a+\beta r-(\beta+b)c+\alpha\theta\right]^2}{9(\beta+b)}.$$

The supplier and retailer collaboratively determine greening level by solving the following model:

$$\max\pi=\max\pi_{\mathrm{S}}(\theta)\times\pi_{\mathrm{R}}(\theta)$$
$$=\left\{\frac{\left[a+\beta r-(\beta+b)c+\alpha\theta\right]^2}{9(\beta+b)}-I\theta^2\right\}\times\left\{\frac{\left[a+\beta r-(\beta+b)c+\alpha\theta\right]^2}{9(\beta+b)}\right\}.$$

By solving $\mathrm{d}\pi/\mathrm{d}\theta=0$, we have

$$\theta^{VNCP*}=\begin{cases}-\dfrac{C_1}{\alpha}\\ -\dfrac{C_1\left\{3C_2+\left[9I(\beta+b)-4\alpha^2\right]\right\}}{4\alpha C_3}\\ \dfrac{C_1\left\{3C_2-\left[9I(\beta+b)-4\alpha^2\right]\right\}}{4\alpha C_3}\end{cases}.$$

If $I>\dfrac{3\alpha^2}{4(\beta+b)}$, then the third value of θ^{VNCP*} is positive. Substituting θ^{VNCP*} into $w(\theta)$ and $m(\theta)$ yields w^{VNCP*} and m^{VNCP*}.

Theorem 6 is proved.

From Theorem 6, the optimal retail price, the optimal profits of the supplier and the retailer are as follows:

$$p^{VNCP*}=\frac{C_1\left[C_2+9I(\beta+b)\right]}{2(\beta+b)C_3}+c,$$

$$\pi_{\mathrm{S}}{}^{VNCP*}=\frac{IC_1^2\left\{3C_2-\left[9I(\beta+b)-4\alpha^2\right]\right\}}{8\alpha^2C_3},$$

$$\pi_{\mathrm{R}}{}^{VNCP*}=\frac{C_1^2\left[C_2+9I(\beta+b)\right]^2}{16(\beta+b)C_3^2}.$$

Remark 6. If we do not consider the reference price, then the optimal policies in the VNCP game reduce to

$$w^{VNCP*}=\frac{(\alpha-bc)\left[\sqrt{Ib\left(9Ib+8\alpha^2\right)}+9Ib\right]}{4b\left(9Ib-\alpha^2\right)}+c,$$

$$m^{VNCP*}=\frac{(\alpha-bc)\left[\sqrt{Ib\left(9Ib+8\alpha^2\right)}+9Ib\right]}{4b\left(9Ib-\alpha^2\right)},$$

$$\theta^{VNCP*}=\frac{(\alpha-bc)\left[3\sqrt{Ib\left(9Ib+\alpha^2\right)}-\left(9Ib-\alpha^2\right)\right]}{4\alpha\left(9Ib-\alpha^2\right)},$$

$$p^{VNCP*}=\frac{(\alpha-bc)\left[\sqrt{Ib\left(9Ib+8\alpha^2\right)}+9Ib\right]}{2b\left(9Ib-\alpha^2\right)}+c,$$

$$\pi_{\mathrm{S}}{}^{VNCP*}=\frac{I(\alpha-bc)^2\left[3\sqrt{Ib\left(9Ib+8\alpha^2\right)}-\left(9Ib-4\alpha^2\right)\right]}{8\alpha^2\left(9Ib-\alpha^2\right)},$$

$$\pi_{\mathrm{R}}{}^{VNCP*}=\frac{(\alpha-bc)^2\left[\sqrt{Ib\left(9Ib+8\alpha^2\right)}+9Ib\right]^2}{16b\left(9Ib-\alpha^2\right)^2}.$$

V. Model Comparison

We discuss the optimal strategies derived in the previous sections with different policies in this section.

Proposition 1. The greening level meets the conditions that

$\theta^{VN*}>\theta^{RS*}>\theta^{SS*}$; $\theta^{SS*}<\theta^{SSCP*}$; $\theta^{RS*}>\theta^{RSCP*}$ and $\theta^{VN*}<\theta^{VNCP*}$.

Proof. $\theta^{VN*}-\theta^{RS*}=\dfrac{\alpha\left[2I(\beta+b)-\alpha^2\right]\left[a+\beta r-(\beta+b)c\right]}{2\left[6I(\beta+b)-\alpha^2\right]\left[4I(\beta+b)-\alpha^2\right]}$,

$$\theta^{RS*}-\theta^{SS*}=\frac{\alpha^3\left[a+\beta r-(\beta+b)c\right]}{2\left[8I(\beta+b)-\alpha^2\right]\left[4I(\beta+b)-\alpha^2\right]}.$$

Since $I>\dfrac{3\alpha^2}{4(\beta+b)}$, we can obtain $\theta^{VN*}-\theta^{RS*}>0$ and $\theta^{RS*}-\theta^{SS*}>0$, that is $\theta^{VN*}>\theta^{RS*}>\theta^{SS*}$.

$$\theta^{SSCP*}-\theta^{SS*}=\frac{2A_1\left[A_2-I(b+\beta)\right]}{\alpha A_3}.$$

Since $I>\dfrac{3\alpha^2}{4(\beta+b)}$ and $A_2=\sqrt{I(\beta+b)\left[I(\beta+b)+\alpha^2\right]}$ $>I(\beta+b)$,we can obtain $\theta^{SSCP*}-\theta^{SS*}>0$, that is $\theta^{SS*}<\theta^{SSCP*}$.

$$\theta^{RS*}-\theta^{RSCP*}=\frac{B_1\left\{32I^2(\beta+b)^2+\alpha^4-4\left[4I(\beta+b)-\alpha^2\right]B_2\right\}}{2\alpha B_3\left[4I(\beta+b)-\alpha^2\right]}.$$

Let $\lambda_1=32I^2(\beta+b)^2+\alpha^4$ and $\lambda_2=4\left[4I(\beta+b)-\alpha^2\right]B_2$, we can obtain

$$\lambda_1^2-\lambda_2^2=\alpha^4\left\{32I(\beta+b)\left[8I(\beta+b)-\alpha^2\right]+\alpha^4\right\}.$$

Since $I>\dfrac{3\alpha^2}{4(\beta+b)}$, we can obtain $\lambda_1^2-\lambda_2^2>0$, that is $\lambda_1>\lambda_2$. Since $\lambda_1>\lambda_2$, we can obtain $\theta^{RS*}>\theta^{RSCP*}$.

$$\theta^{VNCP*}-\theta^{VN*}=\frac{3C_1}{4\alpha C_3\left[6I(\beta+b)-\alpha^2\right]}\times\left\{\left[6I(\beta+b)-\alpha^2\right]C_2-I(\beta+b)\left[18I(\beta+b)+\alpha^2\right]\right\}$$

Let $\lambda_3=\left[6I(\beta+b)-\alpha^2\right]\sqrt{I(b+\beta)\left[9I(\beta+b)+8\alpha^2\right]}$ and $\lambda_4=I(\beta+b)\left[18I(\beta+b)+\alpha^2\right]$, we can get

$$\lambda_3^2-\lambda_4^2=8I(\beta+b)\alpha^2\left\{I(\beta+b)\left[18I(\beta+b)-11\alpha^2\right]+\alpha^4\right.$$

, that is $\lambda_3>\lambda_4$.

Since $\lambda_3>\lambda_4$, we can obtain $\theta^{VNCP*}-\theta^{VN*}>0$, that is $\theta^{VN*}<\theta^{VNCP*}$.

The proof of Proposition 1 is completed.

The results demonstrate that the greening level is the lowest in the SS game, followed by the RS game, with the highest level achieved in the VN game under the decentralized channel policy. The greening level under the SS game is lower than that achieved in SSCP. When the retailer is the leader, the greening level in the RS game is larger than that in the RSCP. When no player is in a dominant position, the greening level in the VNCP is larger than that in the VN game.

The following Propositions can be obtained similar to the proof of the Proposition 1**.**

Proposition 2. The wholesale price meets the conditions that

$w^{SS*}>w^{VN*}>w^{RS*}$; $w^{SS*}<w^{SSCP*}$; $w^{RS*}>w^{RSCP*}$ and $w^{VN*}<w^{VNCP*}$.

The results indicate that the supplier sets the highest wholesale price in the SS game, and the lowest wholesale price in the RS game under the decentralized channel policy. When the supplier is in a dominant position, the wholesale price in the SS game is lower than that in the SSCP. When the retailer is the leader, the wholesale price in the RS game is larger than that in the RSCP. When no player is in a dominant position, the wholesale price in the VN game is lower than that in the VNCP.

Proposition 3. The profit margin of the retailer meets the conditions that

$m^{RS*}>m^{VN*}>m^{SS*}$; $m^{SS*}<m^{SSCP*}$; $m^{RS*}<m^{RSCP*}$ and $m^{VN*}<m^{VNCP*}$.

The results indicate that, the retailer can obtain the highest profit margin in the RS game, and the lowest profit margin in the SS game under the decentralized channel policy. The profit margins in the cooperative policy are all larger than profit margins in decentralized channel policy.

Proposition 4. The retail price meets the conditions that

$p^{SS*}>p^{RS*}>p^{VN*}$; $p^{SS*}<p^{SSCP*}$; $p^{RS*}<p^{RSCP*}$ and $p^{VN*}<p^{VNCP*}$.

The results indicate that, the retailer sets the highest retail price in the SS game, and the lowest retail price in the VN game under the decentralized channel policy. The retail prices in decentralized channel policy are all lower than retail prices in the cooperative policy.

Proposition 5. The supplier's profit meets the conditions that

$\pi_S^{SS*}>\pi_S^{RS*}$; $\pi_S^{SS*}>\pi_S^{SSCP*}$ and $\pi_S^{RS*}>\pi_S^{RSCP*}$.

The results indicate that the profit of the supplier in the SS game is larger than that in the RS game under decentralized channel policy. When the supplier is in a dominant position, the manufacturer obtains more profit in the SS game than that in the SSCP. When the retailer is in a dominant position, the supplier obtains more profit in the RS game than that in the RSCP.

Proposition 6. The retailer's profit meets the conditions that

$\pi_R^{RS*}>\pi_R^{SS*}$; $\pi_R^{SS*}<\pi_R^{SSCP*}$ and $\pi_R^{RS*}>\pi_R^{RSCP*}$.

The results indicate that the retailer's profit in the RS game is larger than that in the SS game under decentralized channel policy. When the manufacturer is in a dominant position, the retailer's profit in the SS game is lower than that in the SSCP. When the retailer is in a dominant position, its profit under the RS game is greater than that achieved in the RSCP.

VI. NUMERICAL EXAMPLE

To illustrate the game-theoretic models proposed above, we present a numerical example in this section. The parameter values are assumed as: the market scale $a=1000$, the sensitivity of price $b=50$, the supplier's marginal cost $c=6$, the sensitivity of greening level $\alpha=40$, and the investment coefficient $I=40$.

The impact of β on the optimal policies is analyzed as follows.

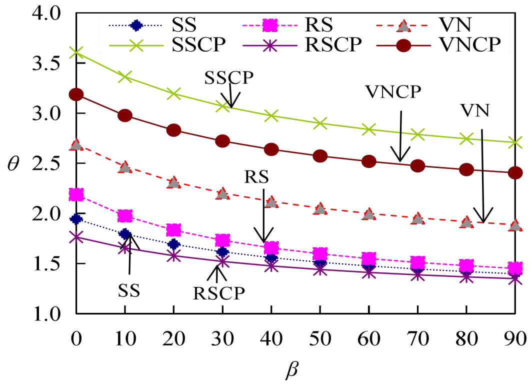

Fig. 1. The greening level with β

Figure 1 illustrates that the supplier sets the lowest greening level in the VNCP, and the highest greening level in the SSCP under the cooperative policy. Moreover, the greening level under the decentralized channel policy is higher than that in the VNCP. This shows that the greening level does not necessarily increase under all cooperative policies.

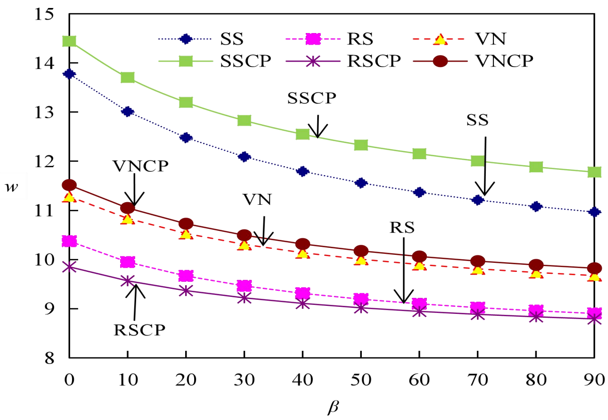

Fig. 2. The wholesale price with β

Figure 2 illustrates that, the supplier sets the highest wholesale price in the SSCP, and the lowest wholesale price in the RSCP under the cooperative policy. Furthermore, the wholesale price decreases as β increases, indicating a negative relationship between the two.

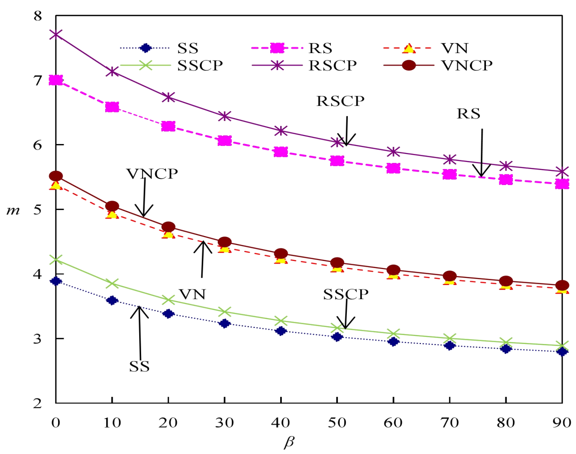

Fig. 3. The profit margin with β

Figure 3 illustrates that, the retailer obtain the highest profit margin in the RSCP, and the lowest profit margin in the SSCP under the cooperative policy. Moreover, the profit margin declines as β increases, indicating a negative sensitivity to consumer reference effects.

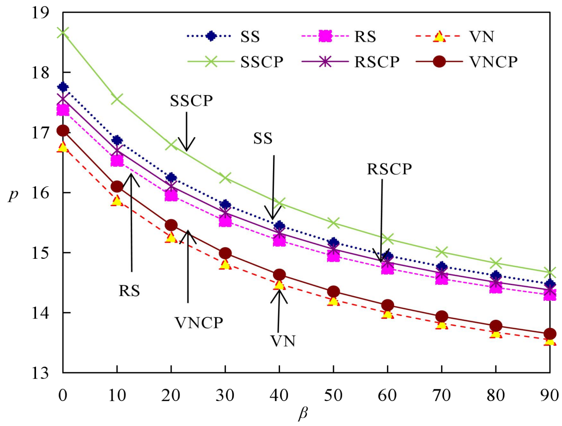

Fig. 4. The retail price with β

Figure 4 illustrates that, the retailer sets the lowest retail price in the VNCP, and the highest retail price in the SSCP. Furthermore, the retail price increases as β decreases.

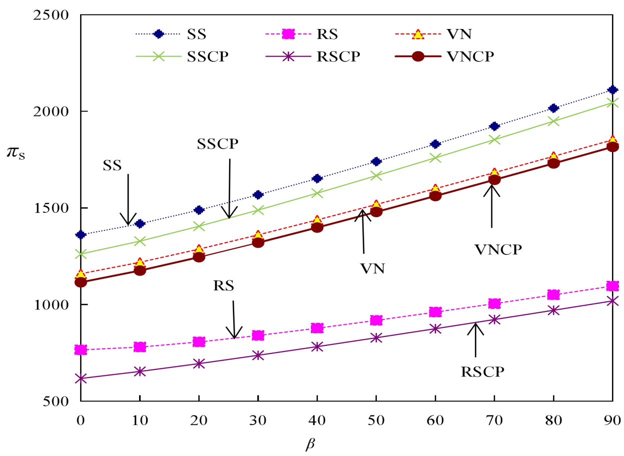

Fig. 5. The manufacture's profit with β

Figure 5 illustrates that, the supplier achieves the highest profit in the SSCP, and the lowest profit in the RSCP under the cooperative policy. Moreover, the manufacture's profit is an increasing function of β.

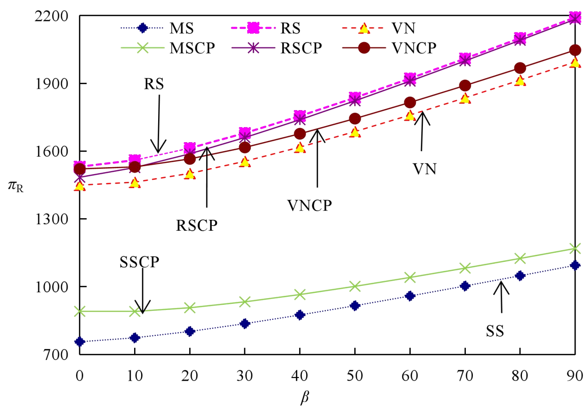

Fig. 6. The retailer's profit with β

Figure 6 illustrates that, the retailer achieves the highest profit when it holds a dominant position in the RSCP, and the lowest profit in the SSCP under the cooperative policy. Meanwhile, the supplier's profit increases as β rises, indicating a positive impact of consumer's reference effects on the supplier's profitability.

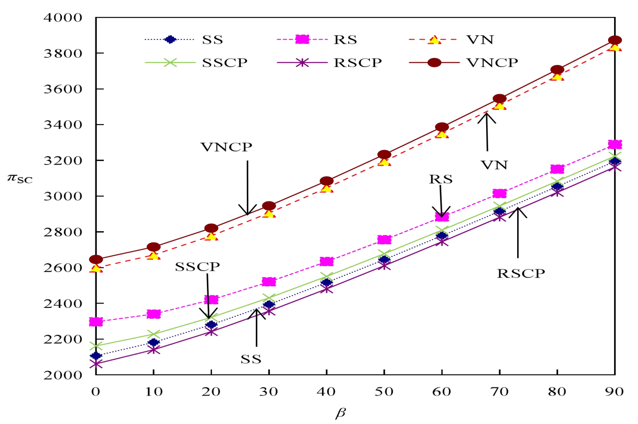

Fig. 7. The supply chain's profit with β

Figure 7 illustrates that, under the cooperative policy, the total supply chain profit is highest in the VNCP, followed by the SSCP, with the lowest profit observed in the RSCP. Moreover, the supply chain profit increases as β rises.

It can also be seen from the above Figures, the optimal policies at β=0 are just the results without considering the customer's reference price. By comparing the optimal strategies with and without the reference price effect, the results show that both the supplier's and the retailer's profits are higher when consumer reference pricing is taken into account. This indicates that both parties can benefit from incorporating consumer's reference effects into their decision-making processes.

VII. Conclusion

This paper investigates the pricing and greening level strategies under decentralized and cooperative policies when the customer's reference price effect is considered in a green supply chain. We also analyze the impact of the reference price coefficient on the greening level, wholesale price, margin profit, retail price and the profits of the supply chain members. Based on the aforementioned results, the following conclusions can be drawn.

First, the supplier's profit is lower in the cooperative policy than in the decentralized policy. When the retailer does not act as the leader, both the greening level and the retailer's profit are enhanced under the cooperative policy. In contrast, when the retailer is the leader, the cooperative policy leads to a decrease in both the greening level and the retailer's profit.

Second, both the supplier's profit and the retailer's profit increase as the reference price coefficient rises. In contrast, the pricing decisions, wholesale price, greening level, and profit margin decrease with the reference price coefficient increasing.

Third, both the retailer's and the supplier's profits are enhanced when consumer reference pricing is taken into account. However, the reference price effect leads to a reduction in both the greening level and the retail price offered to consumers.

There are several promising directions for future research. First, we only investigate linear demand function of the green products. It remains to consider non-linear demand function for future research. Second, we do not consider coordination mechanisms in green supply chains with reference price effects. Future research could explore the application of cost-sharing and revenue-sharing mechanisms for coordinating such supply chains in the presence of reference price effects. Finally, it would also be valuable to extend the model to settings involving multiple suppliers or multiple retailers, where reference price effects may play a more complex and strategic role in influencing pricing and sustainability strategies

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