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Research Article

Equilibrium Decisions on Pricing and the Greenness Degree in Supply Chains under Single- and Cross-Distribution Channels of Green and Nongreen Products and Government Subsidies

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Rapid economic growth and industrialization have brought us material abundance and greater convenience, while also causing socio-environmental problems such as the rapid depletion of resources, unexpected natural disasters, and environmental destruction. For these reasons, environmental issues have attracted public and governmental attention around the world over the past few decades. As a result, environmental sustainability has become a critical indicator for evaluating the success and efficiency of supply chain management schemes. For a sustainable supply chain, many governments are employing subsidy policies to encourage consumers to purchase environment-friendly (green) products. This article considers a supply chain composed of two competing manufacturers and two retailers. The first manufacturer produces a green product, while the second manufacturer produces a nongreen product. Each of the two retailers can sell only a green product, only a nongreen product, or both green and nongreen products. In the market, consumers purchasing the first manufacturer's green products can receive certain subsidies from the government. The amounts of the government subsidies that a consumer receives depend on the greenness degree of the product. Using a three-stage Stackelberg game framework, this article discusses equilibrium decisions on pricing and greenness for four different distribution channel structures. Major findings of this study reveal that (i) the government subsidy has a positive impact on the greenness degree and the demand for green products; (ii) the government subsidy level depends on the manufacturers' distribution channel strategy types; and (iii) the greater the environmentally negative impact of a green product, the lower the level of the government subsidy paid for purchasing green products. Based on these findings, this article suggests that policymakers focus on establishing the policies that encourage the purchase of green products for the sustainability of a society and a supply chain.

1. Introduction

The impact of climate change and global warming on quality of life has recently increased. One of the main causes of this is believed to be rapid economic growth and, as a result, a worsening of the environment. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [1], the Earth's average temperature may increase from a minimum of 1.1~2.9°C to a maximum of 2.4~6.4°C during the twenty-first century, and the rate of global warming is expected to be even faster. With global warming melting sea ice, polar bear populations have plummeted by nearly half in the last decade, and the recent strong storms caused by climate change have had disastrous impacts in South-East Asian countries. Because developing countries are more vulnerable to climate change than advanced countries and given that economic growth and urbanization are expected to progress in the future, extreme weather events threaten the further development of middle-income countries and can even overburden high-income countries. As such, rapid industrialization and economic growth have brought people material abundance and greater convenience while also causing socio-environmental problems such as the rapid depletion of resources, unexpected natural disasters, and environmental destruction. For these reasons, environmental issues have attracted public and governmental attention around the world, and they are also affecting consumer consumption patterns. Consumers have become more aware of environmental degradation and of how their consumption behaviors affect the level of pollution. Thus, consumers' purchasing patterns are becoming more environmentally friendly, and for ecologically minded consumers, protecting the environment has become the first priority when purchasing products [2].

International environmental regulations, which have emerged as a new nontariff trade barrier and the shift by consumers to environmentally friendly consumption patterns, are demanding environmentally friendly supply chain management strategies for many manufacturers. Profitability improvements and cost leadership have been the main goals of supply chain management over the past few decades. However, as people are becoming more conscious about the protection of the environment from pollutant caused by human beings, businesses are adopting green technology to procure green products to save the environment from pollution [3]. The increasing rate of environmental deterioration has shifted this focus to socio-environmental issues; in the context of supply chain research, this has led to more concerns about the sustainability of the supply chain. Gradually, more manufacturers are developing "green" or "sustainable" products made of eco-friendly materials and are increasing their investments in less environmentally harmful manufacturing concepts, such as reuse, refurbishment, recycling, remanufacturing, green product design, product recovery, and waste management. As manufacturers and consumers become more interested in green products, more retailers in the supply chain are also putting green products on their shelves and displaying them. Consumers are now paying attention to sustainable green and organic products and looking for retail outlets that operate in accordance with green methods and green principles. Greening is taking place in many retail sectors, such as clothing and apparel (Ecocentrik Apparel, Natural Clothing Company, and Element Ecowear), furniture (The Old Wood, Eco Select Furniture, and Vermont Woods Studios), and household cleaning products (Wunder Budder). Due to the unprecedented popularity of the green products, traditional large retailers such as Walmart and Tesco are selling green products to their customers alongside existing nongreen products. Walmart has made significant advances in positioning itself to include more green practices in their supply chain operations by enacting a strict policy to cut off suppliers whose manufacturing and distribution methods contribute to environment deterioration. As more retailers deal with green products as well as nongreen products, the distribution channel strategies of manufacturers have a substantial impact on the profitability and sustainability of the supply chain.

Although consumers are aware of the positive impact of green products on the environment, many studies have reported a discrepancy or "gap" between consumers' favorable attitudes and actual purchasing practices [4–7]. Hughner et al. [8] revealed that while many consumers showed a positive attitude toward buying organic food (67%), only a few consumers (4%) actually bought such products. Similarly, according to Defra [9], 30% of consumers in the UK expressed concerns about the environment, but they rarely translated their concerns into the purchasing of green products. This discrepancy is referred to as "green purchasing inconsistency" or the "green attitude-behavior gap," which signifies that consumers' positive attitudes toward green products do not always translate into action. One way to bridge this gap is to encourage consumers to purchase green products by providing subsidies to those who are planning to purchase such products. Recently, car manufacturers have developed environmentally friendly vehicles such as hydrogen-fuel-cell vehicles and plug-in hybrid electric vehicles to mitigate the vast carbon dioxide emissions from cars that use fossil fuels. South Korea will offer more than 827 million USD in subsidies to people who buy electric and hydrogen-fuel-cell electric vehicles in 2020 to promote the use of eco-friendly vehicles that do not emit the greenhouse gases largely responsible for global warming. The Chinese government also plans to phase out subsidies for all electrified vehicles by the end of 2021. The purpose of these government policies is to protect the environment by subsidizing green products and to enhance the profitability and sustainability of the supply chain at the same time.

As such, establishing greening strategies as part of a supply chain management plan is an important task for the sustainability and profitability of supply chain members. With regard to this article, the main research questions are as follows:

(i) Does the government subsidy level affect pricing and greening decisions?

(ii) Does the government subsidy level depend on the manufacturers' distribution channel strategies?

(iii) Does the government subsidy level have a positive or negative impact on the profitability and sustainability of the supply chain?

(iv) How should the government subsidy level be determined in view of profitability and sustainability in the supply chain?

The main purpose of this study is to answer to the research questions using a game-theoretical framework. The detailed objective and contribution of the study are summarized as follows:

(i) This study investigates the relationship between the government's decision on subsidy and the manufacturer's decision on production. This relationship helps supply chain participants establish their own best strategies in supply chains.

(ii) This study identifies the relationship between the government's decision on subsidy and the manufacturer's decision on distribution channel design. This helps the manufacturers in supply chain distribute their products more efficiently.

(iii) This study explores the government's socially best decisions on subsidy. This helps policymakers formulate the policies that can benefit the sustainability and profitability of supply chains.

In this article, two types of manufacturers are assumed: one producing green (environmentally friendly) products and the other producing nongreen (ordinary) products. They compete against each other in a Cournot fashion to maximize their own profits. Cournot competition is an economic model that describes an industry structure in which firms compete on quantity, with decisions made independently of each other and simultaneously [10]. This article develops various game models under various distribution channel structures and suggests an equilibrium decision pertaining to each game model. This article also investigates the effects of the government subsidy level on pricing and greening decisions. In terms of social welfare, this article determines the equilibrium level of the government subsidy. Various numerical examples are presented to support the major findings.

The remainder of this article is organized as follows. Section 2 presents a review of the relevant literature. Section 3 reviews the notations used and the assumptions in the article. Section 4 presents an equilibrium decision of each of the distribution channel structures. Section 5 defines social welfare and determines the government subsidy level. In Section 6, a brief numerical experiment is presented. Section 7 deals with some managerial insights that managers of the business industry get benefit from the findings of this study. The last section provides a summary of the article, presents the conclusion, and provides some directions for future research.

2. Literature Review

This section reviews the relevant literature considering two different streams of research in this area: government subsidies and distribution channel strategies.

A government subsidy or government incentive is a form of financial aid or support extended to an economic sector (business or individual) generally with the aim of promoting certain economic and social policies. Government subsidies can be cash payments and intermediate goods and services provided freely or at nominal prices from governments to suppliers [11]. In the mainstream of economics, government subsidies can be divided into two types: producer subsidy and consumer subsidy. Producer (production) subsidies ensure producers are better off by supplying market price support or payments to factors of production. Consumer (consumption) subsidies commonly reduce the price of products/services to consumers. The effect of a subsidy is to boost the supply and demand by the amount of the subsidy. If a producer receives the subsidy, an increase in the price resulting from the marginal subsidy on production leads to the increase in the supply, shifting the supply curve to the right. If a consumer receives the subsidy, a lower price of a product resulting from the marginal subsidy on consumption increases the demand of a product, also shifting the demand curve to the right. Mitra and Webster [12] analyzed the impacts of government subsidies as a means to promote remanufacturing activities and found that the production subsidy increases remanufacturing activities. They also found that the manufacturer's profit decreases while the remanufacturer's profit increases when the subsidy is provided only to the remanufacturer. Sheu [13] investigated the negotiation problem between producers and reverse-logistics suppliers under the government financial intervention. Using an asymmetrical Nash bargaining game framework, the article showed that the financial intervention by the government is not always beneficial for the profitability of the supply chain members as well as the overall social welfare. Ma et al. [14] focused on the influences of the consumer subsidy on the equilibrium decisions of the members in the dual-channel closed-loop supply chain. They revealed that every consumer purchasing a new product is a beneficiary of the various levels of the government subsidy and the consumer subsidy is conducive to the expansion of the supply chain. Hu et al. [15] proposed the oligopoly game model to explore the competition in the market with both green and ordinary products and asserted that product characteristics and market structures substantially impact the government tax and subsidy policies. Wang et al. [16] analyzed the impact of four subsidy policies on the development of the recycling and remanufacturing industry and found that the combination of several subsidy policies has much more positive effects on remanufacturing promotion. Hafezalkotob [17] surveyed a price competition model between green and regular supply chains under governmental financial intervention, investigating the effects of the environmental protection and revenue-seeking policies by governments on various supply chains. Hafezalkotob [18] extended the work of Hafezalkotob [17], assuming the energy-savings, cooperation, and the sustainable development of the supply chain. Madani and Rasti-Barzoki [19] also studied green supply chains in the context of government intervention and showed that increases in government subsidies lead to increases in the demand for and the degree of greenness of green products. Jena et al. [20] developed four closed-loop supply chain models with which to assess different scenarios of government subsidies, suggesting that governments can maximize the profit of the supply chain and incentivize manufacturers who participate in remanufacturing activities by subsidizing only these manufacturers. He et al. [21] investigated a dual-channel closed-loop supply chain in which a government subsidy is provided to consumers purchasing remanufactured products. Their article showed that when the government subsidy level is relatively low, manufacturers will sell new products directly. Otherwise, manufacturers will sell remanufactured products. Wang et al. [22] investigated the effects of government subsidies on pricing decisions in reverse supply chains of e-waste and found that the remanufacturing utilization rate has a great effect on the equilibrium strategy pertaining to the allocation of the government subsidy. Huang et al. [23] developed game models to address the effects of green loans and government subsidies on the promotion of green innovations by enterprises, showing that government subsidies can effectively incentivize green innovation and improve environmental quality levels. Chen et al. [24] presented game models in which a government determines the amount of its subsidies for a supply chain composed of one manufacturer and one retailer conducting a research joint venture on a sustainable product. Their article suggested that governments should not use multiple types of subsidies simultaneously for any cost-reduction research and development efforts. Liu et al. [25] examined the decision problems of a retailer-dominated supply chain considering corporate social responsibility (CSR) under a government subsidy and found that a certain level of government subsidy can promote supply chain members to undertake CSR and can enhance the performance of the supply chain and social welfare. Wan and Hong [26] developed several Stackelberg game models to investigate the impacts of subsidy policies and transfer pricing policies on the closed-loop supply chain with dual collection channels and found that either remanufacturing or recycling subsidies stimulate the consumption, increase the recovery, and consequently improve the supply chain members' profits. Recently, Sana [27] dealt with a newsvendor inventory model in view of green product marketing of CSR firms. In Sana [27]'s model, a comparison between green and non-green marketing is analyzed considering government subsidies and taxes. Shi et al. [28] developed four green supply chain models considering government subsidy policy and retailer's fairness concerns and showed that the government subsidies to both a manufacturer and a retailer lessen the adverse effect of retailers' fairness concerns and enhance the efficiency of environmental governance. Evolutionary game models and simulation studies of green supply chains under the subsidy policy can be found in Zhao et al. [29] and the references therein.

This work is also related to the literature on distribution channel strategies in supply chains. A variety of distribution channel structures are common in supply chains. Many studies have shown that the profitability of a supply chain depends largely on the structure of the product's distribution channel. McGuire and Staelin [30] discussed the relationship between product substitutability and the equilibrium distribution structure in a duopoly market where each manufacturer distributes its products through a single exclusive retailer. This article asserted that a decentralized channel structure is likely to be adopted by a manufacturer when the competition between products intensifies. Choi [31] dealt with a duopoly common retailer channel and studied the effect of price competition among the members of the channel. The article observed that product differentiation helps manufacturers, whereas it hurts retailers. Conversely, while store differentiation helps retailers, it hurts manufacturers. Moner-Colonques et al. [32] examined an asymmetric noncooperative game between two manufacturers who decide upon the number of retailers and suggested that when product differentiation is strong and brand asymmetry is moderate, the two manufacturers prefer a cross-distribution channel in equilibrium. Wu and Mallik [33] assumed that distribution channel configurations are determined endogenously by a Nash equilibrium state between manufacturers and retailers. They found that manufacturers should strategically use a cross-distribution channel to optimize their profits. Edirisinghe et al. [34] discussed the implications of the distribution channel power on the stability of the supply chain in a setting where multiple manufacturers distribute substitutable products through a common retailer. Their paper found that an imbalance of the channel power leads to a decrease in supply chain profits, and the more balanced the agents are the greater their profits, regardless of the product competition. Bian et al. [35] studied equilibrium distribution channel strategies in a mixed market, assuming that public firms are concerned with social welfare while private firms maximize their profit. In their paper, they found that the equilibrium channel structure depends on the market competition mode (Bertrand or Cournot competition), the form of vertical contract, and the degree of product substitutability. Bian et al. [36] analyzed manufacturers' distribution channel strategies under environmental taxation and suggested that a monopolistic manufacturer can benefit from a decentralized channel structure when its technology is sufficiently polluting and that duopolistic manufacturers are more likely to decentralize their distribution channels when their technologies are more environmentally damaging. Nie et al. [37] investigated the effects of a cross online-and-offline channel (OOC) on two competing retailers' equilibrium decisions and showed that when the cross-channel effect is insignificantly negative or positive, such retailers prefer the OOC strategy, although they face the prisoners' dilemma. Bian et al. [38] discussed dynamic interactions between manufacturers' distribution channel strategies and collusion incentives. They suggested that a single-distribution channel does not always facilitate collusion between manufacturers and held that the selection of the distribution channel mainly depends on the discount factor and on the degree of product

Table 1: Notations.

Indices	
i, j	Manufacturers and retailers ($i, j = 1, 2$)
Decision variables	
g	Greenness degree of a product
q_i	Manufacturer i's selling quantity
q_{ij}	Manufacturer i's selling quantity distributed retailer j ($q_i = q_{ii} + q_{ij}$)
s	Government subsidy level
w_i	Manufacturer i's wholesale price
Parameters	
c_m	Cost coefficient of greenness degree
e	Cost coefficient of the environmental impact of products
f_i	Fixed cost for manufacturer i to open a new distribution channel
β	Consumer value discount for green products ($0 < \beta < 1$)
ρ	Environmental impact discount of green products ($0 < \rho < 1$)
Functions	
p_i	Retail price of manufacturer i's product
π_{mi}	Manufacturer i's profit
π_{ri}	Retailer i's profit
π_s	Supply chain profit ($\pi_s = \pi_{m1} + \pi_{m2} + \pi_{r1} + \pi_{r2}$)
SW	Social welfare

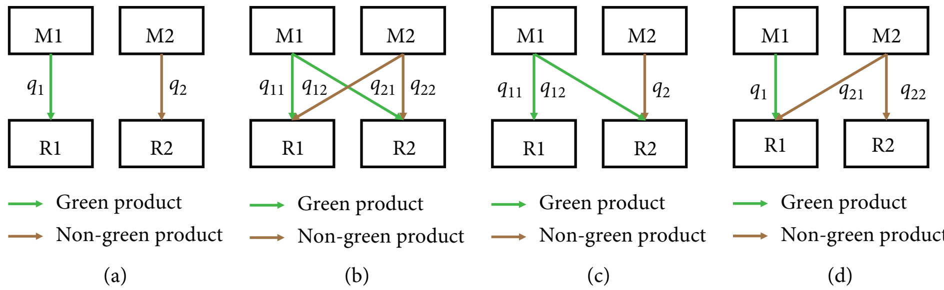

Figure 1: Four distribution channel structures. (a) SS. (b) CC. (c) CS. (d) SC.

differentiation. Readers may refer to Tsay and Agrawal [39] to review of this stream of work.

As discussed above, much in-depth research on government subsidies and distribution channel strategies has been conducted over the past few decades. Governmental financial intervention is an important factor when evaluating the success and efficiency of a supply chain for sustainable growth. In addition, the distribution channel structure plays a very important role in determining the profitability of the supply chain. However, most studies assumed that government subsidies are exogenous. To the best of the author's knowledge, some of them dealt with governmental equilibrium decisions, but they did not consider the impacts of different distribution channel structures by manufacturers. The only paper dealing with all of these issues in a reverse supply chain is that by He et al. [21]. Therefore, this study focuses on how the eco-friendliness of a manufacturer and financial intervention by a government affect the profits of supply chain members under various distribution channel structures.

3. Model Assumptions and Notations

3.1. Notations. This article uses the notations given in Table 1.

3.2. Assumptions. Consider a supply chain composed of two manufacturers and two retailers. In this supply chain, the manufacturers provide consumers with substitutable products. The first manufacturer (M1) produces a green (eco-friendly) product, while the second manufacturer (M2) produces a nongreen (ordinary) product. To stimulate the purchase of the green product, the government subsidizes consumers who purchase M1's green product. All products produced by the two manufacturers are distributed via two retailers (R1 and R2). Each manufacturer can distribute their products through either one retailer or both retailers. Under this supply chain configuration, the following assumptions are made:

Assumption 1. If a manufacturer chooses to distribute through a single retailer, the channel structure is called a single-distribution channel. A cross-distribution channel represents the channel structure by which a manufacturer distributes its products through both retailers. Hence, the following four different distribution channel structures can be defined: the single-single structure (SS), cross-cross structure (CC), cross-single structure (CS), and single-cross structure (SC). This study assumes these four different distribution channel structures (see Figure 1). A similar assumption can be found in earlier works [33–38].

Assumption 2. There is a three-stage game involved in the supply chain. In the first stage of the game, the government announces the subsidy level s, which is applied to M1's green product. In the second stage, M1 determines its wholesale price w_1 and greenness degree g of its green product. At the same time, M2 sets its wholesale price w_2. By specifying the values of s, g, w_1, and w_2, in the last stage of the game, R1 and R2 independently and simultaneously determine the ordering quantity of the manufacturers' products q_1 and q_2. All decisions are assumed to be made in a steady-state period.

Assumption 3. According to Assumption 1, each manufacturer can distribute its product through different retailers; thus, it follows that $q_i = q_{ii} + q_{ij}$ for $i = 1, 2$ and $j = 3 - i$, where q_{ij} is manufacturer i's selling quantity distributed through retailer j. We assume that the products ordered from retailers are consumed entirely in the market.

Assumption 4. There are two types of products (green and nongreen products) in the market and the potential market size for each product is assumed to be scaled to one. Consumers have idiosyncratic valuations of nongreen products with respect to their willingness-to-pay v, which follows a uniform distribution in the interval of $[0, 1]$. This assumption is widely accepted when modeling consumers' heterogeneity [40–42].

Assumption 5. While green products are suitable for protecting the environment, consumers tend to recognize that the performance of green products is worse than that of ordinary (nongreen) products and that the green products may appear to be more expensive [43]. Due to people's tendency to prefer avoiding losses over making equivalent gains, consumers may hesitate to purchase eco-friendly products [44]. Therefore, it is reasonable to assume that for the green product, consumers value each unit at a discount $\beta \in (0, 1)$. With regard to the sustainability of the supply chain, the government provides a subsidy to a consumer who buys a green product, which is proportional to the greenness degree of the green product. Therefore, the net utility of a consumer who purchases a green product and a nongreen product equals $u_1 = \beta v - p_1 + gs$ and $u_2 = v - p_2$, respectively, where p_i is the retail price of the i^{th} manufacturer's product. From several previous studies [14, 21, 41, 42], the inverse linear demand function of each product is given by

$$\begin{cases} p_1(q_1, q_2) = \beta(1 - q_1 - q_2) + gs, \\ p_2(q_1, q_2) = 1 - \beta q_1 - q_2. \end{cases} \quad (1)$$

In order to ensure non-negative demand for each product, the inequalities $gs + \beta p_2 > p_1$ and $1 - gs - \beta + p_1 > p_2$ should be met.

Assumption 6. The investment in greening the product is assumed to be an increasing and convex function of the greenness degree of M1's product. Hence, the greenness cost can be expressed as $c_m g^2/2$, where c_m is the cost coefficient of the greenness degree. Also assume that manufacturer i incurs fixed cost f_i to open another distribution channel. To focus on the effects of the distribution channel and on government intervention in the form of a subsidy, the two manufacturers' production costs are assumed to be constant and normalized to zero. Similarly, the two retailers' operational costs are also normalized to zero. Allowing nonzero production and operational costs will not qualitatively change our results. A similar assumption can be found in Xu et al. [45].

Under Assumptions 1–6, this article develops the game-theoretical models to determine the equilibrium behavior of each participant in the supply chain.

4. Equilibrium Analysis with a Given Government Subsidy

This section presents the equilibrium result of each of the distribution channel structures with a given government subsidy level.

4.1. SS Structure: Both M1 and M2 Adopt a Single-Distribution Channel. First, we discuss the SS structure where M1's green product (M2's nongreen product) is exclusively distributed through R1 (R2) (see Figure 1(a)). Throughout the paper, the SS structure is regarded as a benchmark model. The profit function of each member in the supply chain is given by

$$\begin{cases} \pi_{r1} = (p_1 - w_1)q_1, \\ \pi_{r2} = (p_2 - w_2)q_2, \\ \pi_{m1} = w_1 q_1 - \dfrac{c_m g^2}{2}, \\ \pi_{m2} = w_2 q_2. \end{cases} \quad (2)$$

With a given government subsidy, the decision sequence in the SS structure is

$$\begin{cases} \max\limits_{w_1, g} \pi_{m1} \\ \max\limits_{w_2} \pi_{m2} \end{cases} \longrightarrow \begin{cases} \max\limits_{q_1} \pi_{r1}, \\ \max\limits_{q_2} \pi_{r2}. \end{cases} \quad (3)$$

Applying backward induction to equation (3), the equilibrium values of the decision variables for each player are obtained. Let the superscript $l \in \{SS, CC, CS, SC\}$ denote the equilibrium values in the four distribution channel structures. Table 2 presents the equilibrium solutions of equation (3). All proofs in this article are given in Appendix A.

4.2. CC Structure: Both M1 and M2 Adopt a Cross-Distribution Channel. Next, we analyze the CC structure, where each manufacturer distributes its product via both retailers (see Figure 1(b)). Recall that with the CC structure, $q_i = q_{ii} + q_{ij}$, for $i = 1, 2$ and $j = 3 - i$ because each manufacturer can distribute its product through both retailers. For manufacturer i, additional fixed costs f_i are incurred to open another distribution channel. Hence, the profit function of each member in the supply chain is given by

$$\begin{cases} \pi_{r1} = (p_1 - w_1)q_{11} + (p_2 - w_2)q_{21}, \\ \pi_{r2} = (p_1 - w_1)q_{12} + (p_2 - w_2)q_{22}, \\ \pi_{m1} = w_1(q_{11} + q_{12}) - \dfrac{c_m g^2}{2} - f_1, \\ \pi_{m2} = w_2(q_{21} + q_{22}) - f_2. \end{cases} \quad (4)$$

With the given government subsidy, the decision sequence in the CC structure is

$$\begin{cases} \max\limits_{w_1, g} \pi_{m1}, \\ \max\limits_{w_2} \pi_{m2}, \end{cases} \longrightarrow \begin{cases} \max\limits_{q_{11}, q_{21}} \pi_{r1}, \\ \max\limits_{q_{12}, q_{22}} \pi_{r2}. \end{cases} \quad (5)$$

By backward induction, the equilibrium values of the decision variables for each player are obtained, as shown in Table 2. Note that in the CC structure, the profits of the two retailers are identical.

4.3. CS Structure: M1 Adopts a Cross-Distribution Channel, While M2 Adopts a Single-Distribution Channel. In the CS structure, M1 distributes its green products through both R1 and R2, while M2 distributes its nongreen products only through R2 (see Figure 1(c)). In this case, it follows that $q_1 = q_{11} + q_{12}$ because only green products are distributed via both retailers. For M1, additional fixed costs f_1 are incurred to open another distribution channel. Hence, the profit function of each member in the supply chain is given by

Table 2: Equilibrium decisions in each distribution channel structure.

	$l=SS$	$l=CC$	$l=CS$	$l=SC$
g^l	$2s\beta A_1(6-\beta)$	$2s\beta A_2(1-\beta)$	$5s\beta A_4(1-\beta)(4-\beta)$	$4s\beta A_9(1-\beta)$
w_1^l	$c_m\beta^2 A_1(4-\beta)(6-\beta)$	$3\beta A_0A_2(1-\beta)$	$30\beta A_0A_4(1-\beta)$	$8\beta A_0A_9(1-\beta)$
w_2^l	$A_1(4-\beta)(c_m\beta(8-3\beta)-2s^2)$	$2A_2(1-\beta)(3A_0-s^2)$	$2A_4A_5(1-\beta)$	$4A_9(1-\beta)(4A_0-s^2)$
q_1^l	$2c_m\beta A_1(6-\beta)$	$2A_0A_2$	$5A_0A_4(4-\beta)$	$4A_0A_9$
q_2^l	$A_1(2c_m\beta(8-3\beta)-4s^2)$	$4A_2(3A_0-s^2)/3$	$A_4(3A_0(8-\beta)-2s^2(4-\beta))$	$2A_9/3(4-\beta)(4A_0-s^2)$
q_{11}^l	N/A	A_0A_2	$A_4(2A_0(11-2\beta)-s^2(4-\beta))$	N/A
q_{12}^l	N/A	A_0A_2	$A_4(s^2(4-\beta)-A_0(2+\beta))$	N/A
q_{21}^l	N/A	$2A_2(3A_0-s^2)/3$	N/A	$A_9/3(2A_0(8-5\beta)-s^2(4-\beta))$
q_{22}^l	N/A	$2A_2(3A_0-s^2)/3$	N/A	$A_9/3(2A_0(8+\beta)-s^2(4-\beta))$
p_1^l	$c_m\beta^2 A_1(6-\beta)^2$	$\beta A_2/3(9A_0(2-\beta)-2s^2)$	$\beta A_4(2A_0(26-17\beta)-s^2(4-\beta))$	$\beta A_9/3(2A_0(26-17\beta)-s^2(4-\beta))$
p_2^l	$A_1(6-\beta)(c_m\beta(8-3\beta)-2s^2)$	$A_2/3(3A_0(8-5\beta)-2s^2(4-3\beta))$	A_4A_6	$A_9/3(2A_0(32-23\beta)-s^2(16-13\beta))$
π_{m1}^l	$2c_m\beta^2A_1^2(6-\beta)^2(c_m\beta(4-\beta)-s^2)$	$2A_0^2A_2^2(3A_0-s^2)/c_m-f_1$	$25c_m\beta^2A_4^2A_7/2-f_1$	$8\beta A_0A_9^2(1-\beta)(4A_0-s^2)$
π_{m2}^l	$2A_1^2(4-\beta)(c_m\beta(8-3\beta)-2s^2)^2$	$8A_2^2/3$ (1−β){(3{A_{{0}}}−{s^{{2}}})^{{2}}}−{f_{{2}}}	$2A_4^2A_5^2(1-\beta)$	$8A_9^2/3(1-\beta)(4-\beta)(4A_0-s^2)^2-f_2$
π_{r1}^l	$4c_m^2\beta^3A_1^2(6-\beta)^2$	$A_2^2(4s^4+3c_m\beta A_3)/9$	$\beta A_4^2(2A_0(11-2\beta)-s^2(4-\beta))^2$	$A_9^2A_{10}/9$
π_{r2}^l	$4A_1^2(c_m\beta(8-3\beta)-2s^2)^2$	$A_2^2(4s^4+3c_m\beta A_3)/9$	$A_4^2A_8$	$A_9^2/9(2A_0(8+\beta)-s^2(4-\beta))^2$

Note. The values of A_0 to A_{10} are given in Appendix C.

$$\begin{cases}\pi_{r1}=(p_1-w_1)q_{11},\\ \pi_{r2}=(p_1-w_1)q_{12}+(p_2-w_2)q_2,\\ \pi_{m1}=w_1(q_{11}+q_{12})-\dfrac{c_mg^2}{2}-f_1,\\ \pi_{m2}=w_2q_2.\end{cases} \tag{6}$$

With the given government subsidy, the decision sequence in the CS structure is

$$\begin{cases}\max\limits_{w_1,g}\pi_{m1},\\ \max\limits_{w_2}\pi_{m2},\end{cases}\longrightarrow\begin{cases}\max\limits_{q_{11}}\pi_{r1},\\ \max\limits_{q_{12},q_2}\pi_{r2}.\end{cases} \tag{7}$$

Via backward induction, the equilibrium values of the decision variables for each player are obtained, as presented in Table 2.

4.4. SC Structure: M1 Adopts a Single-Distribution Channel, While M2 Adopts a Cross-Distribution Channel. In the SC structure, as opposed to the CS structure, M1 distributes its green products only through R1, while M2 distributes its nongreen products through both R1 and R2 (see Figure 1(d)). In this case, it follows that $q_2=q_{21}+q_{22}$ because only nongreen products are distributed via both retailers. For M2, additional fixed costs f_2 are incurred to open another distribution channel. Hence, the profit function of each member in the supply chain is given by

$$\begin{cases}\pi_{r1}=(p_1-w_1)q_1+(p_2-w_2)q_{21},\\ \pi_{r2}=(p_2-w_2)q_{22},\\ \pi_{m1}=w_1q_1-\dfrac{c_mg^2}{2},\\ \pi_{m2}=w_2(q_{21}+q_{22})-f_2.\end{cases} \tag{8}$$

With the given government subsidy, the decision sequence in the CS structure is

$$\begin{cases}\max\limits_{w_1,g}\pi_{m1},\\ \max\limits_{w_2}\pi_{m2}.\end{cases}\longrightarrow\begin{cases}\max\limits_{q_1,q_{21}}\pi_{r1},\\ \max\limits_{q_{22}}\pi_{r2}.\end{cases} \tag{9}$$

With backward induction, the equilibrium values of the decision variables for each player are obtained in Table 2.

4.5. Impacts of the Government Subsidy Level. This subsection discusses the impact of the government subsidy level on the equilibrium decisions and profits of the supply chain members and provides some managerial insight. To avoid negative demand for each product, the following inequalities are assumed to hold in each distribution channel structure:

$$\begin{cases}0\le s<s_U^{SS}=\sqrt{c_m\beta(4-\beta)}\ \text{in the SS strucutre},\\ 0\le s<s_U^{CC}=\sqrt{3c_m\beta(1-\beta)}\ \text{in the CC strucutre},\\ 0\le s<s_U^{CS}=\sqrt{\dfrac{12c_m\beta(1-\beta)}{4-\beta}}\ \text{in the CS strucutre},\\ 0\le s<s_U^{SC}=\sqrt{4c_m\beta(1-\beta)}\ \text{in the SC strucutre}.\end{cases} \tag{10}$$

The above equation indicates that the government subsidy should not be too high; otherwise, the green products will squeeze the nongreen products out of the market. At this stage, the following proposition are presented.

Proposition 1. *In each of the distribution channel structures,*

(1) *The government subsidy level has a positive impact on the greenness degree of a green product*

(2) *The government subsidy level has a positive (negative) impact on the wholesale price of a green (nongreen) product*

(3) The government subsidy level has a positive (negative) impact on the selling quantity of a green (nongreen) product

(4) The government subsidy level has a positive (negative) impact on the retail price of a green (nongreen) product

Proposition 2 presents the important fact that the equilibrium decision of each supply chain member depends on the government subsidy level. The government subsidy is available only to consumers who purchase M1's green products, but (Cournot) competition between the manufacturers exists in the supply chain, meaning that all decision behaviors of the supply chain members are dependent on the government subsidy. More specially, the greenness degree of M1's product increases with the government subsidy because the higher the government subsidy, the higher the utility (or preference) of the consumer's green product, while the utility of the nongreen product decreases. The increased (decreased) utility of M1's green product (M2's green product) directly has a positive (negative) impact on its ordering quantity. In other words, as the government subsidy level increases, consumer preferences for the green product (nongreen product) will increase, which will increase (decrease) the demand for the green product (nongreen product) in the market. If the demand for the nongreen product decreases with an increase in the government subsidy level, it is obvious that M2's profit falls. To prevent a decline in the demand for the nongreen product, M2 will choose a strategy that lowers the wholesale price of the nongreen product, which in turn lowers its retail price. Once again, the higher the government subsidy level, the higher the greenness degree of M1's product. As indicated in M1's profit functions, the cost of greening the product increases exponentially. To compensate for the increased costs associated with the greening of the product, M1 will utilize a strategy to raise the wholesale price of its green product, which results in an increase in its retail price. Even if the retail price of the green product rises, the high demand for the green product will continue because the government subsidizes the purchase of the green product.

Unlike Proposition 1, the profit of each supply chain member has different properties in each distribution channel structure. At this point, Proposition 2 is given.

Proposition 2. *The profit of each of the supply chain members has the following properties:*

(1) For all distribution channel structures (i.e., $\forall l \in \{SS, CC, CS, SC\}$), if $0 \leq s < t_{m1}^{l}$ ($t_{m1}^{l} \leq s < s_{U}^{l}$), the government subsidy has a positive (negative) impact on M1's profit.

(2) In the SS and CS structures in which M2 adopts a single-distribution channel (i.e., $\forall l \in \{SS, CS\}$), if $0 \leq s < t_{m2}^{l}$ ($t_{m2}^{l} \leq s < s_{U}^{l}$), the government subsidy has a negative (positive) impact on M2's profit. Meanwhile, in the CC and SC structures in which M2 adopts a cross-distribution channel, the government subsidy always has a negative impact on M2's profit.

(3) For all distribution channel structures, the government subsidy has a positive impact on R1's profit.

(4) In the SS structure, if $0 \leq s < t_{r2}^{SS}$ ($t_{r2}^{SS} \leq s < s_{U}^{SS}$), the government subsidy has a negative (positive) impact on R2's profit. Meanwhile, in the CC, CS, and SC structures, the government subsidy always has a positive impact on R2's profit.

The values of t_{m1}^{l}, t_{m2}^{l}, and t_{r2}^{SS} are given in Appendix C.

Proposition 2 reveals that the all profits of the supply chain members are functions of the government subsidy. This fact is also obvious because the profit consists of the price and demand of a product, which are all affected by the government subsidy. Regardless of the type of distribution channel structure, as the government subsidy level increases, M1's profit initially increases to a certain level; that is, it has a maximum and then decreases drastically. In other words, there exists an optimal value of the government subsidy level t_{m1}^{l} that maximizes M1's profit in all distribution channel structures. An increasing government subsidy increases M1's sales revenue but exponentially increases its greening cost. For this reason, there exists a threshold of the government subsidy level until which M1's (net) profit increases, and if the government subsidy level exceeds this threshold, the cost of greening the product will be too high, which will adversely affect M1's profit. If M2 distributes its nongreen products through only one retailer, specifically R2, M2's profit initially decreases to a certain level; that is, it has a minimum and then increases. In the SS and CS structures, there exists a threshold of the government subsidy level, which minimizes M2's profit; therefore, it is not suggested that the government subsidy level approaches t_{m2}^{l}. On the other hand, if M2 distributes the products through both retailers, its profit decreases consistently with an increase in the government subsidy level. From this fact, the channel choice can be an important decision for M2. In all distribution channel structures, R1's profit always increases with the government subsidy level. In all distribution channel structures, R1 delivers M1's green products to consumers. An increasing government subsidy boosts the demand for green products and R1's profit increases accordingly. If at least one of the manufacturers adopts the cross-distribution channel structure, R2's profit increases consistently with an increase in the government subsidy level. If both manufactures adopt the single-distribution channel structure, R2's profit initially decreases to a certain level; that is, it has a minimum and then increases. If each manufacturer adopts a single channel, the government subsidy level should not approach t_{r2}^{SS} in order to prevent R2's profit from being minimized. As such, each manufacturer's channel choice has an influence on R2's profit. Figure 2 is given to illustrate Proposition 2 with the following parameter settings: $\beta = 0.5$ and $c_m = 50$.

One interesting question arises at this point: in each of the distribution channel structures, how does the trend of the supply chain profit change when the government subsidy level is increased? Proposition 3 provides an answer to this question.

Proposition 3. *In the SS structure, the government subsidy always has a positive impact on the supply chain profit.*

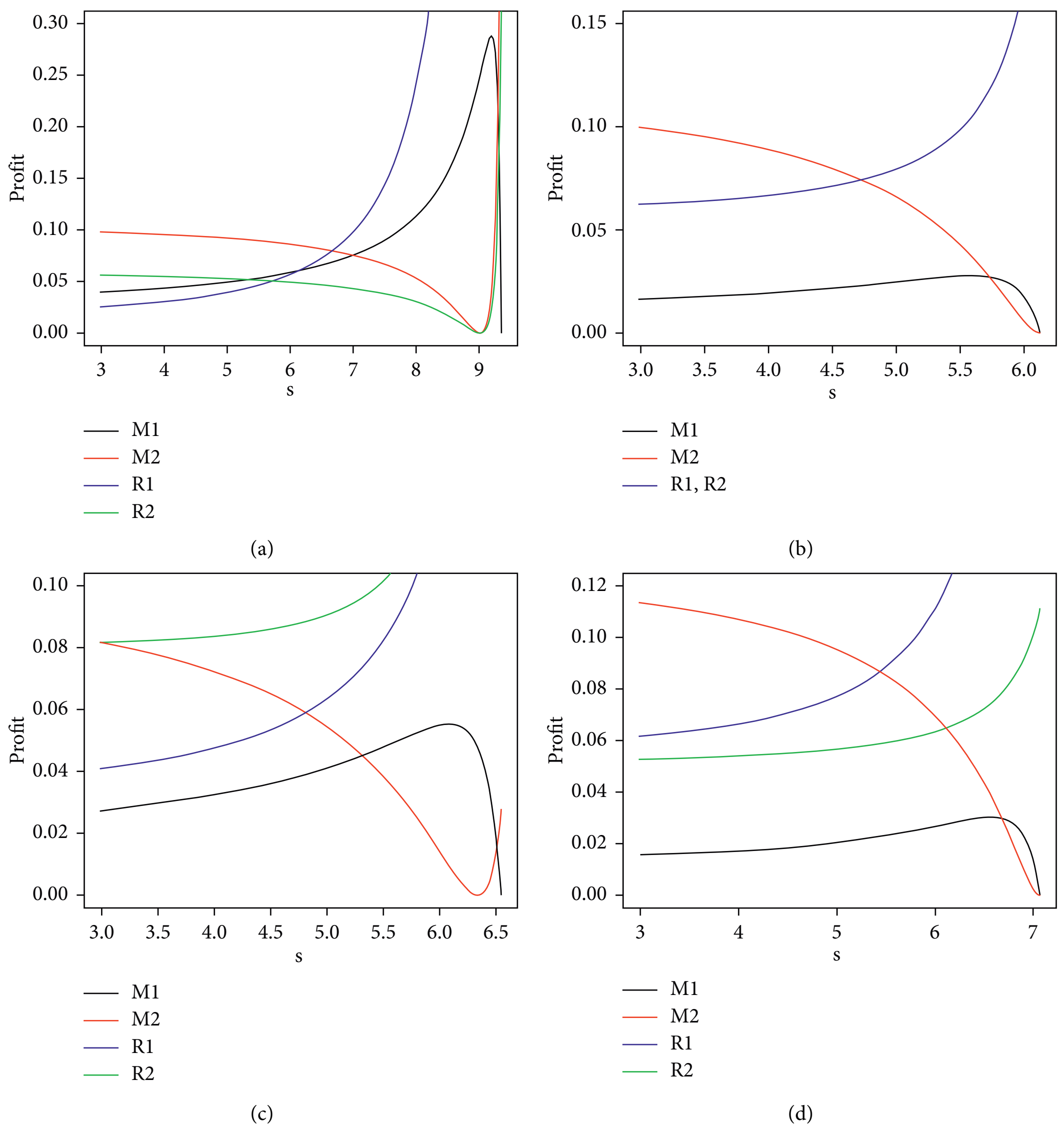

Figure 2: Profits of supply chain members vs. government subsidy level. (a) SS. (b) CC. (c) CS. (d) SC.

Meanwhile, in the CC, CS, and SC structures, if $0 \leq s < t_s^l$ $(t_s^l \leq s < s_U^l)$, *the government subsidy has a negative (positive) impact on the supply chain profit. The values of* t_s^l *are given in Appendix C.*

Note that the supply chain profit is defined as the sum of the profits of all members. Proposition 3 reveals that once at least one of the manufacturers distributes products via both retailers, the supply chain profit is minimal at a certain value of the government subsidy level t_s^l. Therefore, the government subsidy level should not approach t_s^l, not only for profitability but also for the sustainability of the supply chain. On the other hand, when each manufacturer distributes its products exclusively via a single retailer, a higher government subsidy level guarantees greater supply chain profits. Figure 3 illustrates Proposition 3 with the following parameter settings: $\beta = 0.9$ and $c_m = 50$.

4.6. Manufacturer's Channel Choice. This subsection discusses each manufacturer's distribution channel decision. Comparison between each manufacturer's profits under different distribution channel structures results in Propositions 4 and 5.

Proposition 4. *Consider the situation in which both manufacturers currently adopt the single-distribution channel. For each manufacturer, the decision to open a new distribution channel is as follows:*

(1) *Both manufacturers are willing to open a new channel at the same time when* $f_1 < \theta_1^{CC} = 2A_0^2/c_m (A_2^2 (3A_0 - s^2) - A_{13})$ *and* $f_2 < \theta_2^{CC} = 2/3 (4A_2^2 (1 - \beta)(3A_0 - s^2)^2 - A_{14})$

(2) *If only M1 plans to open a new channel and* $f_1 < \theta_1^{CS} = A_0^2/c_m (25A_4^2 A_7/2 (1 - \beta)^2 - 2A_{13})$, *M1 is willing to open a new channel to distribute its green products via another retailer*

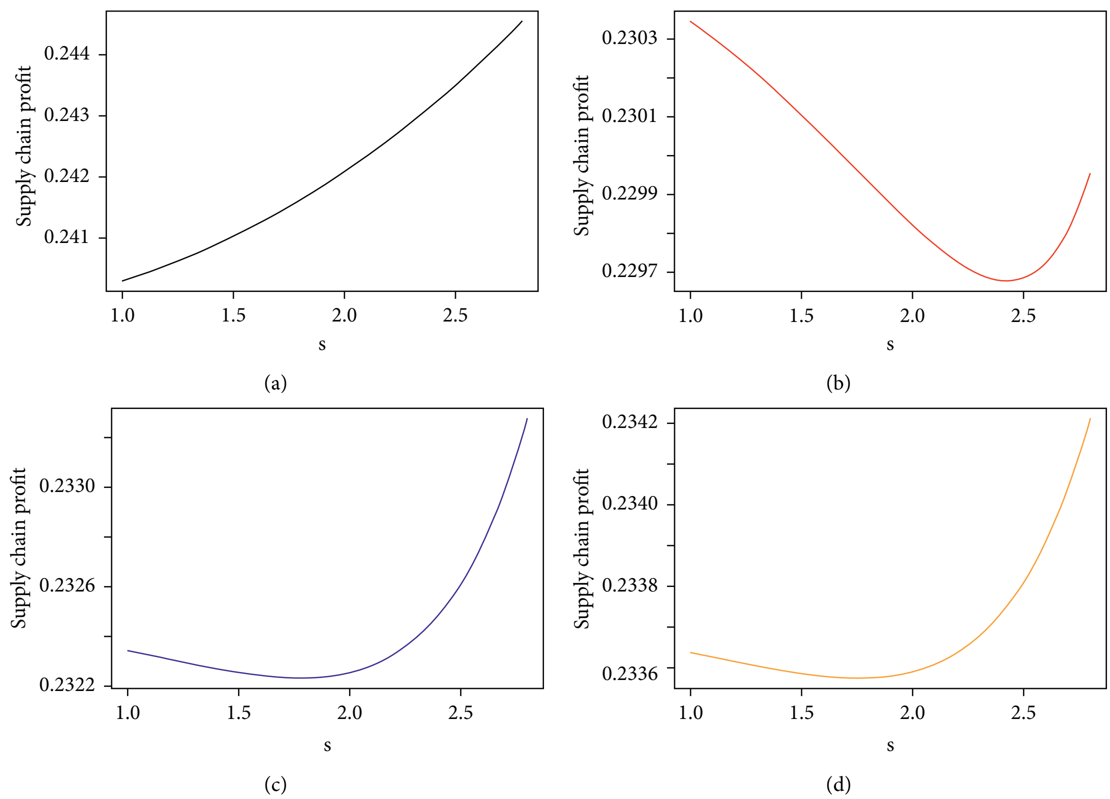

FIGURE 3: Supply chain profit vs. government subsidy level. (a) SS. (b) CC. (c) CS. (d) SC.

(3) If only M2 plans to open a new channel and $f_2 < \theta_2^{SC} = 2/3\,(4A_9^2(4-5\beta+\beta^2)(4A_0-s^2)^2 - A_{14})$, M2 is willing to open a new channel to distribute its nongreen products via another retailer

The values of A_{13} and A_{14} are given in Appendix C.

Proposition 5. *Consider the situation in which one manufacturer currently adopts the single-distribution channel, while the other uses the cross-distribution channel. For each manufacturer, the decision to open a new distribution channel is as follows:*

(1) If $f_1 < \phi_1^{CC} = 2A_0^2/c_m\,(A_2^2(3A_0-s^2) - 4A_9^2(4A_0\ -s^2))$, M1 is willing to open a new channel to distribute its green products via another retailer

(2) If $f_2 < \phi_2^{CC} = 2(1-\beta)/3\,(4A_2^2(3A_0-s^2)^2 - 3A_4^2A_5^2)$, M2 is willing to open a new channel to distribute its nongreen products via another retailer

Propositions 4 and 5 show that the fixed cost of opening a new channel plays a key role in the decision of the manufacturer's channel. If the fixed cost is sufficiently high, the manufacturer will be reluctant to distribute its product via a new retailer and will maintain the current distribution channel structure. However, if the conditions in Propositions 4 and 5 are met, opening a new channel guarantees a higher profit and the manufacturer will be motivated to distribute its product via a new retailer. Propositions 4 and 5 also indicate that the manufacturer's best decision with regard to the channel choice depends on the fixed cost. Varying the value of the fixed cost, Figure 4 plots the manufacturers' profits with the following parameter settings: $\beta = 0.15$, $c_m = 250$, $s = 9.5\,(a)$, $s = 7.5\,(b)$, $f_2 = 0\,(a)$, and $f_1 = 0\,(b)$. Take M1's channel choice strategy as an example (see Figure 4(a)). If both manufacturers currently adopt the single-distribution channel and both want to expand their distribution channel, M1's fixed cost of opening a new channel should not exceed θ_1^{CC} to ensure that $\pi_{m1}^{CC} > \pi_{m1}^{SS}$. If only M1 plans to expand, M1's fixed cost of opening a new channel should not exceed θ_1^{CS} to ensure that $\pi_{m1}^{CS} > \pi_{m1}^{SS}$. Finally, if M2 currently maintains the cross-distribution channel and M1 wants to expand its distribution channel, M1's fixed cost of opening a new channel should not exceed ϕ_1^{CC} to ensure that $\pi_{m1}^{CC} > \pi_{m1}^{SC}$. When the fixed cost is greater than θ_1^{CS}, M1 will then forever abandon any plan to open a new channel, regardless of the channel structure selected by M2. For brevity, we omit M2's channel expansion plan, but similar arguments hold for M2 (see Figure 4(b)). As such, the manufacturers' distribution channel choices differ according to the range of the fixed cost.

5. Government's Equilibrium Decision of the Subsidy Level

Thus far, this article has regarded the government subsidy level as an exogenous parameter. However, henceforth, the government subsidy level is regarded as an endogenous decision variable. In reality, a government may have a goal when implementing financial intervention [18, 46]. Assume

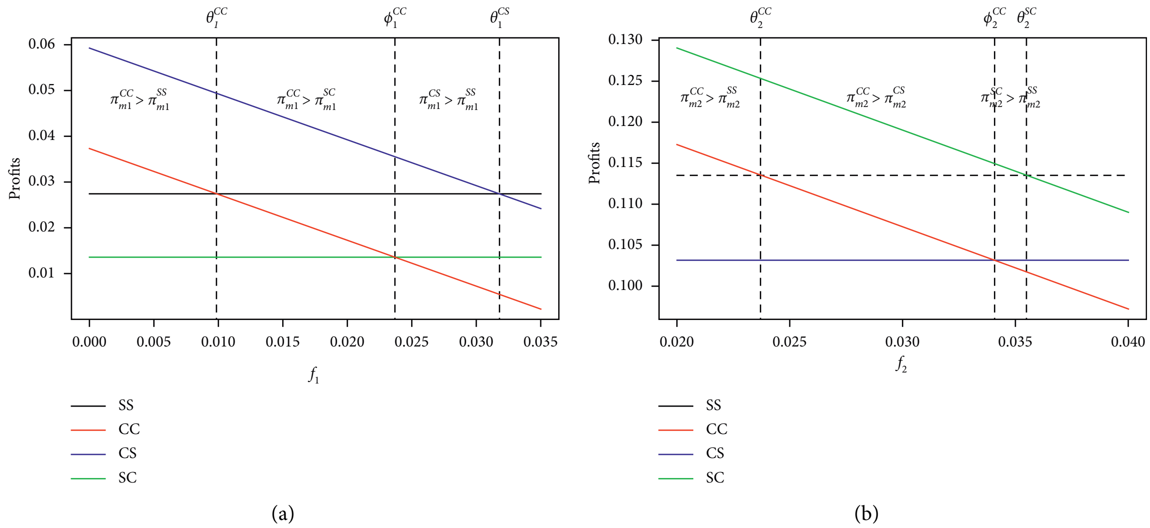

Figure 4: Manufacturer's profit vs. fixed cost. (a) M1's profit. (b) M2's profit.

that the following possible objective is considered by a government: the government wants to maximize social welfare. By determining the government subsidy level s, the government will achieve this objective. All related proofs in Section 5 are given in Appendix B.

This section determines the government subsidy level to maximize social welfare. To do this, this section initially formulates the revenue and the cost terms separately and then integrates them to derive the objective function of the government problem, which is social welfare in this case.

(1) Supply chain profit π_s^l: the supply chain profit is defined as the sum of the profits of all members participating in the supply chain. In each of the distribution channel structures, it has the form of

$$\pi_s^l = \pi_{m1}^l + \pi_{m2}^l + \pi_{r1}^l + \pi_{r2}^l, \text{For} \in \{SS, CC, CS, SC\}. \quad (11)$$

(2) Consumer surplus S_c^l: in economics, a consumer surplus, also known as an economic surplus and a Marshallian surplus, is the difference between the maximum price consumers are willing to pay and the actual price they pay. Therefore, it can be formulated as

$$S_c^l = \int_{p_1^l}^{p_1^{\max}} q_1^l \mathrm{d}p_1 + \int_{p_2^l}^{p_2^{\max}} q_2^l \mathrm{d}p_2 = \frac{1}{2}\left(q_1^l\left(\beta + gs - p_1^l\right) + q_2^l\left(1 - p_2^l\right)\right), \text{For} \in \{SS, CC, CS, SC\}, \quad (12)$$

where according to equation (1), $p_i^l = p_i(q_1^l, q_2^l)$ and $p_i^{\max} = p_i(0,0)$ for $i = 1, 2$.

(3) Environmental impact cost E_g^l: the government wants to minimize environmental degradation, while the manufacturers distribute products in the supply chain. Let parameter e and ρ denote the unit environmental impact of nongreen products and the unit environmental impact discount of green products relative to nongreen products, respectively. Thus, the unit environmental impact of green products is ρe. The lower the value of ρ, the more environmentally beneficial the green products in comparison with nongreen products. A similar assumption can be found in He et l. [21]. Consequently, the environmental impact cost is given by

$$E_g^l = e\left(\rho q_1^l + q_2^l\right), \text{For} \in \{SS, CC, CS, SC\}. \quad (13)$$

(4) Government expenditure X_g^l: the government expenditure is defined as the total government subsidies provided to consumers who purchase M1's green products. Therefore, it can be formulated as

$$X_g^l = g^l s q_1^l, \text{For} \in \{SS, CC, CS, SC\}. \quad (14)$$

With equations (11)–(13), social welfare is defined as

$$SW^l(s) = \pi_s^l + S_c^l - E_g^l - X_g^l, \text{For} \in \{SS, CC, CS, SC\}. \quad (15)$$

Before determining the equilibrium government subsidy level, it is important to analyze the properties of the consumer surplus, environmental impact cost, and government expenditure. Propositions 6 and 7 are given.

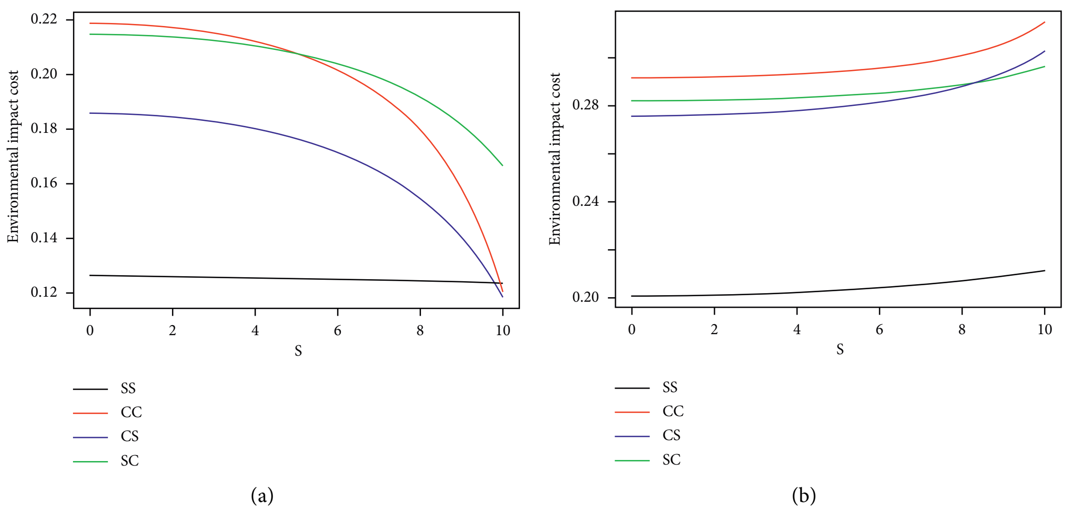

Figure 5: Environmental impact cost vs. government subsidy level. (a) $\rho = 0.1$. (b) $\rho = 0.8$.

Proposition 6. *In all the distribution channel structures, the government subsidy level has a positive impact on consumer surplus and government expenditures.*

Proposition 6 says that a higher government subsidy level yields greater consumer surplus. Due to the associated government subsidy, the purchase of green products results in more surplus. As M1's demand for green products increases, the competition between the two manufacturers intensifies, lowering the retail price of nongreen products. Thus, consumers also gain a greater level of surplus from nongreen products. In short, a higher level of the government subsidy increases overall consumer surplus. It is revealed from Proposition 6 that government expenditures increase as the government subsidy level increases. It is obvious that a higher government subsidy level increases not only the greenness degree but also the demand for M1's green product, resulting in increased government expenditures for green products.

Proposition 7. *In each of the distribution channel structures, the environmental impact cost increases (decreases) when $\rho > t_g^l$ ($\rho < t_g^l$). The values of t_g^l are given in Appendix C.*

Proposition 7 implies that the increase or decrease in the environmental impact cost depends on the range in which ρ belongs. In other words, the environmental impact cost will decrease (increase) when the unit environmental impact discount of green products is lower (larger) than the threshold t_g^l. Figure 5 depicts Proposition 7 with the following parameters settings: $e = 0.5$, $\beta = 0.8$, $c_m = 250$, $f_1 = f_2 = 0$, $\rho = 0.1\,(a)$, and $\rho = 0.8\,(b)$. It can be observed from Figure 5 that when ρ is low (high), E_g^l consistently decreases (increases). As mentioned above, the smaller the value of ρ, the less impact the green product has on the environment. Hence, when the value of ρ is small, an increase in the government subsidy increases the demand for green products, having less of an impact on the environment and resulting in a decrease in the environmental impact cost. On the other hand, when the value of ρ is high, the impact of the green products on the environment becomes similar to that of the nongreen products. If this is the case, an increase in the government subsidy level increases the demand for green products, resulting in an increase in the environmental impact cost.

Let s_g^l denote the equilibrium level of the government subsidy. For each of the distribution channel structures, s_g^l is expressed as

$$s_g^l = \underset{0 \leq s < s_U^l}{\arg\max}\ SW^l(s), \text{For} \in \{SS, CC, CS, SC\}. \tag{16}$$

At this point, the final proposition of this article is presented as follows:

Proposition 8. *In each of the distribution channel structures, if $\rho < t_g^l$, then s_g^l is given by*

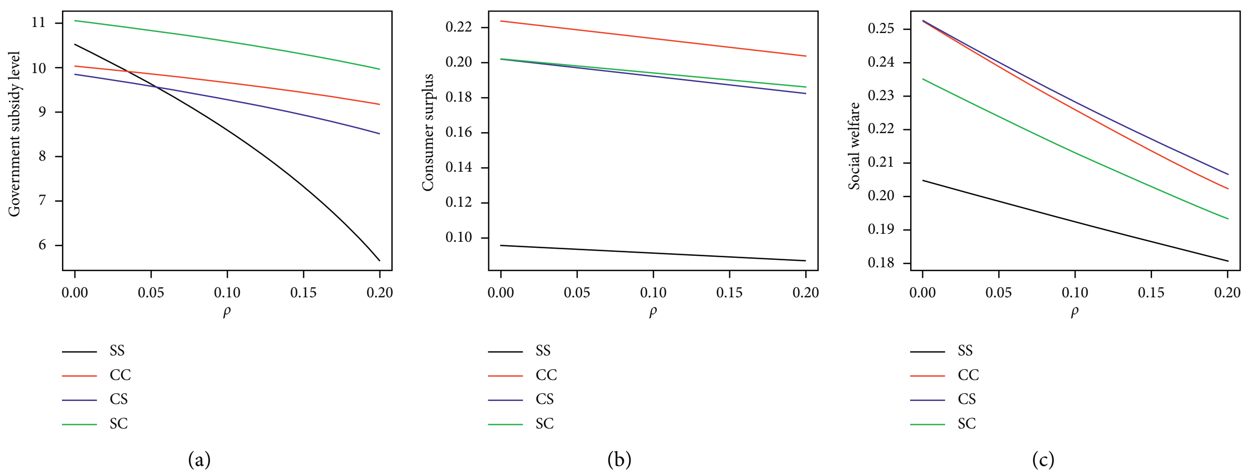

Figure 6: Government subsidy level, consumer surplus, and social welfare vs. unit environmental impact discount of green products.

$$s_g^l = \begin{cases} \sqrt{\dfrac{c_m\beta\left(\beta^2(4+\beta)(6-\beta)-2e(4-\beta)(16-\beta)(\rho(8-\beta)-2\beta)\right)}{2(\beta(6-\beta)(20-3\beta)-2e(8-\beta)(\rho(8-\beta)-2\beta))}}, \text{if } l=SS, \\ \sqrt{\dfrac{3A_0(\beta(\beta-1)(4+3\beta)-6e(4-\beta)(\rho(2-\beta)-\beta))}{2(\beta(1-\beta)(14-9\beta)-6e(2-\beta)(\rho(2-\beta)-\beta))}}, \text{if } l=CC, \\ \sqrt{\dfrac{4A_0(5\beta(\beta-1)(4+5\beta)-3e(16-7\beta)(\rho(8-5\beta)-3\beta))}{(4-\beta)(25\beta(1-\beta)(4-3\beta)-2e(8-5\beta)(\rho(8-5\beta)-3\beta))}}, \text{if } l=CS, \\ \sqrt{\dfrac{2A_0(4\beta(\beta-1)(4+5\beta)-3e(16-7\beta)(\rho(8-5\beta)-\beta(4-\beta)))}{2\beta(1-\beta)(56-41\beta)3e(8-5\beta)(\rho(8-5\beta)-\beta(4-\beta))}}, \text{if } l=SC. \end{cases} \tag{17}$$

Or, if $\rho > t_g^l$, then $s_g^l = 0$, for $l \in \{SS, CC, CS, SC\}$.

Proposition 8 reveals that the government will be motived to provide subsides to consumers when the impact of the green products on environmental degradation is relatively low. Conversely, when the environmental impact of green products is relatively high, the government will not have any incentive to subsidize the green products, even if they can reduce pollution to some extent. Although the distribution of green products is a good way to protect the environment, the government will not create a subsidy policy unless the impact on environmental degradation by green products is low enough. Therefore, when developing and distributing a green product, its manufacturer should consider the environmental impacts of the green product, such as recyclability, remanufacturability, disassemblability, and disposability, among others. The following corollary supports this argument:

Corollary 1. *When the government provides subsidies for green products, s_g^l decreases in ρ.*

Corollary 1 implies that the greater the environmental impact of green products, the lesser the government subsidies green products, which not only worsens the consumer surplus but also reduces social welfare. Figure 6 records the equilibrium level of the government subsidy, the consumer surplus, and the social welfare while varying ρ from 0 to 0.2. Figure 6 confirms Corollary 1 for all distribution channel structures.

6. Numerical Experiment

The parameter β in this study indicates consumers' value discount for a green product or, equivalently, a fraction of their willingness-to-pay for a green product. Note that if $\beta = 0$, consumers are not willing to purchase the green product. If $\beta = 1$, consumers recognize that a green product is the perfect substitute for a nongreen product and are willing to pay the same amount for either product. In this section, a numerical experiment is carried out to investigate the effect of β on the equilibrium decisions. The main dataset used for the analysis is as follows: $c_m = 50$, $e = 0.5$, $f_1 = f_2 = 0$, and $\rho = 0.1$. When varying β from 0.1 to 0.9, Figure 7 records the equilibrium quantities of the decision. As the value of β increases, the followings are observed:

(i) In the SS structure, the government subsidy level consistently increases. On the other hand, in the CC, CS, and SC structures, the government subsidy level

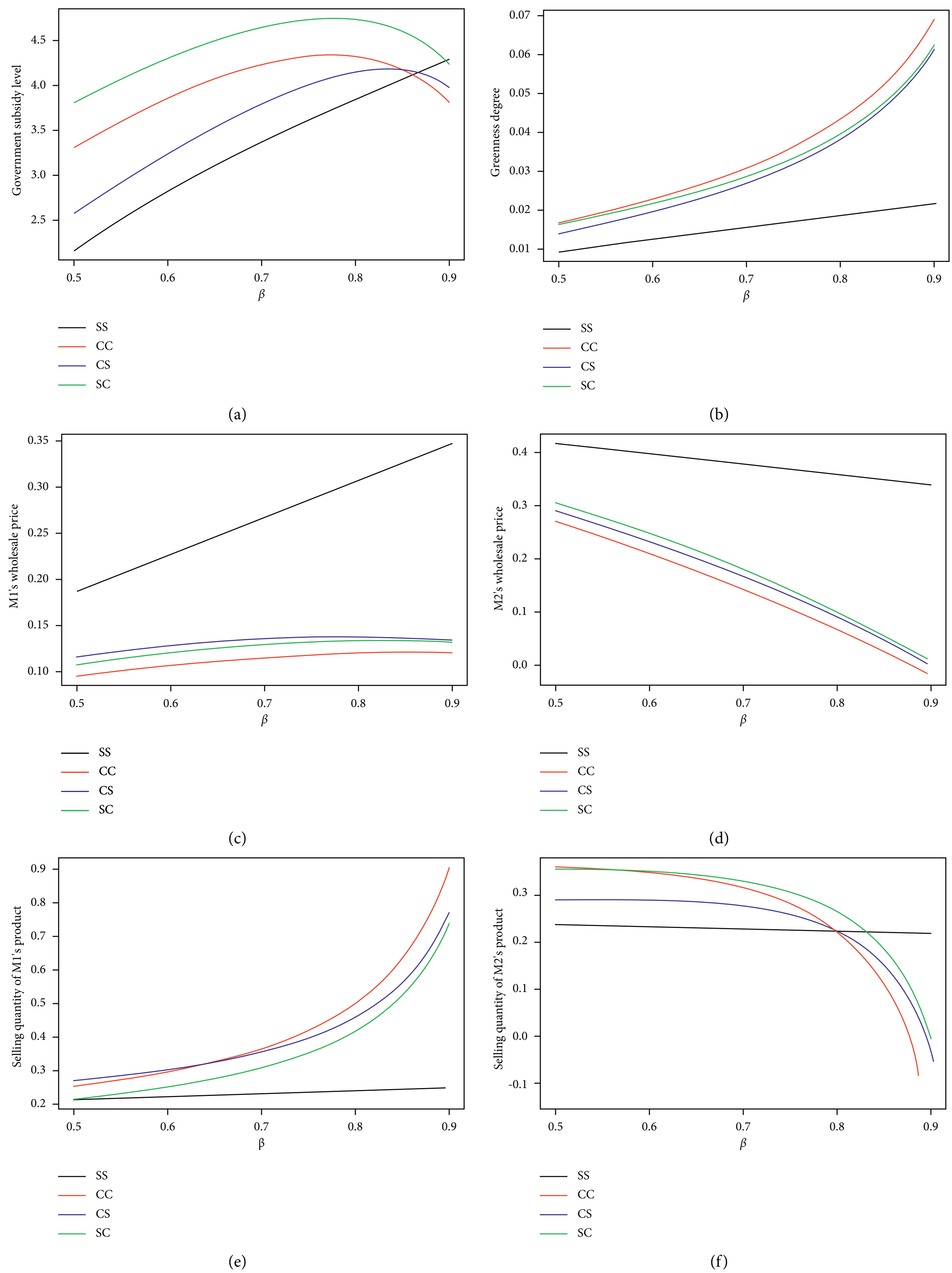

Figure 7: Equilibrium decisions vs. β.

initially increases to a certain level; that is, it has a maximum and then decreases.

(ii) In all structures, the greenness degree increases.

(iii) In the SS structure, M1's wholesale price consistently increases. On the other hand, in the CC, CS, and SC structures, M1's wholesale price initially

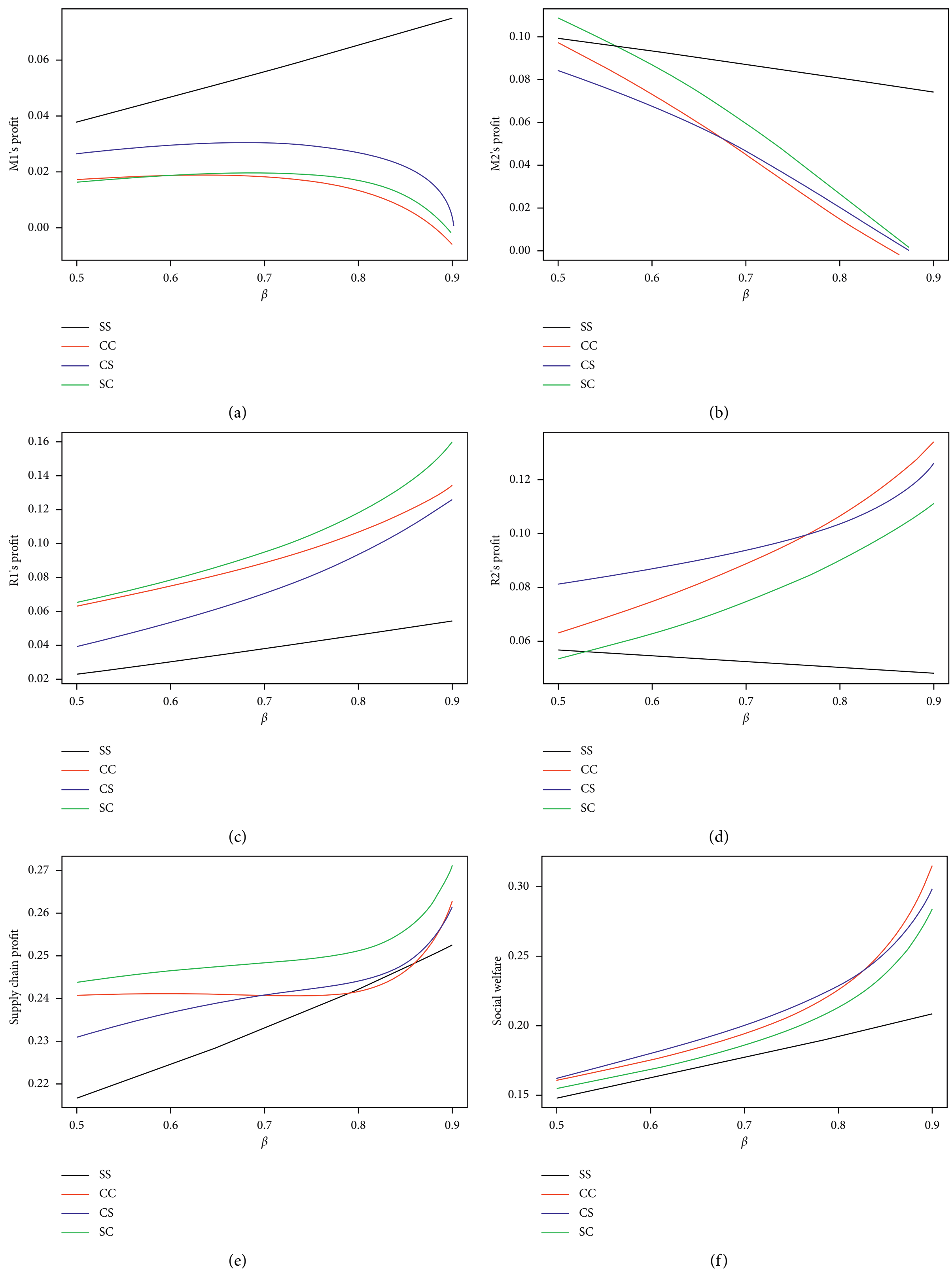

FIGURE 8: Equilibrium profits and social welfare vs. β.

increases to a certain level; that is, it has a maximum and then decreases.

(iv) In all structures, M2's wholesale price decreases.

(v) In all structures, the selling quantity of M1's green product increases, while that of M's nongreen product decreases.

Table 3: First-order derivatives of the equilibrium decision.

	$l = SS$	$l = CC$	$l = CS$	$l = SC$
$\partial g^l/\partial s$	$2\beta A_1^2(6-\beta)(c_m\beta(4-\beta)(16-\beta)$ $+2s^2(8-\beta))$	$2A_0A_2^2/c_m(3A_0(4-\beta)+2s^2$ $(2-\beta))$	$5A_0A_4^2(4-\beta)/c_m(6A_0(16-7\beta)$ $+s^2(4-\beta)(8-5\beta))$	$4A_0A_9^2/c_m(2A_0(16-7\beta)$ $+s^2(8-5\beta))$
$\partial w_1^l/\partial s$	$4c_ms\beta^2A_1^2(4-\beta)(6-\beta)(8-\beta)$	$12sA_0^2A_2^2(2-\beta)/c_m$	$60sA_0^2A_4^2(4-\beta)(8-5\beta)/c_m$	$16sA_0^2A_9^2(8-5\beta)/c_m$
$\partial w_2^l/\partial s$	$-8c_ms\beta^2A_1^2(4-\beta)(6-\beta)$	$-12sA_0^2A_2^2/c_m$	$-60sA_0^2A_4^2(4-\beta)^2/c_m$	$-48sA_0^2A_9^2/c_m$
$\partial q_1^l/\partial s$	$8c_ms\beta A_1^2(6-\beta)(8-\beta)$	$8sA_0A_2^2(2-\beta)$	$10sA_0A_4^2(4-\beta)^2(8-5\beta)$	$8sA_0A_9^2(8-5\beta)$
$\partial q_1^l/\partial s$	$-16c_ms\beta^2A_1^2(6-\beta)$	$-8s\beta A_0A_2^2$	$-30s\beta A_0A_4^2(4-\beta)^2$	$-8s\beta A_0A_9^2(4-\beta)$
$\partial p_1^l/\partial s$	$4c_ms\beta^2A_1^2(6-\beta)^2(8-\beta)$	$4sA_0^2A_2^2(8-3\beta)/c_m$	$20sA_0^2A_4^2(4-\beta)(32-17\beta)/c_m$	$8sA_0^2A_9^2(24-13\beta)/c_m$
$\partial p_2^l/\partial s$	$-8c_ms\beta^2A_1^2(6-\beta)^2$	$-8sA_0^2A_2^2/c_m$	$-50sA_0^2A_4^2(4-\beta)^2/c_m$	$-32sA_0^2A_9^2/c_m$

Table 4: First-order derivatives of the equilibrium profits.

	$l = SS$	$l = CC$	$l = CS$	$l = SC$
$\partial \pi_{m1}^l/\partial s$	$4A_{11}(6-\beta)(c_m\beta(4-\beta)(16-3\beta)$ $-2s^2(8-\beta))$	$4sA_0^2A_2^3(3A_0(4-3\beta)-2s^2$ $(2-\beta))/c_m$	$25A_{12}(6A_0(16-13\beta)$ $-s^2(4-\beta)(8-5\beta))/c_m$	$16sA_0^2A_9^3(2A_0(16-13\beta)-s^2$ $(8-5\beta))/c_m$
$\partial \pi_{m2}^l/\partial s$	$-32A_{11}(c_m\beta(8-3\beta)-2s^2)$	$-32sA_0^2A_2^3(3A_0-s^2)/c_m$	$-120A_{12}(3A_0(8-\beta)-2s^2$ $(4-\beta))/c_m$	$-64sA_0^2A_9^3(4-\beta)$ $(4A_0-s^2)/c_m$
$\partial \pi_{r1}^l/\partial s$	$32c_m\beta A_{11}(6-\beta)(8-\beta)$	$16sA_0^2A_2^3(6A_0-s^2)/3c_m$	$80A_{12}(2A_0(11-2\beta)-s^2$ $(4-\beta))/c_m$	$32sA_0^2A_9^3(4A_0(16-7\beta)-s^2$ $(4-\beta))/3c_m$
$\partial \pi_{r2}^l/\partial s$	$-64A_{11}(c_m\beta(8-3\beta)-2s^2)$	$16sA_0^2A_2^3(6A_0-s^2)/3c_m$	$-20A_{12}(A_0(16-7\beta)+2s^2$ $(4-\beta))/c_m$	$32sA_0^2A_9^3(2A_0(8+\beta)-s^2$ $(4-\beta))/3c_m$
$\partial \pi_s^l/\partial s$	$4\beta A_{11}(6-\beta)(c_m\beta(64-12\beta+3\beta^2)$ $+2s^2)$	$4sA_0^2A_2^3(3A_0(4-9\beta)+2s^2$ $(2+3\beta))/3c_m$	$25A_{12}(2A_0(32-41\beta)$ $+5s^2\beta(4-\beta))/c_m$	$16sA_0^2A_9^3(2A_0(32-41\beta)+s^2$ $(8+7\beta))/3c_m$

Note. The values of A_{11} and A_{12} are given in Appendix C.

Figure 7 implies that when each manufacturer distributes its products through a single exclusive retailer, the greater the substitutability of a green product, the more subsidies the government pays. However, if at least one manufacturer decides to distribute its product via both retailers, there exists a maximum government subsidy level. This trend can be found in M1's wholesale price. As β increases, more consumers will think that a green product can replace a nongreen product in the market. This will increase not only the demand but also the greenness degree of the green product. Conversely, by lowering its wholesale price, M2 attempts to prevent a decline in the demand for its nongreen product. According to the values of β, Figure 8 also plots the obtained profits and social welfare. As the value of β increases, the followings are observed:

(i) In the SS structure, M1's profit consistently increases. On the other hand, in the CC, CS, and SC structures, M1's profit initially increases to a certain level; that is, it has a maximum and then decreases.

(ii) In all structures, M2's profit decreases.

(iii) In all structures, R1's profit increases.

(iv) In the SS structure, R2's profit consistently decreases. On the other hand, in the CC, CS, and SC structures, M2's profit increases.

(v) In all structures, the supply chain profit increases, but its trend is S-shaped.

(vi) In all structures, social welfare increases.

Figure 8 indicates that the profit trends of the manufacturers are consistent with their wholesale price trends. It should be noted that in the SS structure, R2's profit decreases in β. This occurs because R2 cannot deliver M1's green product in the SS structure, which adversely affects R2's profit. Figure 8 also indicates that if a green product is highly substitutable for a nongreen product, the profitability of the supply chain and the level of social welfare will increase. Therefore, it can be suggested that for the sustainability of a society and a supply chain, policymakers should focus on establishing policies that encourage the purchase of green products.

7. Managerial Insights

This section deals with key managerial insights summarized as follows:

(i) In all the distribution channels considered in this study, the more environmentally friendly a product is designed, the more government subsidies for the product will benefit the green product producers in the supply chain. This insight will lead manufacturers to produce more environmentally friendly products, which has a positive impact on the well-being of the society.

(ii) Through this study, it is understood that the government's subsidy policy has a great influence on the design of distribution channels in the supply chain. Since the distribution channel structure has a significant impact on the profitability and sustainability of the entire supply chain, the government needs to cooperate with the supply chain participants in the process of determining the subsidy level.

(iii) This study shows that the environmental degradation of the green products affects the government's subsidy level. Even if a product is labeled as an eco-friendly product, the government may be reluctant subsidize the product if it has a negative impact on the environment. Therefore, it is very important for manufacturers to determine the optimal degree of greening when designing eco-friendly products.

8. Conclusion

This paper discussed the equilibrium decisions of pricing and greening in a supply chain consisting of two competing manufacturers and two retailers under a government subsidy policy. This paper assumed four different distribution channel structures, established a three-stage game model for each of them, and solved the models analytically. Extensive numerical experiments were conducted to support our findings. This paper answers the research questions posed in Section 1:

(i) As the government subsidy level increases, a green product becomes greener, leading to increases (decreases) in the wholesale price, the retail price, and the demand for the green product (nongreen product). For more details, see Proposition 1.

(ii) For each manufacturer, the fixed cost of opening a new distribution channel has a maximum, which depends on the government subsidy level. For more details, see Propositions 4 and 5.

(iii) The profits of all supply chain members are affected in all cases by the government subsidy; therefore, it is obvious that the supply chain profit depends on the government subsidy level. It should be noted that if at least one of the manufacturers selects a cross-distribution channel, the supply chain profit is minimal at a certain value of the government subsidy level. For more details, see Proposition 3.

(iv) To determine the optimal level of the government subsidy, policymakers must consider not only the supply chain profit but also the environmental effects of the products. The greater the environmental effects of the products are, the lower the government subsidy level should be, thus decreasing consumer surplus and social welfare at the same time. For more details, see Proposition 8 and Corollary 1.

This paper provides several recommendations for supply chain participants that undertake sustainability efforts. However, there are also limitations that can be expanded upon and improved in future research. (1) Uncertain demand: while this paper assumes that the retailers sell all products that they order, the assumption of uncertain demand levels for products is more realistic. This type of stochastic demand may lead to different results. (2) Retailer's sustainability effort: this paper assumes that only manufacturers are involved in sustainability efforts. However, an extended model can assume that retailers can participate in sustainability activities, such as green retailing and/or green marketing. (3) Collusion strategy: this paper does not consider any collusion strategies between manufacturers. A comparative analysis among other supply chain cooperation strategies will provide more meaningful managerial insights. (4) Multiple participants: multiple manufacturers and retailers either collaborate or compete in various supply chains. It would be worthwhile to analyze a supply chain with more complex but realistic conditions.

Appendix

A. Proofs for Section 4

Proof of the SS structure in Table 2

Because $\partial^2\pi_{r1}/\partial q_1^2 = -2\beta < 0$ and $\partial^2\pi_{r2}/\partial q_2^2 = -2 < 0$, π_{ri} is strictly concave with respect to (w.r.t) q_i for $i = 1, 2$. Thus, solving the first-order conditions (FOCs) of the retailers yields

$$\begin{cases} q_1 = \dfrac{2gs + \beta - 2w_1 + \beta w_2}{\beta(4-\beta)}, \\ \\ q_2 = \dfrac{2 - gs - \beta + w_1 - 2w_2}{4-\beta}. \end{cases} \quad \text{(A.1)}$$

Integrating equation (A.1) into the manufacturers' problem, M1's Hessian matrix is obtained as follows:

$$\mathbf{H}_{m1}^{SS} = \begin{pmatrix} -\dfrac{4}{\beta(4-\beta)} & \dfrac{2s}{\beta(4-\beta)} \\ \\ \dfrac{2s}{\beta(4-\beta)} & -c_m \end{pmatrix}. \quad \text{(A.2)}$$

Define Δ_k^l as the leading principal minor of order k in $\mathbf{H}_{m1}^l$ for $l \in \{SS, CC, CS, SC\}$. We then find that $\Delta_1^{SS} < 0$. If the condition $c_m\beta(4-\beta) > s^2$ is met, $\Delta_2^{SS} > 0$, implying that M1's profit is strictly concave with respect to w_1 and g. M2's profit is also strictly concave with respect to w_2 because $\partial^2\pi_{m2}/\partial w_2^2 = -4/4 - \beta < 0$. By solving the FOCs of the manufacturers' problem, the equilibrium decisions and profits of all supply chain members are determined, as presented in Table 2. This completes the proof.

Proof of the CC structure in Table 2.

The Hessian matrix of retailer i is given by

$$\mathbf{H}_{ri}^{CC} = \begin{pmatrix} -2\beta & -2\beta \\ -2\beta & -2 \end{pmatrix}, \quad i = 1, 2. \quad \text{(A.3)}$$

Define Ξ_k^l as the leading principal minor of order k in $\mathbf{H}_{ri}^l$, for $l \in \{CC, CS, SC\}$ and $i = 1, 2$. Because $\Xi_1^{CC} = -2\beta < 0$ and $\Xi_2^{CC} = 4\beta(1-\beta) > 0$, the profit function of retailer i is strictly concave with respect to its own ordering quantities. Accordingly, solving FOCs of retailers' problem gives

$$\begin{cases} q_{11} = q_{12} = \dfrac{gs - w_1 + \beta w_2}{3\beta(1-\beta)}, \\ \\ q_{21} = q_{22} = \dfrac{1 - gs - \beta + w_1 - w_2}{3(1-\beta)}. \end{cases} \tag{A.4}$$

By integrating equation (A.4) into the manufacturers' problem, M1's Hessian matrix is obtained as follows:

$$\mathbf{H}_{m1}^{CC} = \begin{pmatrix} -\dfrac{4}{3\beta(1-\beta)}, & \dfrac{2s}{3\beta(1-\beta)}, \\ \\ \dfrac{2s}{3\beta(1-\beta)}, & -c_m. \end{pmatrix} \tag{A.5}$$

We then have that $\Delta_1^{CC} < 0$. If the condition $3c_m\beta(1-\beta) > s^2$ is met, $\Delta_2^{CC} > 0$, implying that M1's profit is strictly concave with respect to w_1 and g. M2's profit is also strictly concave with respect to w_2 because $\partial^2\pi_{m2}/\partial w_2^2 = -4/(31-\beta) < 0$. By solving the FOCs of the manufacturers' problem, the equilibrium decisions and profits of all supply chain members are determined, as shown in Table 2. This completes the proof.

Proof of the CS structure in Table 2.

Because $\partial^2\pi_{r1}/\partial q_{11}^2 = -2\beta < 0$, R1's profit is strictly concave with respect to the ordering quantity q_{11}. Letting $\mathbf{H}_{r2}^{CS}$ be the Hessian matrix of R2's problem, it follows that $\mathbf{H}_{r2}^{CS} = \mathbf{H}_{ri}^{CC}$. Hence, R2's profit function is also strictly concave with respect to its own ordering quantities q_{12} andq_2 . Solving FOCs of retailers' problem leads to

$$\begin{cases} q_{11} = \dfrac{gs + \beta - w_1}{3\beta}, \\ \\ q_{12} = \dfrac{(gs - w_1)(2+\beta) + 3\beta w_2 - \beta(1-\beta)}{6\beta(1-\beta)}, \\ \\ q_2 = \dfrac{1 - gs - \beta + w_1 - w_2}{2(1-\beta)}. \end{cases} \tag{A.6}$$

Integrating equation (A.6) into the manufacturers' problem, M1's Hessian matrix is obtained as follows:

$$\mathbf{H}_{m1}^{CS} = \begin{pmatrix} -\dfrac{4-\beta}{3\beta(1-\beta)} & \dfrac{s(4-\beta)}{6\beta(1-\beta)} \\ \\ \dfrac{s(4-\beta)}{6\beta(1-\beta)} & -c_m \end{pmatrix}. \tag{A.7}$$

We then have that $\Delta_1^{CS} < 0$. If the condition $12c_m\beta(1-\beta) > s^2(4-\beta)$ is met, $\Delta_2^{CS} > 0$, implying that M1's profit is strictly concave with respect to w_1 and g. M2's profit is also strictly concave with respect to w_2 because $\partial^2\pi_{m2}/\partial w_2^2 = -1/1-\beta < 0$. By solving the FOCs of the manufacturers' problem, the equilibrium decisions and profits of all supply chain members are determined, as shown in Table 2. This completes the proof.

Proof of the SC structure in Table 2.

Letting $\mathbf{H}_{r1}^{SC}$ be the Hessian matrix of R1's problem, it follows that $\mathbf{H}_{r1}^{SC} = \mathbf{H}_{ri}^{CC}$. Hence, R1's profit function is strictly concave with respect to its own ordering quantities q_1 and q_{21}. Because $\partial^2\pi_{r2}/\partial q_{22}^2 = -2$, R2's profit is also strictly concave with respect to the ordering quantity q_{22}. Solving the FOCs of the retailers' problem leads to

$$\begin{cases} q_1 = \dfrac{gs - w_1 + \beta w_2}{2\beta(1-\beta)}, \\ \\ q_{21} = \dfrac{2(1-\beta) - 3(gs - w_1) - w_2(2+\beta)}{6(1-\beta)}, \\ \\ q_{22} = \dfrac{1 - w_2}{3}. \end{cases} \tag{A.8}$$

Integrating equation (A.8) into the manufacturers' problem, M1's Hessian matrix is obtained as follows:

$$\mathbf{H}_{m1}^{SC} = \begin{pmatrix} -\dfrac{1}{\beta(1-\beta)} & \dfrac{s}{2\beta(1-\beta)} \\ \\ \dfrac{s}{2\beta(1-\beta)} & -c_m \end{pmatrix}. \tag{A.9}$$

We then have that $\Delta_1^{SC} < 0$. If the condition $4c_m\beta(1-\beta) > s^2$ is met, $\Delta_2^{SC} > 0$, implying that M1's profit is strictly concave with respect to w_1 and g. M2's profit is also strictly concave with respect to w_2 because $\partial^2\pi_{m2}/\partial w_2^2 = -4-\beta/3(1-\beta) < 0$. By solving the FOCs of the manufacturers' problem, the equilibrium decisions and profits of all supply chain members are determined, as shown in Table 2. This completes the proof.

Proof of Proposition 1. The first-order derivatives of the equilibrium greenness degree and wholesale prices with respect to the government subsidy level are displayed in Table 3. Table 3 shows that $\partial g^l/\partial s > 0$, $\partial w_1^l/\partial s > 0$, $\partial w_2^l/\partial s < 0$, $\partial q_1^l/\partial s < 0$, $\partial q_2^l/\partial s < 0$, $\partial p_1^l/\partial s < 0$, and $\partial p_2^l/\partial s < 0$ for all distribution channel structures. This completes the proof. □

Proof of Proposition 2. The first-order derivatives of the equilibrium profits with respect to the government subsidy level are displayed in Table 4. For M1's profit, it can be shown that

$$\frac{\partial\pi_{m1}^l}{\partial s} = \begin{cases} > 0, \text{if } 0 \le s < t_{m1}^l, \\ \\ < 0, \text{if } t_{m1}^l \le s < s_U^l, \end{cases} \tag{A.10}$$

for all $l \in \{SS, CC, CS, SC\}$. Meanwhile, for M2's profit, it can be shown that

$$\frac{\partial \pi_{m2}^{l}}{\partial s} = \begin{cases} < 0, \text{if } 0 \le s < t_{m2}^{l}, l \in \{SS, CS\}, \\ > 0, \text{if } t_{m2}^{l} \le s < s_{U}^{l}, l \in \{SS, CS\}, \\ < 0, \text{if } l \in \{CC, SC\}. \end{cases} \quad \text{(A.11)}$$

Regardless of the distribution channel structure, R1's profit increases in s:

$$\frac{\partial \pi_{r1}^{l}}{\partial s} > 0, \forall l \in \{SS, CC, CS, SC\}. \quad \text{(A.12)}$$

Finally, it can be shown that

$$\frac{\partial \pi_{r2}^{l}}{\partial s} = \begin{cases} < 0, \text{if } 0 \le s < t_{r2}^{l}, \quad l = SS, \\ > 0, \text{if } t_{r2}^{l} \le s < s_{U}^{l} \quad l = SS, \\ > 0, \text{if } l \in \{CC, CS, SC\}. \end{cases} \quad \text{(A.13)}$$

Summarizing equations (A.10) to (A.13) results in Proposition 2. This completes the proof. □

Proof of Proposition 3. The first-order derivatives of the equilibrium profit of the supply chain with respect to the government subsidy level are presented in the last row of Table 4. The following relationship can be obtained:

$$\frac{\partial \pi_{s}^{l}}{\partial s} = \begin{cases} > 0, \text{if } l = SS, \\ < 0, \text{if } 0 \le s < t_{s}^{l}, l \in \{CC, CS, SC\}, \\ > 0, \text{if } t_{s}^{l} \le s < s_{U}^{l}, l \in \{CC, CS, SC\}. \end{cases} \quad \text{(A.14)}$$

Equation (A.14) describes Proposition 3. This completes the proof. □

Proof of Proposition 4. By comparing each manufacturer's profits among the distribution channel structures, it is obtained that

$$\begin{cases} \pi_{m1}^{CC} - \pi_{m1}^{SS} = \dfrac{2A_0^2}{c_m}\left(A_2^2\left(3A_0 - s^2\right) - A_{13}\right) - f_1, \\ \pi_{m2}^{CC} - \pi_{m2}^{SS} = \dfrac{2}{3}\left(4A_2^2(1-\beta)\left(3A_0 - s^2\right)^2 - A_{14}\right) - f_2, \\ \pi_{m1}^{CS} - \pi_{m1}^{SS} = \dfrac{A_0^2}{c_m}\left(25A_4^2A_7/2(1-\beta)^2 - 2A_{13}\right) - f_1, \\ \pi_{m2}^{SC} - \pi_{m2}^{SS} = \dfrac{2}{3}\left(4A_9^2\left(4 - 5\beta + \beta^2\right)\left(4A_0 - s^2\right)^2 - A_{14}\right) - f_2. \end{cases} \quad \text{(A.15)}$$

From equation (A.15), the following is determined:

$$\begin{cases} \pi_{m1}^{CC} > \pi_{m1}^{SS} \text{ if } f_1 < \dfrac{2A_0^2}{c_m}\left(A_2^2\left(3A_0 - s^2\right) - A_{13}\right), \\ \pi_{m2}^{CC} > \pi_{m2}^{SS} \text{ if } f_2 < \dfrac{2}{3}\left(4A_2^2(1-\beta)\left(3A_0 - s^2\right)^2 - A_{14}\right), \\ \pi_{m1}^{CS} > \pi_{m1}^{SS} \text{ if } f_1 < \dfrac{A_0^2}{c_m}\left(\dfrac{25A_4^2A_7}{2(1-\beta)^2} - 2A_{13}\right), \\ \pi_{m2}^{SC} > \pi_{m2}^{SS} \text{ if } f_2 < \dfrac{2}{3}\left(4A_9^2\left(4 - 5\beta + \beta^2\right)\left(4A_0 - s^2\right)^2 - A_{14}\right). \end{cases} \quad \text{(A.16)}$$

Equation (A.16) describes Proposition 4. This completes the proof. □

Proof of Proposition 5. By comparing each manufacturer's profits among the distribution channel structures, it is obtained that

$$\begin{cases} \pi_{m1}^{CC} - \pi_{m1}^{SC} = \dfrac{2A_0^2}{c_m}\left(A_2^2\left(3A_0 - s^2\right) - 4A_9^2\left(4A_0 - s^2\right)\right) - f_1, \\ \pi_{m2}^{CC} - \pi_{m2}^{CS} = \dfrac{2(1-\beta)}{3}\left(4A_2^2\left(3A_0 - s^2\right)^2 - 3A_4^2A_5^2\right) - f_2. \end{cases} \quad \text{(A.17)}$$

From equation (A.17), it can be determined that

$$\begin{cases} \pi_{m1}^{CC} > \pi_{m1}^{SS} \text{ if } f_1 < \dfrac{2A_0^2}{c_m}\left(A_2^2\left(3A_0 - s^2\right) - 4A_9^2\left(4A_0 - s^2\right)\right), \\ \pi_{m2}^{CC} > \pi_{m2}^{SS} \text{ if } f_2 < \dfrac{2(1-\beta)}{3}\left(4A_2^2\left(3A_0 - s^2\right)^2 - 3A_4^2A_5^2\right). \end{cases} \quad \text{(A.18)}$$

Equation (A.18) describes Proposition 5. This completes the proof. □

B. Proofs for Section 5

Proof of Proposition 6. The first-order derivatives of the consumer surplus with respect to the government subsidy level are presented as follows:

$$\begin{cases} \dfrac{\partial S_c^{SS}}{\partial s} = 32A_{15}\left(c_m\beta(8 - 3\beta) - s^2\right), \\ \dfrac{\partial S_c^{CC}}{\partial s} = \dfrac{32sA_0^2A_2^3\left(6A_0 - s^2\right)}{3c_m}, \\ \dfrac{\partial S_c^{CS}}{\partial s} = \dfrac{50A_{12}\left(A_0(56 - 11\beta) - 2s^2(4 - \beta)\right)}{c_m}, \\ \dfrac{\partial S_c^{SC}}{\partial s} = \dfrac{32sA_0^2A_9^3\left(A_0(56 - 11\beta) - 2s^2(4 - \beta)\right)}{3c_m}, \end{cases} \quad \text{(B.1)}$$

where the value of A_{15} is given in Appendix C. If the inequalities in equation (10) are met, it follows that $\partial S_c^l/\partial s > 0$ for $\forall l \in \{SS, CC, CS, SC\}$. In addition, because $\partial g^l/\partial s > 0$ and $\partial q_1^l/\partial s > 0$ from Proposition 1, it is also true that, for $\forall l \in \{SS, CC, CS, SC\}$,

$$\frac{\partial X_g^l}{\partial s} = sq_1^l \frac{\partial g^l}{\partial s} + g^l q_1^l + g^l s \frac{\partial q_1^l}{\partial s} > 0. \tag{B.2}$$

This completes the proof. □

Proof of Proposition 7. The first-order derivatives of the environmental impact cost with respect to the government subsidy level are presented as follows:

$$\begin{cases} \dfrac{\partial E_g^{SS}}{\partial s} = 8c_m es\beta A_1^2 (6-\beta)(\rho(8-\beta) - 2\beta), \\ \dfrac{\partial E_g^{CC}}{\partial s} = 8esA_0 A_2^2 (\rho(2-\beta) - \beta), \\ \dfrac{\partial E_g^{CS}}{\partial s} = 10esA_0 A_4^2 (4-\beta)^2 (\rho(8-5\beta) - 3\beta), \\ \dfrac{\partial E_g^{SC}}{\partial s} = 8esA_0 A_9^2 (\rho(8-5\beta) - \beta(4-\beta)). \end{cases} \tag{B.3}$$

It follows from equation (B.3) that $\partial E_g^l/\partial s > (<)0$ when $\rho > (<) t_g^l$ for $l = \{SS, CC, CS, SC\}$. This completes the proof. □

Proof of Proposition 8. By taking the SS structure as an example, the proof of Proposition 8 is described. The first-order derivative of social welfare with respect to the government subsidy level is presented as follows:

$$\frac{\partial S\, W^{SS}}{\partial s} = 4c_m s\beta(6-\beta)(A_{16} - A_{17}), \tag{B.4}$$

where the values of A_{16} and A_{17} are given in Appendix C. If $\rho > t_g^{SS}$, then $\partial S\, W^{SS}/\partial s < 0$, implying that SW^{SS} is a decreasing function of s and that it reaches its maximum at $s = 0$. If $\rho < t_g^{SS}$ and $0 \le s < s_g^{SS}$ $(s_g^{SS} \le s < s_U^{SS})$, then $\partial S\, W^{SS}/\partial s > (<)0$, implying that SW^{SS} is a unimodal function of s and that it reaches its maximum at $s = s_g^{SS}$. For the CC, CS, and SC structures, the same arguments hold, but their proofs are omitted for brevity. This completes the proof. □

Proof of Corollary 1. The first-order derivatives of the government subsidy level with respect to the unit environmental impact discount for green products are presented as follows:

$$\begin{cases} \dfrac{\partial s_g^{SS}}{\partial \rho} = -\dfrac{c_m e\beta^2 (6-\beta)(8-\beta)(640 - \beta(12-\beta)(26-\beta))}{s_g^{SS}\left(\beta(4e(8-\beta) + (6-\beta)(20-3\beta)) - 2e\rho(8-\beta)^2\right)^2} < 0, \\ \dfrac{\partial s_g^{CC}}{\partial s} = -\dfrac{9eA_0^2 (2-\beta)(32 - 3\beta(8-\beta))}{c_m s_g^{CC}\left(\beta(6e(2-\beta) + (1-\beta)(14-9\beta)) - 6e\rho(2-\beta)^2\right)^2} < 0, \\ \dfrac{\partial s_g^{CS}}{\partial s} = -\dfrac{10eA_0^2 (8-5\beta)(1024 - 5\beta(220 - 53\beta))}{c_m s_g^{CS}(4-\beta)\left(\beta(6e(8-5\beta) + 25(1-\beta)(4-3\beta)) - 2e\rho(8-5\beta)^2\right)^2} < 0, \\ \dfrac{\partial s_g^{SC}}{\partial s} = -\dfrac{18eA_0^2 (8-5\beta)(320 - \beta(336 - 79\beta))}{c_m s_g^{SC}\left(\beta(3e(4-\beta)(8-5\beta) + 2(1-\beta)(56-41\beta)) - 3e\rho(8-5\beta)^2\right)^2} < 0. \end{cases} \tag{B.5}$$

Equation (B.5) describes Corollary 1. This completes the proof. □

C. Notations

$$
\begin{aligned}
&A_0\\
A_1 &= \left(c_m\beta(4-\beta)(16-\beta)-2s^2(8-\beta)\right)^{-1},\\
A_2 &= \left(3A_0(4-\beta)-2s^2(2-\beta)\right)^{-1},\\
A_3 &= (1-\beta)\left(3A_0(4+5\beta)-4s^2(2+\beta)\right),\\
A_4 &= \left(6A_0(16-7\beta)-s^2(4-\beta)(8-5\beta)\right)^{-1},\\
A_5 &= 3A_0(8-\beta)-2s^2(4-\beta),\\
A_6 &= A_0\left(72-59\beta+5\beta^2\right)-s^2(4-\beta)(6-5\beta),\\
A_7 &= (1-\beta)^2(4-\beta)\left(12A_0-s^2(4-\beta)\right),\\
A_8 &= s^4(4-\beta)^2(4-3\beta)+A_0\left(A_0(16-7\beta)\left(36+\beta-\beta^2\right)-4s^2(4-\beta)\left(24-16\beta+\beta^2\right)\right),\\
A_9 &= \left(2A_0(16-7\beta)-s^2(8-5\beta)\right)^{-1},\\
A_{10} &= s^4(4-\beta)^2+4A_0\left(A_0(4+5\beta)(16-7\beta)-s^2(4-\beta)(8+\beta)\right),\\
A_{11} &= c_m s\beta^2A_1^3(6-\beta),\\
A_{12} &= sA_0^2A_4^3(4-\beta)^2,\\
A_{13} &= \frac{A_1^2(6-\beta)^2}{(1-\beta)^2}\left(c_m\beta(4-\beta)-s^2\right),\\
A_{14} &= 3A_1^2(4-\beta)\left(c_m\beta(8-3\beta)-2s^2\right)^2,\\
A_{15} &= \frac{sA_0^2A_1^3(6-\beta)^2}{c_m(1-\beta)^2},\\
A_{16} &= c_m\beta\left(\beta^2(4+\beta)(6-\beta)-2e(4-\beta)(16-\beta)(\rho(8-\beta)-2\beta)\right),\\
A_{17} &= -2s^2(\beta(6-\beta)(20-3\beta)-2e(8-\beta)(\rho(8-\beta)-2\beta)),
\end{aligned}
\tag{c.1}
$$

$$
\begin{aligned}
& t_{m1}^{SS} \\
& t_{m1}^{CC} = \sqrt{\frac{3A_0(4-3\beta)}{2(2-\beta)}}, \\
& t_{m1}^{CS} = \sqrt{\frac{6A_0(16-13\beta)}{(4-\beta)(8-5\beta)}}, \\
& t_{m1}^{SC} = \sqrt{\frac{2A_0(16-13\beta)}{8-5\beta}}, \\
& t_{m2}^{SS} = t_{r2}^{SS} \\
& t_{m2}^{CS} = \sqrt{\frac{3A_0(8-\beta)}{2(4-\beta)}}, \\
& t_{s}^{CC} = \sqrt{\frac{3A_0(9\beta-4)}{2(2+3\beta)}}, \\
& t_{s}^{CS} = \sqrt{\frac{2A_0(41\beta-32)}{5\beta(4-\beta)}}, \\
& t_{s}^{SC} = \sqrt{\frac{2A_0(41\beta-32)}{8+7\beta}}, \\
& t_{g}^{SS} = \frac{2\beta}{8-\beta}, \\
& t_{g}^{CC} = \frac{\beta}{2-\beta}, \\
& t_{g}^{CS} = \frac{3\beta}{8-5\beta}, \\
& t_{g}^{SC} = \frac{\beta(4-\beta)}{8-5\beta}.
\end{aligned}
$$

Data Availability

There are no data used to support the findings of this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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