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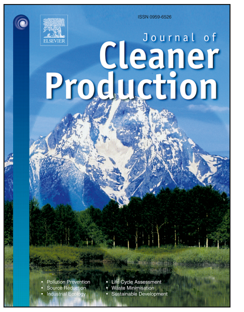

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Strategic investment for green product development and green marketing in a supply chain

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Abstract: Growing environmental awareness among consumers and corporate environmental responsibility prompt enterprises to pay more attention to green operations. Green practices, such as green product development (GPD) and green marketing strategies, affect the sustainability of a supply chain. This paper considers four scenarios to determine who is more suitable to implement GPD or green marketing in a supply chain consisting of a manufacturer and a retailer regarding products with green attributes. Several findings are derived. First, there is a significant interaction between GPD and green marketing decisions. These two important decisions should be considered simultaneously in a supply chain. Second, when the green marketing cost factor is sufficiently high, the manufacturer, retailer, whole supply chain, environment, and consumers will benefit from the scenario where the manufacturer leads in both GPD and green marketing, which may explain the common practice of the manufacturer conducting both GPD and green marketing. From the retailer's perspective, adopting both GPD and green marketing is always a bad choice. The environmental impact and consumer surplus are also investigated. For improving the environment and enhancing consumer surplus, it is best to enhance consumers' awareness of a product's green degree and enable the consumers to derive more positive utility from green marketing.

Keywords: supply chain; green product development; green marketing; green degree; environmental impact.

1 Introduction

Environmental issues, such as global warming and environmental pollution, are hot topics throughout the world because they relate closely to the safety of human beings and the health of the human body. People are becoming increasingly aware of environmental issues, and this influences their purchase decisions. According to an

Accenture global survey, more than 80% of interviewees consider a product's environmental performance when making a purchase decision (Agrawal et al., 2012). "Green product" has become a popular term in recent years. According to the Organisation for Economic Cooperation and Development (2009), green products reflect the prevention, limitation, reduction, or correction of harmful environmental impacts on the water, air, and soil. Unleaded gasoline, environmentally friendly detergents, recycled paper products, ozone-friendly sprays, and green organic foods, among many others, are considered green products (Schlegelmilch, 1996; Titerington et al., 1996). To be recognized and trusted by consumers, eco-labels are provided for some categories that have a great environmental impact. Eco-labels are certification marks or seals of approval to verify the environmental qualities of a certain product for consumers (Atson and Rosenthal, 2014). They are commonplace in Europe (e.g., the Blue Angel in Germany and the Nordic Swan in Scandinavia) and are growing in use in other countries, such as the United States and China. Green products with eco-labels are usually evaluated in terms of the environmental impact throughout the whole life cycle, from material acquisition, to manufacturing, to consumer use, to recycling. According to the international trade practice, only those products with eco-labels can be called green products. However, not all product categories have such a certification, and producing totally green products is costly and expensive for consumers. The seller may announce some green attributes (Jiang et al., 2021) or environmental features (Li et al., 2021) of their products to satisfy consumers' green demand. For instance, Apple states that it is using more recycled materials than ever, like the 40% recycled content in the MacBook Air with retina display, and the 99% recycled tungsten in iPhone 12 and Apple Watch Series 6 (Apple, 2021). According to H&M, green sourced cotton (e.g., organic, recycled, and better cotton) accounted for about 43% of all cotton used by the company in 2018 and it aims to reach the goal of using only 100% recycled or other sustainably sourced materials by 2030. In some regions of the Middle East, more than 80% of consumers are highly concerned about the environmental performance of products, and one third of them prioritize buying green products (Wang and Hou, 2020).

In this paper, we consider products with green attributes, including those products that have eco-labels.

As a critical market-driven factor, consumers' environmental awareness affects enterprises' green operations. Many firms integrate green product development (GPD) into their strategies. GPD practices include investing in emissions abatement technologies, using recyclable materials, and promoting energy saving products (Swami and Shah, 2013; Dong et al., 2016; Lai et al., 2019; Murali et al., 2019;). Since green products are assessed according to their environmental impact across the whole product life cycle, if the GPD strategy can reduce the product's negative environmental impact, the product is assumed to be greener. Investing in GPD enhances the green degree of the product. The green degree is usually termed the greenness level (Dong et al., 2019) or green performance (Du et al., 2019) in the literature. Green degree reflects the environmentally friendly quality of a product. It can also represent the percentage of reduction in emissions generated by each unit of a product with green attributes compared with the regular product. For example, it can be quantified by the amount of organic cotton used in products by H&M and Mango (Dong et al., 2019; Guo et al., 2019), the amount of recyclable packaging used by Coca-Cola (Coca-Cola Company, 2021), and the amount of recycled tungsten used in iPhone 12 and Apple Watch Series 6 (Apple, 2021). If a product has an eco-label, the green degree is assumed to be high. If a product with green attribute has no eco-label, the green degree is used to measure its green quality.

Many manufacturers have invested in GPD. For example, with the design of the Apple M1 chip, Mac mini reduced its overall carbon footprint by 34%. Apple switched from using flexes to lower-carbon alternatives in certain applications-one of many changes that helped to reduce the total carbon footprint of the iPad (8^{th} generation) by 7% (Apple, 2021). Gree, one of the biggest manufacturers of appliances in China, has reduced its carbon emissions by about 9064.4 tons per year by applying a new generation of refrigeration technologies in its air conditioner production (Zhang et al., 2020). Some giant manufacturers, such as Huawei, P&G, and Siemens, have integrated environmental protection into their product development strategies (Biswas et al., 2018). The Coca-Cola Company (2021) launched the World Without Waste initiative to design more recyclable packaging and reduce packaging waste in 2018. However, manufacturers are not alone in pursuing GPD. Many retailers are also taking actions to invest in GPD. For instance, H&M invested in a large number of green technology innovators to develop green features that can be embedded in products (Jiang et al., 2021). Some apparel retailers have adopted organic cotton to enhance their environmental performance, such as Marks &Spencer, Mango, and Timberland (Guo et al., 2020). Wal-Mart increased its investment in energy-saving products that can enhance the efficiency of the most energy-intensive products by 25% (Dai et al., 2017). However, retailers usually focus on product material or design when investing in GPD. Production is still performed by manufacturers. Investing in GPD can enhance the green degree of products and hence increase demand for those products, which can benefit both players in the supply chain. However, investing in GPD demands capital and the manufacturer may bear more marginal production costs. Who has the stronger motivation to invest in GPD in the context of a supply chain—the manufacturer or the retailer? Who is more suitable to invest in GPD from the perspective of the supply chain? Only a few papers in the literature have considered different GPD allocation models.

Green marketing is regarded as an effective tool to inform consumers about green performance of a product and further stimulates demand (Rahbar and Abdul Wahid, 2011). One type of green marketing is green advertising. Green advertising provides information about a green product and enhances consumers' social responsibility. For example, the electric vehicle producer Tesla, organic food retailer Whole foods, and sustainable fashion brand Patagonia all use green advertising to promote their green products. Another tool is to obtain an eco-label. Red Star Macalline, the largest furniture platform operator in China, tries to push all the products sold on the platform to get an eco-label. Red Star Macalline invests in advertising, such as billboards, trade shows, and other promotion activities, to recommend green products, which has a great impact on market competition. Similar to GPD investment, the following question is generated:

Who is more suitable to undertake green marketing—the manufacturer or the retailer? Either of them can lead in green marketing. For example, manufacturers can apply the eco-label to their products or use green advertising. Retailers can also implement green advertising. However, green marketing also requires huge capital. Who has the stronger motivation to invest in green marketing is another interesting issue.

GPD and green marketing are both very important issues and each one requires relatively large investment. There may be interactions between them. We jointly consider GPD and green marketing in this paper. Four scenarios are investigated: the manufacturer leads in both GPD and green marketing, the retailer leads in both GPD and green marketing; the manufacturer leads in GPD and the retailer leads in green marketing; and the retailer leads in GPD and the manufacturer leads in green marketing. We address the following research questions.

(i) What is the interaction between the GPD and green marketing decisions?

(ii) Which scenario is best for the manufacturer, the retailer, the whole supply chain, the environment, and total consumer surplus, respectively?

(iii) What are the influences of the sensitivity of utility on green degree and green marketing effort level?

(iv) What impact do the investment cost factors of GPD and green marketing have on optimal decisions and profits?

We contribute to the literature by combining GPD and green marketing strategies for the first time to explore the interaction between these two important decisions regarding products with green attributes. We explore the optimal strategy from the perspective of each player, the whole supply chain, consumers, and the environment. Though there has been a great deal of research on GPD or green marketing over the past several years, there is limited research integrating these two important decisions. This paper fills this gap.

2 Literature Review

As this paper concerns green product development (GPD) and green marketing, we will review the related literature as follows.

2.1 Green product development

GPD has been a hot issue in recent years that numerous scholars have studied (Dong et al. 2019; Ranjan and Jha, 2019; Shen et al., 2019a; Shu et al., 2020; Zhang et al., 2020; Li et al., 2021b). There are two streams of literature. One studies the GPD strategy to determine whether a firm should produce green products. For example, Dong et al. (2019) study strategic investment in GPD. They develop a two-period model in which either the retailer or the manufacturer can decide to invest in GPD in the second period. Their results show that manufacturers investing in GPD are dominant. Shen et al. (2019a) study manufacturers' product line design strategies: only selling non-green products, only selling green products, and selling both non-green and green products. They find that no matter how high or low the product quality difference is, whether a single product line or a two-product line strategy is optimal depends on the consumers' willingness to pay for responsibility. Zhang et al. (2020) develop a game-theoretical model to study the green investment decisions of two horizontally differentiated firms in the presence of quality competition. They find that when green investment and quality investment are substitutes, no firm decides to make green investments, whereas when green investment and quality investment are complements, whether a firm makes a green investment depends on the green investment efficiency. The above studies investigate whether to invest in green technology and produce green products.

Another stream of literature focuses on how to manufacture and sell green products. Ranjan and Jha (2019) investigate a supply chain where a manufacturer offers a new substitutable green product through a direct channel and a non-green product through a retailer. They examine three models—centralized, decentralized, and collaboration. The green quality level in the collaboration model is the highest among the three scenarios. If the manufacturer offers a high green level product or dominates in the channel, the retailer puts more effort into selling the non-green product. When the manufacturer has less bargaining power, it must invest more in greening the product. Shu et al. (2020)

investigate the impact of retail competition on GPD in fashion apparel, and they find that the fiercer the competition, the lower the greenness degree. Xiao and Choi (2019) investigate the quality and greenness decisions and product line choice of a green manufacturer. Consumers can choose between the low-end and high-end product with different quality and greenness level and the manufacturer decides whether to offer a single product or two products. Their results show that the manufacturer extends the product line when the unit fit cost, the quality cost, the market scale of low-segment consumers, and the environmental responsibility level are sufficiently low. Product quality and greenness may be distorted from the efficient quality and greenness due to the consideration of cannibalization effect. Jiang et al. (2021) consider a supply chain consisting of one original equipment manufacturer (OEM) and one contract manufacturer (CM) that owns a self-brand product. Firms can invest in professional green technology innovators (GTIs) to innovate green features that can be embedded in the design of final products. The GTIs charge price premiums depending on the greenness levels. They study whether the OEM and the CM should co-invest in a joint GTI when there is a capital constraint. In contrast to Shu et al. (2020), Jiang (2021) finds that downstream competition stimulates upstream green innovation. Dong et al. (2016) study the manufacturer's sustainability investment and the retailer's ordering decision under cap-and-trade regulation. They find that sustainability investment efficiency has a significant negative impact on the retailer's order quantity and the manufacturer's sustainability investment. Li et al. (2020) study the green product design problem of a supply chain consisting of one manufacturer and two retailers, where one retailer has fairness concern. They consider two different green products: a marginal-intensive green product and a development-intensive green product. Their results show that the retailer that has a fairness concern will earn a smaller market share. Zhang et al. (2018) explore pricing and greenness level decisions by considering three different settings: non-information sharing, decentralized supply chain with information sharing, and centralized supply chain. Since the retailer's profit can be more dramatically improved with higher consumer sensitivity to greenness level, they suggest that the retailer should take a more active role than the manufacturer in promoting green products and educating consumers about the benefits of using green products. Without information sharing, overestimation of demand can induce the manufacturer to set a higher greenness level. Gao et al. (2020) consider two types of green products—a cost-intensive green product and a development-intensive green product—to explore the pricing decisions given the government's subsidy and green standard, and then study the optimal decisions of the government. They find that a growing green standard can increase the environmental benefits of development-intensive green products continuously. However, it is not always good to set increasing green standards for marginal cost-intensive green products. Li et al. (2021a) investigate a dual-channel supply chain where a manufacturer sells substitutable green products to its downstream subsidiary as well as an independent retailer. They find that decentralized encroachment is more beneficial to the manufacturer, but it harms the retailer.

2.2 Green marketing

Consumers' green purchasing behavior is associated with their knowledge of products' environmental performance (Hong and Guo, 2019). Thus, green marketing is necessary to stimulate the demand for products with green attributes. Some studies indicate that products' environmentally friendly characteristics can be a persuasive selling point (Atkinson and Rosenthal, 2014). Green advertising is one method that companies can use to position their products as green products in the minds of consumers (Eren-Erdogmus et al., 2016), and it plays an important role in marketing. Green advertising is different from traditional advertising. Green advertising can increase the public's environmental awareness and thus increase the demand for green products (Easterling et al., 1996). When a new green product is launched, green advertising is the major way to promote and educate consumers. Green advertising reveals information about the product's green performance, educates consumers, and enhances consumers' sustainability responsibility. Another effective green marketing tool is the eco-label, which is a certification mark or seal of approval to verify a product's greenness (Rahbar and Abdul Wahid, 2011). An eco-label can increase demand due to its positive image. Wang et al. (2020) study the effect of matching green product types with anthropomorphic advertising images on consumer responses through experiments to find the effective way of advertising green products. They find that there exists a significant matching effect between green product types and anthropomorphic advertising images. Kao et al. (2020) investigate the impact of advertising design and environment-protecting emotion on the advertising effect combining the self-reference effect and argument quality. The results show that an advertising design with self-reference and a strong argument has the best advertising effect.

Though green marketing has been studied extensively in marketing literature (Kautish et al., 2019), there is scant research on green marketing in the area of operations management. Du et al. (2019) study a supply chain consisting of one platform and two competing manufacturers selling green products on the platform. The platform determines the level of green advertising investment given the green levels of two products. They find that the platform can make more profit using the Promote the Best (PB) strategy rather than the Promote by Performance (PP) strategy, although the former requires more investment. Shen et al. (2019b) investigate the advertising and pricing decisions of a green product when there is a competing non-green product. They assess both simultaneous and sequential pricing strategies and find that the sequential pricing strategy is more profitable than the simultaneous pricing strategy for both green and non-green supply chains. Ghosh et al. (2021) study a supply chain consisting of one manufacturer and many retailers and consider advance payment and trade credit policy. They propose that the manufacturer provides a trade credit facility for financially constrained retailers and a wholesale price discount for financially strong retailers that will make advance payments.

2.3 Research gap

From the previous review, we can deduce that the research gaps in the fields of green product development (GPD) and green marketing are mainly as follows. First, in the field of GPD, most papers assume that manufacturers lead in GPD. It is rare to see literature considering the retailer as a leader in GPD (Guo et al., 2020). Only a few studies have considered both the manufacturer and the retailer leading in GPD (Ghosh and Shah, 2012; Dong et al., 2019; Li et al., 2021b). However, no study jointly considers the manufacturer's and retailer's adoption of green marketing. To fill the research gap and explore the interaction between these two important decisions regarding products with green attributes, four scenarios are considered and decisions and profits under these four scenarios are compared. Second, in the field of green marketing, most papers assume that it is the retailer who leads in green marketing (Ghosh et al., 2021; Du et al., 2019; Shen et al., 2019b). No papers have considered the manufacturer leading in green marketing. For example, the manufacturer can pursue national advertising or get a green label for its green product. This paper considers green marketing pursued by both the retailer and the manufacturer. Table 1 shows a comparison between this paper and other relevant papers.

Table 1. Comparison between this paper and other relevant papers, where M denotes manufacturer and R denotes retailer.

Article	M leads in GPD	R leads in GPD	Both lead in GPD	M leads in green marketing	R leads in green marketing	Both lead in green marketing
Hong et al. (2019)	√					
Ranjan and Jha (2019)	√					
Li et al. (2021a)	√					
Guo et al. (2020)		√				
Ghosh and Shah (2012)			√			
Dong et al. (2019)			√			
Li et al. (2021b)			√			
Ghosh et al. (2021)					√	

Shen et al. (2019b)					√	
Du et al. (2019)					√	
This paper			√			√

3 Basic Model

This paper jointly considers the decision in a supply chain to pursue green degree and green marketing efforts. The supply chain is formed by a manufacturer (denoted by M) and a retailer (R). The manufacturer produces products and wholesales them to the retailer. Then the retailer decides the retail prices and sells to consumers. Owing to the increasing environmental awareness of consumers, many companies undertake green product development (GPD) to add green attributes or environmental features to their final products, aiming to enhance their social reputation and attract consumers. GPD requires financial investment. Who is more suitable to lead in GPD from the perspective of the supply chain, the manufacturer or the retailer? Besides, green marketing is essential to inform consumers about the green attributes and green performance of a product. Therefore, there will be investment in green marketing efforts besides investment in GPD. Who is more suitable to lead in green marketing, and is there an interaction between the GPD and green marketing decisions? This paper considers these two important decisions jointly to answer the research questions. Four scenarios are considered in this paper: (1) scenario MB: the manufacturer leads in both GPD and green marketing; (2) scenario RB: the retailer leads in both GPD and green marketing; (3) scenario MR: the manufacturer leads in GPD and the retailer leads in green marketing; and (4) scenario RM: the retailer leads in GPD while the manufacturer leads in green marketing.

Consumers are heterogeneous and their valuation, v, for one unit of the product due to its functionality is uniformly distributed over the interval $[0,\overline{v}]$ with density one (Chiang et al., 2003; Shi, 2019) and each consumer can only buy one unit. Thus, the consumers' expected utility of consuming one unit of product is $U = v + \alpha g + \beta s - p$. g is the green degree of the product with green attributes, which reflects the green quality or level of environmental friendliness of the product. Green products may arouse consumers' emotions, such as protective feelings toward the environment (Bei and Simpson, 1995), and satisfy consumers' environmental sustainability needs. Therefore, we assume that the green degree of the product has a positive impact on consumers' utility. α is the sensitivity of consumers' utility of the green degree of the product. s is the green marketing effort, which also has a positive effect on consumers' utility (Du et al., 2019). For example, green marketing may convince consumers that their choice of a product with green attributes can reduce their negative impact on the environment. β is the sensitivity of consumers' utility of the green marketing effort.

Consumers buy the product only when they can derive a non-negative utility, i.e., $U \geq 0$. Only when the condition $v \geq p - \alpha g - \beta s$ is satisfied will they buy the product. Since v is uniformly distributed over the interval $[0, \bar{v}]$ with density one, the demand for the product can be derived as equation (1).

$$q = \bar{v} + \alpha g + \beta s - p \tag{1}$$

Assume that the marginal production cost per unit of the manufacturer is c_0 when GPD is not considered. When GPD is implemented, the cost of producing the product with green attributes can be higher or lower. A linear function is used here, following Song et al. (2017) and Li et al. (2021b). θ denotes the effect of GPD on the manufacturer's marginal production cost, which can be positive or negative.

$$c = c_0 + \theta g \tag{2}$$

According to the common assumption of diminishing returns on investment relating to the green degree and marketing effort in the relevant literature, the investment in GPD and green marketing expenditure are given in quadratic forms, i.e., $\eta g^2 / 2$ and $\gamma s^2 / 2$, respectively (Choi, 2017; Zhang et al., 2013; Shen et al., 2019b; Li et al., 2021b).

Game-theoretical models are built in four scenarios. In this supply chain, we assume that the manufacturer has more bargaining power over price than the retailer.

Thus, the manufacturer acts as the leader in setting the price. The manufacturer and the retailer play a Stackelberg game over the wholesale and retail prices. Usually, investment in GPD is a long-term decision made ahead of the green marketing decision. Green marketing is also a relatively long-term decision that cannot be altered immediately because marketing expenditures are usually planned before the selling season. However, wholesale and retail prices are usually short-term decisions that can be easily altered. Consequently, for the time sequence in each game, the GPD decision is made ahead of all other decisions. Then the green marketing decision is made. Subsequently, the manufacturer determines the wholesale price and the retailer determines the retail price. The detailed time sequence is described in each scenario.

Notations are shown in Table 2.

Table 2. Table of notations

Parameter	Meaning of the parameter
α	Sensitivity of consumers' utility of the green degree of the product, $0<\alpha<1$
β	Sensitivity of consumers' utility of the green marketing effort $0<\beta<1$
g	Green degree of the product
s	Green marketing effort
η	Coefficient of GPD investment cost
γ	Coefficient of green marketing cost
θ	Effect of GPD on the manufacturer's marginal production cost
q	Demand for the product
p	Retail price of the product
w	Wholesale price of the manufacturer
c_0	Marginal production cost per unit of the manufacturer without considering GPD
v	Consumer's valuation of one unit of product due to its functionality

4 Equilibrium Analysis

4.1 Scenario MB: The manufacturer leads in both GPD and green marketing

In this scenario, the manufacturer leads in both GPD and green marketing. The time sequence is as follows.

(i) Stage 1: the manufacturer decides green degree g, green marketing effort s, and wholesale price w.

(ii) Stage 2: the retailer decides the retail price of product p.

The profit functions of both parties are as follows.

$$\pi_M^{MB} = (w-c)q - \eta g^2/2 - \gamma s^2/2 \tag{3}$$

$$\pi_R^{MB} = (p-w)q \tag{4}$$

The second term of equation (3) represents the investment cost of GPD and the third term represents the green marketing cost. By using backward induction, we can obtain the following result.

Proposition 1. In scenario MB, if $\eta > (\alpha-\theta)^2/4$ and $\gamma > \beta^2\eta/[4\eta-(\alpha-\theta)^2]$, the equilibrium is as follows. The wholesale price, green degree, and green marketing effort of the manufacturer are $w^{MB*} = \frac{\bar{v}\gamma[2\eta+\theta(\alpha-\theta)] - c_0[\beta^2\eta+\gamma(\alpha^2-2\eta-\alpha\theta)]}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}$, $g^{MB*} = \frac{(\bar{v}-c_0)\gamma(\alpha-\theta)}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}$, and $s^{MB*} = \frac{\beta\eta(\bar{v}-c_0)}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}$, respectively. The retail price of the retailer is $p^{MB*} = \frac{\bar{v}\gamma[3\eta+\theta(\alpha-\theta)] - c_0[\beta^2\eta+\gamma(\alpha^2-\eta-\alpha\theta)]}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}$. The demand for the green product is $q^{MB*} = \frac{(\bar{v}-c_0)\gamma\eta}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}$. The profits of the manufacturer and the retailer are $\pi_M^{MB*} = \frac{(\bar{v}-c_0)^2\gamma\eta}{2\{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta\}}$ and $\pi_R^{MB*} = \frac{(\bar{v}-c_0)^2\gamma^2\eta^2}{\{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta\}^2}$, respectively.

To satisfy the positivity of decisions, $\alpha \geq \theta$ and $\bar{v} \geq c_0$ must also be satisfied.

From Proposition 1, we can obtain the following Lemma 1.

Lemma 1. When the manufacturer leads in both GPD and green marketing,

(i) g^{MB*} and s^{MB*} decrease with η, γ, and θ.

(ii) π_M^{MB*} and π_R^{MB*} decrease with η, γ, and θ.

Lemma 1(i) shows the sensitivity of the green degree of the product and the green marketing effort of the manufacturer to key parameters. The green degree of the product and green marketing level of the manufacturer both decrease with the coefficient of investment cost in GPD (η), coefficient of the green marketing cost (γ), and the effect of green marketing on the manufacturer's marginal production cost (θ). The reason for this may be that with a high cost, the manufacturer will invest a lower green degree and less green marketing effort. Lemma 1(ii) shows the sensitivity of the manufacturer's and retailer's profits to key parameters. Both parties' profits decrease with the coefficient of investment cost in GPD (η), coefficient of the green marketing cost (γ), and the effect of green marketing on the manufacturer's marginal production cost (θ). ***From Lemma 1, we can see that there is an interaction between GPD and green marketing through cost factors. One decision can be influenced by the cost factor of the other decision.***

4.2 Scenario RB: The retailer leads in both GPD and green marketing

In this scenario, the retailer leads in both GPD and green marketing. The time sequence is as follows.

(i) Stage 1: the retailer decides green degree g and green marketing effort s.

(ii) Stage 2: the manufacturer decides wholesale price w.

(iii) Stage 3: the retailer decides retail price p.

The profit functions of both parties are denoted as follows.

$$\pi_M^{RB} = (w - c)q \tag{5}$$

$$\pi_R^{RB} = (p - w)q - \frac{\eta g^2}{2} - \frac{\gamma s^2}{2} \tag{6}$$

By using backward induction, we can obtain the following result.

Proposition 2. In scenario RB, if $\eta > (\alpha-\theta)^2/8$ and $\gamma > \beta^2\eta/[8\eta-(\alpha-\theta)^2]$, the equilibrium is as follows. The retail price, green degree, and green marketing effort of the retailer are $p^{RB*} = \frac{\bar{v}\gamma[6\eta+\theta(\alpha-\theta)]-c_0[\beta^2\eta+\gamma(\alpha^2-2\eta-\alpha\theta)]}{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta}$, $g^{RB*} = \frac{(\bar{v}-c_0)\gamma(\alpha-\theta)}{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta}$,

and $s^{RB*} = \frac{(\bar{v}-c_0)\beta\eta}{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta}$, respectively. The wholesale price of the manufacturer is

$w^{RB*} = \frac{\bar{v}\gamma[4\eta+\theta(\alpha-\theta)]-c_0[\beta^2\eta+\gamma(\alpha^2-4\eta-\alpha\theta)]}{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta}$. The demand for the green product is

$q^{RB*} = \frac{2(\bar{v}-c_0)\gamma\eta}{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta}$. The profits of the manufacturer and the retailer are

$\pi_M^{RB*} = \frac{8(\bar{v}-c_0)^2\gamma^2\eta^2}{\{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta\}^2}$ and $\pi_R^{RB*} = \frac{(\bar{v}-c_0)^2\gamma\eta}{2\{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta\}}$, respectively.

The conditions $\eta > (\alpha-\theta)^2/8$ and $\gamma > \beta^2\eta/[8\eta-(\alpha-\theta)^2]$ ensure the existence of the equilibrium. The condition $\alpha \geq \theta$ satisfies the positivity of decision. From Proposition 2, we can get the following Lemma 2.

Lemma 2. When the retailer leads in both GPD and green marketing,

(i) g^{RB*} and s^{RB*} decrease with η, γ, and θ.

(ii) π_M^{RB*} and π_R^{RB*} decrease with η, γ, and θ.

The result is similar to that of Lemma 1. We omit the analysis to save space.

4.3 Scenario MR: The manufacturer leads in GPD and the retailer leads in green marketing

In this scenario, the manufacturer leads in GPD and the retailer leads in green marketing. The time sequence is as follows. Since GPD and green marketing are both long-term decisions, this is a four-stage game. We assume that the GPD decision is made ahead of all other decisions, since investing in GPD is usually a long-term decision and is difficult to change in a short time. The time sequence is as follows.

(i) Stage 1: the manufacturer decides green degree g.

(ii) Stage 2: the retailer decides green marketing effort s.

(iii) Stage 3: the manufacturer decides wholesale price w.

(iv) Stage 4: the retailer decides retail price p.

The profit functions of both parties are denoted as follows.

$$\pi_M^{MR} = (w - c_0 - \theta g)q - \eta g^2 / 2 \tag{7}$$

$$\pi_R^{MB} = (p - w)q - \gamma s^2 / 2 \tag{8}$$

By using backward induction, we can obtain the following result.

Proposition 3. In scenario MR, if $\eta > 16\gamma^2(\alpha - \theta)^2 / (\beta^2 - 8\gamma)^2$ and $\gamma > \beta^2 / 8$, the equilibrium is as follows. The wholesale price and green degree of the manufacturer are $w^{MR*} = \dfrac{4\bar{v}\gamma\{-\beta^2\eta + 4\gamma[2\eta + (\alpha - \theta)\theta]\} + c_0\{\beta^4\eta + 4\gamma\{-3\beta^2\eta + 4\gamma[2\eta + \alpha(-\alpha + \theta)]\}\}}{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[-4\eta + (\alpha - \theta)^2]\}}$ and $g^{MR*} = \dfrac{16(\bar{v} - c_0)\gamma^2(\alpha - \theta)}{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[(\alpha - \theta)^2 - 4\eta]\}}$, respectively. The retail price and advertising effort of the retailer are $p^{MR*} = \dfrac{2\bar{v}\gamma\{-3\beta^2\eta + 8\gamma[3\eta + (\alpha - \theta)\theta]\} + c_0\{\beta^4\eta + 2\gamma\{-5\beta^2\eta + 8\gamma[\eta + \alpha(-\alpha + \theta)]\}\}}{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[-4\eta + (\alpha - \theta)^2]\}}$ and $s^{MR*} = \dfrac{(\bar{v} - c_0)\beta(8\gamma - \beta^2)\eta}{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[(\alpha - \theta)^2 - 4\eta]\}}$, respectively. Demand for the green product is $q^{MR*} = \dfrac{2(\bar{v} - c_0)(8\gamma - \beta^2)\gamma\eta}{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[(\alpha - \theta)^2 - 4\eta]\}}$. The profits of the manufacturer and retailer are $\pi_M^{MR*} = \dfrac{8(\bar{v} - c_0)^2\gamma^2\eta}{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[-4\eta + (\alpha - \theta)^2]\}}$ and $\pi_R^{MR*} = \dfrac{(\bar{v} - c_0)^2(8\gamma - \beta^2)^3\gamma\eta^2}{2\{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[-4\eta + (\alpha - \theta)^2]\}\}^2}$, respectively.

The conditions $\eta > 16\gamma^2(\alpha - \theta)^2 / (\beta^2 - 8\gamma)^2$ and $\gamma > \beta^2 / 8$ ensure the existence of the equilibrium.

From Proposition 3, we can obtain the following Lemma 3.

Lemma 3. When the manufacturer leads in GPD and the retailer leads in green marketing,

(i) g^{MR*} and s^{MR*} decrease with γ,η, and θ.

(ii) π_M^{MR*} and π_R^{MR*} decrease with γ,η, and θ.

The result is similar to the results of Lemmas 1 and 2. We omit the analysis to save space.

4.4 Scenario RM: The retailer leads in GPD and the manufacturer leads in green marketing

In this scenario, the retailer leads in GPD and the manufacturer leads in green marketing. The time sequence is as follows. Since GPD and green marketing are long-term decisions, this is a four-stage game.

(i) Stage 1: the retailer decides green degree g.

(ii) Stage 2: the manufacturer decides green marketing effort s.

(iii) Stage 3: the manufacturer decides wholesale price w.

(iv) Stage 4: the retailer decides retail price p.

The profit functions of both parties are denoted as follows.

$$\pi_M^{RM} = (w-c)q - \gamma s^2/2 \tag{9}$$

$$\pi_R^{RM} = (p-w)q - \eta g^2/2 \tag{10}$$

By using backward induction, we can obtain Proposition 4.

Proposition 4. In scenario RM, if $\eta > 8\gamma(\alpha-\theta)^2/(\beta^2-8\gamma)^2$ and $\gamma > \beta^2/4$, the equilibrium is as follows. The wholesale price and green marketing effort level of the manufacturer are

$$w^{RM*} = \frac{2\bar{v}\gamma\{-\beta^2\eta+\gamma[4\eta+(\alpha-\theta)\theta]\}+c_0\{\beta^4\eta+2\gamma\{-3\beta^2\eta+\gamma[4\eta+\alpha(-\alpha+\theta)]\}\}}{\beta^4\eta-2\gamma\{4\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}}$$ and

$s^{RM*} = \frac{(\bar{v}-c_0)\beta(\beta^2-4\gamma)\eta}{\beta^4\eta-2\gamma\{4\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}}$, respectively. The retail price and green degree of the retailer are $p^{RM*} = \frac{\bar{v}\gamma\{-3\beta^2\eta+2\gamma[6\eta+(\alpha-\theta)\theta]\}+c_0\{\beta^4\eta+\gamma\{-5\beta^2\eta+2\gamma[2\eta+\alpha(-\alpha+\theta)]\}\}}{\beta^4\eta-2\gamma\{4\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}}$

and $g^{RM*} = \frac{2(\bar{v}-c_0)\gamma^2(\alpha-\theta)}{\beta^4\eta-2\gamma\{4\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}}$, respectively. Demand for the green product is $q^{RM*} = \frac{(\bar{v}-c_0)(4\gamma-\beta^2)\gamma\eta}{\beta^4\eta-2\gamma\{4\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}}$. The profits of the manufacturer and retailer are $\pi_M^{RM*} = \frac{(16\gamma-\beta^2)(\bar{v}-c_0)^2(8\gamma-\beta^2)^2\gamma\eta^2}{2\{\beta^4\eta-8\gamma\{2\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}\}^2}$ and $\pi_R^{RM*} = \frac{(\bar{v}-c_0)^2\gamma^2\eta}{\beta^4\eta-2\gamma\{4\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}}$, respectively.

The conditions $\eta > 8\gamma(\alpha-\theta)^2/(\beta^2-8\gamma)^2$ and $\gamma > \beta^2/4$ ensure the existence of a solution. To satisfy the positivity of decision, $\alpha \geq \theta$ must be satisfied.

Lemma 4. When the retailer leads in GPD and the manufacturer leads in green marketing,

(i) g^{RM*} and s^{RM*} decrease with γ, η, and θ.

(ii) π_M^{RM*} and π_R^{RM*} decrease with γ, η, and θ.

The result is similar to the results of Lemmas 1, 2, and 3. We omit the analysis to save space.

5. Comparison

In this section, we will compare the green degree, green marketing effort, and profits under four different scenarios. Equilibrium of four scenarios is showed in Table 3.

Table 3. Equilibrium decisions and profits of four scenarios (MB, RB, MR, RM)

	MB	RB	MR	RM
	$\eta > (\alpha-\theta)^2/4$ $\gamma > \frac{\beta^2\eta}{4\eta-(\alpha-\theta)^2}$	$\eta > (\alpha-\theta)^2/8$ $\gamma > \frac{\beta^2\eta}{8\eta-(\alpha-\theta)^2}$	$\eta > \frac{16\gamma^2(\alpha-\theta)^2}{(\beta^2-8\gamma)^2}$ $\gamma > \beta^2/8$	$\eta > \frac{2\gamma^2(\alpha-\theta)^2}{(\beta^2-4\gamma)^2}$ $\gamma > \beta^2/4$
Green degree	$(\bar{v}-c_0)\gamma(\alpha-\theta)/G$	$(\bar{v}-c_0)\gamma(\alpha-\theta)/J$	$16(\bar{v}-c_0)\gamma^2(\alpha-\theta)/K$	$2(\bar{v}-c_0)\gamma^2(\alpha-\theta)/L$
Green marketing effort	$\beta\eta(\bar{v}-c_0)/G$	$(\bar{v}-c_0)\beta\eta/J$	$(\bar{v}-c_0)\beta(8\gamma-\beta^2)\eta/K$	$(\bar{v}-c_0)\beta(\beta^2-4\gamma)\eta/L$
Profit of manufacturer	$(\bar{v}-c_0)^2\gamma\eta/(2G)$	$8(\bar{v}-c_0)^2\gamma^2\eta^2/J^2$	$8(\bar{v}-c_0)^2\gamma^2\eta/K$	$(16\gamma-\beta^2)(\bar{v}-c_0)^2(8\gamma-\beta^2)^2\gamma\eta^2/(2L^2)$
Profit of retailer	$(\bar{v}-c_0)^2\gamma^2\eta^2/G^2$	$(\bar{v}-c_0)^2\gamma\eta/(2J)$	$(\bar{v}-c_0)^2(8\gamma-\beta^2)^3\gamma\eta^2/(2K^2)$	$(\bar{v}-c_0)^2\gamma^2\eta/L$

In table 3, $G=\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta$, $J=\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta$, $K=\beta^4\eta-16\gamma\{\beta^2\eta+\gamma[(\alpha-\theta)^2-4\eta]\}$, and $L=\beta^4\eta-2\gamma\{4\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}$.

By comparing green degrees in the four scenarios, we can derive the following results.

Proposition 5. The equilibrium of green degree of the product in the four scenarios has the following properties.

(i) $g^{MB*} > g^{RB*}$, $g^{MB*} > g^{MR*}$, and when $\beta^2/4 < \gamma < \beta^2/2$, $g^{MB*} < g^{RM*}$. When $\gamma > \beta^2/2$, $g^{MB*} > g^{RM*}$.

(ii) $g^{MR*} > g^{RB*}$ and $g^{RM*} > g^{RB*}$.

Proposition 5(i) shows that the green degree under scenario MB is always higher than that under scenario RB. The green degree under scenario MB is also higher than that under scenario MR. When the advertising cost factor is sufficiently high ($\gamma > \beta^2/2$), the green degree under scenario MB is higher than that of scenario RM. However, when the green marketing cost factor is relatively low ($\beta^2/4 < \gamma < \beta^2/2$), the greenness level under scenario MB is lower than that of scenario RM.

From Proposition 5(i), when the green marketing cost factor is sufficiently high, the green degree under scenario MB is the highest among the four scenarios.

However, if the green marketing cost factor is sufficiently low, the green degree in scenario RM is the highest. Propositions 5(i) and (ii) show that the green degree under scenario RB is the lowest among the four scenarios because $g^{RB*} < g^{MB*}$, $g^{RB*} < g^{MR*}$, and $g^{RB*} < g^{RM*}$. ***That is, when the retailer leads in both GPD and green marketing, the green degree is always the lowest.***

Due to complexity, we use a numerical example to illustrate more results. These parameter values satisfy the assumptions needed in all four scenarios and ensure positive demands and profits.

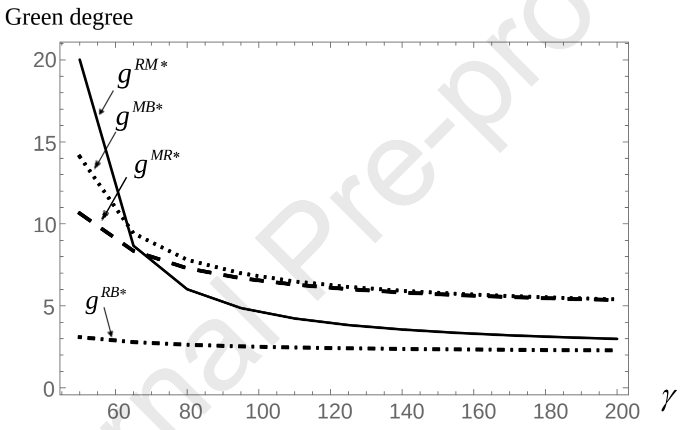

Fig. 1. The impact of γ on green degree

($\bar{v} = 1000, c_0 = 60, \alpha = 30, \beta = 11, \eta = 1600, \theta = 3$)

Fig. 1 shows that the green degree decreases with γ. ***That is, when the cost of investing in green marketing becomes expensive, the GPD investment level will be negatively impacted, which is an interesting result***. When γ is sufficiently low, the greenness effort in scenario RM is the highest. However, when γ is sufficiently high, the greenness effort in scenario MB is the highest. When γ becomes larger, the greenness effort in scenarios MB and MR becomes closer and is much higher than that in scenarios RM and RB.

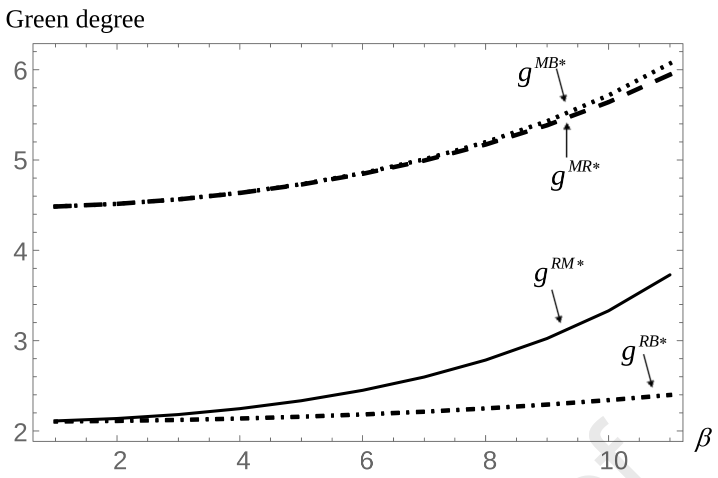

Fig. 2. The impact of β on green degree

From Fig. 2, when β increases, the green degree also increases, which is an interesting result. ***That is, when consumers' utility is more sensitive to green marketing effort, the product's green degree will also be enhanced.*** From equation (1), demand increases with β. When demand is enhanced, the green degree will also be enhanced. ***This echoes the practice of the government subsidizing consumers to stimulate demand. Demand has a positive effect on the firm's motivation to enhance green degree of products.*** When the manufacturer leads in GPD, the green degree is much higher than that in the scenario where the retailer leads in GPD.

By comparing the green marketing levels of the four scenarios, we can derive the following proposition.

Proposition 6. The equilibrium green marketing effort under the four scenarios has the following properties.

(i) $s^{MB*} > s^{RB*}$.

(ii) When $\beta^2/4 < \gamma < \beta^2/2$, $s^{MB*} < s^{RM*}$; when $\gamma > \beta^2/2$, $s^{MB*} > s^{RM*}$.

(iii) $s^{RB*} < s^{MR*}$.

Proposition 6(i) shows that the green marketing level under scenario MB is higher than that under scenario RB. When the investment cost factor in green marketing is sufficiently high, the green marketing level under scenario MB is higher than that under scenario RM. When $\beta^2/4<\gamma<\beta^2/2$, the result is the opposite. Proposition 6(iii) indicates that the green marketing effort under scenario RB is lower than that under scenario MR.

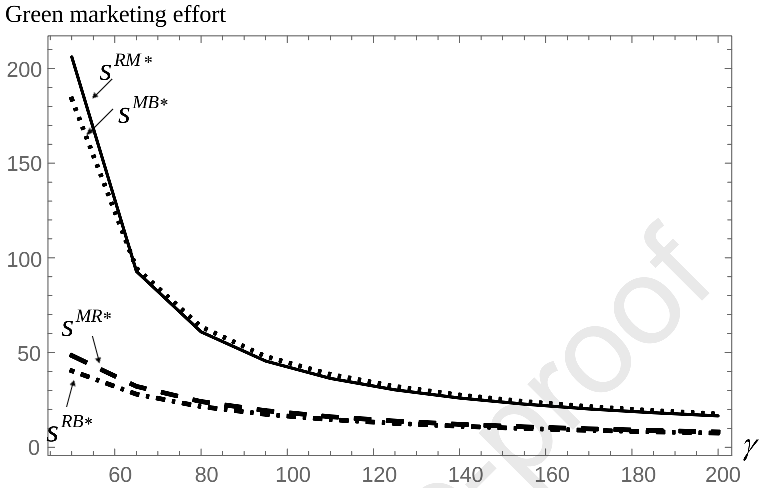

Fig. 3. The impact of γ on green marketing effort

($\bar{v}=1000, c_0=60, \alpha=30, \beta=11, \eta=1600, \theta=3$)

From Fig. 3, when γ is sufficiently low, the green marketing effort in scenario RM is the highest. However, when γ is sufficiently high, that in scenario MB is the highest. However, there is little difference between scenarios MB and RM or between scenarios MR and RB. However, the green marketing effort in scenario MB or RM is significantly higher than that in scenario MR or RB. When γ increases, the green marking effort will be reduced.

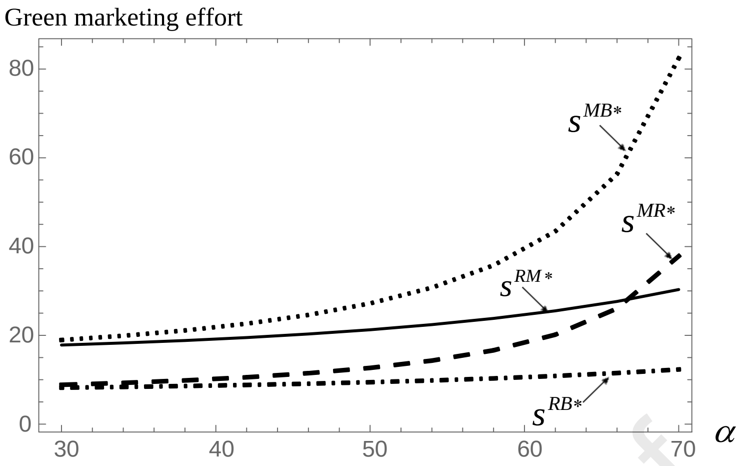

Fig. 4. The impact of α on green marketing effort

($\bar{v}=1000, c_0=60, \beta=8, \eta=1600, \theta=3, \gamma=130$)

Fig. 4 illustrates the impact of α on green marketing effort. ***When α increases, the green marketing effort will also increase, which is an interesting result. When consumers are more sensitive to the green degree of the product, the green marketing effort is positively impacted. Fig. 2 and Fig. 4 show that there is an interaction between GPD and green marketing decisions. One decision can be influenced by the sensitivity of consumers' utility of another decision.***

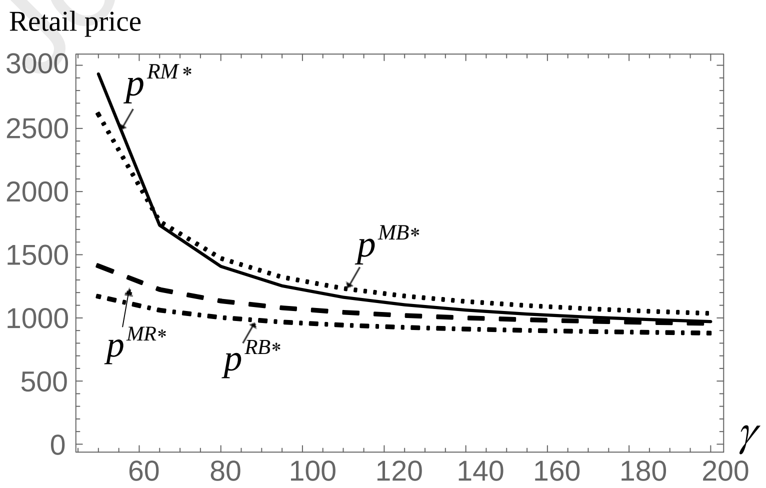

Fig. 5. The impact of γ on retail price

($\bar{v}=1000, c_0=60, \alpha=30, \beta=11, \eta=1600, \theta=3$)

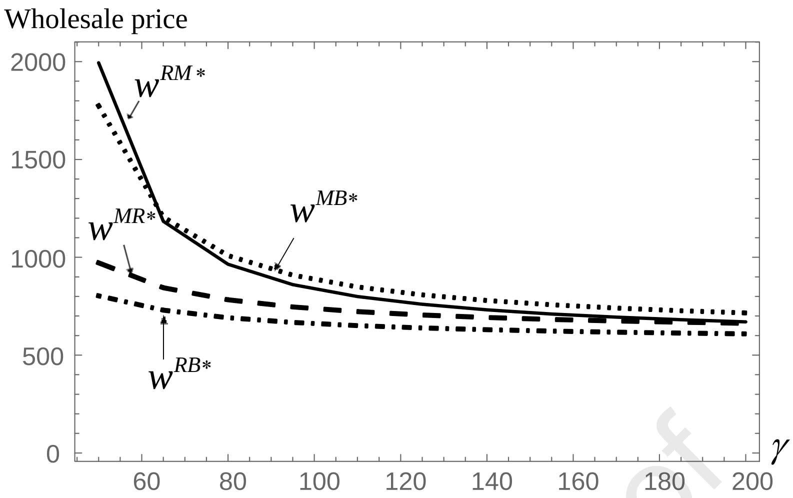

Fig. 6. The impact of γ on wholesale price

($\bar{v} = 1000, c_0 = 60, \alpha = 30, \beta = 11, \eta = 1600, \theta = 3$)

Fig. 5 and Fig. 6 show the impact of γ on retail price and wholesale price, respectively. When γ is sufficiently low, the retail and wholesale prices in scenario RM are the highest. However, when γ is sufficiently high, the retail and wholesale prices in scenario MB are the highest.

Proposition 7. The equilibrium profits of the manufacturer have the following properties: $\pi_M^{MB*} > \pi_M^{MR*}$, $\pi_M^{MB*} > \pi_M^{RB*}$, and $\pi_M^{MR*} > \pi_M^{RB*}$.

Proposition 7 shows that the manufacturer's profit under scenario MB is higher than that under scenario MR. ***That is, when the manufacturer leads in both GPD and green marketing, the profit is higher than that in the scenario where the manufacturer leads in GPD and the retailer leads in green marketing.*** The profit of the manufacturer under scenario MB is higher than that under scenario RB. However, π_M^{MB*} may be higher or lower than π_M^{RM*} according to different parameter values. We will use numerical examples to illustrate.

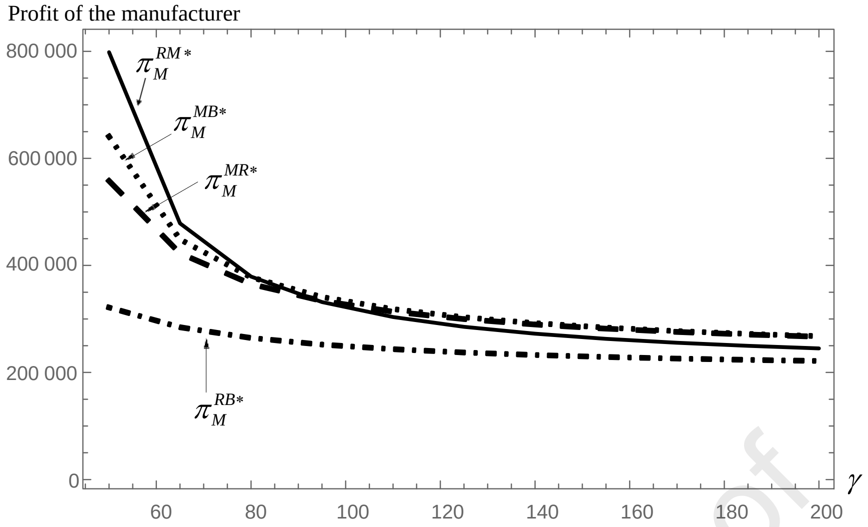

Fig. 7. The impact of γ on the profit of the manufacturer

($\bar{v} = 1000, c_0 = 60, \alpha = 60, \beta = 8, \eta = 1600, \theta = 3$)

Fig. 7 shows the impact of γ on the manufacturer's profit. When γ is sufficiently low, the profit of the manufacturer in scenario RM is the highest. However, when γ is sufficiently high, the profit of the manufacturer in scenario MB is the highest. However, there is little difference between scenarios MB and MR. Scenario RB is the worst case for the manufacturer. The management insight here is that ***when γ is sufficiently high, the manufacturer will prefer scenarios MB and MR. The manufacturer would like to lead in GPD. According to Proposition 7, leading in both GPD and green marketing is the best scenario for the manufacturer. However, when γ is sufficiently low, the manufacturer will prefer scenario RM, where the retailer leads in GPD and the manufacturer leads in green marketing.***

Proposition 8. The equilibrium profits of the retailer have the following property: $\pi_R^{RB*} < \pi_R^{RM*}$.

Proposition 8 indicates that the retailer's profit under scenario RB is lower than that under scenario RM. When the retailer leads in both GPD and green marketing, the profit of the retailer is lower than that in the scenario where the retailer leads in GPD and the manufacturer leads in green marketing. ***That is, from the perspective of the***

retailer, pursuing both GPD and green marketing is not a good idea. Due to complexity, more results will be derived through numerical examples.

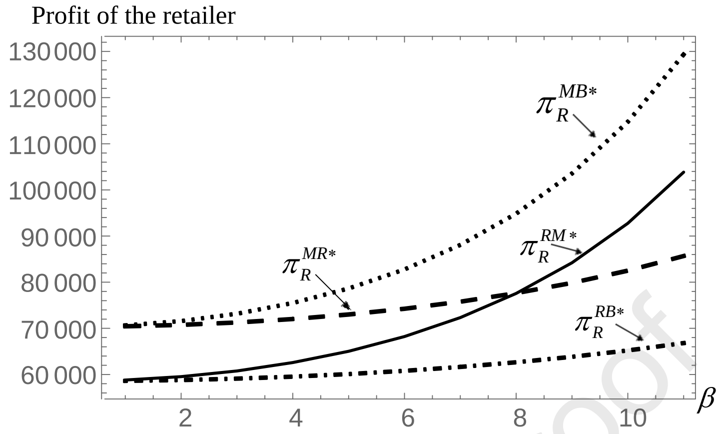

Fig. 8. The impact of β on the profit of the retailer

From Fig. 8, the retailer prefers scenario MB, in which the manufacturer leads in both GPD and green marketing. When β is sufficiently low, scenario MR is better than scenario RM. However, when β is sufficiently high, the retailer will prefer scenario RM to scenario MR. The higher the sensitivity of consumers' utility of the green marketing effort, the higher the retailer's profit. The profits of the manufacturer and the whole supply chain also increase with β. However, due to space limitations, we omit figures.

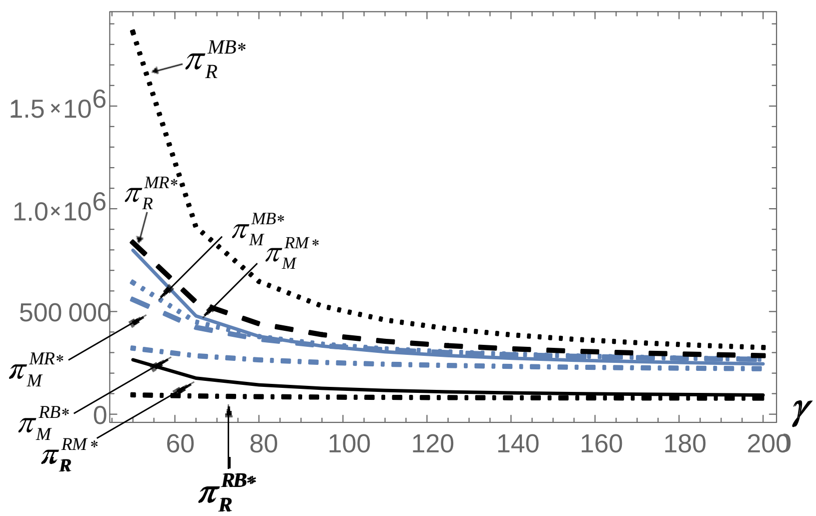

Fig. 9. The impact of γ on the profits of the retailer and the manufacturer

($\bar{v}=1000, c_0=60, \alpha=60, \beta=8, \eta=1600, \theta=3$)

Fig. 9 shows the retailer's and manufacturer's profits. π_M^{MB*} is higher than π_R^{RB*}. That is, when the manufacturer leads in both GPD and green marketing, the manufacturer's profit is higher than that of the retailer when the retailer leads in both. This result is similar to that of Li et al. (2021b), which find that the manufacturer is always more profitable than the retailer when they are both leaders in GPD. π_M^{MR*} is higher than π_R^{RM*}. However, π_R^{MR*} is higher than π_M^{RM*}. Both parties' profits decrease with γ (coefficient of green marketing cost).

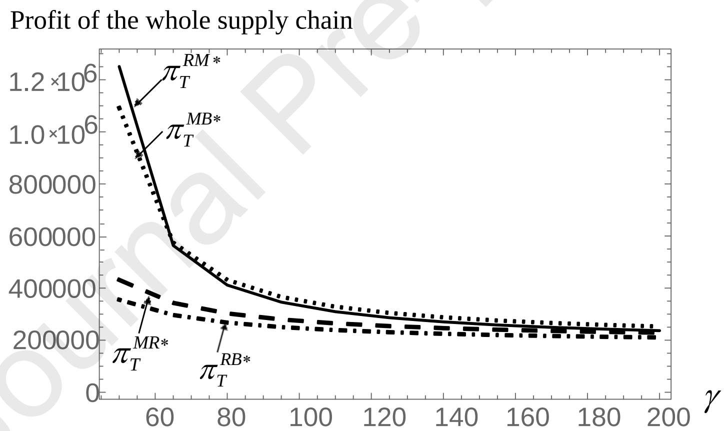

Fig. 10. The impact of γ on the profit of the whole supply chain

($\bar{v}=1000, c_0=60, \alpha=30, \beta=11, \eta=1600, \theta=3$)

From Fig. 10, the profit of the whole supply chain decreases with γ. When γ is sufficiently low, scenario RM is the optimal setting for the supply chain and scenario RB is the worst case. However, when γ is sufficiently high, the supply chain would prefer scenario MB. However, there is little difference among the four scenarios when γ is sufficiently high.

6. Environmental impact and consumer surplus

In previous sections, we discussed the decisions and profits from the firm's perspective in four scenarios. In this part, we will explore the environmental impact to address the question of which scenario is more environmentally friendly.

Carbon emissions levels are used to measure the environmental impact of a GPD initiative (Agrawal et al., 2012; Zhang et al., 2020). According to Zhang et al. (2020), there is an initial unit emission e. After investing in GPD, the firm's per unit emission will decrease to $e-k\delta$, where δ is the greenness investment level and k represents the environmental improvement coefficient measuring the environmental improvement efficiency of green investment. Therefore, in this paper, we use the carbon emissions saved to measure the effects of different strategies on the environment.

Hence, we calculate the total carbon emissions saved regarding total products consumed by consumers in the four scenarios as follows.

$$ES^{MB*}=kg^{MB*}q^{MB*}=\frac{k(\bar{v}-c_0)^2\gamma^2\eta(\alpha-\theta)}{\{\beta^2\eta+\gamma[(\alpha-\theta)^2-4\eta]\}^2} \tag{11}$$

$$ES^{RB*}=kg^{RB*}q^{RB*}=\frac{2k(\bar{v}-c_0)^2\gamma^2\eta(\alpha-\theta)}{\{\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}^2} \tag{12}$$

$$ES^{MR*}=kg^{MR*}q^{MR*}=\frac{32k(\bar{v}-c_0)^2(8\gamma-\beta^2)\gamma^3\eta(\alpha-\theta)}{\{\beta^4\eta-16\gamma\{\beta^2\eta+\gamma[(\alpha-\theta)^2-4\eta]\}\}^2} \tag{13}$$

$$ES^{RM*}=kg^{RM*}q^{RM*}=\frac{2k(\bar{v}-c_0)^2(4\gamma-\beta^2)\gamma^3\eta(\alpha-\theta)}{\{\beta^4\eta-2\gamma\{4\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}\}^2} \tag{14}$$

where k measures the environmental improvement efficiency of GPD.

Due to the complexity of the analytic results, we use numerical examples to illustrate the carbon emissions amounts saved in the four scenarios.

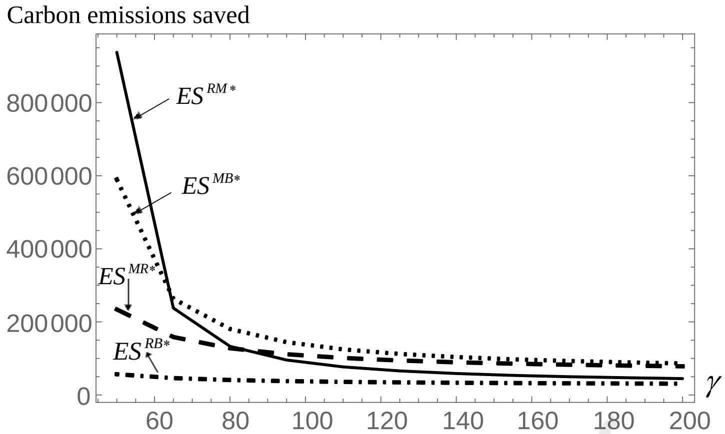

Fig. 11. The impact of γ on the total carbon emissions saved

($\bar{v}=1000, c_0=60, \alpha=30, \beta=11, \eta=1600, \theta=3, k=50$)

From Fig. 11, we can see that when γ is sufficiently low, in scenario RM, the carbon emissions saved are the highest, whereas in scenario RB, they are the lowest. ***In scenarios MB and RM, the carbon emissions saved are substantially higher than that in scenario MR or RB.*** However, when γ is sufficiently high, MB is the best scenario from the environmental perspective. However, scenarios MB and MR show very little difference when γ is sufficiently high. ***That is, it is preferable for the environment that the manufacturer leads in GPD.***

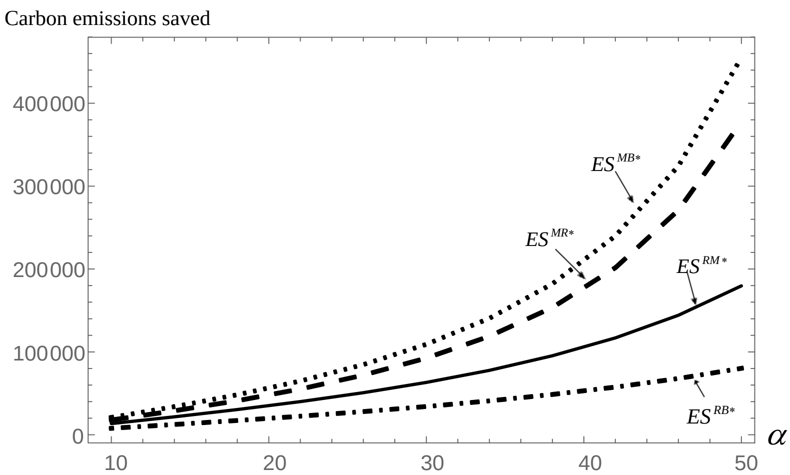

Fig. 12. The impact of α on the total carbon emissions saved

($\bar{v}=1000, c_0=60, \beta=11, \eta=1600, \theta=3, k=50, \gamma=130$)

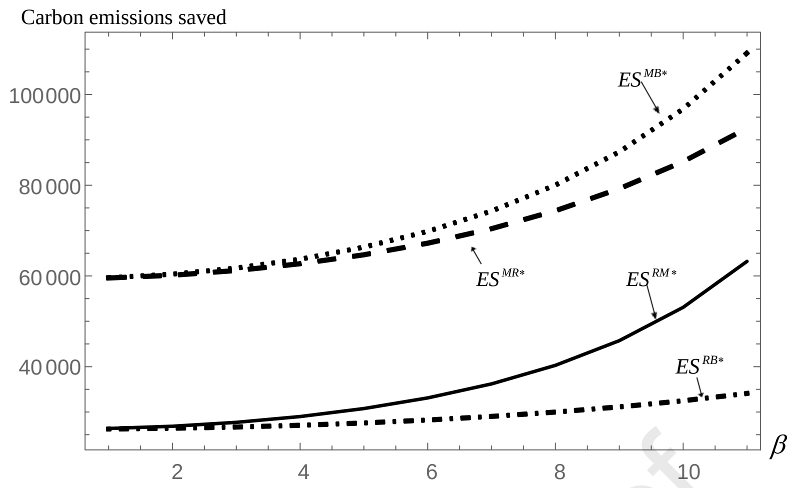

Fig. 13. The impact of β on the total carbon emissions saved

($\bar{v} = 1000, c_0 = 60, \alpha = 30, \eta = 1600, \theta = 3, k = 50, \gamma = 130$)

From Fig. 12 and Fig. 13, we observe that when consumers are sensitive to the green degree or green marketing effort, there will be greater carbon emissions savings. ***The management insight here is that in order to improve the environment, it is advisable to enhance consumers' awareness of the green degree of the product and enable the consumers to derive more positive utility from green marketing.***

Next, we will discuss total consumer surplus in the four scenarios. Consumer surplus is the difference between the willingness to pay (WTP) and the retail price, indicating the consumer's net gain from the trade. Here, consumer surplus is equal to utility because we assume that each consumer can buy only one product. The total consumer surplus (CS) is the total surplus of consumers who buy the product (Esenduran et al., 2017; Ma et al., 2020). In the basic model, we know that each consumer's expected utility is $U = v + \alpha g + \beta s - p$, where v is uniformly distributed over the interval $[0, \bar{v}]$ with density one. To ensure positive utility, the condition $v \geq p - \alpha g - \beta s$ must be satisfied. Thus, the valuation of consumer who has incentive to purchase the product is uniformly distributed in the interval $v \in [p - \alpha g - \beta s, \bar{v}]$ with density one. The total consumer surplus is the sum of each consumer's utility which is different across each consumer. Hence, the total consumer surplus can be derived from the following equation according to Esenduran et al. (2017) and Ma et al. (2020)

$$CS = \int_{p-\alpha g-\beta s}^{\bar{v}} (v+\alpha g+\beta s-p)dv = (\bar{v}+\alpha g+\beta s-p)^2/2 \tag{15}$$

Then we can derive following consumer surplus in the four scenarios under equilibrium solutions by substituting optimal green degree, green marketing effort and retail price from Proposition 1, 2, 3 and 4 into equation (15).

$$CS^{MB*} = \frac{(\bar{v}-c_0)^2\gamma^2\eta^2}{2\{\beta^2\eta+\gamma[(\alpha-\theta)^2-4\eta]\}^2} \tag{16}$$

$$CS^{RB*} = \frac{2(\bar{v}-c_0)^2\gamma^2\eta^2}{\{\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}^2} \tag{17}$$

$$CS^{MR*} = \frac{2(\bar{v}-c_0)^2(\beta^2-8\gamma)^2\gamma^2\eta^2}{\{\beta^4\eta-16\gamma\{\beta^2\eta+\gamma[(\alpha-\theta)^2-4\eta]\}\}^2} \tag{18}$$

$$CS^{RM*} = \frac{(\bar{v}-c_0)^2(\beta^2-4\gamma)^2\gamma^2\eta^2}{2\{\beta^4\eta-2\gamma\{4\beta^2\eta+\gamma[(\alpha-\theta)^2-8\eta]\}\}^2} \tag{19}$$

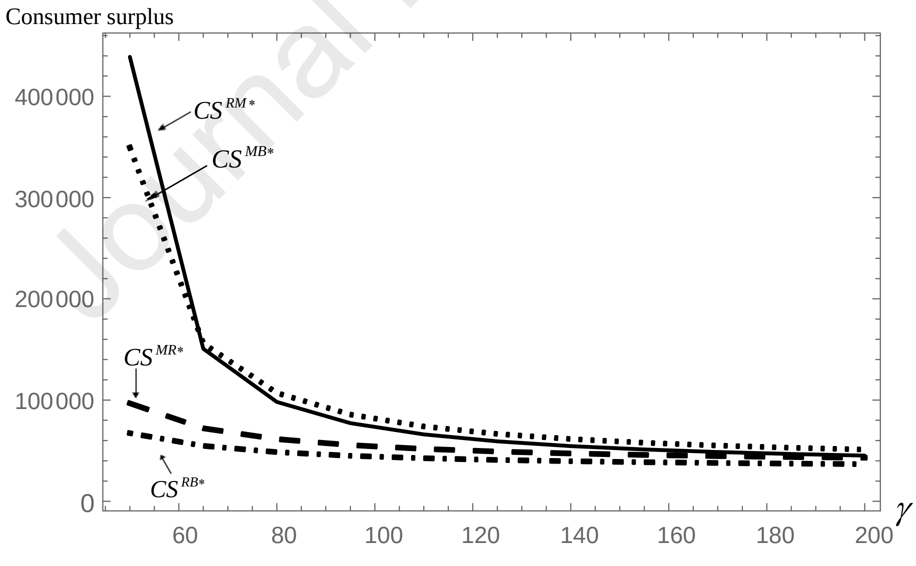

Fig. 14. The impact of γ on consumer surplus

($\bar{v}=1000, c_0=60, \alpha=30, \beta=11, \eta=1600, \theta=3$)

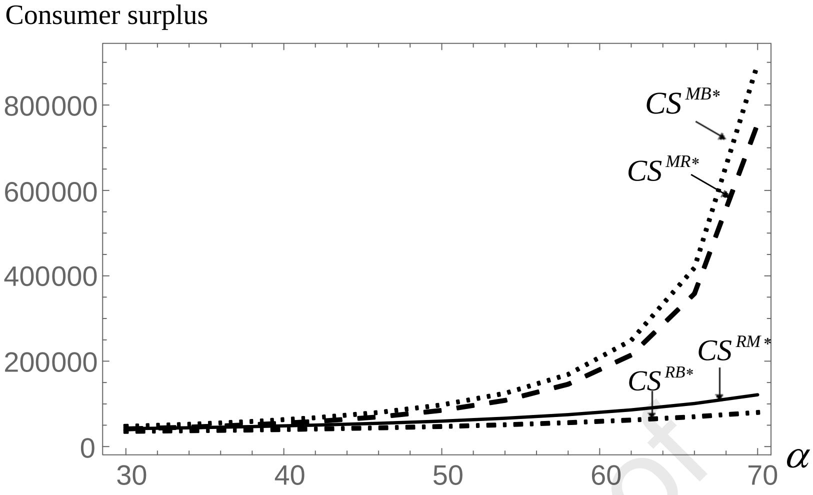

Fig. 15. The impact of β on consumer surplus

($\bar{v}=1000, c_0=60, \beta=8, \eta=1600, \theta=3, \gamma=130$)

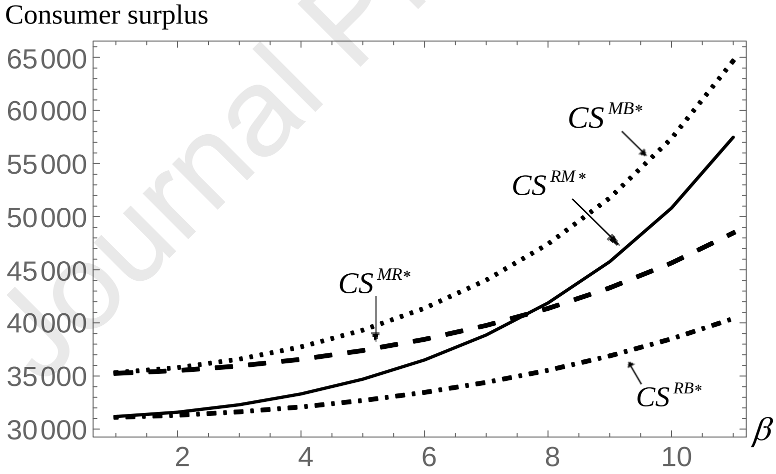

Fig. 16. The impact of β on consumer surplus

($\bar{v}=1000, c_0=60, \beta=8, \alpha=30, \eta=1600, \theta=3, \gamma=130$)

From Fig. 14, we can see that when γ is sufficiently low, consumers will prefer scenario RM. However, when γ is sufficiently high, consumers will prefer scenario MB. Fig. 15 and Fig. 16 illustrate the impact of α or β on consumer surplus. Consumer surplus increases with them.

7. Conclusions

This paper jointly studied the green product development (GPD) and green marketing strategies of a supply chain consisting of one manufacturer and one retailer. To explore who is more suitable to lead these two strategies, we developed game models in four different scenarios and compared the optimal decisions and profits. Then we analyzed which scenario is best from the environmental and consumer perspectives.

We derived some important results. First, there is an interaction between GPD and green marketing through cost factors. One decision can be influenced by the investment cost factor of another decision. One decision can also be influenced by the sensitivity of consumers' utility regarding another decision. This finding implies that companies, such as Apple, and retailers, such as H&M, should consider both GPD and green marketing to make an optimal decision. Second, when the green marketing cost factor is sufficiently high, the green degree and green marketing effort under scenario MB are the highest among the four scenarios. However, when the green marketing cost factor is sufficiently low, the green degree and green marketing in scenario RM are the highest. Similar results are derived for retail price and wholesale price. This result differs from that of Li et al. (2021b), who find that the product's greenness is always higher when the manufacturer leads in GPD. Our results show that under certain circumstances, when the retailer leads in GPD and the manufacturer leads in green marketing, the green degree is the highest. When the retailer leads in both GPD and green marketing, the green degree and green marketing effort are always the lowest among the four scenarios. Third, when the green marketing cost factor is sufficiently high, the manufacturer, whole supply chain, environment, and consumers all get the highest benefit from scenario MB among the four scenarios. However, when the green marketing cost factor is sufficiently low, scenario RM is optimal for them. In practice, scenario RM is rarely seen, which indicates that the green marketing cost factor is relatively expensive. From the retailer's perspective, pursuing both GPD and green marketing is the worst case, making scenario MB the optimal solution. This finding may explain why it is usually the manufacturer that pursues both GPD and green marketing, such as Apple, Coca-

Cola, and Tesla. Though some retailers may adopt GPD or green marketing, such as H&M, their incentives are not high enough from analysis. This result is consistent with Dong et al. (2019), who observe that the manufacturer leads in investing in GPD is dominating. However, GPD is the only strategy they considered. Fourth, to improve the environment and enhance consumer surplus, it is best to enhance consumers' awareness of green products and enable the consumers to derive more positive utility from green marketing, which can also increase the profits of both supply chain members and the whole supply chain. Fifth, when the manufacturer leads in both GPD and green marketing, the profit of the manufacturer is higher than that of the retailer leading in both GPD and green marketing, which is consistent with Li et al. (2021b).

This paper has some limitations that point to directions for future research. First, the demand for green products is deterministic in this paper. However, for newly developed green products, as there is little or no historical data available in practice, consumer demand may not be easily or accurately estimated. Therefore, in a future study, one can consider the case with uncertain demand. Second, this paper assumed that the manufacturer leads the pricing game in the supply chain. However, in practice, the retailer may have greater power than the manufacturer. Third, we assumed that the investment cost factor of GPD or green marketing is the same for the manufacturer and the retailer. Future research may consider that the investment cost factors of GPD and green marketing are different for different supply chain members. Finally, the results were derived using theoretical modelling and numerical examples and therefore need tests with real data collected from selected firms in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Proof of Proposition 1. Because $\frac{\partial^2 \pi_R^{MB}}{\partial p^2} = -2 < 0$, π_R^{MB} is a concave function of p. By solving the first-order condition $\frac{\partial \pi_R^{MB}}{\partial p}=0$, we can get the reaction function as $p^{MB}(w,g,s)=\frac{(\overline{v}+w+g\alpha+s\beta)}{2}$. By inserting $p^{MB}(w,g,s)$ into the manufacturer's profit function, we can get $\pi_M^{MB}(w,g,s)$. The Hessian matrix of $\pi_M^{MB}(w,g,s)$ over (w,g,s) is $H=\begin{bmatrix} -1 & (\alpha+\theta)/2 & \beta/2 \\ (\alpha+\theta)/2 & -\eta-\alpha\theta & -\beta\theta/2 \\ \beta/2 & -\beta\theta/2 & -\gamma \end{bmatrix}$. Because $-1<0$, $\begin{vmatrix} -1 & (\alpha+\theta)/2 \\ (\alpha+\theta)/2 & -\eta-\alpha\theta \end{vmatrix}=[4\eta-(\alpha-\theta)^2]/4$, $|H|=\{\beta^2\eta+\gamma[(\alpha-\theta)^2-4\eta]\}/4$, only when $[4\eta-(\alpha-\theta)^2]/4>0$ and $|H|=\{\beta^2\eta+\gamma[(\alpha-\theta)^2-4\eta]\}/4<0$, $\pi_M^{MB}(w,g,s)$ is a concave function over (w,g,s). As a result, following conditions must be satisfied: $\eta>(\alpha-\theta)^2/4$ and $\gamma>\frac{\beta^2\eta}{4\eta-(\alpha-\theta)^2}$. By solving the first-order conditions $\frac{\partial \pi_M^{MB}(w,g,s)}{\partial w}=0$, $\frac{\partial \pi_M^{MB}(w,g,s)}{\partial g}=0$, and $\frac{\partial \pi_M^{MB}(w,g,s)}{\partial s}=0$ together, we can get the optimal decisions of the manufacturer as follows: $g^{MB*}=\frac{(\overline{v}-c_0)\gamma(\alpha-\theta)}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}$, $s^{MB*}=\frac{\beta\eta(\overline{v}-c_0)}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}$ and $w^{MB*}=\frac{\overline{v}\gamma[2\eta+\theta(\alpha-\theta)]-c_0[\beta^2\eta+\gamma(\alpha^2-2\eta-\alpha\theta)]}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}$. The optimal retail price is $p^{MB*}=\frac{\overline{v}\gamma[3\eta+\theta(\alpha-\theta)]-c_0[\beta^2\eta+\gamma(\alpha^2-\eta-\alpha\theta)]}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}$. The profit of the manufacturer and the retailer are $\pi_M^{MB*}=\frac{(\overline{v}-c_0)^2\gamma\eta}{2\{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta\}}$ and $\pi_R^{MB*}=\frac{(\overline{v}-c_0)^2\gamma^2\eta^2}{\{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta\}^2}$, respectively.

Proof of Lemma 1(i). Taking the first order derivative of g^{MB*} and s^{MB*} with respect to γ, we have $\frac{\partial g^{MB*}}{\partial \gamma}=-\frac{(\overline{v}-c_0)\beta^2\eta(\alpha-\theta)}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}$. Note that $\overline{v}>c_0$ and $\alpha\geq\theta$ must be satisfied. Thus, g^{MB*} decreases with γ. Taking the first order derivative of s^{MB*} with respect to γ, we have $\frac{\partial s^{MB*}}{\partial \gamma}=-\frac{(\bar{v}-c_0)\beta\eta[4\eta-(\alpha-\theta)^2]}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}$. Because $\eta>\alpha^2+\alpha\theta+\theta^2$ and $4\eta-(\alpha-\theta)^2>0$ can be derived. Thus, $\frac{\partial s^{MB*}}{\partial \gamma}<0$, s^{MB*} decreases with γ. (ii) Because $\frac{\partial g^{MB*}}{\partial \eta}=\frac{(\bar{v}-c_0)(\beta^2-4\gamma)\gamma(\alpha-\theta)}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}$ and $\gamma>\beta^2/4$, g^{MB*} decreases with η. $\frac{\partial s^{MB*}}{\partial \eta}=-\frac{(\bar{v}-c_0)\beta\gamma(\alpha-\theta)^2}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}<0$, s^{MB*} decreases with η. (iii) Because $\frac{\partial g^{MB*}}{\partial \theta}=-\frac{(\bar{v}-c_0)\gamma\{\gamma[4\eta+(\alpha-\theta)^2]-\beta^2\eta\}}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}<0$ and $\frac{\partial s^{MB*}}{\partial \theta}=\frac{2(c_0-\bar{v})\beta\gamma\eta(\alpha-\theta)}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}<0$, according to the concavity condition of scenario MB, g^{MB*} and s^{MB*} decrease with θ.

Proof of Lemma 1(ii). Taking the first order derivative of π_M^{MB*} and π_R^{MB*} with respect to γ, we have $\frac{\partial \pi_M^{MB*}}{\partial \gamma}=-\frac{(c_0-\bar{v})^2\beta^2\eta^2}{2\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}<0$ and $\frac{\partial \pi_R^{MB*}}{\partial \gamma}=-\frac{(c_0-\bar{v})^2\beta^2\eta^2}{2\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}<0$, therefore π_M^{MB*} and π_R^{MB*} decrease with γ.Taking the first order derivative of π_M^{MB*} and π_R^{MB*} with respect to η, we have $\frac{\partial \pi_M^{MB*}}{\partial \eta}=-\frac{(c_0-\bar{v})^2\gamma^2(\alpha-\theta)^2}{2\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}<0$ and $\frac{\partial \pi_R^{MB*}}{\partial \eta}=\frac{2(c_0-\bar{v})^2\gamma^3\eta(\alpha-\theta)^2}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^3}<0$. Taking the first order derivative of π_M^{MB*} and π_R^{MB*} with respect to θ, we have $\frac{\partial \pi_M^{MB*}}{\partial \theta}=-\frac{(c_0-\bar{v})^2\gamma^2\eta(\alpha-\theta)}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2}<0$ and $\frac{\partial \pi_R^{MB*}}{\partial \theta}=\frac{4(c_0-\bar{v})^2\gamma^3\eta^2(\alpha-\theta)}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^3}<0$.

Proof of Proposition 2. Because $\frac{\partial^2 \pi_R^{RB}}{\partial p^2}=-2<0$, π_R^{MB} is a concave function of p. By solving the first-order condition $\frac{\partial \pi_R^{RB}}{\partial p}=0$, we can get the reaction function as

$p^{RB}(w,g,s)=\frac{(\bar{v}+w+g\alpha+s\beta)}{2}$. By inserting $p^{RB}(w,g,s)$ into the manufacturer's profit function, we can get $\pi_M^{RB}(w,g,s)$. Because $\frac{\partial^2\pi_M^{RB}(w,g,s)}{\partial w^2}=-1<0$, $\pi_M^{RB}(w,g,s)$ is a concave function of w. By solving the first-order condition $\frac{\partial\pi_M^{RB}(w,g,s)}{\partial w}=0$, we can get the reaction function of the manufacturer as $w^{RB}(g,s)=\frac{c_0+\bar{v}+s\beta+g(\alpha+\theta)}{2}$. Then inserting $w^{RB}(g,s)$ into $p^{RB}(w,g,s)$, we can get $p^{RB}(g,s)$. By inserting $w^{RB}(g,s)$ and $p^{RB}(g,s)$ into the retailer's function $\pi_R^{RB}(w,g,s)$, we can get $\pi_R^{RB}(g,s)$. Because $\frac{\partial^2\pi_R^{RB}(g,s)}{\partial g^2}=\frac{(\alpha-\theta)^2-8\eta}{8}$ and $\frac{\partial^2\pi_R^{RB}(g,s)}{\partial g^2}\times\frac{\partial^2\pi_R^{RB}(g,s)}{\partial s^2}-\left(\frac{\partial^2\pi_R^{RB}(g,s)}{\partial g\partial s}\right)^2$ $=\frac{-\beta^2\eta-\gamma[(\alpha-\theta)^2-8\eta]}{8}$. Only when $\frac{\partial^2\pi_R^{RB}(g,s)}{\partial g^2}<0$ and $\frac{\partial^2\pi_R^{RB}(g,s)}{\partial g^2}\times\frac{\partial^2\pi_R^{RB}(g,s)}{\partial s^2}-\left(\frac{\partial^2\pi_R^{RB}(g,s)}{\partial g\partial s}\right)^2>0$, $\pi_R^{RB}(g,s)$ is a concave function. That is $\eta>\frac{(\alpha-\theta)^2}{8}$ and $\gamma>\frac{\beta^2\eta}{8\eta-(\alpha-\theta)^2}$, which means that the greenness investment and advertising expenditure are not too cheap. By solving the first order conditions $\frac{\partial\pi_R^{RB}(g,s)}{\partial g}=0$ and $\frac{\partial\pi_R^{RB}(g,s)}{\partial s}=0$ together, we can get the optimal decisions of the manufacturer as follows: $g^{RB*}=\frac{(\bar{v}-c_0)\gamma(\alpha-\theta)}{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta}$ and $s^{RB*}=\frac{(\bar{v}-c_0)\beta\eta}{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta}$. Then we can get the optimal wholesale price $w^{RB*}=\frac{\bar{v}\gamma[4\eta+\theta(\alpha-\theta)]-c_0[\beta^2\eta+\gamma(\alpha^2-4\eta-\alpha\theta)]}{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta}$. The optimal retail price is $p^{RB*}=\frac{\bar{v}\gamma[6\eta+\theta(\alpha-\theta)]-c_0[\beta^2\eta+\gamma(\alpha^2-2\eta-\alpha\theta)]}{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta}$. The profit of the manufacturer and the retailer are $\pi_M^{RB*}=\frac{8(\bar{v}-c_0)^2\gamma^2\eta^2}{\{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta\}^2}$ and $\pi_R^{RB*}=\frac{(\bar{v}-c_0)^2\gamma\eta}{2\{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta\}}$, respectively.

The condition $\eta>\frac{(\alpha-\theta)^2}{8}$ and $\gamma>\frac{\beta^2\eta}{8\eta-(\alpha-\theta)^2}$ ensures the concavity of the solution. In order to satisfy the positivity of decision, $\alpha\geq\theta$ must be satisfied.

Proof of Lemma 2. Taking the first order derivative of g^{RB*} and s^{RB*} with respect to γ, we have $\frac{\partial g^{RB*}}{\partial \gamma} = -\frac{(\bar{v}-c_0)\beta^2\eta(\alpha-\theta)}{\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^2}$. Note that $\bar{v}>c_0$ and $\alpha \geq \theta$ must be satisfied. Thus, g^{RB*} decreases with γ. Taking the first order derivative of s^{RB*} with respect to γ, because $\eta > \frac{(\alpha-\theta)^2}{8}$, we have $\frac{\partial s^{RB*}}{\partial \gamma} = -\frac{(\bar{v}-c_0)\beta\eta[8\eta-(\alpha-\theta)^2]}{\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^2} < 0$. Thus, s^{RB*} decreases with γ. Because $\frac{\partial g^{RB*}}{\partial \eta} = \frac{(\bar{v}-c_0)(\beta^2-8\gamma)\gamma(\alpha-\theta)}{\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^2}$, when $\gamma > \frac{\beta^2}{8}$, g^{RB*} decreases with η; or else, increases with η. From Proposition 2, $\gamma > \frac{\beta^2\eta}{8\eta-(\alpha-\theta)^2} > \frac{\beta^2}{8}$, g^{RB*} decreases with η. $\frac{\partial s^{RB*}}{\partial \eta} = -\frac{(\bar{v}-c_0)\beta\gamma(\alpha-\theta)^2}{\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^2} < 0$, s^{RB*} decreases with η. Because $\frac{\partial g^{RB*}}{\partial \theta} = \frac{(c_0-\bar{v})\gamma\{\gamma[8\eta+(\alpha-\theta)^2]-\beta^2\eta\}}{\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}^2} < 0$, $\frac{\partial s^{RB*}}{\partial \theta} = \frac{2(c_0-\bar{v})\beta\gamma\eta(\alpha-\theta)}{\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^2} < 0$, according to the concavity condition of scenario MB, g^{RB*} and s^{RB*} decreases with θ. Taking the first order derivative of π_M^{RB*} and π_R^{RB*} with respect to γ, we have $\frac{\partial \pi_M^{RB*}}{\partial \gamma} = \frac{16(c_0-\bar{v})^2\beta^2\eta^3\gamma}{\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^3} < 0$ and $\frac{\partial \pi_R^{RB*}}{\partial \gamma} = -\frac{(c_0-\bar{v})^2\beta^2\eta^2}{2\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^2} < 0$, according to the concavity condition of scenario RB, therefore π_M^{RB*} and π_R^{RB*} decrease with γ. Taking the first order derivative of π_M^{RB*} and π_R^{RB*} with respect to η, we have $\frac{\partial \pi_M^{RB*}}{\partial \eta} = \frac{16(c_0-\bar{v})^2\gamma^3\eta(\alpha-\theta)^2}{\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^3} < 0$ and $\frac{\partial \pi_R^{RB*}}{\partial \eta} = \frac{(c_0-\bar{v})^2\gamma^2(\alpha-\theta)^2}{2\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^3} < 0$, π_M^{RB*} and π_R^{RB*} decrease with η. Taking the first order derivative of π_M^{RB*} and π_R^{RB*} with respect to θ, according to the concavity condition of scenario RB, we have $\frac{\partial \pi_M^{RB*}}{\partial \theta} = -\frac{32(c_0-\bar{v})^2\gamma^2\eta^2(\alpha-\theta)}{\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^3} < 0$ and $\frac{\partial \pi_R^{RB*}}{\partial \theta} = -\frac{(c_0-\bar{v})^2\gamma^2\eta(\alpha-\theta)}{\{\beta^2\eta+\gamma[-8\eta+(\alpha-\theta)^2]\}^2} < 0$, therefore, π_M^{RB*} and π_R^{RB*} decrease with θ.

Proof of Proposition 3. Because $\frac{\partial^2 \pi_R^{MR}}{\partial p^2} = -2 < 0$, π_R^{MR} is a concave function of p. By solving the first-order condition $\frac{\partial \pi_R^{MR}}{\partial p} = 0$, we can get the reaction function as $p^{MR}(w,g,s) = \frac{(\bar{v} + w + g\alpha + s\beta)}{2}$. By inserting $p^{MR}(w,g,s)$ into the manufacturer's profit function, we can get $\pi_M^{MR}(w,g,s)$. Because $\frac{\partial^2 \pi_M^{MR}(w,g,s)}{\partial w^2} = -1 < 0$, $\pi_M^{MR}(w,g,s)$ is a concave function of ω. By solving the first-order condition $\frac{\partial \pi_M^{MR}(w,g,s)}{\partial w} = 0$, we can get the reaction function of the manufacturer as $w^{MR}(g,s) = \frac{c_0 + \bar{v} + s\beta + g(\alpha+\theta)}{2}$. Then inserting $w^{MR}(g,s)$ into the $p^{MR}(\omega,g,s)$, we can get $p^{MR}(g,s)$. By inserting $w^{MR}(g,s)$ and $p^{MR}(g,s)$ into the retailer's function $\pi_R^{MR}(w,g,s)$, we can get $\pi_R^{MR}(g,s)$. Because $\frac{\partial^2 \pi_R^{MR}(g,s)}{\partial s^2} = \frac{(\beta^2 - 8\gamma)}{8}$, when $\gamma > \frac{\beta^2}{8}$, $\pi_R^{MR}(g,s)$ is a concave function of s. By solving the first-order condition, we can get $s^{MR}(g) = \frac{\beta[\bar{v} - c_0 + g(\alpha-\theta)]}{8\gamma - \beta^2}$. By inserting $s^{MR}(g)$ into $\omega^{MR}(g,s)$ and $p^{MR}(g,s)$, we can get $\omega^{MR}(g)$ and $p^{MR}(g)$. Finally, we can get $\pi_M^{MR}(g)$. Because $\frac{\partial^2 \pi_M^{MR}(g)}{\partial g^2} = \frac{-\beta^4\eta + 16\gamma\{\beta^2\eta + \gamma[-4\eta + (\alpha-\theta)^2]\}}{(\beta^2 - 8\gamma)^2}$, only when $\frac{\partial^2 \pi_M^{MR}(g)}{\partial g^2} < 0$, $\pi_M^{MR}(g)$ is a concave function of g. That is $\eta > \frac{16\gamma^2(\alpha-\theta)^2}{(\beta^2 - 8\gamma)^2}$. By solving the first-order condition $\frac{\partial \pi_M^{MR}(g)}{\partial g} = 0$, we can get the optimal greenness effort $g^{MR*} = \frac{16(\bar{v} - c_0)\gamma^2(\alpha-\theta)}{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[(\alpha-\theta)^2 - 4\eta]\}}$. Then, we can get the optimal decisions of the manufacturer and the retailer as follows: $s^{MR*} = \frac{(\bar{v} - c_0)\beta(8\gamma - \beta^2)\eta}{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[(\alpha-\theta)^2 - 4\eta]\}}$,

$$w^{MR*} = \frac{4\bar{v}\gamma\{-\beta^2\eta + 4\gamma[2\eta + (\alpha-\theta)\theta]\} + c_0\{\beta^4\eta + 4\gamma\{-3\beta^2\eta + 4\gamma[2\eta + \alpha(-\alpha+\theta)]\}\}}{\beta^4\eta - 16\gamma\{\beta^2\eta + \gamma[-4\eta + (\alpha-\theta)^2]\}}$$ and

$p^{MR*}=\dfrac{2\bar{v}\gamma\{-3\beta^2\eta+8\gamma[3\eta+(\alpha-\theta)\theta]\}+c_0\{\beta^4\eta+2\gamma\{-5\beta^2\eta+8\gamma[\eta+\alpha(-\alpha+\theta)]\}\}}{\beta^4\eta-16\gamma\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}}$ .The profit of the manufacturer and the retailer are $\pi_M^{MR*}=\dfrac{8(\bar{v}-c_0)^2\gamma^2\eta}{\beta^4\eta-16\gamma\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}}$ and $\pi_R^{MR*}=\dfrac{(\bar{v}-c_0)^2(8\gamma-\beta^2)^3\gamma\eta^2}{2\{\beta^4\eta-16\gamma\{\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]\}\}^2}$, respectively.

The condition $\eta>\dfrac{16\gamma^2(\alpha-\theta)^2}{(\beta^2-8\gamma)^2}$ and $\gamma>\dfrac{\beta^2}{8}$ ensures the concavity of the solution.

Proof of Lemma 3. Taking the first order derivative of g^{MR*} and s^{MR*} with respect to γ, we have $\dfrac{\partial g^{MR*}}{\partial\gamma}=\dfrac{32(\bar{v}-c_0)\beta^2(\beta^2-8\gamma)\gamma\eta(\alpha-\theta)}{\{\beta^4\eta-16\gamma[\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]\}^2}$. Note that $\bar{v}>c_0$ and $\alpha\geq\theta$ must be satisfied. According to the concavity condition of scenario MR, g^{MR*} decreases with γ. Taking the first order derivative of s^{MR*} with respect to γ ,we have $\dfrac{\partial s^{MR*}}{\partial\gamma}=\dfrac{8\beta\eta(\bar{v}-c_0)[4\alpha^2\gamma(4\gamma-\beta^2)-\eta(\beta^2-8\gamma)^2-8\alpha\gamma\theta(4\gamma-\beta^2)+4\gamma\theta^2(4\gamma-\beta^2)]}{\{\beta^4\eta-16\gamma[\beta^2\eta-4\eta\gamma+\gamma(\alpha-\theta)^2]\}^2}$, when $\eta>\dfrac{4\gamma(4\gamma-\beta^2)(\alpha-\theta)^2}{(\beta^2-8\gamma)^2}$, $\dfrac{\partial s^{MR*}}{\partial\gamma}<0$, thus, s^{MR*} decreases with γ ; or else s^{MR*} increases with γ . From Proposition 3, $\eta>\dfrac{16\gamma^2(\alpha-\theta)^2}{(\beta^2-8\gamma)^2}$. As a result, $\eta>\dfrac{4\gamma(4\gamma-\beta^2)(\alpha-\theta)^2}{(\beta^2-8\gamma)^2}$ is satisfied. Thus, s^{MR*} decreases with γ . According to the concavity condition of scenario MR, $\dfrac{\partial g^{MR*}}{\partial\eta}=-\dfrac{16(\bar{v}-c_0)(\beta^2-8\gamma)^2\gamma^2(\alpha-\theta)}{\{\beta^4\eta-16\gamma[\beta^2\eta-4\gamma\eta+\gamma(\alpha-\theta)^2)]\}^2}<0$, $\dfrac{\partial s^{MR*}}{\partial\eta}=-\dfrac{16\beta\gamma^2(\bar{v}-c_0)(8\gamma-\beta^2)(\alpha-\theta)^2}{\{\beta^4\eta-16\gamma[\beta^2\eta-4\gamma\eta+\gamma(\alpha-\theta)^2]\}^2}<0$, g^{MR*} decreases with η , s^{MR*} decreases with η . According to the concavity condition of scenario MB, $\dfrac{\partial g^{MR*}}{\partial\theta}=-\dfrac{16\gamma^2(\bar{v}-c_0)}{\beta^4\eta-16\gamma[\beta^2\eta-4\gamma\eta+\gamma(\alpha-\theta)^2)]}<0$, $\dfrac{\partial s^{MR*}}{\partial\theta}=-\dfrac{32\beta\gamma^2\eta(\bar{v}-c_0)(\alpha-\theta)(8\gamma-\beta^2)}{\{\beta^4\eta-16\gamma[\beta^2\eta-4\eta\gamma+\gamma(\alpha-\theta)^2]\}^2}<0$, g^{MR*} and s^{MR*} decrease with θ.Taking the first order derivative of π_M^{MR*} and π_R^{MR*} with respect to

γ , according to the concavity condition of scenario MR, we have $\frac{\partial \pi_M^{MR*}}{\partial \gamma} = -\frac{16(\bar{v}-c_0)^2(8\gamma-\beta^2)\beta^2\gamma\eta^2}{\{\beta^4\eta-16\gamma[\beta^2\eta-4\eta\gamma+\gamma(\alpha-\theta)^2]\}^2} < 0$ and $\frac{\partial \pi_R^{MR*}}{\partial \gamma} = -\frac{\beta^2(\bar{v}-c_0)^2(\beta^2-8\gamma)^2\eta^2[\beta^4\eta-16\gamma(\beta^2\eta-4\gamma\eta-3\gamma(\alpha-\theta)^2)]}{2\{\beta^4\eta-16\gamma[\beta^2\eta-4\eta\gamma+\gamma(\alpha-\theta)^2)]\}^3} < 0$, therefore π_M^{MR*} and π_R^{MR*} decrease with γ. Taking the first order derivative of π_M^{MR*} and π_R^{MR*} with respect to η , according to the concavity condition of scenario MR, we have $\frac{\partial \pi_M^{MR*}}{\partial \eta} = -\frac{128\gamma^4(\bar{v}-c_0)^2(\alpha-\theta)^2}{\{\beta^4\eta-16\gamma[\beta^2\eta-4\eta\gamma+\gamma(\alpha-\theta)^2]\}^2} < 0$, $\frac{\partial \pi_R^{MR*}}{\partial \eta} = -\frac{16(c_0-\bar{v})^2(8\gamma-\beta^2)^3\gamma^3\eta(\alpha-\theta)^2}{\{\beta^4\eta-16\gamma[\beta^2\eta-4\eta\gamma+\gamma(\alpha-\theta)^2]\}^3} < 0$, π_M^{MR*} and π_R^{MR*} decrease with η. Taking the first order derivative of π_M^{MR*} and π_R^{MR*} with respect to θ , according to the concavity condition of scenario MR, we have $\frac{\partial \pi_M^{MR*}}{\partial \theta} = -\frac{256\gamma^4\eta(c_0-\bar{v})^2(\alpha-\theta)}{\{\beta^4\eta-16\gamma[\beta^2\eta-4\eta\gamma+\gamma(\alpha-\theta)^2]\}^2} < 0$, $\frac{\partial \pi_R^{MR*}}{\partial \theta} = -\frac{32(c_0-\bar{v})^2(8\gamma-\beta^2)^3\gamma^3\eta^2(\alpha-\theta)}{\{\beta^4\eta-16\gamma[\beta^2\eta-4\eta\gamma+\gamma(\alpha-\theta)^2]\}^3} < 0$, therefore π_M^{MR*} and π_R^{MR*} decrease with θ.

Proof of Proposition 4. Because $\frac{\partial^2 \pi_R^{RM}}{\partial p^2} = -2 < 0$, π_R^{RM} is a concave function of p . By solving the first-order condition $\frac{\partial \pi_R^{RM}}{\partial p} = 0$, we can get the reaction function as $p^{MR}(w,g,s) = \frac{\bar{v}+w+g\alpha+s\beta}{2}$. By inserting $p^{RM}(w,g,s)$ into the manufacturer's profit function, we can get $\pi_M^{RM}(w,g,s)$. Because $\frac{\partial^2 \pi_M^{RM}(w,g,s)}{\partial w^2} = -1 < 0$, $\pi_M^{RM}(w,g,s)$ is a concave function of ω. By solving the first-order condition $\frac{\partial \pi_M^{RM}(w,g,s)}{\partial w} = 0$, we can get the reaction function of the manufacturer as $w^{RM}(g,s) = \frac{c_0+\bar{v}+s\beta+g(\alpha+\theta)}{2}$. Then inserting $w^{RM}(g,s)$ into the $p^{RM}(\omega,g,s)$, we can get $p^{RM}(g,s)$. By inserting $\omega^{RM}(g,s)$ and $p^{RM}(g,s)$ into the retailer's function $\pi_R^{RM}(w,g,s)$, we can get $\pi_R^{RM}(g,s)$. When $\frac{\partial^2 \pi_M^{RM}(g,s)}{\partial s^2} = \frac{(\beta^2-4\gamma)}{4} < 0$, $\pi_M^{RM}(g,s)$ is a concave function of s . That is when

$\gamma > \frac{\beta^2}{4}$. By solving the first-order condition, we can get $s^{RM}(g) = \frac{\beta[\bar{v} - c_0 + g(\alpha - \theta)]}{4\gamma - \beta^2}$. By inserting $s^{RM}(g)$ into $\omega^{RM}(g,s)$ and $p^{RM}(g,s)$, we can get $w^{RM}(g)$ and $p^{RM}(g)$. Finally, we can get $\pi_R^{RM}(g)$. Because $\frac{\partial^2 \pi_R^{RM}(g)}{\partial g^2} = \frac{-\beta^4\eta + 2\gamma\{4\beta^2\eta + \gamma[-8\eta + (\alpha-\theta)^2]\}}{(\beta^2 - 4\gamma)^2}$, only when $\frac{\partial^2 \pi_R^{RM}(g)}{\partial g^2} < 0$, $\pi_R^{RM}(g)$ is a concave function of g. That is $\eta > \frac{2\gamma^2(\alpha-\theta)^2}{(\beta^2 - 4\gamma)^2}$. By solving the first-order condition $\frac{\partial \pi_M^{MR}(g)}{\partial g} = 0$, we can get the optimal greenness effort $g^{RM*} = \frac{8(\bar{v} - c_0)\gamma^2(\alpha-\theta)}{\beta^4\eta - 8\gamma\{2\beta^2\eta + \gamma[(\alpha-\theta)^2 - 8\eta]\}}$. Then, we can get the optimal decisions of the manufacturer and the retailer as follows:

$$s^{RM*} = \frac{(\bar{v} - c_0)\beta(\beta^2 - 8\gamma)\eta}{\beta^4\eta - 8\gamma\{2\beta^2\eta + \gamma[(\alpha-\theta)^2 - 8\eta]\}},$$

$$w^{RM*} = \frac{4\bar{v}\gamma\{-\beta^2\eta + 2\gamma[4\eta + (\alpha-\theta)\theta]\} + c_0\{\beta^4\eta + 4\gamma\{-3\beta^2\eta + 2\gamma[4\eta + \alpha(-\alpha+\theta)]\}\}}{\beta^4\eta - 8\gamma\{2\beta^2\eta + \gamma[(\alpha-\theta)^2 - 8\eta]\}}, \text{ and}$$

$$p^{RM*} = \frac{2\bar{v}\gamma\{-3\beta^2\eta + 4\gamma[6\eta + (\alpha-\theta)\theta]\} + c_0\{\beta^4\eta + 2\gamma\{-5\beta^2\eta + 4\gamma[2\eta + \alpha(-\alpha+\theta)]\}\}}{\beta^4\eta - 8\gamma\{2\beta^2\eta + \gamma[(\alpha-\theta)^2 - 8\eta]\}}.$$

The profit of the manufacturer and the retailer are $\pi_M^{MR*} = \frac{(16\gamma - \beta^2)(\bar{v} - c_0)^2(8\gamma - \beta^2)^2\gamma\eta^2}{2\{\beta^4\eta - 8\gamma\{2\beta^2\eta + \gamma[-8\eta + (\alpha-\theta)^2]\}\}^2}$ and $\pi_R^{MR*} = \frac{4(\bar{v} - c_0)^2\gamma^2\eta}{\beta^4\eta - 8\gamma\{2\beta^2\eta + \gamma[-8\eta + (\alpha-\theta)^2]\}}$, respectively.

The condition $\eta > \frac{2\gamma^2(\alpha-\theta)^2}{(\beta^2 - 4\gamma)^2}$ and $\gamma > \frac{\beta^2}{4}$ ensure the concavity of the solution. In order to satisfy the positivity of decision, $\alpha \geq \theta$ must be satisfied.

Proof of Lemma 4. Taking the first order derivative of g^{RM*} and s^{RM*} with respect to γ, we have $\frac{\partial g^{RM*}}{\partial \gamma} = -\frac{16\beta^2(\bar{v} - c_0)\gamma\eta(8\gamma - \beta^2)(\alpha-\theta)}{\{\beta^4\eta - 8\gamma[2\beta^2\eta - 8\eta\gamma + \gamma(\alpha-\theta)^2]\}^2}$. Note that $\bar{v} > c_0$ and $\alpha \geq \theta$ must be satisfied. According to the concavity condition of scenario RM, $\frac{\partial g^{RM*}}{\partial \gamma} < 0$,

g^{RM*} decreases with γ. Taking the first order derivative of s^{RM*} with respect to γ ,we have $\frac{\partial s^{RM*}}{\partial \gamma}=\frac{-4\beta\eta(\bar{v}-c_0)[\alpha^2\gamma(\beta^2-2\gamma)+(\beta^2-4\gamma)^2\eta+2\alpha\gamma\theta(2\gamma-\beta^2)+\gamma\theta^2(\beta^2-2\gamma)]}{\{\beta^4\eta-8\gamma[2\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]\}^2}$, when $\eta>\frac{\gamma(2\gamma-\beta^2)(\alpha-\theta)^2}{(\beta^2-4\gamma)^2}$, $\frac{\partial s^{RM*}}{\partial \gamma}<0$, thus, s^{RM*} decreases with γ ;or else, s^{RM*} increases with γ .From Proposition 4, $\eta>\frac{2\gamma^2(\alpha-\theta)^2}{(\beta^2-4\gamma)^2}$. That is, $\eta>\frac{\gamma(2\gamma-\beta^2)(\alpha-\theta)^2}{(\beta^2-4\gamma)^2}$ is satisfied. s^{RM*} decreases with γ . According to the concavity condition of scenario RM, $\frac{\partial g^{RM*}}{\partial \eta}=-\frac{8\gamma^2(\bar{v}-c_0)(\beta^2-8\gamma)^2(\alpha-\theta)}{\{\beta^4\eta-8\gamma[2\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]\}^2}<0$, $\frac{\partial s^{RM*}}{\partial \eta}=-\frac{8\beta\gamma^2(\bar{v}-c_0)(8\gamma-\beta^2)(\alpha-\theta)^2}{\{\beta^4\eta-8\gamma[2\beta^2\eta-8\gamma\eta+\gamma(\alpha-\theta)^2]\}^2}<0$, g^{RM*} and s^{RM*} decreases with η . According to the concavity condition of scenario RM, $\frac{\partial g^{RM*}}{\partial \theta}=-\frac{8\gamma^2(\bar{v}-c_0)}{\beta^4\eta-8\gamma[2\beta^2\eta-8\gamma\eta+\gamma(\alpha-\theta)^2)]}<0$, $\frac{\partial s^{RM*}}{\partial \theta}=-\frac{16\beta\gamma^2\eta(\bar{v}-c_0)(\alpha-\theta)(8\gamma-\beta^2)}{\{\beta^4\eta-8\gamma[2\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]\}^2}<0$, g^{RM*} and s^{RM*} decreases with θ. Taking the first order derivative of π_M^{RM*} and π_R^{RM*} with respect to γ , according to the concavity condition of scenario MR, we have $\frac{\partial \pi_M^{RM*}}{\partial \gamma}=\frac{\beta^2\eta^2(\bar{v}-c_0)^2(\beta^2-4\gamma)^2\{\beta^4\eta+2\gamma\{-4\beta^2\eta+\gamma[8\eta+3(\alpha-\theta)^2]\}\}}{2\{-\beta^4\eta+2\gamma[4\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]\}^3}$. From Proposition 4, we have $-\beta^4\eta+2\gamma[4\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]<0$. Thus, when $\beta^4\eta+2\gamma\{-4\beta^2\eta+\gamma[8\eta+3(\alpha-\theta)^2]>0$, $\frac{\partial \pi_M^{RM*}}{\partial \gamma}<0$, π_M^{RM*} decreases with γ . That is $\eta>-\frac{6\gamma^2(\alpha-\theta)^2}{(\beta^2-4\gamma)^2}$, which is satisfied absolutely.

$\frac{\partial \pi_R^{RM*}}{\partial \gamma}=-\frac{8\beta^2\eta^2\gamma(\bar{v}-c_0)^2(8\gamma-\beta^2)}{\{\beta^4\eta-8\gamma[2\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2)]\}^2}<0$, therefore π_R^{RM*} decreases with γ . Taking the first order derivative of π_M^{RM*} and π_R^{RM*} with respect to η, according to the concavity condition of scenario RM, we have $\frac{\partial \pi_M^{RM*}}{\partial \eta}=-\frac{8\gamma^3(\bar{v}-c_0)^2(\alpha-\theta)^2(16\gamma-\beta^2)(\beta^2-8\gamma)^2}{\{\beta^4\eta-8\gamma[2\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]\}^3}<0$, $\frac{\partial \pi_R^{RM*}}{\partial \eta}=-\frac{32(c_0-\bar{v})^2\gamma^4(\alpha-\theta)^2}{\{\beta^4\eta-8\gamma[2\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]\}^2}<0$

π_M^{RM*} and π_R^{RM*} decrease with η. Taking the first order derivative of π_M^{RM*} and π_R^{RM*} with respect to θ, according to the concavity condition of scenario RM, we have $\frac{\partial \pi_M^{RM*}}{\partial \theta} = -\frac{16\gamma^3\eta^2(c_0-\bar{v})^2(\alpha-\theta)(16\gamma-\beta^2)(\beta^2-8\gamma)^2}{\{\beta^4\eta-8\gamma[2\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]\}^3}<0$, $\frac{\partial \pi_R^{RM*}}{\partial \theta} = -\frac{64\gamma^4\eta(c_0-\bar{v})^2(\alpha-\theta)}{\{\beta^4\eta-8\gamma[2\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]\}^2}<0$, therefore π_M^{RM*} and π_R^{RM*} decrease with θ.

Proof of Proposition 5. (i) Because $\frac{g^{MB*}}{g^{RB*}} = 1+\frac{4\gamma\eta}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}>1$, $\frac{g^{MB*}}{g^{MR*}} = 1+\frac{\beta^4\eta}{16\gamma\{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta\}}>1$ according to the concavity conditions of equilibrium, thus, $g^{MB*}>g^{RB*}$, $g^{MB*}>g^{MR*}$. Because $\frac{g^{MB*}}{g^{RM*}} = 1+\frac{(\beta^4-6\beta^2\gamma+8\gamma^2)\eta}{2\gamma\{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta\}}$, let $f_1(\gamma)=\beta^4-6\beta^2\gamma+8\gamma^2$. Because $\partial^2 f_1(\gamma)/\partial\gamma^2 = 16>0$, $f_1(\gamma)$ is a convex function of γ. Solving $f_1(\gamma)=0$, we can get two roots $\{\beta^2/4, \beta^2/2\}$. Thus, when $\beta^2/4<\gamma<\beta^2/2$, $f_1(\gamma)<0$, $g^{MB*}<g^{RM*}$. When $\gamma>\beta^2/2$, $g^{MB*}>g^{RM*}$.

(ii) $\frac{g^{RB*}}{g^{MR*}} = 1+\frac{(\beta^4-64\gamma^2)\eta}{16\gamma\{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta\}}$. From the concavity condition of scenario MR, we know that $8\gamma>\beta^2$, thus, $64\gamma^2>\beta^4$, $g^{RB*}<g^{MR*}$. $\frac{g^{RB*}}{g^{RM*}} = 1+\frac{\beta^2(\beta^2-6\gamma)\eta}{2\gamma\{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta\}}$. Because $\gamma>\beta^2/4, \beta^2-6\gamma<0$, thus, $g^{RB*}<g^{RM*}$.

Proof of Proposition 6. (i) Because $\frac{s^{MB*}}{s^{RB*}} = 1+\frac{4\gamma\eta}{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta}>1$, according to the concavity conditions of equilibrium, $s^{MB*}>s^{RB*}$. $1-\frac{s^{MB*}}{s^{RM*}} = \frac{(\beta^2-2\gamma)\gamma(\alpha-\theta)^2}{(4\gamma-\beta^2)\{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta\}}$. Because $\gamma>\beta^2/4$ and $\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta>0$, when $\beta^2/4<\gamma<\beta^2/2$, $s^{MB*}<s^{RM*}$. When $\gamma>\beta^2/2$, $s^{MB*}>s^{RM*}$.

(ii) $1-\frac{s^{RB*}}{s^{MR*}}=\frac{\gamma(\beta^2+8\gamma)(\alpha-\theta)^2}{(8\gamma-\beta^2)[\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta]}$, note that $\gamma>\frac{\beta^2}{8}$ and $\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta>0$,

$1-\frac{s^{RB*}}{s^{MR*}}>0$. As a result, $s^{RB*}<s^{MR*}$.

Proof of Proposition 7. Since $\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta>0$, we have $\frac{\pi_M^{MB*}}{\pi_M^{MR*}}=1+\frac{\beta^4\eta}{16\gamma\{\gamma[4\eta-(\alpha-\theta)^2]-\beta^2\eta\}}>1$. Thus, $\pi_M^{MB*}>\pi_M^{MR*}$. According to the concavity conditions of equilibrium, $\beta^2\eta+\gamma[-4\eta+(\alpha-\theta)^2]<0$, we have $1-\frac{\pi_M^{MB*}}{\pi_M^{RB*}}=\frac{[\beta^2\eta+\gamma(\alpha-\theta)^2]^2}{16\gamma\eta\{\beta^2\eta+\gamma[4\eta-\gamma(\alpha-\theta)^2]\}}<0$. Thus, $\pi_M^{MB*}>\pi_M^{RB*}$. Because $1-\frac{\pi_M^{RB*}}{\pi_M^{MR*}}=\frac{\gamma[2\beta^2\eta+\gamma(\alpha-\theta)^2](\alpha-\theta)^2}{[\beta^2\eta-8\eta\gamma+\gamma(\alpha-\theta)^2]^2}>0$, we have $\pi_M^{RB*}<\pi_M^{MR*}$.

Proof of Proposition 8. According to the concavity condition of equilibrium, we have

$\beta^2-6\gamma<0$ and $\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta>0$, $\frac{\pi_R^{RB*}}{\pi_R^{RM*}}=1+\frac{\beta^2(\beta^2-6\gamma)\eta}{2\gamma\{\gamma[8\eta-(\alpha-\theta)^2]-\beta^2\eta\}}<1$.

Thus, $\pi_R^{RB*}<\pi_R^{RM*}$.

Highlights:

- Green product development (GPD) and green marketing are jointly studied.
- Conducting both GPD and green marketing by the manufacturer benefits all parties.
- It’s always a bad choice for the retailer to adopt both GPD and green marketing.
- Enhancing consumer’s awareness on green degree improves environment.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: