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OPTIMAL STRATEGIES FOR GREEN SUPPLY CHAINS WITH COMPETITION BETWEEN GREEN AND TRADITIONAL SUPPLIERS

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Abstract. We consider a green supply chain that consists of a traditional supplier, a green supplier, and a manufacturer. We investigate the optimal strategies for the suppliers' raw material prices, and the manufacturer's production and green raw material ordering. In particular, we consider three price competition models: the traditional supplier-led model, the green supplier-led model, and the Nash game model. The results indicate that the more dominant the green supplier, the more likely the green material price will be higher than the traditional material price. In addition, the manufacturers' product greenness level is the lowest under the green supplier-led model and the highest under the traditional supplier-led model. We also find that, as the manufacturer's yield uncertainty increases, the prices of traditional and green raw materials both decrease with respect to the manufacturer's product greenness level. Moreover, as customers' green preference increases, the price of green raw materials increases, the price of traditional raw materials decreases, and the product greenness level increases.

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1. Introduction

With the advancement of economic globalization and the attention of governments to environmental issues, green production has become not only an essential means to enhance the competitiveness of many enterprises but also an essential strategy for the sustainable development of domestic and foreign enterprises [1,2]. Therefore, the concept of environmental protection and green production have been introduced into green supply chain management, and green raw material procurement is extremely significant content among it [3,4]. Raw material procurement affects the production of green products to a certain extent, and many enterprises improve the greenness of their products by investing in green raw materials [5,6]. There are more and more products using a high percentage of green materials, such as 100% recycled fabric in Ford's hybrids seats, 75% plants and recycled raw materials in P&G's laundry detergent-Tide PurClean (https://tide.com/en-us/shop/type/liquid/tide-purclean-honey-lavender), and 100% organic cotton in Nike's related products [6]. In addition, consumers are increasingly attracted to green products and are willing to pay a premium for them [7,8].

Keywords. Green supply chain, yield uncertainty, green preference, supplier competition, greenness level.

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According to the Bemporad Baranowski Marketing Group (BBMG) report on consumer awareness of green consumption, 67% of Americans are more likely to buy green products [9].

In reality of supply chain management, downstream producers often face the problem of choosing between green raw materials and traditional raw materials. Due to price and cost reasons, green raw materials are often in competition with traditional raw materials as substitutions. For example, Second China Green Printing Enterprise Survey shows that suppliers of green raw materials, such as varnish and fountain solution, are in a different position in the market than traditional raw material suppliers, and that price changes between green and traditional raw materials deeply affect the green print production of printing enterprises (www.pack.cn). A similar situation exists in the steel industry. According to 7th China Steel Raw Material Market High-End Forum held in 2018, there is a substitution relationship between upstream green raw materials (scrap) as well as traditional raw materials (iron ore), while there are price differences between iron ore and scrap, among other issues (www.chinadevelopment.com.cn). Another example is epoxy resin, which is a green raw material that is widely used in industries such as electronics and automobiles. However, product manufacturers may substitute it with traditional raw materials to reduce production costs. That is not good for the green development of enterprises (www.shhorse.com). In addition, green pesticides such as hetero-cyclic pesticides and bio-pesticides exist in the agricultural supply chain as green alternatives to traditional pesticides (*e.g.*, organochlorines, organophosphates, etc.), and green pesticides compete with traditional chemical pesticides in the market on price [10]. Thus, the price competition strategy among upstream raw material suppliers influences downstream firms' green production decisions.

Most importantly, with development and growth of green raw material suppliers, the channel structure of the supply chain shows a trend of diversification. There exists both power structure dominated by green raw material suppliers and power structure dominated by traditional raw material suppliers. Markets dominated by suppliers of green raw materials include, for example, the battery supply market for electric bicycles. As green raw material can substitute conventional battery (lead-acid battery), Zinc-nickel battery is the dominant player in the supply market [11]. Markets dominated by traditional raw material suppliers are mainly piezoelectric materials and raw materials of steel manufacturing. Compared to potassium sodium niobate (the green raw material), lead zirconate titanate (the traditional raw material) is the leader [12]. And between iron ore (the traditional raw material) and steel scrap (the green raw material), iron ore still dominates the raw materials market [13]. Therefore, it is important to investigate the price competition strategy between green suppliers and traditional suppliers under the traditional raw material supplier-led, green raw material supplier-led, and Nash game for downstream firms' green production.

Manufacturers usually face yield uncertainty. For example, in agricultural supply chain, external factors such as weather, pests, and diseases often lead to fluctuations in agricultural output [14, 15]. Therefore, for a given amount of agricultural inputs, the actual output of agricultural products can differ from the planned output. The yield uncertainty also exists in the production process of environmentally friendly electronic products with green raw material inputs such as rare earth [16], and effective electronic product output is often uncertain due to the process characteristics of the product as well as the manufacturing process [17]. When downstream manufacturers face risks caused by yield uncertainty, they may adjust their ordering strategies regarding green and traditional raw materials to maximize profits and reduce costs. That may affect the greenness of the final product. To our best knowledge, there has been no literature focusing on how to yield uncertainty affects both the price competition strategy among upstream raw material suppliers and downstream manufacturers' green raw material ordering strategy.

Based on above considerations, we consider a supply chain consisting of a green raw material supplier, a traditional raw material supplier, and a green product manufacturer, where the suppliers and the manufacturer obey a sequential game, where suppliers first decide on the optimal wholesale prices of raw materials, and manufacturer then makes production decision and raw material ordering decision. We assume that the manufacturer faces yield uncertainty and that there is price competition between green raw material supplier and traditional raw material supplier. We analyze the suppliers' price strategies and the manufacturer's production and green raw material ordering strategies under three competition modes: Nash game among suppliers, Stackelberg game with green supplier-led, and Stackelberg game with traditional supplier-led, respectively.

In this paper, we intend to find the answers to the following questions. (1) For a green supply chain with pricing competition of green and traditional raw material suppliers under yield uncertainty, what are the optimal "level of greening" reached and the price of raw materials under different pricing competition modes? (2) How does the price competition strategy between green and traditional raw material suppliers affect the manufacturer's production of green products? (3) How do the yield uncertainty, consumers' green preference, and green learning cost affect key decisions like prices of green and traditional raw materials and the greenness level?

This work reveals how power dynamics affect pricing strategies of traditional and green suppliers. We find that more dominant the green supplier is compared to traditional supplier, the more likely the price of green raw materials is higher. In addition, the product greenness level is the lowest under the price competition model dominated by the green supplier, and the highest under the price competition model dominated by the traditional supplier. As yield uncertainty or consumers' green preferences increases, the product greenness level increases, while it decreases as green learning costs increase.

The rest of the paper is organized as follows. First, we review relevant literature and describe the motivation and highlights of our paper in Section 2. In Section 3, we give the model formulation. We derive the optimal strategies of the supply chain under the traditional supplier-led, the green supplier-led, and the Nash game models in Section 4. In Section 5, we present some numerical illustrations and discuss the results further. Finally, we give the concluding remarks and some suggestions for future research in Sections 6 and 7. All proofs of propositions are given in the Appendix A.

2. Review on literature and motivations

In this section, we review the related literature from three aspects: operations management of green supply chains, horizontal price competition, and yield uncertainty. Besides this, we also give the motivation and highlights of this paper.

2.1. Operations management of green supply chains

In the existing research on green supply chain management, how to improve greenness level of the final product is a hot topic discussed by many scholars. The literature on this issue can be classified into two types: green technology input strategies and green raw material procurement strategies. Heydari *et al.* [18] and Li *et al.* [19] investigate how consumers' preference for green products affects manufacturers' production strategies, and the results show that consumers' preference for green products is an effective factor in promoting manufacturers' green production strategies. In a study of green supply chain pricing strategies consisting of manufacturers and retailers, Liu and Yi [20], Gao *et al.* [21] consider the effects of advertising investment and eco-label on the wholesale price and greenness of products respectively. Their results indicate that the wholesale price of the product is negatively related to advertising investment and eco-label, while product greenness is positively related to eco-label and negatively related to advertising investment. Sun *et al.* [22], Song and Wang [23] both consider the green technology investment strategy of manufacturers, and they find that government policy incentives can motivate manufacturers to increase green technology investment. Zhang and Zhou [24] consider the product volume competition between e-tailers and manufacturers, and they find that a "win–win" sales model is also conducive to environmental sustainability when the manufacturer's production technology is sufficiently green. Zhang *et al.* [25] design revenue-sharing contracts to coordinate green supply chains, to motivate retailers to engage in green production practices such as waste recycling. In addition, there is some literature on price competition among green supply chain members. Jamali and Rasti-Barzoki [26], Ma and Zhang [27] focus on price competition strategies between green and non-green manufacturers. Zhu and He [28] consider both price competition between retailers and green competition between manufacturers in their research of green supply chains. Li *et al.* [29,30] both investigate price competition between substitutable green products produced by the manufacturer and products sold by the retailer in a dual-channel supply chain, and the results show that manufacturers can always benefit from consumers' green awareness increasing.

For supply chain green raw material procurement strategy, scholars mainly focus on green supplier selection and evaluation, green procurement practice application, and green raw material procurement game analysis. Shi *et al.* [31] evaluate and select green suppliers by virtue of green supplier index evaluation system. Bala *et al.* [32] conduct a case study on the selection of green suppliers, and their findings show that working with green suppliers is beneficial to the green development of the Universitat Autonoma de Barcelona (UAB). Lo [33] conducts an analysis of the application of green procurement practices in a Taiwanese high-tech company that includes raw material suppliers (upstream) and manufacturers (midstream) as well as branded companies (downstream) and finds that the uncertainty encountered by companies in implementing green production is related to their position in the supply chain. In particular, the closer a company is to the upstream of the green supply chain, the higher the uncertainty of competition, while the closer it is to the downstream, the higher the uncertainty of demand. Some scholars consider green raw material procurement strategy in supply chain from the perspective of game analysis. Cao *et al.* [34] focus on the problem of hiding the greenness of raw materials in green procurement and design an incentive mechanism based on the information asymmetry of the raw materials' greenness. Rogezer *et al.* [16] consider the price uncertainty, demand uncertainty, and yield uncertainty of green raw materials such as rare earth elements to investigate the impacts of raw material uncertainty on the manufacturer's production and cost. Guo *et al.* [6] measure the greenness level of the product by the green materials used in the product development process, and they investigate the effects of retailer competition on the manufacturer's green material sourcing strategy based on demand uncertainty and conclude that price competition among retailers is not conducive to improving the green level of products. Pal and Sarkar [35] consider that manufacturer can source raw materials from both collectors and suppliers, where used products from collectors as converted raw materials can increase the greenness of products, and they prove that green innovation efforts are always beneficial in improving supply chain profits.

Yield uncertainty is prevalent in the manufacturing industry due to perturbations such as technology, equipment, raw materials, processes, management, and unexpected events, Hu *et al.* [36] prove that yield uncertainty can affect manufacturers' raw material sourcing strategies. In addition, Xie [37] and Manteghi *et al.* [38] find that price competition among raw material suppliers also affects manufacturers' production and sourcing decisions. In the case of Chinese steel manufacturing, steel manufacturers are faced with yield uncertainty due to processes and other reasons. Moreover, the production process of crude steel is such that many steel manufacturers often turn to sourcing more scrap steel due to the significant increase in the price of iron ore (`http://www.100ppi.com`). In the agricultural supply chain, farmers also face yield uncertainty and price competition between traditional agricultural inputs (chemical pesticides, fertilizers, etc.) and green agricultural inputs (bio-pesticides, organic fertilizers, etc.) [39]. In addition, in supply chains such as chemical, electronic, and mechanical engineering, the uncertainty of manufacturers' yield and price competition between raw material suppliers are key factors influencing manufacturers' green production inputs. Based on the above, in conjunction with the green raw material sourcing of the manufacturer studied in this paper, we believe that yield uncertainty and horizontal price competition between suppliers need to be considered, which will be significant research. However, none of the above-mentioned literature considers the impacts of manufacturer's yield uncertainty on green raw material sourcing strategies and product greenness. In addition, to our best knowledge, there is no published work on green raw material sourcing strategies in scenarios of horizontal price competition between green raw material suppliers and traditional raw material suppliers.

2.2. Horizontal price competition

Horizontal price competition between retailers, manufacturers, and suppliers in supply chains has gained more and more interest from researchers. Rajagopalan *et al.* [40] construct a supply chain model of a manufacturer supplying products to two retailers and consider price competition between the two retailers. Their findings suggest that moderate price competition benefits retailers but harms manufacturers. Wei *et al.* [41] consider the price competition strategy between multiple retailers in a two-channel supply chain, and by analyzing the pricing decisions under different game models, they propose that the retail channel has the highest product price under the Stackelberg game. Zhao *et al.* [42] focus on horizontal price competition among manufacturers and analyze the optimal pricing decisions for substitutable products under different power structures and competitive strategies. Zhao *et al.* [43] also discuss the pricing decisions of two competing manufacturers in an ambiguous demand environment for a supply chain consisting of two competing manufacturers and one retailer. Some scholars consider horizontal price competition between suppliers. Zhao *et al.* [44] consider sales model selection for two suppliers in an e-commerce platform and investigate the price competition and service competition strategies between them with demand uncertainty. Liu *et al.* [45] analyze supply chain coordination issue with price competition and quality competition among suppliers under random market demand. Their results show that the degree of horizontal price competition between suppliers is negatively correlated with retailers' order quantity, and the total profit of the supply chain decreases as the degree of competition increases.

Some scholars consider the price competition strategy between manufacturers in green supply chains based on demand uncertainty. Jamali and Rasti-Barzoki [26] consider the price competition strategy between green product manufacturers and non-green product manufacturers, stating that product pricing strategy is crucial in the market competition between green and non-green products. Xi and Zhang [46] study a two-parallel agricultural supply chain consisting of traditional agricultural producers and green agricultural producers and analyze the production, fertilizer-saving level, and emission reduction efforts decisions by constructing a price competition model. Ma *et al.* [27] focus on price competition between two manufacturers producing complementary products and find that when only one manufacturer invests in green production, the traditional manufacturer benefits from producing complementary products.

None of the above-mentioned literature has considered the impacts of market structure on green supply chain strategies. In fact, pricing and production strategies can vary under different leadership structures. Chen *et al.* [47] consider pricing and production strategies under the Bertrand game, the traditional manufacturer-led Stackelberg game, and the green manufacturer-led Stackelberg game. The results show that the retailer's optimal strategy is related to the manufacturer's market structure and that regardless of the changes in consumers' environmental awareness and green cost effect, traditional manufacturers always tend to compete with green manufacturers on price. In addition, green manufacturers are willing to be the leader only when consumers' environmental awareness is relatively high or the green cost effect is relatively low. Gao *et al.* [48] consider three types of price games: original manufacturer-led, re-manufacturer-led, and non-dominant in their study on product quality strategy. The results show that, under the re-manufacturer-led mode, when the value of a re-manufactured product is high, both the quality and price of the product increase significantly. Sharma *et al.* [49] and Srivastava *et al.* [50] have studied green investment strategies under different power structures, and they find that when the dominant supply chain player is responsible for green investment, both the followers and the supply chain can maximize profits.

However, none of the above-mentioned literature on price competition strategies has examined the impacts of yield uncertainty, which is common in the production of agricultural products, chemicals, and electronics, on horizontal price competition strategies. Further, to our best knowledge, no research has been published on the impacts of horizontal price competition between upstream traditional and green raw material suppliers on downstream manufacturers' green production. Actually, it's meaningful to consider the impacts of different leadership structures between traditional and green suppliers on green raw material pricing strategies and downstream manufacturers' green raw material procurement strategies. That is the main focus of this paper.

2.3. Yield uncertainty

Yield certainty exists in many common supply chains such as agriculture, electronics, and coal. It has received more and more attention from researchers and the research on yield uncertainty in supply chains can date back to the batch planning study of Yano and Li [51], who provide a detailed overview of yield uncertainty-related research. Yield uncertainty has been considered by many scholars as an important feature of agricultural supply chains. For example, Li *et al.* [52] analyze the optimization of seasonal agricultural production strategies based on output uncertainty, and Peng and Pang [53] design a risk compensation and advance payment mechanism

TABLE 1. Comparison of most related existing literature and this paper.

Papers	Green supply chain management		Price competition	Power structures	Yield uncertainty	Consumers' preference
	Green technology input	Green raw material procurement				
Guo *et al.* [6]		√	√			√
Peng *et al.* [14]	√				√	√
Rogezer *et al.* [16]		√			√	
Heydari *et al.* [18]	√					√
Li *et al.* [19]	√					√
Zhu and He [28]	√					√
Chen *et al.* [48]	√		√	√		√
Gao *et al.* [49]			√	√		√
Cong *et al.* [59]	√				√	√
This study		√	√	√	√	√

(APRC) to address the financial constraints of suppliers facing yield uncertainty. Besides, there are a growing number of studies on supply chain manufacturing, remanufacturing, and coordination strategies that take yield uncertainty into consideration. Lu and Xu [54] consider manufacturers that produce both high-end and low-end products and their results show that under yield uncertainty, manufacturers tend to reduce the production of high-end products and their profit level will also decrease. Zhu *et al.* [55] argue that product remanufacturing is susceptible to output uncertainty, and they analyze the effect of yield uncertainty on remanufacturing decisions by comparing three output stochastic models. Kristiano and Helo [56] design a decision support system to determine the remanufacturing capability under stochastic product output. By constructing a Stackelberg game model, Zare *et al.* [57] analyze the risk-sharing mechanism of suppliers with yield uncertainty and its impacts on the overall interest of the supply chain, and they find that risk-sharing contracts can coordinate the supply chain.

Very few scholars have considered yield uncertainty in green supply chains. Peng *et al.* [14] and Cong *et al.* [58] investigate the mechanism by which yield uncertainty affects a manufacturer's input of low-carbon technologies, using a green supply chain that includes a manufacturer and a supplier. However, they did not consider the competition model between green suppliers and traditional suppliers. The following question remains open. How does the yield uncertainty of manufacturers affect their sourcing strategies for green and traditional raw materials, and thus the greenness of their products? That is the problem we try to solve in this paper (Tab. 1).

2.4. Motivations and highlights

Based on the above literature review, we can see that green supply chain management has become important topic. However, there are few works on the price competition between green raw material suppliers and traditional raw material suppliers under manufacturers' uncertain yield and consumers' green preferences. Aiming at filling the gap, we consider a green supply chain consisting of a traditional supplier, a green supplier, and a manufacturer facing yield uncertainty and consumers' green preferences. We analyze the impact of uncertain yield and green preferences on the optimal strategies of green and traditional raw material suppliers under different power structures and compare the greenness level of products under different competitive models.

This research is innovative in three aspects. (1) To our best knowledge, this is the first paper to consider price competition between suppliers of green raw materials and traditional raw materials under different power structures in green supply chains. (2) We consider yield uncertainty, consumer green preferences, and horizontal price competition among suppliers in the study of green raw material sourcing strategies. (3) The pricing

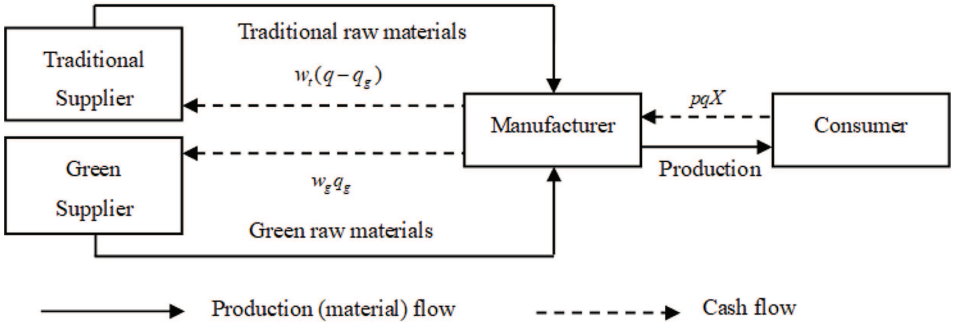

FIGURE 1. The supply chain decision-making model under yield uncertainty and consumer preferences.

strategy of suppliers and the green raw material sourcing strategy of manufacturers under traditional raw material supplier-led, green raw material supplier-led, and Nash game models are investigated separately, and the study shows that the greenness level of the product is the lowest in the green supplier-led model and the highest in the traditional supplier-led model.

3. Problem formulation and model setup

We consider a green supply chain that consists of one manufacturer with yield uncertainty, and two suppliers, one supplies traditional raw materials, and the other supplies green raw materials. The production flows and cash flows of the supply chain are illustrated in Figure 1. Since consumers have green preferences, the manufacturer has the motivation to improve the greenness level of its products by using more green raw materials. There is a substitution effect between green raw material and traditional raw material, and price competitions exist between the suppliers. We consider three price competition models: traditional supplier-led model (denoted by TS), green supplier-led model (denoted by GS), and Nash game model (denoted by NG).

The notations and meaning are given in Table 2. Here subscript t is used for the traditional supplier, subscript g is used for the green supplier.

To make the model more realistic, we propose the following assumptions.

Assumption 1. *The manufacturer faces yield uncertainty.*

We assume that the output of the manufacturer is uncertain, that is, if the manufacturer's planned yield is q, then its actual output is qX, where X is the random variable to describe the uncertainty in the manufacturer's product output. Similar assumptions have been used in Peng *et al.* [59] and Shi *et al.* [60].

Assumption 2. *Since the manufacturing process complexity and quality of green raw materials is higher than that of traditional raw materials, it is assumed that the production cost of green raw materials is higher than that of traditional raw materials, that is* $c_g > c_t$. *Similar assumptions can be seen in Yang et al. [61] and Du et al. [62].*

Assumption 3. *Without loss of generality, we assume that one unit of raw material is required for one unit of the final product and that the green raw material is a 1:1 substitution relationship with the traditional raw material. When the manufacturer's purchases of green raw materials are g, the manufacturer's purchases of traditional raw materials are:*

$$q_t = q - q_g \quad (q_g \leq q). \tag{1}$$

TABLE 2. Variables and notations.

Notations	Meaning
X	The manufacturer's production yield random variable ($\mathbf{E}[X]=1$), $Var(X)=\sigma^2$
p	The retail price per unit of the product
a	The choke price without greenness preference
b	The sensitivity coefficient of market prices to product output
q	The production of the product, the decision variable of the manufacturer
q_t	The manufacturer's purchase of traditional raw materials
q_g	The purchase of green raw materials, the decision variable of the manufacturer
θ_g	The greenness level of the product, expressed as $\theta_g=\frac{q_g}{q}$
w_t	The wholesale price per unit of traditional materials, the decision variable of the traditional supplier
w_g	The wholesale price per unit of green materials, the decision variable of the green supplier
α	The manufacturer's learning cost factor for green production
c_t	The production cost per unit of the traditional materials
c_g	The production cost per unit of the green materials
λ	The consumers' preference coefficient of the greenness of the product
π_m,π_t,π_g	The profit of the manufacturer, the traditional supplier, and the green supplier, respectively

If green raw materials and traditional raw materials are not a 1:1 substitution relationship, they can be transformed into a 1:1 substitution relationship by changing the unit of measurement, cost, price, etc. The greenness level of a product is quantified as amount of green raw materials used in the production process per unit of product [63]. Therefore, we use the proportion of green raw material inputs per unit of product, *i.e.*, $\theta_g=\frac{q_g}{q}$, to indicate greenness level of the product.

Consumers usually have preferences for the greenness of the product [64]. Here is the following assumption regarding the greenness preference:

Assumption 4. *Consumers have preferences for the greenness of the product and the inverse demand function of the product is as follows:*

$$p=a-bqX+\lambda\theta_g. \tag{2}$$

In the inverse demand function given by (2), a represents the choke price without greenness preference and it is usually much larger than w_t and w_g, b represents sensitivity of market prices to product output, and λ represents the greenness preference, which measures the sensitivity of market prices to the green level of the product. Similar assumptions have been used in Long *et al.* [65] and Cai *et al.* [66].

Assumption 5. *Manufacturers use the green raw material for the production process at a learning cost, given by a quadratic function of the amount of the green raw material as follows [68, 69]:*

$$C(g)=\frac{1}{2}\alpha q_g^2 \tag{3}$$

where α represents the manufacturer's learning cost coefficient for green production.

Similar assumptions have been made in Niu *et al.* [67], Swami and Shah [68], Ghosh and Shah [69] and Ji *et al.* [70]. Another thing we want to point out is that the learning cost α is usually large since green production investments are one-time investments [68, 69].

4. Optimal strategies of the supply chain

In this paper, we consider both the leader-follower game between suppliers and manufacturers and the price game relationship between traditional and green suppliers in the following order. First, the traditional raw material supplier and the green raw material supplier need to decide on their optimal wholesale prices based on their own interests. In this stage, we consider three price game scenarios: a Stackelberg game dominated by the traditional supplier, a Stackelberg game dominated by the green supplier, and a Nash game with equal status for both sides. Then, the manufacturer makes decisions on the optimal amount of production and the amount of green raw materials to be sourced, aiming to maximize the expected profit. The problem can be solved using backward induction.

4.1. Profit functions

The manufacturer orders both traditional and green raw materials with different wholesale prices. In particular, the cost to order the green material is $w_g q_g$, and the cost to order the traditional material is $w_t(q - q_g)$. In addition, the learning cost for green production is $\frac{1}{2}\alpha q_g^2$, and the product sales revenue is pqX. Based on the inverse demand function $p = a - bqX + \lambda\theta_g$, and $\mathbf{E}[X] = 1, Var(X) = \sigma^2$, the manufacturer's expected profit is given by

$$\begin{aligned}\pi_m &= \left[pqX - w_t(q - q_g) - w_g q_g - \frac{1}{2}\alpha q_g^2\right] \\ &= (a + \lambda\theta_g - w_t)q - bq^2\left(1 + \sigma^2\right) - (w_g - w_t)q_g - \frac{1}{2}\alpha q_g^2. \end{aligned} \tag{4}$$

In addition, it is easy to get he profit function for the traditional supplier

$$\pi_t = (w_t - c_t)(q - q_g), \tag{5}$$

and the profit function for the green supplier is

$$\pi_g = (w_g - c_g)q_g. \tag{6}$$

4.2. The manufacturer's optimal production and ordering strategies

For any given prices of the green and traditional materials, the manufacturer makes decisions on production and green material ordering with the goal of maximizing the expected profit. Thus, the manufacturer's decision problem is

$$\max_{q, q_g} \pi_m. \tag{7}$$

Proposition 1. *The manufacturer's optimal production q^* and green material purchase q_g^* are given by*

$$\begin{cases} q^* = \frac{a - w_t}{2b(1+\sigma^2)} \\ q_g^* = \frac{\lambda + w_t - w_g}{\alpha}. \end{cases} \tag{8}$$

(The proof of Prop. 1 is given in Appendix A.1.)

Typically, the optional production q^* and the optimal green material purchase q_g^* should satisfy $q_g^* < q^*$ (see Assumption 3). According to Assumption 5, the manufacturer's learning cost coefficient for green production α is usually large, which implies that q_g^* is small. In addition, the choke price a denotes the maximum price that consumers can accept for the product, and it is typically much bigger than w_t and w_g. Therefore, we should have that $q_g^* \leq q^*$.

4.3. Optimal pricing strategies for traditional and green suppliers

The traditional and green suppliers make raw material price decisions based on the manufacturer's optimal production and ordering decisions (see Prop. 1). Next, we solve the optimal wholesale price strategies (w_t^*, w_g^*) of traditional and green suppliers under the traditional supplier-led Stackelberg game, the green supplier-led Stackelberg game, and the Nash game.

4.3.1. The Stackelberg game dominated by the traditional supplier

In Stackelberg game dominated by the traditional supplier, firstly, the traditional supplier sets the wholesale price $w_t^{\mathrm{TS}^*}$ by maximizing the profit, and then the green supplier sets the wholesale price $w_g^{\mathrm{TS}^*}$. The game model is solved *via* the backward induction method. The decision models of the green and traditional suppliers are

$$\max_{w_t} \pi_t \quad \text{s.t.} \quad \begin{cases} \max\limits_{w_g} \pi_g \\ \text{s.t.} \quad \text{Eq. (8)}. \end{cases} \tag{9}$$

Proposition 2. *Under the dominance of the traditional supplier, the optimal wholesale price decisions of traditional supplier $w_t^{\mathrm{TS}^*}$ and green supplier $w_g^{\mathrm{TS}^*}$ are*

$$\begin{cases} w_t^{\mathrm{TS}^*} = \frac{\alpha a - b\left(1+\sigma^2\right)(\lambda - c_g)}{2A} + \frac{c_t}{2} \\ w_g^{\mathrm{TS}^*} = \frac{\alpha a - b\left(1+\sigma^2\right)(\lambda - c_g)}{4A} + \frac{c_t + 2(\lambda + c_g)}{4} \end{cases} \tag{10}$$

where

$$A = \alpha + b\left(1+\sigma^2\right). \tag{11}$$

(The proof of Prop. 2 is given in Appendix A.2.)

Plugging (10) into (8), we obtain that the manufacturer's optimal decisions on the production and green material procurement under traditional supplier-led model are

$$\begin{cases} q^{\mathrm{TS}^*} = \frac{aB + b\left(1+\sigma^2\right)(\lambda - c_g)}{4b(1+\sigma^2)A} - \frac{c_t}{4b(1+\sigma^2)} \\ q_g^{\mathrm{TS}^*} = \frac{aB + b\left(1+\sigma^2\right)(\lambda - c_g)}{4\alpha A} + \frac{c_t}{4\alpha} \end{cases} \tag{12}$$

where A is given by (11) and B is given by

$$B = \alpha + 2b\left(1+\sigma^2\right). \tag{13}$$

4.3.2. The Stackelberg game dominated by the green supplier

In Stackelberg game dominated by green supplier, green supplier determines the wholesale price $w_g^{\mathrm{GS}^*}$ by maximizing its own profit, and then the traditional supplier sets the wholesale price $w_t^{\mathrm{GS}^*}$. We can solve the problem by backward induction. The decision models of the traditional and green suppliers are

$$\max_{w_g} \pi_g \qquad \text{s.t.} \quad \begin{cases} \max\limits_{w_t} \pi_t \\ \text{s.t.} \quad \text{Eq. (8)}. \end{cases} \tag{14}$$

Proposition 3. *Under the dominance of the green supplier, the optimal wholesale prices of the traditional material $w_t^{\mathrm{GS}^*}$ and the green material $w_g^{\mathrm{GS}^*}$ are*

$$\begin{cases} w_t^{\mathrm{GS}^*} = \frac{\alpha a + b\left(1+\sigma^2\right)c_t}{4A} + \frac{\alpha a - 2b\left(1+\sigma^2\right)(\lambda - c_g)}{4B} + \frac{c_t}{2} \\ w_g^{\mathrm{GS}^*} = \frac{\alpha(a - c_t) + 2(\lambda + c_g)A}{4A} + \frac{c_t}{2} \end{cases} \tag{15}$$

where A, B are given by (11) and (13), respectively.

(The proof of Prop. 3 is given in Appendix A.3.)

Plug (15) into (8), and we can obtain that the manufacturer's optimal production and green raw material ordering under the traditional supplier-led model are

$$\begin{cases} q^{\mathrm{GS}^*} = \frac{3\alpha a + b\left(1+\sigma^2\right)(4a - c_t)}{8b(1+\sigma^2)A} - \frac{\alpha - 2b\left(1+\sigma^2\right)(\lambda - c_g)}{8b(1+\sigma^2)B} - \frac{c_t}{4b(1+\sigma^2)} \\ q_g^{\mathrm{GS}^*} = \frac{\alpha a + 2(\lambda - c_g)A}{4\alpha B} + \frac{c_t}{4\alpha}. \end{cases} \tag{16}$$

TABLE 3. Product greenness equilibrium solution for different game models.

Models	θ_g
TS	$\frac{b(1+\sigma^2)[\alpha(a+\lambda-c_g)+(\lambda+c_t-c_g)A]}{\alpha[aB+b(1+\sigma^2)(\lambda-c_g)-c_tA]}$
GS	$\frac{2b(1+\sigma^2)A[\alpha a+2(\lambda-c_g)A]+c_tB}{\alpha^2[2B+b(1+\sigma^2)]+b(1+\sigma^2)\alpha[(4a-c_t)B+2(\lambda-c_g)A]-2c_t\alpha A}$
NG	$\frac{b(1+\sigma^2)[\alpha a+c_tB+(2\lambda-c_g)A]}{\alpha[(a-c_t)B+b(1+\sigma^2)(a+\lambda-c_g)]}$

4.3.3. The Nash game model

In Nash game model, the equilibrium prices of traditional and green materials are obtained through the optimal material price functions of both parties. The decision models for traditional and green suppliers are

$$\begin{cases} \max\limits_{w_t} \pi_t \\ \max\limits_{w_g} \pi_g. \end{cases} \tag{17}$$

Proposition 4. *Under the Nash game model, the optimal wholesale price decisions of the traditional supplier* $w_t^{\mathrm{NG}^*}$ *and the green supplier* $w_g^{\mathrm{NG}^*}$ *are*

$$\begin{cases} w_t^{\mathrm{NG}^*} = \frac{\alpha(a+c_t)+b(1+\sigma^2)(2c_t+c_g-\lambda)}{A+B} \\ w_g^{\mathrm{NG}^*} = \frac{\alpha a+2\lambda A+(c_t+2c_g)B}{2(A+B)}. \end{cases} \tag{18}$$

(The proof of Prop. 4 is given in Appendix A.4.)

Plugging (18) into (8), we have the production decision and green raw material ordering decision of the manufacturer under the Nash game model as

$$\begin{cases} q^{\mathrm{NG}^*} = \frac{(a-c_t)B+b(1+\sigma^2)(a+\lambda-c_g)}{2b(1+\sigma^2)(A+B)} \\ q_g^{\mathrm{NG}^*} = \frac{\alpha a+2(\lambda-c_g)A}{2\alpha(A+B)}. \end{cases} \tag{19}$$

Combining Propositions 2–4, we can obtain the greenness of the product under the three game models as shown in Table 3.

5. DISCUSSION AND NUMERICAL ANALYSIS

In this section, we discuss and compare the pricing strategies of traditional and green suppliers under the three gaming models, as well as the production and raw material sourcing strategies of the manufacturer. In addition, we use a numerical example to illustrate the effects of consumers' green preferences, yield uncertainty, and coefficient of green production learning cost on the pricing strategies of raw materials, procurement strategies of raw materials, and production strategies.

In China, farmers face yield uncertainty and they need to make decisions on using traditional agricultural inputs (chemical pesticides, fertilizers, etc.) and/or green agricultural inputs (bio-pesticides, organic fertilizers, etc.). Moreover, there is price competition between traditional agricultural input suppliers and green agricultural input suppliers in the market. Therefore, it is meaningful to consider the agricultural production industry in China as an example. In particular, we choose values of parameters based on research data of agricultural cultivation in July 2019 in Sancang Town, Dongtai City, Yancheng City, Jiangsu Province, where 8424 tons of watermelons grown locally are sold at 1000–3000 (CNY/Ton) in the market. We take the market price of watermelons as 2000 (CNY/Ton), and assume that $a = 3000$, $b = 100$. The production cost of the traditional raw material supplier is $c_t = 100$ (CNY/Ton) and the production cost of the green raw material supplier is $c_g = 200$ (CNY/Ton). The learning cost of green production is usually high, and we assume $\alpha = 1000$. The variance of the yield uncertainty variable X is assumed to be $\sigma^2 = 0.5$. In addition, we set the greenness preference coefficient $\lambda = 50$ in the numerical analysis unless stated otherwise.

5.1. Comparison of equilibrium results

In this part, we compare wholesale raw material prices, manufacturer's production, and green raw material procurement decisions under three models, and the following parameters will be used as thresholds for the consumer green preference factor in the comparison process (see Props. 5 and 6): $\lambda_1 = c_g - c_t$, $\lambda_2 = \frac{\alpha a + c_t B - 2c_g A}{2[B+b(1+\sigma^2)]}$, $\lambda_3 = \frac{\alpha a + c_t B - 2c_g A}{2B}$, $\lambda_4 = \frac{\alpha(a-c_g)-(c_g-c_t)A}{A+B}$.

Lemma 1. $\lambda_1 < \lambda_2 < \lambda_3 < \lambda_4$.

(The proof of Lem. 1 is given in Appendix A.5.)

For convenience, we refer to $\lambda < \lambda_1$ as very low green preference, $\lambda_1 < \lambda < \lambda_2$ as low green preference, $\lambda_2 < \lambda < \lambda_3$ as fair green preference, $\lambda_3 < \lambda < \lambda_4$ as high green preference and $\lambda > \lambda_4$ as very high green preference, respectively.

Proposition 5.

$$(1)\quad w_t^{\mathrm{TS}^*} > w_t^{\mathrm{GS}^*} > w_t^{\mathrm{NG}^*};\quad (2)\quad \begin{cases} w_g^{\mathrm{TS}^*} > w_g^{\mathrm{GS}^*} > w_g^{\mathrm{NG}^*}, & 0 < \lambda < \lambda_1 \\ w_g^{\mathrm{GS}^*} > w_g^{\mathrm{TS}^*} > w_g^{\mathrm{NG}^*}, & \lambda_1 < \lambda < \infty \end{cases}.$$

(The proof of Prop. 5 is given in Appendix A.6.)

Proposition 5 shows that traditional material price is the highest under traditional supplier-led model, followed by the green supplier-led case, and the lowest under Nash game model. Meanwhile, green material price is the lowest under Nash game model. When the green preference is very low ($0 < \lambda < \lambda_1$), the green material price is the highest under the traditional supplier-led model. When the green preference is not very low ($\lambda_1 < \lambda < \infty$), the green material price is the highest under the green supplier-led model. The prices of traditional and green raw materials are the lowest under the Nash game, which indicates that price competition under the green supplier-led or the traditional supplier-led can increase the market price of raw materials.

Proposition 6.

$$(1)\quad \begin{cases} w_t^{\mathrm{GS}^*} > w_g^{\mathrm{GS}^*}, & 0 < \lambda < \lambda_2 \\ w_t^{\mathrm{GS}^*} < w_g^{\mathrm{GS}^*}, & \lambda_2 < \lambda < \infty \end{cases};\quad (2)\quad \begin{cases} w_t^{\mathrm{NG}^*} > w_g^{\mathrm{NG}^*}, & 0 < \lambda < \lambda_3 \\ w_t^{\mathrm{NG}^*} < w_g^{\mathrm{NG}^*}, & \lambda_3 < \lambda < \infty \end{cases};$$

$$(3)\quad \begin{cases} w_t^{\mathrm{TS}^*} > w_g^{\mathrm{TS}^*}, & 0 < \lambda < \lambda_4 \\ w_t^{\mathrm{TS}^*} < w_g^{\mathrm{TS}^*}, & \lambda_4 < \lambda < \infty \end{cases}.$$

(The proof of Prop. 6 is given in Appendix A.7.)

Proposition 6 shows that when the green preference coefficient is large, the green material price is higher than the traditional raw material price under the traditional supplier-led, the green supplier-led, and Nash game models. Specifically, under green supplier-led model, when green preference is at fair level, the green raw material price is higher than the traditional raw material price. Under the Nash game model, when the green preference is at a high level, the green material price is higher than the traditional material price. In addition, under traditional supplier-led model, when the green preference is at a very high level, green material price will

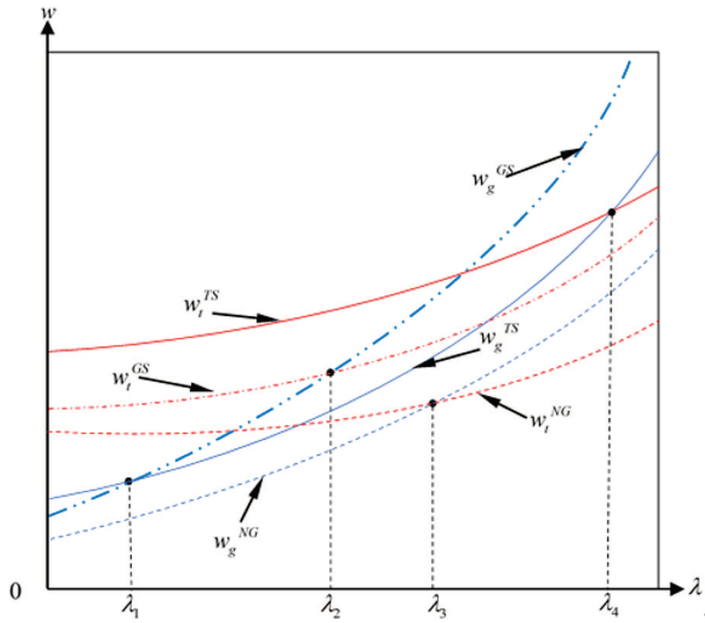

FIGURE 2. Wholesale raw material pricing strategy diagram.

be higher than the traditional material price. This suggests that there is a strong correlation between the prices of green and traditional raw materials and the degree of green preference of consumers under different game models.

From Propositions 5 and 6, the wholesale pricing strategies of the traditional and green suppliers are shown in Figure 2.

Proposition 7. (1) $q^{\mathrm{NG}^*} > q^{\mathrm{GS}^*} > q^{\mathrm{TS}^*}$; (2) $q_g^{\mathrm{TS}^*} > q_g^{\mathrm{NG}^*} > q_g^{\mathrm{GS}^*}$;
(3) $\theta_g^{\mathrm{TS}^*} > \theta_g^{\mathrm{NG}^*} > \theta_g^{\mathrm{GS}^*}$.

(The proof of Prop. 7 is given in Appendix A.8.)

Proposition 7 shows that the manufacturer's product output is the highest in Nash game model, followed by green supplier-led model, and the lowest in the traditional supplier-led model. As we can see from Figure 2, in Nash game model, both green and traditional raw materials have lowest market prices, which can increase the manufacturer's enthusiasm for production. Under the traditional supplier-led model, the traditional raw material price and the green raw material price are high (see Prop. 5), so the manufacturer's output is the lowest in this model compared to other two models. The greenness level of the manufacturer's product is the highest in the traditional supplier-led model and the lowest in the green supplier-led model.

Proposition 7 also shows that manufacturer's product greenness level (in terms of the ratio of green material) under the traditional supplier-led model is the highest, while manufacturer's product greenness level under the green supplier-led model is the lowest, which is consistent with the results shown in Figures 3–5. In other words, the green supplier-led model is not necessarily beneficial for green raw material usage or the improvement of product greenness.

Combining Proposition 6, we find that the stronger the dominant position of the green supplier, the more likely that the green raw material price will be higher than the traditional material price, which can discourage the downstream manufacturer to purchase green raw material or increase the product greenness level. Under the traditional supplier-led model, the green supplier is more likely to increase sales of the green raw material using a low-price strategy, which is actually beneficial to the products' greenness level improvement.

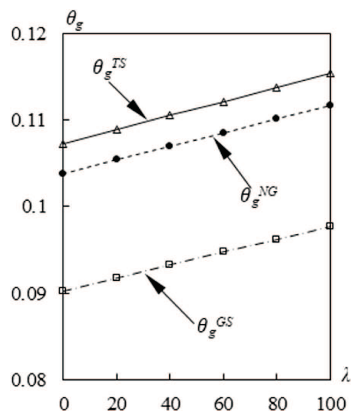

FIGURE 3. θ_g with respect to λ.

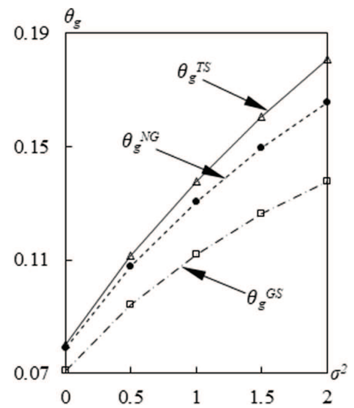

FIGURE 4. θ_g with respect to σ^2.

5.2. Sensitivity analysis

5.2.1. The impacts of the consumers' green preference

Proposition 8.

$$(1)\quad \frac{dw_t^{\mathrm{TS}^*}}{d\lambda} < 0, \quad \frac{dw_g^{\mathrm{TS}^*}}{d\lambda} > 0, \quad \frac{dq^{\mathrm{TS}^*}}{d\lambda} > 0, \quad \frac{dq_g^{\mathrm{TS}^*}}{d\lambda} > 0, \quad \frac{d\theta_g^{\mathrm{TS}^*}}{d\lambda} > 0;$$

$$(2)\quad \frac{dw_t^{\mathrm{GS}^*}}{d\lambda} < 0, \quad \frac{dw_g^{\mathrm{GS}^*}}{d\lambda} > 0, \quad \frac{dq^{\mathrm{GS}^*}}{d\lambda} > 0, \quad \frac{dq_g^{\mathrm{GS}^*}}{d\lambda} > 0, \quad \frac{d\theta_g^{\mathrm{GS}^*}}{d\lambda} > 0;$$

$$(3)\quad \frac{dw_t^{\mathrm{NG}^*}}{d\lambda} < 0, \quad \frac{dw_g^{\mathrm{NG}^*}}{d\lambda} > 0, \quad \frac{dq^{\mathrm{NG}^*}}{d\lambda} > 0, \quad \frac{dq_g^{\mathrm{NG}^*}}{d\lambda} > 0, \quad \frac{d\theta_g^{\mathrm{NG}^*}}{d\lambda} > 0.$$

(The proof of Prop. 8 is given in Appendix A.9.)

According to Proposition 8 and Figure 3, under all the three-game models we consider (the traditional supplier dominance, the green supplier dominance, and Nash game), as the consumers' green preference coefficient λ increases, the green material price increases, while the traditional material price decreases. In addition, the manufacturers' product output and green material order increase as λ increases. In other words, with the increase in consumers' green preference coefficient, the green level of the final product continues to improve.

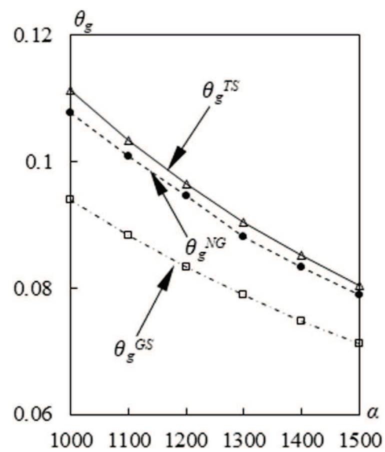

FIGURE 5. θ_g with respect to α.

Proposition 8 reveals that, to promote motivate manufacturers to increase product output and green level, green consumerism should be promoted to increase consumers' greenness preferences. Moreover, as the green preference improves, the price and purchase of green raw material increase accordingly, and the green material supplier can benefit from it. Therefore, the green material supplier can increase consumers' green preference and product recognition through cooperation with manufacturers and advertisements.

5.2.2. The impacts of the yield uncertainty

Proposition 9.

$$(1)\quad \frac{dw_t^{\mathrm{TS}^*}}{d\sigma^2} < 0, \quad \frac{dw_g^{\mathrm{TS}^*}}{d\sigma^2} < 0, \quad \frac{dq^{\mathrm{TS}^*}}{d\sigma^2} < 0, \quad \frac{dq_g^{\mathrm{TS}^*}}{d\sigma^2} < 0, \quad \frac{d\theta_g^{\mathrm{TS}^*}}{d\sigma^2} > 0;$$
$$(2)\quad \frac{dw_t^{\mathrm{GS}^*}}{d\sigma^2} < 0, \quad \frac{dw_g^{\mathrm{GS}^*}}{d\sigma^2} < 0, \quad \frac{dq^{\mathrm{GS}^*}}{d\sigma^2} < 0, \quad \frac{dq_g^{\mathrm{GS}^*}}{d\sigma^2} < 0, \quad \frac{d\theta_g^{\mathrm{GS}^*}}{d\sigma^2} > 0;$$
$$(3)\quad \frac{dw_t^{\mathrm{NG}^*}}{d\sigma^2} < 0, \quad \frac{dw_g^{\mathrm{NG}^*}}{d\sigma^2} < 0, \quad \frac{dq^{\mathrm{NG}^*}}{d\sigma^2} < 0, \quad \frac{dq_g^{\mathrm{NG}^*}}{d\sigma^2} < 0, \quad \frac{d\theta_g^{\mathrm{NG}^*}}{d\sigma^2} > 0.$$

(The proof of Prop. 9 is given in Appendix A.10.)

Proposition 9 shows that under all the three models, as the volatility of the manufacturer's output increases, the prices of green and traditional materials, the manufacturer's product yield, and the purchase volume of green raw materials are decreasing. The reason is, as the manufacturer's yield uncertainty increases, the manufacturer tends to reduce production inputs in order to mitigate risks. In addition, the demand for green and traditional raw materials decreases, so green and traditional suppliers need to reduce raw material prices to promote raw material sales.

Interestingly, Proposition 9 and Figure 4 suggest that greenness of the manufacturer's production increases with respect to yield uncertainty. That is, as the uncertainty of product output increases, the manufacturer reduces the production but increases the greenness level of the product by increasing the ratio of green raw materials per unit of product. Actually, green production would be a strategic choice for companies facing risks and pressures, and they should establish partnerships with green raw material suppliers to move forward along the green production path.

5.2.3. The impacts of the coefficient of green production learning cost

Proposition 10.

$$(1)\quad \frac{dw_t^{\mathrm{TS}^*}}{d\alpha} > 0, \quad \frac{dw_g^{\mathrm{TS}^*}}{d\alpha} > 0, \quad \frac{dq^{\mathrm{TS}^*}}{d\alpha} < 0, \quad \frac{dq_g^{\mathrm{TS}^*}}{d\alpha} < 0, \quad \frac{d\theta_g^{\mathrm{TS}^*}}{d\alpha} < 0;$$
$$(2)\quad \frac{dw_t^{\mathrm{GS}^*}}{d\alpha} > 0, \quad \frac{dw_g^{\mathrm{GS}^*}}{d\alpha} > 0, \quad \frac{dq^{\mathrm{GS}^*}}{d\alpha} < 0, \quad \frac{dq_g^{\mathrm{GS}^*}}{d\alpha} < 0, \quad \frac{d\theta_g^{\mathrm{GS}^*}}{d\alpha} < 0;$$
$$(3)\quad \frac{dw_t^{\mathrm{NG}^*}}{d\alpha} > 0, \quad \frac{dw_g^{\mathrm{NG}^*}}{d\alpha} > 0, \quad \frac{dq^{\mathrm{NG}^*}}{d\alpha} < 0, \quad \frac{dq_g^{\mathrm{NG}^*}}{d\alpha} < 0, \quad \frac{d\theta_g^{\mathrm{NG}^*}}{d\alpha} < 0.$$

(The proof of Prop. 10 is given in Appendix A.11.)

Proposition 10 shows that, regardless of the competitive model between the green supplier and the traditional manufacturer, as the green production learning cost coefficient increases, the prices of green and traditional raw materials will increase, while the manufacturer's product output and green raw material order will decrease. In addition, it can be seen from Figure 5 that the greenness level of the product decreases as the coefficient of green production learning costs increases.

6. Managerial insights

In this section, we present some important managerial insights to help supply chain stakeholders make optimal decisions to increase the procurement of green raw materials and improve the greenness level of final products. (1) Under green supplier-led model, although the price of green raw materials is higher than in the other models, the purchase of green raw materials is also minimal. Moreover, green suppliers can increase consumers' green preferences and recognition of green products through advertising, etc. (2) Faced with risk of yield uncertainty, the greenness level of the product increases, revealing that green production would be a strategic choice for manufacturing companies with risks and pressures. And manufacturers can also establish partnerships with upstream green suppliers to get higher returns for themselves. (3) The government can subsidize the risk of yield fluctuations and green production costs in the manufacturer's production processes to motivate it to increase production and green raw materials purchases, in order to increase the greenness level of the final product. The green supplier can also contribute to increased sales of green raw materials by sharing the risk and the cost of green production with the manufacturer.

7. Conclusions

In this paper, we examine the optimal strategies for raw material prices, production, and green material procurement of a green supply chain consisting of a green supplier, a traditional supplier, and a manufacturer and we consider three models of the competition between the green supplier and the traditional supplier. We further discuss the impacts of yield uncertainty, consumers' green preferences, and the manufacturer's learning costs on optimal strategies.

The findings are summarized as follows. (1) In contrast to Nash game, price competition in traditional supplier-led or green supplier-led raises the price of raw materials. Moreover, the more dominant the green supplier is in power structure, the more likely price of green raw materials will be higher than traditional raw materials. (2) The greenness level of final products is the lowest under the price competition model in the green supplier-led and the highest under the traditional supplier-led price competition model. (3) As consumers' green preference improves, the green material price increases and the traditional material price decreases. Meanwhile, the greenness level of products increases. (4) As yield uncertainty increases, the wholesale prices of green and traditional raw materials, the manufacturers' product yield, and green raw material procurement all decrease. Interestingly, the greenness level of production increases with respect to yield uncertainty. (5) The increase in green production learning costs will lead to increases in the price of green and traditional raw materials, which finally leads to a decrease in the greenness level of the product.

This study has some limitations, which can be subjects of future research. For example, in this paper, only the price competition between a traditional supplier and a green supplier is considered. But in reality, there is price competition between green and traditional manufacturers, and between green and traditional supply chains. We can establish competition models between a traditional manufacturer and a green manufacturer, or between a traditional supply chain and a green supply chain in the future. Moreover, we only assume that the product output has randomness, while in reality, for a certain green raw material input, the greenness level of the product also has randomness. So in the future, we can study the effect of greenness uncertainty on the green raw material input strategy.

Appendix A.

A.1. Proof of Proposition 1

Deriving from (4), we can get that

$$\frac{\partial \pi_m}{\partial q} = a - w_t - 2bq(1+\sigma^2), \quad \frac{\partial \pi_m}{\partial q_g} = \lambda + w_t - w_g - \alpha q_g,$$
$$\frac{\partial^2 \pi_m}{\partial q^2} = -2b(1+\sigma^2), \quad \frac{\partial^2 \pi_m}{\partial q_g^2} = -\alpha, \quad \frac{\partial^2 \pi_m}{\partial q \partial q_g} = \frac{\partial^2 \pi_m}{\partial q_g \partial q} = 0.$$

So we can get a Hessian of $\pi_m(q, q_g)$ as follows.

$$H = \begin{bmatrix} -2b(1+\sigma^2) & 0 \\ 0 & -\alpha \end{bmatrix}.$$

Since $H_{11} = -2b(1+\sigma^2) < 0$, so we can see that $\det(H) = 2b\alpha(1+\sigma^2) > 0$ according to assumption. Therefore, H is negative definite, and the manufacturer's optimum production q^* and optimum order of green raw materials q_g^* are both present. Let $\frac{\partial \pi_m}{\partial q} = 0$ and $\frac{\partial \pi_m}{\partial q_g} = 0$, so we can get (8).

A.2. Proof of Proposition 2

Deriving from (9) relates to w_g, we can get that

$$\frac{\partial \pi_g^{\mathrm{TS}^*}}{\partial w_g} = \frac{\lambda + w_t - 2w_g + c_g}{\alpha}, \quad \frac{\partial^2 \pi_g^{\mathrm{TS}^*}}{\partial w_g^2} = -\frac{2}{\alpha} < 0.$$

Let $\frac{\partial \pi_g^{\mathrm{TS}^*}}{\partial w_g} = 0$, and we can get the optimal wholesale price of green raw materials $w_g^{\mathrm{TS}^*}$.

Substituting the optimal wholesale price of the green raw material $w_g^{\mathrm{TS}^*}$ into (9), and deriving from (9) relates to w_t, we can get that

$$\frac{\partial \pi_t^{\mathrm{TS}^*}}{\partial w_t} = \frac{a - 2w_t + c_t}{2b(1+\sigma^2)} - \frac{\lambda + 2w_t - c_g - c_t}{2\alpha}, \quad \frac{\partial^2 \pi_t^{\mathrm{TS}^*}}{\partial w_t^2} = -\frac{1}{b(1+\sigma^2)} - \frac{1}{\alpha} < 0.$$

Let $\frac{\partial \pi_t^{\mathrm{TS}^*}}{\partial w_t} = 0$, we can get the optimal wholesale price of the traditional raw material $w_t^{\mathrm{TS}^*}$.

A.3. Proof of Proposition 3

From (14), we can obtain that

$$\frac{\partial \pi_t^{\mathrm{GS}^*}}{\partial w_t} = \frac{\alpha(a - 2w_t + c_t) - 2b\big(1+\sigma^2\big)(\lambda + 2w_t - w_g - c_t)}{2b(1+\sigma^2)\alpha}, \quad \frac{\partial^2 \pi_t^{\mathrm{GS}^*}}{\partial w_t^2} = -\frac{1}{b(1+\sigma^2)} - \frac{2}{\alpha} < 0.$$

Let $\frac{\partial \pi_t^{\mathrm{GS}^*}}{\partial w_t} = 0$, we can get $w_t^{\mathrm{GS}^*}$.

Substituting the optimal wholesale price of the green raw material $w_g^{\mathrm{TS}^*}$ into (14), and deriving from (9) relates to w_g, we can get that

$$\frac{\partial \pi_g^{\mathrm{GS}^*}}{\partial w_g} = \frac{2A(\lambda - 2w_g + c_g) + \alpha a + c_t B}{2\alpha B}, \quad \frac{\partial^2 \pi_g^{\mathrm{GS}^*}}{\partial w_g^2} = -\frac{2A}{\alpha B} < 0.$$

Let $\frac{\partial \pi_g^{\mathrm{GS}^*}}{\partial w_g} = 0$, we can get $w_g^{\mathrm{GS}^*}$.

A.4. Proof of Proposition 4

From (17), the following results are available that

$$\frac{\partial \pi_t^{\mathrm{NS}^*}}{\partial w_t} = \frac{\alpha(a - 2w_t + c_t) - 2b\big(1+\sigma^2\big)(\lambda + 2w_t - w_g - c_t)}{2b(1+\sigma^2)\alpha}, \quad \frac{\partial \pi_g^{\mathrm{NS}^*}}{\partial w_g} = -\frac{\lambda + w_t - 2w_g + c_g}{\alpha}.$$

Let $\frac{\partial \pi_t^{\mathrm{NS}^*}}{\partial w_t} = 0$ and $\frac{\partial \pi_g^{\mathrm{NS}^*}}{\partial w_g} = 0$, we can get (18).

A.5. Proof of Lemma 1

According to Assumptions 2, 4 and 5, we can get that

$$\begin{aligned}
\lambda_4 - \lambda_3 &= \frac{b\big(1+\sigma^2\big)\big[\alpha(a - c_t) + 2b\big(1+\sigma^2\big)(c_g - c_t)\big]}{2B(A+B)} > 0,\\
\lambda_3 - \lambda_2 &= \frac{b\big(1+\sigma^2\big)(\alpha a + c_t B - 2c_g A)}{2B[B + b(1+\sigma^2)]} > 0,\\
\lambda_2 - \lambda_1 &= \frac{\alpha[a + 3(c_t - c_g) - c_g] - 8b\big(1+\sigma^2\big)(c_g - c_t)}{2[B + b(1+\sigma^2)]} > 0.
\end{aligned}$$

Since the value of a is much larger than c_t and c_g, so $\lambda_2 > \lambda_1$.

A.6. Proof of Proposition 5

Since $\theta_g > 0$, so we can see that $a + 2(\lambda - c_g) + c_t > 0$. According to Assumptions 2 and 5, we can get the following results from (10), (15) and (18).

$$\begin{aligned}
w_t^{\mathrm{TS}^*} - w_t^{\mathrm{GS}^*} &= \frac{b\big(1+\sigma^2\big)\big\{(a - c_t)\alpha - b\big(1+\sigma^2\big)[c_t + 2(\lambda - c_g)]\big\}}{4AB} > 0,\\
w_t^{\mathrm{TS}^*} - w_t^{\mathrm{NS}^*} &= \frac{b\big(1+\sigma^2\big)\big[(a - c_t)\alpha - b\big(1+\sigma^2\big)\big]}{2A(A+B)} > 0,\\
w_t^{\mathrm{GS}^*} - w_t^{\mathrm{NS}^*} &= \frac{b^2\big(1+\sigma^2\big)^2\big\{[(a + 2(\lambda - c_g) + c_t)]\alpha + 2b\big(1+\sigma^2\big)(c_t + \lambda - c_g)\big\}}{2A(A+B)} > 0.
\end{aligned}$$

Therefore, we can get $w_t^{\text{TS}^*} > w_t^{\text{GS}^*} > w_t^{\text{NS}^*}$.

$$w_g^{\text{TS}^*} - w_g^{\text{NS}^*} = \frac{b\left(1+\sigma^2\right)\left[\alpha(a-c_t) + b\left(1+\sigma^2\right)(c_g - c_t - \lambda)\right]}{4A(A+B)} > 0,$$
$$w_g^{\text{TS}^*} - w_g^{\text{GS}^*} = -\frac{b\left(1+\sigma^2\right)(c_g - c_t - \lambda)}{4A},$$
$$w_g^{\text{GS}^*} - w_g^{\text{NS}^*} = \frac{b\left(1+\sigma^2\right)\left\{[(a+2(\lambda - c_g) + c_t)]\alpha + 2b\left(1+\sigma^2\right)(c_t + \lambda - c_g)\right\}}{4A(A+B)} > 0.$$

So, we can get that $w_g^{\text{TS}^*} > w_g^{\text{NS}^*}$ and $w_g^{\text{GS}^*} > w_g^{\text{NS}^*}$. And when $0 < \lambda \le (c_g - c_t)$, we can see that $w_g^{\text{TS}^*} > w_g^{\text{GS}^*} > w_g^{\text{NS}^*}$, when $(c_g - c_t) < \lambda < \infty$, we can get that $w_g^{\text{GS}^*} > w_g^{\text{TS}^*} > w_g^{\text{NS}^*}$.

A.7. Proof of Proposition 6

From (10), (15) and (18), we can obtain that

$$w_t^{\text{TS}^*} - w_g^{\text{TS}^*} = \frac{\alpha[a - 2(\lambda + c_g) + c_t] - b\left(1+\sigma^2\right)(3\lambda + c_g - c_t)}{4A},$$
$$w_t^{\text{GS}^*} - w_g^{\text{GS}^*} = \frac{\alpha[a - 2(\lambda + c_g) + c_t] - 2b\left(1+\sigma^2\right)(3\lambda + c_g - c_t)}{4B},$$
$$w_t^{\text{NS}^*} - w_g^{\text{NS}^*} = \frac{\alpha[a - 2(\lambda + c_g) + c_t] - 2b\left(1+\sigma^2\right)(2\lambda + c_g - c_t)}{2(A+B)}.$$

Therefore, when $0 < \lambda \le \frac{\alpha(a-c_g)-(c_g-c_t)A}{A+B}$, $0 < \lambda \le \frac{\alpha a + c_t B - 2c_g A}{2[B+b(1+\sigma^2)]}$, $0 < \lambda \le \frac{\alpha a + c_t B - 2c_g A}{2B}$, we can get that $w_t^{\text{TS}^*} > w_g^{\text{TS}^*}$, $w_t^{\text{GS}^*} > w_g^{\text{GS}^*}$, $w_t^{\text{NS}^*} > w_g^{\text{NS}^*}$, respectively.

A.8. Proof of Proposition 7

From (12), (16) and (19), we can get that

$$q^{\text{TS}^*} - q^{\text{GS}^*} = \frac{-\alpha(a-c_t) + 2b\left(1+\sigma^2\right)(\lambda + c_t - c_g)}{8AB} < 0,$$
$$q^{\text{TS}^*} - q^{\text{NS}^*} = \frac{-\alpha(a-c_t) + b\left(1+\sigma^2\right)(c_t + \lambda - c_g)}{4b(1+\sigma^2)A(A+B)} < 0,$$
$$q^{\text{NS}^*} - q^{\text{GS}^*} = \frac{b\left(1+\sigma^2\right)[\alpha a + 2(\lambda - c_g)A + c_t B]}{8AB(A+B)} > 0.$$

So $q^{\text{NS}^*} > q^{\text{GS}^*} > q^{\text{TS}^*}$.

$$q_g^{\text{TS}^*} - q_g^{\text{GS}^*} = \frac{b\left(1+\sigma^2\right)(a + \lambda - c_g)}{4\alpha AB} > 0,$$
$$q_g^{\text{NS}^*} - q_g^{\text{GS}^*} = \frac{b\left(1+\sigma^2\right)(a\alpha + c_t B + 2\lambda A) + 2c_g A^2}{4\alpha B(A+B)} > 0,$$
$$q_g^{\text{NS}^*} - q_g^{\text{TS}^*} = \frac{-b\left(1+\sigma^2\right)\left[\alpha(a-c_t) - b\left(1+\sigma^2\right)c_t\right] - (2\lambda - c_g)\left(A^2 + \alpha B\right)}{4\alpha A(A+B)} > 0.$$

Therefore, we can get that $q_g^{\text{TS}^*} > q_g^{\text{NS}^*} > q_g^{\text{GS}^*}$.

Because of $q^{\mathrm{NS}^*} > q^{\mathrm{GS}^*} > q^{\mathrm{TS}^*}$ and $q_g^{\mathrm{TS}^*} > q_g^{\mathrm{NS}^*} > q_g^{\mathrm{GS}^*}$, we can see that $\theta_g^{\mathrm{TS}^*}$ is the maximum. Furthermore, comparing $\theta_g^{\mathrm{GS}^*}$ and $\theta_g^{\mathrm{NS}^*}$ we can see that

$$\theta_g^{\mathrm{GS}^*} - \theta_g^{\mathrm{NS}^*} = \frac{-(a-c_t)b\big(1+\sigma^2\big)B - 2c_g A^2\big[(a-c_t)B + b\big(1+\sigma^2\big)(a+\lambda-c_g)\big]}{16b(1+\sigma^2)\alpha AB(A+B)q^{\mathrm{GS}}q^{\mathrm{NS}}} < 0.$$

So $\theta_g^{\mathrm{TS}^*} > \theta_g^{\mathrm{NS}^*} > \theta_g^{\mathrm{GS}^*}$.

A.9. Proof of Proposition 8

From (10), (15) and (18), we can get that

$$\frac{dw_t^{\mathrm{TS}^*}}{d\lambda} = -\frac{b(1+\sigma^2)}{2A} < 0, \quad \frac{dw_g^{\mathrm{TS}^*}}{d\lambda} = \frac{\alpha + A}{4A} > 0; \quad \frac{dw_t^{\mathrm{GS}^*}}{d\lambda} = -\frac{b(1+\sigma^2)}{2B} < 0,$$
$$\frac{dw_g^{\mathrm{GS}^*}}{d\lambda} = \frac{1}{2} > 0; \quad \frac{dw_t^{\mathrm{NS}^*}}{d\lambda} = -\frac{b(1+\sigma^2)}{A+B} < 0, \quad \frac{dw_g^{\mathrm{NS}^*}}{d\lambda} = \frac{A}{A+B} > 0.$$

From (12), (16) and (19), we can obtain that

$$\frac{dq^{\mathrm{TS}^*}}{d\lambda} = \frac{1}{4A} > 0, \quad \frac{dq_g^{\mathrm{TS}^*}}{d\lambda} = \frac{A + b\big(1+\sigma^2\big)}{4\alpha A} > 0, \quad \frac{d\theta_g^{\mathrm{TS}^*}}{d\lambda} = \frac{2ab\big(1+\sigma^2\big)A^2}{\alpha[aB + b(1+\sigma^2)(\lambda - c_g) - c_t A]^2} > 0;$$
$$\frac{dq^{\mathrm{GS}^*}}{d\lambda} = \frac{1}{4B} > 0, \frac{dq_g^{\mathrm{GS}^*}}{d\lambda} = \frac{A}{2\alpha B} > 0,$$
$$\frac{d\theta_g^{\mathrm{GS}^*}}{d\lambda} = \frac{4A\big[(a\alpha B - c_0 A) + b\big(1+\sigma^2\big)(2a - c_t)B\big]}{\alpha\{B[3\alpha a + b(1+\sigma^2)(4a - c_t)] - A[\alpha a - 2b(1+\sigma^2)(\lambda - c_g)] - 2c_t A\}^2} > 0;$$
$$\frac{dq^{\mathrm{NS}^*}}{d\lambda} = \frac{1}{2(A+B)} > 0, \quad \frac{dq_g^{\mathrm{NS}^*}}{d\lambda} = \frac{A}{\alpha(A+B)} > 0,$$
$$\frac{d\theta_g^{\mathrm{NS}^*}}{d\lambda} = \frac{b\big(1+\sigma^2\big)\big\{\alpha(a-c_t)B^2 + \alpha A\big[(a-c_t)B - b\big(1+\sigma^2\big)c_g\big]\big\}}{[\alpha(a-c_t)B + \alpha b(1+\sigma^2)(a+\lambda-c_g)]^2} > 0.$$

A.10. Proof of Proposition 9

From (10), (15) and (18), we can get that

$$\frac{dw_t^{\mathrm{TS}^*}}{d\sigma^2} = -\frac{\alpha b(\lambda + a - c_g)}{2A^2} < 0, \quad \frac{dw_g^{\mathrm{TS}^*}}{d\sigma^2} = -\frac{\alpha b(\lambda + a - c_g)}{4A^2} < 0;$$
$$\frac{dw_t^{\mathrm{GS}^*}}{d\sigma^2} = -\frac{\alpha b(\lambda + a - c_g)}{2B^2} - \frac{\alpha b(a - c_t)}{4A^2} < 0, \quad \frac{dw_g^{\mathrm{GS}^*}}{d\sigma^2} = -\frac{\alpha b(a - c_t)}{A^2} < 0;$$
$$\frac{dw_t^{\mathrm{NS}^*}}{d\sigma^2} = -\frac{\alpha b[3a + 2(\lambda - c_g) - c_t]}{(A+B)^2} < 0, \quad \frac{dw_g^{\mathrm{NS}^*}}{d\sigma^2} = -\frac{\alpha b[3a + 2(\lambda - c_g) - c_t]}{2(A+B)^2} < 0.$$

From (12), (16) and (19), we can obtain that

$$\frac{dq^{\mathrm{TS}^*}}{d\sigma^2} = \frac{1}{4A} > 0, \quad \frac{dq_g^{\mathrm{TS}^*}}{d\sigma^2} = \frac{A + b\big(1+\sigma^2\big)}{4\alpha A} > 0,$$
$$\frac{d\theta_g^{\mathrm{TS}^*}}{d\sigma^2} = \frac{2ab\big(1+\sigma^2\big)A^2}{\alpha[aB + b(1+\sigma^2)(\lambda - c_g) - c_t A]^2} > 0;$$
$$\frac{dq^{\mathrm{GS}^*}}{d\sigma^2} = \frac{1}{4B} > 0, \quad \frac{dq_g^{\mathrm{GS}^*}}{d\sigma^2} = \frac{A}{2\alpha B} > 0,$$

$$\frac{d\theta_g^{\mathrm{GS}^*}}{d\sigma^2} = \frac{2a\alpha^2\{aB[\alpha - b(1+\sigma^2)] + c_t(B^2-\alpha)\} + 2b^2(1+\sigma^2)^2(\lambda+2c_t-c_g)}{\alpha^2\{B[3\alpha a + b(1+\sigma^2)(4a-c_t)] - A[\alpha a - 2b(1+\sigma^2)(\lambda-c_g)] - 2c_tA\}^2} > 0;$$

$$\frac{dq^{\mathrm{NS}^*}}{d\sigma^2} = \frac{1}{2(A+B)} > 0, \quad \frac{dq_g^{\mathrm{NS}^*}}{d\sigma^2} = \frac{A}{\alpha(A+B)} > 0,$$

$$\frac{d\theta_g^{\mathrm{NS}^*}}{d\sigma^2} = \frac{b(1+\sigma^2)\{\alpha(a-c_t)B^2 + \alpha A[(a-c_t)B - b(1+\sigma^2)c_g]\}}{[\alpha(a-c_t)B + \alpha b(1+\sigma^2)(a+\lambda-c_g)]^2} > 0.$$

A.11. Proof of Proposition 10

From (10), (15) and (18), we can get that

$$\frac{dw_t^{\mathrm{TS}^*}}{d\alpha} = \frac{b(1+\sigma^2)(a+\lambda-c_g)}{2A^2} > 0, \quad \frac{dw_g^{\mathrm{TS}^*}}{d\alpha} = -\frac{(1+\sigma^2)(a+\lambda-c_g)}{4A} > 0;$$

$$\frac{dw_t^{\mathrm{GS}^*}}{d\alpha} = \frac{b(1+\sigma^2)(a+c_t)}{4A^2} + \frac{2b(1+\sigma^2)(a+\lambda-c_g)}{4B^2} > 0,$$

$$\frac{dw_g^{\mathrm{GS}^*}}{d\alpha} = \frac{b(1+\sigma^2)(a-c_t)}{4A^2} > 0; \quad \frac{dw_t^{\mathrm{NS}^*}}{d\alpha} = \frac{b(1+\sigma^2)[3a+2(\lambda-c_g)-c_t]}{(A+B)^2},$$

$$\frac{dw_g^{\mathrm{NS}^*}}{d\alpha} = \frac{b(1+\sigma^2)[3a+2(\lambda-c_g)-c_t]}{2(A+B)^2} > 0.$$

From (12), (16) and (19), we can obtain that

$$\frac{dq^{\mathrm{TS}^*}}{d\alpha} = -\frac{(a+\lambda-c_g)}{4A^2} < 0, \quad \frac{dq_g^{\mathrm{TS}^*}}{d\alpha} = -\frac{\{a\alpha^2 + c_tA^2 + (\lambda-c_g)[2\alpha A + b^2(1+\sigma^2)]\}}{4\alpha^2A^2} < 0,$$

$$\frac{d\theta_g^{\mathrm{TS}^*}}{d\alpha} = -\frac{b(1+\sigma^2)(a-c_t)[a+2(\lambda-c_g)+c_t]}{[aB+b(1+\sigma^2)(\lambda-c_g)-c_tA]^2} - \frac{b^2(1+\sigma^2)^2(\lambda+c_t-c_g)[2\alpha(a-c_t)+b(1+\sigma^2)(2a+\lambda-c_t-c_g)]}{\alpha^2[aB+b(1+\sigma^2)(\lambda-c_g)-c_tA]^2} < 0;$$

$$\frac{dq^{\mathrm{GS}^*}}{d\alpha} = -\frac{[(a-c_t)B^2 + 2(a+\lambda-c_g)A^2]}{8A^2B^2} < 0,$$

$$\frac{dq_g^{\mathrm{GS}^*}}{d\alpha} = -\frac{\{a\alpha^2 + 2(\lambda-c_g)[A^2+b^2(1+\sigma^2)^2] + c_tB^2\}}{4\alpha^2B^2} < 0,$$

$$\frac{d\theta_g^{\mathrm{GS}^*}}{d\alpha} = -\frac{a\{a[\alpha(A^2-B) + A(\alpha^2-2B) + 2b^2(1+\sigma^2)^2] - c_tb^2(1+\sigma^2)^2\}}{\{B[3\alpha a + b(1+\sigma^2)(4a-c_t)] - A[\alpha a - 2b(1+\sigma^2)(\lambda-c_g)] - 2c_tA\}^2} < 0;$$

$$\frac{dq^{\mathrm{NS}^*}}{d\alpha} = -\frac{[3a+2(\lambda-c_g)-c_t]}{2(A+B)^2} < 0,$$

$$\frac{dq_g^{\mathrm{NS}^*}}{d\alpha} = -\frac{\{(2\lambda-c_g)[2A^2+b^2(1+\sigma^2)^2] + 2c_tA[B+b(1+\sigma^2)] + 2a\alpha^2\}}{2\alpha^2(A+B)^2} < 0,$$

$$\frac{d\theta_g^{\mathrm{NS}^*}}{d\alpha} = -\frac{b(1+\sigma^2)\{\alpha(a-c_t)(a+2\lambda+c_t-c_g)\}}{[\alpha(a-c_t)B + \alpha b(1+\sigma^2)(a+\lambda-c_g)]^2} - \frac{b^2(1+\sigma^2)^2\{[2(\lambda+c_t)-c_g][3a+\lambda-2(c_t-1)-c_g]\}}{[\alpha(a-c_t)B + \alpha b(1+\sigma^2)(a+\lambda-c_g)]^2} < 0.$$

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References

[1] S. Mitra and P.P. Datta, Adoption of green supply chain management practices and their impact on performance: an exploratory study of Indian manufacturing firms. *Int. J. Prod. Res.* **52** (2014) 2085–2107.

[2] Y.G. Yu, X.Y. Han and G.P. Hu, Optimal production for manufacturers considering consumer environmental awareness and green subsidies. *Int. J. Prod. Econ.* **182** (2016) 397–408.

[3] Q.F. Meng, M.W. Li, W.Y. Liu, Z. Li and J. Zhang, Pricing policies of dual-channel green supply chain: considering government subsidies and consumers' dual preferences. *Sustain. Prod. Consump.* **26** (2021) 1021–1030.

[4] Y.P. Jiang, K.R. Li, S.F. Chen, X.L. Fu, S.Y. Feng and Z.S. Zhuang, A sustainable agricultural supply chain considering substituting organic manure for chemical fertilizer. *Sustain. Prod. Consump.* **29** (2022) 432–446.

[5] Z.G. Liu, T.D. Anderson and J.M. Cruz, Consumer environmental awareness and competition in two-stage supply chains. *Eur. J. Oper. Res.* **218** (2012) 602–613.

[6] S. Guo, T.M. Choi and B. Shen, Green product development under competition: a study of the fashion apparel industry. *Eur. J. Oper. Res.* **270** (2019) 523–538.

[7] L. Zhao and Y.X. Zhao, Retailer-driven carbon emission reduction: contract design in the presence of information asymmetry and cap-and-trade. *Environ. Sci. Pollut. R.* **29** (2022) 82855–82872.

[8] Y.T. Lin, H.Y. Sun and S.L. Wang, Designing sustainable products under coproduction technology. *Manuf. Serv. Oper. Manage.* **22** (2020) 1181–1198.

[9] R. Bemporad and M. Baranowski, Conscious consumers are changing the rules of marketing. Are you ready? Highlights from the BBMG conscious consumer report (2007).

[10] A.J. Hruska and M. Corriols, The impact of training in integrated pest management among Nicaraguan Maize farmers: increased net return reduced health risk. *Int. J. Occup. Env. Heal.* **8** (2002) 191–200.

[11] X.Z. Shi, X. Li, Z.J. He and H. Jiang, Dynamic evolution of the zinc-nickel battery industry and evidence from China. *Discrete. Dyn. Nat. Soc.* **2021** (2021) 1992845.

[12] T. Ibn-Mohammed, S.C.L. Koh, I.M. Reaney, A. Acquaye, D. Wang, S. Taylor and A. Genovese, Integrated hybrid life cycle assessment and supply chain environmental profile evaluations of lead-based (lead zirconate titanate) versus lead-free (potassium sodium niobate) piezoelectric ceramics. *Energy Environ. Sci.* **9** (2016) 3495–3520.

[13] J.X. Wu, J. Yang, L.W. Ma, Z. Li and X.S. Shen, A system analysis of the development strategy of iron ore in China. *Resour. Policy* **48** (2016) 32–40.

[14] H.J. Peng, T. Pang and J. Cong, Coordination contracts for a supply chain with yield uncertainty and low-carbon preference. *J. Clean. Prod.* **205** (2018) 291–302.

[15] K. Arifoglu, S. Deo and S.M.R. Iravani, Consumption externality and yield uncertainty in the influenza vaccine supply chain: interventions in demand and supply sides. *Manage. Sci.* **58** (2012) 1072–1091.

[16] P. Rogezer, L. Silbermayr and W. Jammernegg, Sustainable sourcing including capacity reservation for recycled materials: a newsvendor framework with price and demand correlations. *Int. J. Prod. Econ.* **214** (2019) 206–219.

[17] Y. He and J. Zhang, Random yield risk sharing in a two-level supply chain. *Int. J. Prod. Econ.* **112** (2008) 769–781.

[18] J. Heydari, K. Govindan and Z. Basiri, Balancing price and green quality in presence of consumer environmental awareness: a green supply chain coordination approach. *Int. J. Prod. Res.* **59** (2021) 1957–1975.

[19] J. Li, Z.N. Hu, V. Shi and Q. Wang, Manufacturer' encroachment strategy with substitutable green products. *Int. J. Prod. Econ.* **235** (2021) 108102.

[20] P. Liu and S.P. Yi, Pricing policies of green supply chain considering targeted advertising and product green degree in the big data environment. *J. Clean. Prod.* **164** (2017) 1614–1622.

[21] J.Z. Gao, Z.D. Xiao and H.X. Wei, Competition and coordination in a dual-channel green supply chain with an eco-label policy. *Comput. Ind. Eng.* **153** (2021) 107057.

[22] Y.F. Sun, Y.J. Zhang and B. Su, Impact of government subsidy on the optimal R&D and advertising investment in the cooperative supply chain of new energy vehicles. *Energy Policy* **164** (2022) 112885.

[23] H.H. Song and Y. Wang, Enterprises' decision-making under government green subsidy and information asymmetry. *RAIRO: Oper. Res.* **56** (2022) 3871–3893.

[24] X.Y. Zhang and W.H. Hou, The impacts of e-tailer's private label on the sales mode selection: from the perspectives of economic and environmental sustainability. *Eur. J. Oper. Res.* **296** (2021) 601–614.

[25] Z. Zhang, S. Liu and B. Niu, Coordination mechanism of dual-channel closed-loop supply chains considering product quality and return. *J. Clean. Prod.* **248** (2020) 119273.

[26] M.B. Jamali and M. Rasti-Barzoki, A game theoretic approach for green and non-green product pricing chain to chain competitive sustainable and regular dual-channel supply chains. *J. Clean. Prod.* **170** (2018) 1029–1043.

[27] P. Ma and C. Zhang, Pricing strategies for complementary products in green supply chain. *Control Decis.* **33** (2018) 1861–1870.

[28] W.G. Zhu and Y.J. He, Green product design in supply chains under competition. *Eur. J. Oper. Res.* **258** (2017) 165–180.

[29] J. Li, Z.N. Hu, V. Shi and Q. Wang, Manufacturer's encroachment strategy with substitutable green products. *Int. J. Prod. Econ.* **235** (2021) 108102.

[30] J. Li, J. Liang, V. Shi and J. Zhu, The benefit of manufacturer encroachment considering consumer's environmental awareness and product competition. *Ann. Oper. Res.* (2021). DOI: 10.1007/s10479-021-04185-y.

[31] P. Shi, B. Yan, S. Shi and C.X. Ke, A decision support system to select suppliers for a sustainable supply chain based on a systematic DEA approach. *Inf. Technol. Manag.* **16** (2015) 39–49.

[32] A. Bala, P. Munoz and J. Rieradevall, Experiences with greening suppliers. The Universitat Autonoma de Barcelona. *J. Clean. Prod.* **16** (2008) 24–29.

[33] S.M. Lo, Effects of supply chain position on the motivation and practices of firms going green. *Int. J. Oper. Prod. Man.* **34** (2014) 93–114.

[34] J. Cao, X.B. Wu and G.G. Zhou, Design of incentive mechanism for green purchasing with asymmetric information. *Syst. Eng. Theory Pract.* **33** (2013) 106–116.

[35] B. Pal and A. Sarkar, Optimal strategies of a dual-channel green supply chain with recycling under retailer promotional effort. *RAIRO: Oper. Res.* **55** (2021) 415–431.

[36] S.Q. Hu, S. Cheng and X.L. Wang, Procurement strategy determining and supply chain coordination with random yields. *Comput. Intergrated Manuf. Syst.* **27** (2021) 2156–2170.

[37] G. Xie, Cooperative strategies for sustainability in a decentralized supply chain with competing suppliers. *J. Clean. Prod.* **113** (2016) 807–821.

[38] Y. Manteghi, J. Arkat, A. Mahmoodi and H. Farvaresh, A multi-period bi-level model for a competitive food supply chain with sustainability considerations. *J. Clean. Prod.* **325** (2021) 129260.

[39] L.N. Jiang and Z. Zhao, A study on paradox between farmers' purchasing willingness and purchasing behavior of green pesticides: based on 863 farmers' survey data from five provinces in China. *J. China Agric. Univ.* **5** (2017) 163–173.

[40] S. Rajagopaan and N. Xian, Product variety, pricing and differentiation in a supply chain. *Eur. J. Oper. Res.* **217** (2012) 84–93.

[41] C.M. Wei, Z.P. Li and H. Fan, Research on pricing decisions of dual-channel supply chain with multiple competitive retailers under different game frameworks. *Oper. Res. Manage. Sci.* **27** (2018) 63–74.

[42] J. Zhao, J. Wei and Y. Li, Pricing decisions for substitutable products in a two-echelon supply chain with firms different channel powers. *Int. J. Prod. Econ.* **153** (2014) 243–252.

[43] J. Zhao, W.S. Tang, R.Q. Zhao and J. Wei, Pricing decisions for substitutable products with a common retailer in fuzzy environments. *Eur. J. Oper. Res.* **216** (2012) 409–419.

[44] J. Zhao, L. Liu, Y. Wang, X.J. Hu and X.Z. Li, Research on competition and mode selection of suppliers based on e-commerce platform. *Syst. Eng. Theory Pract.* (2019) 2058–2069.

[45] X.M. Liu, L. Zhao, L. Wang and L.L. Ding, Research on risk-reward strategy of dual channel supply chain with stochastic market demand: from the perspective of quality and price competition. *Ch. J. Manage. Sci.* (2019) 73–84.

[46] X. Xi and Y.L. Zhang, Complexity analysis of production, fertilizer-saving level, and emission reduction efforts decisions in a two-parallel agricultural product supply chain. *Chaos Soliton Fract.* **152** (2021) 111358.

[47] S. Chen, X. Wang and Y.B. Wu, Pricing policies in green supply chains with vertical and horizontal competition. *Sustainability* **9** (2017) 2359.

[48] P. Gao, J.J. Nie, Y.M. Lu and Y.X. Zhao, Research on the quality decision on the competitive remanufacturing supply chain under different market leader. *J. Ind. Eng. Eng. Manage.* **30** (2016) 187–195.

[49] V. Sharma, A. Raj and A. Chakraborty, Analysis of power dynamics in sustainable supply chain under non-linear demand setup. *Oper. Manage. Res.* **16** (2022) 18–32.

[50] A. Srivastava, A. Chakraborty and A. Mateen, Role of power imbalance on channel coordination under greening investments. *OPSEARCH* **59** (2022) 1522–1554.

[51] C.A. Yano and H.L. Lee, Lot-sizing with random yields: a review. *Oper. Res.* **43** (1995) 311–334.

[52] J.C. Li, Y.W. Zhou and W.Y. Huang, Production and procurement strategies for seasonal product supply chain under yield uncertainty with commitment-option contracts. *Int. J. Prod. Econ.* **183** (2016) 208–222.

[53] H.J. Peng and T. Pang, Financing strategies for a capital-constrained supplier under yield uncertainty. *J. Ind. Manag. Optim.* **16** (2018) 887–909.

[54] F. Lu and H. Xu, Joint pricing and production decisions with yield uncertainty and downconversion. *Int. J. Prod. Econ.* **197** (2018) 52–62.

[55] X.X. Zhu, M.M. Wang, J. Pei and P.M. Pardalos, Investigating remanufacturing competition with yield uncertainty on market share, profit, and consumer surplus. *Int. T. Oper. Res.* **27** (2019) 2584–2615.

[56] Y. Kristiano and P. Helo, Product architecture modularity implications for operations economy of green supply chains. *Transp. Res. E-Log.* **70** (2014) 128–145.

[57] M. Zare, M. Esmaeili and Y.J. He, Implications of risk-sharing strategies on supply chains with multiple retailers and under random yield. *Int. J. Prod. Econ.* **216** (2019) 413–424.

[58] J. Cong, T. Pang and H.J. Peng, Optimal strategies for capital constrained low-carbon supply chains under yield uncertainty. *J. Clean. Prod.* **256** (2020) 120339.

[59] H.J. Peng, M.H. Zhou and L. Qian, Supply chain coordination with uncertainty in two-echelon yields. *Asia-Pac. J. Oper. Res.* **30** (2013) 1–19.

[60] L.G. Shi, T. Pang and H.J. Peng, Optimal strategies for a capital constrained contract-farming supply chain with yield insurance. *RAIRO: Oper. Res.* **55** (2021) 55–85.

[61] D.Y. Yang, D.P. Song and C.F. Li, Environmental responsibility decisions of a supply chain under different channel leaderships. *Environ. Technol. Innov.* **26** (2022) 102212.

[62] S.F. Du, W.Z. Tang, J.J. Zhao and T.F. Nie, Sell to whom? Firm's green production in competition facing market segmentation. *Ann. Oper. Res.* **270** (2018) 125–154.

[63] M.R. Galbreth and B. Ghosh, Competition and sustainability: the impact of consumer awareness. *Decis. Sci.* **44** (2012) 127–159.

[64] K.B. Chen and T.J. Xiao, Production planning and backup sourcing strategy of a buyer-dominant supply chain with random yield and demand. *Int. J. Syst. Sci.* **46** (2015) 2799–2817.

[65] Q.Q. Long, X.Y. Tao, Y.T. Chen, Y.N. Chen, L. Xu, S.Z. Zhang and J. Zhang, Exploring combined effects of dominance structure, green sensitivity, and green preference on manufacturing closed-loop supply chains. *Int. J. Prod. Econ.* **251** (2022) 108537.

[66] G.G. Cai, Z.G. Zhang and M. Zhang, Game theoretical perspectives on dual-channel supply chain competition with price discounts and pricing schemes. *Int. J. Pro. Econ.* **117** (2009) 80–96.

[67] B. Niu, D. Jin and X. Pu, Coordination of channel members' efforts and utilities in contract farming operations. *Eur. J. Oper. Res.* **255** (2016) 869–883.

[68] S. Swami and J. Shah, Channel coordination in green supply chain management. *J. Oper. Res. Soc.* **64** (2013) 336–351.

[69] A. Ghosh and J. Shah, A comparative analysis of greening policies across supply chain structures. *Int. J. Prod. Econ.* **135** (2012) 568–583.

[70] J.M. Ji, Z.Y. Zhang and L. Yang, Carbon emission reduction decisions in the retail-/dual-channel supply chain with consumers' preference. *J. Clean. Prod.* **141** (2017) 852–867.