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Optimizing Operational and Sustainable Decisions for GASC:

Integrating Outward Altruism and Government Subsidies

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ABSTRACT

This study delves into the operational decision-making and sustainability dynamics within a two-tier green agricultural supply chain (GASC), comprising a manufacturer and a retailer. By developing decision models for the manufacturer, both with and without outward altruism, we explore the intricate interplay of government subsidies, consumer green preferences, and manufacturers' altruistic behavior influencing operational efficiency and sustainability within the GASC based on the Stackelberg Game. Our findings underscore the intricate relationship between these factors and the retail pricing of green agricultural products. Specifically, we demonstrate that while the manufacturer's outward altruism is significant, the combined effects of government subsidies and consumer preferences exert substantial influence on pricing strategies. Moreover, we reveal that government subsidies, consumer preferences for sustainability, and manufacturers' altruistic actions collectively bolster the economic, environmental, and social dimensions of sustainability within the GASC.

KEYWORDS

Green Agricultural Supply Chain (GASC), Government Subsidies, Outward Altruism, Sustainability, Operational Decision

Agriculture stands as a cornerstone of national security, providing the essential resources for human sustenance and progress. Both developing countries such as China and established powers like the United States prioritize agricultural advancement, recognizing its pivotal role in supporting livelihoods (Alizamir et al., 2019). The global food security landscape has become increasingly precarious, with “The State of Food Security and Nutrition in the World 2023” reporting a staggering 735 million individuals grappling with hunger in 2022—a stark surge of 122 million since the onset of the COVID-19 pandemic in 2019 (FAO et al., 2022). Moreover, agriculture, while indispensable, exacts a toll on the environment (such as more GHG emissions, severe soil erosion, and deforestation), contributing to nearly a quarter of the world's greenhouse gas emissions (Qiao et al., 2019). These pressing challenges underscore the imperative situation for the agricultural supply chain to strike a delicate equilibrium between meeting escalating demand and safeguarding the environment for sustainable agricultural practices (Goodarzian et al., 2023).

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While the concept of sustainability lacks a singular definition, it broadly encapsulates the responsible utilization of natural resources to meet current needs while safeguarding future generations' welfare and the developmental prospects of future generations (Brundtland, 1987). Adopting a triple-bottom-line perspective, sustainability encompasses the economic, environmental, and social dimensions of development, heralding a mainstream approach to assessing agricultural supply chain sustainability (Neri et al., 2021; Singh & Srivastava, 2022). Governments worldwide have responded by implementing subsidy policies aimed at incentivizing farmers to embrace environmentally friendly practices, aligning economic development with environmental and social sustainability goals. Notably, countries like China and the United States have devised subsidy programs tailored to bolster green agricultural practices, such as China's No.1 Central Document (*China's 11 No.1 Central Documents on Agriculture*, 2014) and the Agricultural Adjustment Act in the United States (*Agricultural Adjustment Act of 1933*, 1933), signaling a concerted effort to promote sustainable agriculture (Fu et al., 2023; He et al., 2023).

This governmental emphasis on agricultural subsidies has spurred scholars interested in understanding the implications for the sustainability of agricultural supply chains. Concurrently, growing consumer awareness has fueled a preference for green agricultural products, further accentuating the need for sustainable agricultural practices. Despite the significance and complexity of these issues, previous research has predominantly focused on four key dimensions, neglecting crucial aspects and leaving them unexplored. Firstly, the literature has not thoroughly investigated all three dimensions of sustainability simultaneously. Nematollahi and Tajbakhsh (2020) synthesized 247 scientific articles on sustainable agricultural supply chains, revealing an imbalanced focus on economic and environmental sustainability at the expense of social sustainability. Secondly, while significant attention has been given to assessing the government subsidies in economic operations and social performance within green agricultural supply chains (GASCs), it has overlooked the imperative aspect of environmental sustainability (Alizamir et al., 2019; Guo et al., 2022; Qin et al., 2024). Thirdly, research has predominantly focused on inward altruism within enterprises, overlooking the significance of the outward altruism of GASCs. While inward altruism pertains to altruistic behavior among supply chain enterprises, outward altruism involves altruistic actions directed towards consumers. Although studies such as Wang, Yu, et al. (2021) have delved into the effects of the retailers' altruistic behavior towards manufacturers within low-carbon supply chain systems, the literature largely neglects the impact of outward altruism, which can profoundly affect the economic sustainability of the agricultural supply chains. To address the surging demand for green consumption, agricultural firms like Jiangsu Du Family Farm in China exemplify a commendable dedication to consumers by embracing innovative practices. This abstains from using pesticides, chemical fertilizers, and excessive land exploitation in their rice cultivation techniques. Pioneering organic methodologies, their rice is priced at CNY256/kg (Wei et al., 2022). Thereby, agricultural enterprises can enhance the green level of their products through sustainable production technologies, thereby justifying higher prices, as consumers with green preferences often exhibit a willingness to pay more for products with a higher green level. Fourthly, existing literature has investigated how consumers' evolving green preferences influence supply chain pricing and decision-makers profits, yet there has been limited discourse on the broader implications of these preferences for the environmental and social performance of supply chains (Wang and Hou, 2020).

To bridge this research gap, this paper delves into the roles of government subsidies, consumer green preferences, and outward altruism within GASCs, with a focus on addressing four main research questions.

1. How do varying levels of altruism, subsidy, and green preference among consumers affect retailers' formulation of pricing strategies?
2. What are the effects of enterprises' outward altruism on the economic, environmental, and social sustainability dimensions within GASCs?

3. How do government subsidies influence the economic, environmental, and social sustainability dimensions in GASCs?
4. What are the implications do consumers' green preferences for the economic, environmental, and social sustainability of GASCs?

Under the backdrop of governments implementing green subsidies, this paper delves into the intricate dynamics of GASCs, integrating rarely discussed aspects such as outward altruism and consumer green preferences. Through the lens of the Stackelberg Game framework, this study investigates how government subsidies, consumer green preferences, and manufacturers' altruistic behaviors collectively shape operational efficiency and sustainability within GASCs, presenting several novel contributions:

1. Firstly, the paper introduces the concept of outward altruism, a departure from the commonly explored inward altruism, into the operational decision-making of GASCs. It examines how enterprises, external to the supply chain system, demonstrate altruistic behavior towards consumers. While previous literature is predominantly focused on inward altruism within the supply chain, this study expands the scope to include the manufacturer's altruistic behavior towards consumers, thereby enriching our understanding of altruism in supply chain dynamics.
2. Secondly, employing game theory, this study simultaneously evaluates the economic, environmental, and social sustainability of GASCs. Unlike previous research that often examined these dimensions in isolation, this study recognizes the interconnectedness of sustainability aspects. Notably, it sheds light on the social sustainability dimension by considering consumer surplus in economics, a dimension often overlooked in prior studies.
3. Thirdly, the paper meticulously analyzes the impacts of government subsidies, consumer green preferences, and outward altruism on each dimension of GASC sustainability. While past research addressed some of these factors individually, none comprehensively explored their combined influence on all dimensions of sustainability within GASCs.

The remainder of this paper is structured as follows: The next section, “Literature Review,” provides a comprehensive review of relevant literature. In “Problem Description and Hypothesis,” the problem formulation and underlying assumptions are elaborated upon. “Development and Solution of Operational Models for GASC” presents equilibrium solutions for the GASC under three distinct scenarios, examining the impact of different approaches on operational decisions within GASCs. “Sustainability Analysis of GASC” delves into the influence of government subsidies, green preferences, and outward altruism on the sustainability of the GASC. Next, a “Case Study” is presented, and finally, “Conclusion” summarizes the findings, identifies potential limitations, and suggests avenues for future research.

LITERATURE REVIEW

Previous literature extensively addresses three key aspects: sustainability, altruism, and subsidy within the agricultural supply chain, thereby laying a solid groundwork for our investigation.

Sustainability in Agricultural Supply Chain

The evaluation of sustainability within agricultural supply chains is guided by various perspectives, namely weak, strong, and integrated, with the triple-bottom-line approach emerging as a pivotal framework for assessment (Neri et al., 2021; Singh and Srivastava, 2022). While existing research within agricultural supply chains often focuses on singular dimensions—be it economic, environmental, or social (Wei et al., 2023; Cao et al., 2023; Piramuthu 2022; Morais and Silvestre, 2018)—there is a growing acknowledgment of the necessity to holistically consider all three dimensions of sustainability (Nematollahi and Tajbakhsh, 2020).

In the realm of environmental-economic sustainability, Manteghi et al. (2021) utilized game theory to examine the impact of competition and cooperation on systems' profits and greenhouse gas emissions in a food supply chain. Similarly, both Jonkman et al. (2019) and De et al. (2022) developed mixed-integer linear programming models to analyze the interplay between profits and carbon dioxide emissions in food supply chains. Perdana et al. (2023) employed a mixed-method approach integrating quantitative and qualitative surveys to highlight the significant role of effective supply chain governance in reducing food loss and utilizing agricultural waste. Concerning social-economic sustainability, Sunar et al. (2016) proposed a distribution rule to optimize social welfare and production costs through the imposition of emission taxes on primary products. Zhao et al. (2021) developed an integration model to assess the impact of sustainability practices on product quality and financial performance. Hong et al. (2023) investigated contract farming supply chains, emphasizing that maximizing social welfare does not invariably lead to maximizing benefits for farmers, particularly under corporate demand information sharing. Addressing the multifaceted nature of sustainability, Hoang (2021) developed a conceptual framework model for short-food supply chains, revealing their role in augmenting farmers' income, improving consumers' health, and curbing environmental pollution and food waste in Vietnam. Liao et al. (2023) proposed a hybrid method (AHP-Fuzzy-TOPSIS) to evaluate the impact of sustainable supply chain management decisions on economic costs, energy consumption, and food quality within the fresh food supply chain. Meanwhile, Gholian-Jouybari et al. (2023) introduced a stochastic multi-objective programming model to evaluate the economic, environmental, and social performance of agricultural supply chain networks.

However, the existing literature predominantly focuses on either environmental-economic or social-economic sustainability dimensions separately, primarily relying on mathematical programming methodologies (Jonkman et al., 2019; De et al., 2022; Perdana et al., 2023) or empirical methodologies (Hoang 2021; Liao et al., 2023; Wei et al., 2023; Cao et al., 2023). There is limited utilization of game theory approaches, and corporate behavioral preferences such as altruism are often overlooked. Therefore, this paper adopts game theory methods to investigate the impact of altruistic preference behavior on the economic, environmental, and social dimensions of GASCs, a crucial and often neglected aspect.

Altruism in Agricultural Supply Chain

Altruism, a crucial factor influencing supply chain dynamics, has been predominantly explored in terms of inward altruism, where enterprises enhance the welfare of other entities within the supply chain. For instance, Ma et al. (2021) investigates the online-to-offline product service supply chain, revealing that mutual altruistic preferences between manufacturers and retailers help decision-makers in enhancing product and service quality, bolstering brand reputation, and elevating social welfare. Zhu et al. (2023) observes altruistic behavior among dominant e-commerce platforms towards low-carbon manufacturers, with the service level of e-commerce platforms influencing altruistic preferences. Rong et al. (2021) identifies altruistic preferences of dominant manufacturers toward retailers in green supply chains, which can respond effectively to extremely rapid changes in tariff rates. Wang, Yu, et al. (2021) analyzes the altruistic preferences of dominant retailers towards small and medium-sized manufacturers in low-carbon supply chains, highlighting potential trade-offs in-retailer profits. Conversely, Wei et al. (2022), for the first time, introduces the concept of outward altruism, advocating for manufacturer and retailer altruism directed toward consumers to enhance consumer welfare, particularly. The rationale behind this proposition lies in the fact that consumers show a willingness to pay higher prices for products when altruistic manufacturers invest in environmentally friendly technologies.

This analysis reveals two key highlights. First, existing literature has predominantly focused on inward altruism and has demonstrated its significant impact on the operational performance of supply chains, particularly in areas such as green initiatives (Rong et al., 2021; Wang, Yu, et al., 2021). Secondly, while much of the literature on agricultural supply chains operates under the assumption of participants' self-interest, relatively few studies have explored the impact of altruistic preferences on these chains. Indeed, as the global economy grows and environmental degradation worsens, solely relying on self-interest and fairness may not suffice for decision-makers to pursue economic interests. Altruism, especially outward altruism, is deemed more conducive to achieving the goals of sustainable development (Ge & Hu, 2012; Wei et al., 2022). However, it is worth noting that this research did not consider the role of government subsidies in environmentally friendly product contexts.

Subsidies in Agricultural Supply Chain

In agricultural supply chain management, while acknowledging the pivotal role of government interventions in economic operations and social performance, it is equally crucial not to overlook the imperative aspect of environmental sustainability. For instance, Peng and Pang (2019) delves into the nuanced relationship between government subsidies and the risk-aversion level of farmers, unveiling that increasing government subsidies leads to escalated profits for suppliers and distributors. Similarly, Alizamir et al. (2019) scrutinizes the effects of price loss coverage (PLC) and agricultural risk coverage (ARC) on both farmers and consumers, elucidating the consistent benefits of subsidization while also highlighting potential adverse impacts on overall social welfare. Furthermore, Guo et al. (2022) directs their focus toward the intersection of agricultural information dissemination and sustainable development, shedding light on the government's optimal subsidy strategies to foster win-win beneficial outcomes for farmers, environmentally responsible raw materials firms, and overall social welfare under certain conditions. Similarly, Guo et al. (2023) conducts a comprehensive examination of five distinct subsidy mechanisms and their influence on supply chain decision-making processes. Their findings underscore the significant impact of direct subsidies to farmers on product sales and the promotion of the greenness of agricultural products. In a related study, Qin et al. (2024) employs centralized and decentralized decision-making models to explore the effects of five distinct government subsidies on procurement price, retail price, and overall social welfare within the agricultural product supply chain, particularly in adverse weather conditions. They observed that government subsidies implemented within the agricultural product supply chain consistently enhance the output and pricing of agricultural products, thereby augmenting consumer surplus.

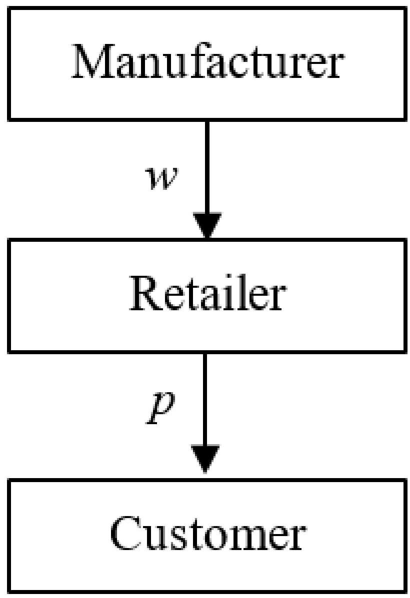
However, it is noteworthy that despite these valuable contributions, a common limitation across these studies is the omission of a holistic assessment of government subsidies on the economic, environmental, and social sustainability of the GASC, concurrently. This gap in the literature calls for further research efforts aimed at elucidating the multifaceted implications of governmental interventions on sustainability outcomes within agricultural supply chains.

PROBLEM DESCRIPTION AND HYPOTHESIS

This paper examines the dynamics of a GASC comprising a manufacturer and a retailer. The manufacturer is dedicated to implementing environmentally sustainable production practices, drawing inspiration from industry leaders such as Inner Mongolia Mengniu Dairy Industry (Group) Co., Ltd. (Hohhot, China), Haitian Seasoning Food Co., Ltd. (Foshan, China), and Beijing Capital Agribusiness Group Co., Ltd. (Beijing, China). Meanwhile, the retailer adopts green marketing strategies aimed at meeting the demand of environmentally conscious consumers in the marketplace. Figure 1 depicts the operational model of a GASC, while and Figure 2 outlines the methodology employed in this study. The research is underpinned by five key assumptions.

Assumption 1. The product demand follows a linear function, as proposed by Sinayi et al. (2018) $q = \alpha - \beta p + \delta g$.

Figure 1. Operation Model of a GASC



Assumption 2. Manufacturers invest in environmental technologies to align with consumer green preferences, thereby reducing chemical usage and promoting the adoption of biodegradable materials, ultimately mitigating pollutant emissions. Following Zerang et al. (2016), the investment cost in environmental technology is described as $\frac{1}{2}\theta g^2$, where θ represents the marginal coefficient. To ensure the relevance of subsequent discussions, this cost is assumed to be sufficiently large relative to other parameters, namely, $2\beta\theta > (\beta k + \delta)^2$.

Assumption 3. The government incentivizes green agricultural development by offering subsidies to farmers and agricultural enterprises (manufacturers). These subsidies, primarily targeted at manufacturers, aimed to encourage investments in environmental protection technologies to reduce agricultural pollutants. Following Yang and Xiao (2017), the subsidy amount per unit of green agricultural product is proportional to the product's green level (i.e., the government subsidy per unit of green agricultural product is kg, where k represents the per-unit subsidy coefficient of green agricultural products).

Assumption 4: Drawing from Perlman et al. (2019), key variables are defined: variable c represents the manufacturer's unit production cost, w denotes the wholesale price of unit production, and p indicates the retail price of the unit product. To ensure the general significance of subsequent discussions, it is assumed that $p > w > c > 0$, $\alpha - \beta c > 0$, and $\alpha - \beta p > 0$.

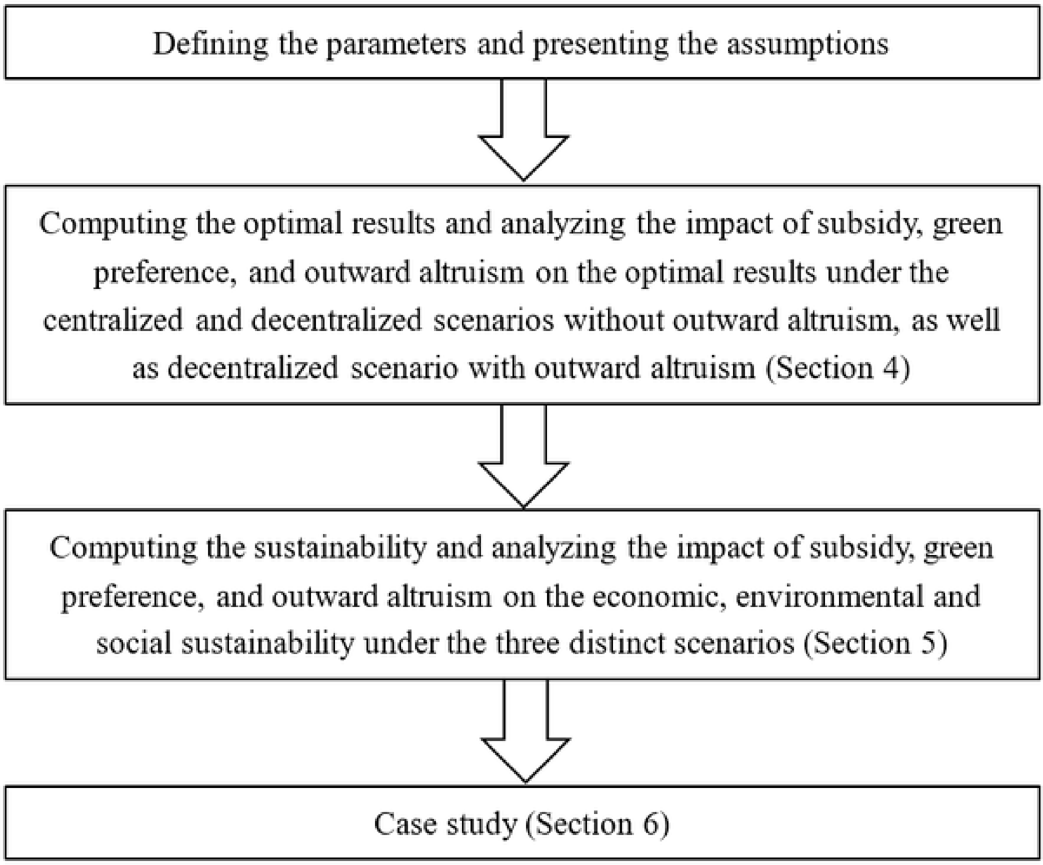
Assumption 5: Consumer surplus is represented by $cs = \frac{(\alpha - \beta p + \delta g)^2}{2\beta}$, under market demand $q = \alpha - \beta p + \delta g$, as per Xie (2016).

For ease of reference, Table 1 provides the symbols and notations utilized throughout this research.

Given the problem description and model assumptions provided, the profit functions of both the manufacturer and the retailer can be formulated as shown in Equation 1 and Equation 2.

$$\pi_m = (kg + w - c)(a - \beta p + \delta g) - \frac{1}{2}\theta g^2 \tag{1}$$

Figure 2. The Methodology Used in This Study



$$\pi_r = (p - w)(a - \beta p + \delta g) \tag{2}$$

DEVELOPMENT AND SOLUTION OF OPERATIONAL MODELS FOR GASC

Centralized Scenario Without Outward Altruism Under Government Subsidies (Model NC)

In the centralized model, both the manufacturer and the retailer collaborate closely, functioning as a unified entity for maximizing their overall profits. Together, they jointly determine the green level g and set the retail price p. Therefore, the profit function of the GASC system can be expressed as, shown in Equation 3, and we obtain the results of the optimization model in Equation 3, as outlined in Proposition 1, that shows that under the centralized scenario, the GASC has certain optimal solutions.

$$\underset{p,g}{Max}\,\pi_{sc} = (p + kg - c)(a - \beta p + \delta g) - \frac{1}{2}\theta g^2 \tag{3}$$

Proposition 1: Under the centralized scenario, the GASC has certain optimal solutions:

Table 1. Parameters and Decision Variable

	Symbol	Definition
Indices	j	Index of the manufacturer/retailer/supply chain $j = \{m, r, sc\}$
	S	Index of scenarios ($S = \{NC, ND, AD\}$), i.e., centralized model without outward altruism/ decentralized model without outward altruism/ decentralized model with outward altruism
Parameters	q	Market demand
	a	The market scale of the green product, $\alpha > 0$
	β	The price sensitivity coefficient of consumers, $\beta > 0$
	δ	Green preference, sensitivity to green level, $\delta > 0$
	θ	Marginal cost of green investment, $\theta > 0$
	c	Unit production cost
	cs	The consumer surplus
	k	Unit subsidy coefficient of green agricultural product, $k > 0$
Decision variables	g	Green level of unit production or unit pollutant emissions reduction
	w	Wholesale price
	p	Retail price
Objectives	π_j^S	Profit function of j under S scenario
	u_m^{AD}	Utility function of manufacturer under AD scenario

$$p^{NC*} = \frac{(\theta - k\delta)(\alpha + \beta c) - \alpha\beta k^2 - \delta^2 c}{2\beta\theta - (\beta k + \delta)^2}, g^{NC*} = \frac{(\beta k + \delta)(\alpha - \beta c)}{2\beta\theta - (\beta k + \delta)^2}, \text{ and } q^{NC*} = \frac{\beta\theta(\alpha - \beta c)}{2\beta\theta - (\beta k + \delta)^2}$$

Proof for all propositions, corollaries, theorems, and remarks can be found in the appendix (Supplementary file).

Decentralized Scenario Without Outward Altruism Under Government Subsidies (Model ND)

In this decentralized model without outward altruism, both the manufacturer and the retailer function as rational economic agents, driven by the goal of maximizing their individual profits by playing a manufacture-dominant Stackelberg game. In this scenario, the manufacturer assumes a dominant position within the GASC system, while the retailer operates in a subordinate capacity. The decision-making process unfolds in this sequence: the manufacturer first determines the wholesale price w and the green level (emissions reduction level) g. Then, the retailer sets the retail price p. In this context, the profits of the manufacturer and the retailer can be expressed as shown in Equation 4, and by employing the reverse induction technique (Zhang et al., 2021), we derive the results of the optimization model in Equation 4, as outlined in Proposition 2, which, under the decentralized scenario, the GASC has certain optimal solutions.

$$\underset{w,g}{Max}\,\pi_m = (kg + w - c)(a - \beta p + \delta g) - \frac{1}{2}\theta g^2$$

$$s.t.$$

$$\underset{p}{Max}\,\pi_r = (p - w)(a - \beta p + \delta g) \tag{4}$$

Proposition 2: Under the decentralized scenario, the GASC has certain optimal solutions:

$$w^{ND*} = \frac{(2\theta - k\delta)(\alpha + \beta c) - \alpha\beta k^2 - \delta^2 c}{4\beta\theta - (\beta k + \delta)^2}, p^{ND*} = \frac{2\alpha\theta + (\theta - k\delta)(\alpha + \beta c) - \alpha\beta k^2 - \delta^2 c}{4\beta\theta - (\beta k + \delta)^2},$$

$$g^{ND*} = \frac{(\beta k + \delta)(\alpha - \beta c)}{4\beta\theta - (\beta k + \delta)^2} q^{ND*} = \frac{\beta\theta(\alpha - \beta c)}{4\beta\theta - (\beta k + \delta)^2}, \pi_m{}^{ND*} = \frac{\theta(\alpha - \beta c)^2}{2[4\beta\theta - (\beta k + \delta)^2]}, \text{ and}$$

$$\pi_r{}^{ND*} = \frac{\beta\theta^2(\alpha - \beta c)^2}{[4\beta\theta - (\beta k + \delta)^2]^2}$$

From Proposition 2, Corollary 1 is achieved.

According to Corollary 1, as consumer green preferences increase, several factors experience an uptrend: the wholesale price, retail price, green level, market demand, and profits of both manufacturer and retailer. This phenomenon arises due to the heightened consumer preference for green agricultural products, necessitating manufacturers to incur higher emission reduction costs to enhance the green level of their products. To safeguard their profits, manufacturers correspondingly adjust wholesale prices upward. Moreover, as consumers' green preferences escalate, market demand naturally increases. Consequently, retailers respond by adjusting retail prices of agricultural products to capitalize on the heightened demand and maximize profits.

Corollary 1: Under the scenario, with the increase of, the operation of the GASC follows certain rules: $\frac{\partial w^{ND*}}{\partial\delta} > 0$, $\frac{\partial p^{ND*}}{\partial\delta} > 0$, $\frac{\partial g^{ND*}}{\partial\delta} > 0$, $\frac{\partial q^{ND*}}{\partial\delta} > 0$, $\frac{\partial \pi_m{}^{ND*}}{\partial\delta} > 0$, and $\frac{\partial \pi_r{}^{ND*}}{\partial\delta} > 0$.

Decentralized Scenario With Outward Altruism Under Government Subsidies (Model AD)

In this scenario, the manufacturer exhibits altruism toward consumers, prioritizing consumer surplus, as described by Wei et al. (2022), where the utility function is defined

as $u_m = \pi_m + \eta_m c_s$. Here, the altruistic force η_m represents the manufacturer's degree of concern for consumer surplus relative to self-interest. Greater altruism implies a higher consideration of consumer surplus in decision-making processes. Specifically, when $\eta_m = 0$, it represents the traditional self-interest scenario assumed in classical economics, where the manufacturer solely prioritizes its own interests, disregarding those of others. However, according to Wei et al. (2021), the altruistic force is bounded by $0 < \eta_m < 1$, indicating that although the manufacturer exhibits altruism towards consumers, it still prioritizes self-interest. Utilizing Equation 1 and the expression for consumer surplus, the utility function under the manufacturer's outward altruism and the profit function for the retailer are calculated, as shown in Equation 5.

$$\underset{g,w}{Max}\,u_m = (kg + w - c)(a - \beta p + \delta g) - \frac{1}{2}\theta g^2 + \eta_m \frac{(a - \beta p + \delta g)^2}{2\beta} s.t.$$

$$\underset{p}{Max}\,\pi_r = (p - w)(a - \beta p + \delta g) \tag{5}$$

By employing the reverse induction technique, we obtain the results of the optimization model in Equation 5, as outlined in Proposition 3, which under the scenario, the GASC has certain optimal solutions.

Proposition 3: Under the scenario, the GASC has certain optimal solutions:

$$w^{AD*} = \frac{(2\theta - k\delta)(\alpha + \beta c) - \alpha\beta k^2 - \delta^2 c - a\eta_m\theta}{\beta\theta(4 - \eta_m) - (\beta k + \delta)^2}, p^{AD*} = \frac{\alpha\theta(2 - \eta_m) + (\theta - k\delta)(\alpha + \beta c) - \alpha\beta k^2 - \delta^2 c}{\beta\theta(4 - \eta_m) - (\beta k + \delta)^2},$$

$$g^{AD*} = \frac{(\beta k + \delta)(\alpha - \beta c)}{\beta\theta(4 - \eta_m) - (\beta k + \delta)^2}, q^{AD*} = \frac{\beta\theta(\alpha - \beta c)}{\beta\theta(4 - \eta_m) - (\beta k + \delta)^2}, \pi_m{}^{AD*} = \frac{\theta(\alpha - \beta c)^2 [2\beta\theta(2 - \eta_m) - (\beta k + \delta)^2]}{2[\beta\theta(4 - \eta_m) - (\beta k + \delta)^2]^2},$$

$$\pi_r{}^{AD*} = \frac{\beta\theta^2(\alpha - \beta c)^2}{[\beta\theta(4 - \eta_m) - (\beta k + \delta)^2]^2}, \text{ and } u_m{}^{AD*} = \frac{\theta(\alpha - \beta c)^2}{2[\beta\theta(4 - \eta_m) - (\beta k + \delta)^2]^2}$$

From Proposition 3, Corollary 2 is achieved.

Impact of Government Subsidies

According to Corollary 2, as the government subsidy coefficient increases, there is a simultaneous rise in the green level, market demand, and retailer's profits. This can be attributed to the relationship between the total amount of government subsidy and both the green level of the product and sales volume. An escalation in the government subsidy rate incentivizes manufacturers to enhance the green level of agricultural products and broaden their sales reach. Consequently, an increase in the government subsidy rate promotes manufacturers to attract more consumers with green preferences by improving the green level of their products. The resultant increase in market demand, in turn, amplifies the retailer's profit margins. Corollary 2 shows that under the scenario, with the rise of k, the GASC that considers altruism meets certain conditions.

Corollary 2: Under the scenario, with the rise of, the GASC that considers altruism meets: $\frac{\partial g^{AD*}}{\partial k} > 0$, $\frac{\partial q^{AD*}}{\partial k} > 0$, and $\frac{\partial \pi_r{}^{AD*}}{\partial k} > 0$.

Corollary 3 establishes conditions under which the wholesale and retail prices are influenced by green preferences and subsidy levels. When the threshold of the joint effect surpasses 0, an escalation in the subsidy level leads to a simultaneous increase in both the wholesale and retail prices. Conversely, if this condition is not met, the outcome is reversed. This phenomenon occurs because if the subsidy fails to adequately compensate for the manufacturer's environmentally friendly investment, the manufacturer endeavors to offset the gap by progressively raising the wholesale price, prompting the retailer to make corresponding adjustments. Conversely, in scenarios where the subsidy increases, the manufacturer lowers the wholesale price, prompting the retailer to correspondingly reduce the retail price.

Corollary 3: If $\varepsilon - 2\beta^2 k\theta > 0$, there is $\frac{\partial w^{AD*}}{\partial k} > 0$ with the rise of k; otherwise, if $\varepsilon - 2\beta^2 k\theta < 0$, there is $\frac{\partial w^{AD*}}{\partial k} < 0$ with the enhancement of k. Meanwhile, if $\varepsilon + 2\beta\theta\delta > 0$, there is $\frac{\partial p^{AD*}}{\partial k} > 0$ with the rise of k; otherwise, if $\varepsilon + 2\beta\theta\delta < 0$, there is $\frac{\partial p^{AD*}}{\partial k} < 0$ with the rise of k; where $\varepsilon = \delta(\beta k + \delta)^2 - 2\beta^2 k\theta - \eta_m\beta\theta\delta$.

According to Corollary 4, when the manufacturer's outward altruistic preference level is low (i.e., below a certain threshold of $\frac{2}{3}$), the manufacturer’s profit increases with the augmentation of government subsidy. This effect can be attributed to the relatively slow increase in the green level compared to the government subsidy and the marginal cost of green investment, especially when the altruistic preference level is high (i.e., above $\frac{2}{3}$), and the consumer's green preference is low, the relationship between the manufacturer's profit and the government subsidy coefficient becomes contingent upon this threshold. Initially, an increase in the government's subsidy ratio augments the manufacturer's revenue. Nonetheless, as the subsidy ratio continues to rise, the manufacturer's profit eventually starts to decline. This phenomenon occurs because a low subsidy ratio imposes revenue constraints, thereby reducing the manufacturer's altruistic preference level. Consequently, the manufacturer can find a balance between enhancing the green level and maximizing profits through the subsidy. However, a surge in the subsidy ratio elevates the manufacturer's altruistic preference coefficient, leading to a rapid escalation in green level, compared to the government subsidy and the marginal cost of green investment. This results in a significant decrease in the manufacturer's profits. Therefore, if the manufacturer exhibits a higher level of outward altruistic preference, excessively high levels of green subsidy will ultimately undermine the manufacturer's interests.

Corollary 4: If $0 < \eta_m < \frac{2}{3}$, there is $\frac{\partial \pi_m^{AD*}}{\partial k} > 0$ with the enhancement of k; if $\frac{2}{3} < \eta_m < 1$ and $0 < \frac{\delta^2}{\beta\theta} < \frac{4-3\eta_m}{2}$, when $0 < k < \frac{-\delta + \sqrt{\beta\theta(4-3\eta_m)}}{\beta}$, there is $\frac{\partial \pi_m^{AD*}}{\partial k} > 0$ with the rise of k; if $\frac{2}{3} < \eta_m < 1$ and $0 < \frac{\delta^2}{\beta\theta} < \frac{4-3\eta_m}{2}$, when $\frac{-\delta + \sqrt{\beta\theta(4-3\eta_m)}}{\beta} < k < \frac{-\delta + \sqrt{2\beta\theta}}{\beta}$, there is $\frac{\partial \pi_m^{AD*}}{\partial k} < 0$ with the rise of k.

Impact of Consumer Green Preferences

According to Corollary 5, an increase in consumer green preference leads to an increase in the green level, market demand, retail price, and retailer profits, consistent with Corollary 1. This association can be explained by the fact that heightened green preferences entail higher emissions reduction costs for the manufacturers, motivating them to raise the wholesale price to maintain profitability. As consumers' demand for green agricultural products grows, the market demand naturally surges. In response to this demand, and driven by self-interest, manufacturers intensify their efforts to reduce emissions, leading to increased investment in emission reduction and consequent improvement in the green level. Subsequently, as manufacturers elevate the wholesale price, retailers adjust the retail price accordingly to safeguard their own profits.

Corollary 5: Under the scenario, as δ increases, the GASC that considers the altruism exhibits: $\frac{\partial g^{AD*}}{\partial \delta} > 0$, $\frac{\partial q^{AD*}}{\partial \delta} > 0$, $\frac{\partial p^{AD*}}{\partial \delta} > 0$, and $\frac{\partial \pi_r^{AD*}}{\partial \delta} > 0$.

Corollary 6 introduces a shift in the relationship between the wholesale price and consumer green preference, contrast to the findings of Corollary 1. When the impact of green preference on the wholesale price surpasses that of the manufacturer's outward altruism, the wholesale price rises with an increase in consumer green preference. Conversely, the wholesale price decreases as consumer green preference rises. This phenomenon can be attributed to manufacturers balancing the relationship between consumer green preference and the marginal cost of green production by regulating their level of altruistic preference.

Corollary 6: If $2\theta\delta(2-\eta_m) - k(\beta k + \delta)^2 - \beta k\theta\eta_m > 0$, there is $\frac{\partial w^{AD*}}{\partial \delta} > 0$ with the rise of δ; otherwise, if $2\theta\delta(2-\eta_m) - k(\beta k + \delta)^2 - \beta k\theta\eta_m < 0$, there is $\frac{\partial w^{AD*}}{\partial \delta} < 0$ with the enhancement of δ.

According to Corollary 7, when the manufacturer's outward altruistic preference is low (i.e., below a certain threshold of $\frac{2}{3}$), the manufacturer's profit increases with the rise in green preference. This trend emerges because, with a low level of outward altruistic preference, the manufacturer witnesses a rapid increase in market demand due to investments in emissions reduction, leading to an increase in profits as green preference intensifies. However, when the manufacturer's level of outward altruistic preference is high (i.e., above $\frac{2}{3}$), the relationship between the manufacturer's profit and varying green preference thresholds becomes more nuanced.

Corollary 7: If $0 < \eta_m < \frac{2}{3}$, there is $\frac{\partial \pi_m^{AD*}}{\partial \delta} > 0$ with the rise of δ; if $\frac{2}{3} < \eta_m < 1$, when $k \in (0, \delta_1)$, with the increase of δ, $\frac{\partial \pi_m^{AD*}}{\partial \delta} > 0$, and when $k \in (\delta_1, \delta_2)$, it meets $\frac{\partial \pi_m^{AD*}}{\partial \delta} < 0$, where $\delta_1 = -\beta k + \sqrt{\beta\theta(4 - 3\eta_m)}$, $\delta_2 = -\beta k + \sqrt{2\beta\theta}$.

In scenarios characterized by low green consumer preference, the manufacturer observes a diminished consumer willingness to purchase green products, leading to reduced investment in emissions reduction for agricultural products. Consequently, the manufacturer's profit increases as consumers' green preference strengthens. Conversely, when green consumer preference is high, consumers exhibit a strong inclination to purchase green agricultural products, prompting the manufacturer to enhance the green level of agricultural products by increasing investment in emissions reduction. This results in a disproportionately large increase in the manufacturer's investment costs, leading to a decrease in profits as green consumer preference strengthens.

Impact of Outward Altruism

Corollary 8 posits that under the decentralized model with outward altruism, the green level, market demand, retailer's profit, and manufacturer's utility all experience an increase. However, the manufacturer's wholesale price and profit decreases as the manufacturer actively prioritizes consumers' green demands and welfare. Despite potentially diminishing the manufacturer's interests, outward altruistic behavior serves to reduce emissions, caters to consumer green needs, enhances social welfare, and fosters cooperation among supply chain members. Additionally, this behavior increases the manufacturer's utility and motivates it to act in an outwardly altruistic manner.

Corollary 8: Under the scenario, as η_m increases, the GASC, considering altruism, exhibits: $\frac{\partial g^{AD*}}{\partial \eta_m} > 0$, $\frac{\partial q^{AD*}}{\partial \eta_m} > 0$, $\frac{\partial \pi_r^{AD*}}{\partial \eta_m} > 0$, $\frac{\partial u_m^{AD*}}{\partial \eta_m} > 0$, $\frac{\partial w^{AD*}}{\partial \eta_m} < 0$, and $\frac{\partial \pi_m^{AD*}}{\partial \eta_m} < 0$.

In Corollary 9, the escalation of outward altruistic preference imposes constraints on the retail price, influenced by both consumers' green preference and the threshold of government subsidy coefficients. Firstly, when consumers exhibit low green preference, retail prices decline as outward altruistic preference increases. Conversely, the outcome reverses when consumers demonstrate high enthusiasm for green agricultural products. This association arises because in scenarios where consumer interest in green products is low, retailers adjust retail prices downward to stimulate market demand. Conversely, elevated consumer enthusiasm coupled with the manufacturer's outward altruistic preference results in heightened green product levels and increased market demand, promoting consumers to willingly pay higher prices for green agricultural products.

Corollary 9: If $0 < \frac{\delta^2}{\beta\theta} < \frac{1}{2}$, there is $\frac{\partial p^{AD*}}{\partial \eta_m} < 0$ with the rise of η_m; if $1 < \frac{\delta^2}{\beta\theta} < 2$, there is $\frac{\partial p^{AD*}}{\partial \eta_m} > 0$ with the rise of η_m; if $\frac{1}{2} < \frac{\delta^2}{\beta\theta} < 1$, when $0 < k < \frac{\beta\theta - \delta^2}{\beta\delta}$, there is $\frac{\partial p^{AD*}}{\partial \eta_m} < 0$ with the rise of η_m; if $\frac{1}{2} < \frac{\delta^2}{\beta\theta} < 1$, when $\frac{\beta\theta - \delta^2}{\beta\delta} < k < \frac{\sqrt{2\beta\theta} - \delta}{\beta}$, there is $\frac{\partial p^{AD*}}{\partial \eta_m} > 0$ with the rise of η_m.

Secondly, when consumers display a moderate level of green preference, variations in retail prices closely correlate with government subsidy coefficients. If the government subsidy coefficient drops below a certain threshold, retail prices decrease with the escalation of outward altruistic preference. Conversely, retail prices increase as outward altruistic preference intensifies. In the case where consumers exhibit a moderate level of interest in green agricultural products and the government offers minimal subsidies to manufacturers, they may demonstrate outward altruistic preference by lowering wholesale prices. Consequently, retailers adjust retail prices proportionately. Therefore, higher levels of government subsidies render manufacturer preference behavior towards consumers more advantageous in achieving an optimal green product level. In such scenarios, retailers adjust retail prices accordingly to ensure the sustainability of the supply chain system's revenue.

Comparative Analysis of the Retail Price Under Three Scenarios

As per Remark 1, in the three scenarios, the retail price of green agricultural products is influenced by both consumers' green preferences and the threshold of government subsidy coefficients. Firstly, when consumers exhibit low green preferences, the retail price of green agricultural products is the highest in the decentralized decision-making without outward altruism scenario, followed by that in decentralized decision-making with outward altruism, and the lowest in the centralized decision-making model. Conversely, the outcome reverses when consumers demonstrate high enthusiasm for green agricultural products. Secondly, when consumers display a moderate level of green preferences, the retail price is closely correlated with government subsidy coefficients. If the government subsidy coefficient drops below a certain threshold, the retail price of green agricultural products is the highest in the decentralized decision-making without outward altruism scenario, followed by that in decentralized decision-making with outward altruism, and the lowest in the centralized decision-making case. Conversely, the outcome reverses when the government subsidy coefficient ascends above a certain threshold. This reasonable explanation is demonstrated in Corollary 9. This conclusion deviates from the commonly held belief that retail prices are always lowest under centralized decision-making and exhibits some similarities to the research findings of Wang, Shen, et al. (2021).

Remark 1: In the three different decision models, certain rules apply: if $0 < \frac{\delta^2}{\beta\theta} < \frac{1}{2}$, then $p^{NC*} < p^{AD*} < p^{ND*}$; if $1 < \frac{\delta^2}{\beta\theta} < 2$, then$p^{ND*} < p^{AD*} < p^{NC*}$; if $\frac{1}{2} < \frac{\delta^2}{\beta\theta} < 1$, and$0 < k < \frac{\beta\theta - \delta^2}{\beta\delta}$, then $p^{NC*} < p^{AD*} < p^{ND*}$; if $\frac{1}{2} < \frac{\delta^2}{\beta\theta} < 1$, and $\frac{\beta\theta - \delta^2}{\beta\delta} < k < \frac{\sqrt{2\beta\theta} - \delta}{\beta}$, then $p^{ND*} < p^{AD*} < p^{NC*}$.

SUSTAINABILITY ANALYSIS OF GASC

Economic Sustainability of GASC

The economic sustainability of agricultural supply chains is assessed through the lens of the triple-bottom-line approach, which encompasses three dimensions of sustainable development: economic, environmental, and social (Neri et al., 2021; Singh & Srivastava, 2022). In this context, economic sustainability is quantified by evaluating the total profits generated by manufacturers and retailers within the GASC. Higher total profits signify greater economic sustainability within the supply chain. Formally, Equation 6 delineates the economic sustainability of the GASC.

$$S_{ec} = \pi_m + \pi_r = (p - c)(\alpha - \beta p + \delta g) - \frac{1}{2}\theta g^2 \tag{6}$$

By substituting p^* and g^* under three scenarios into the model in Equation 6, we derive the results of the economic sustainability of the GASC, as outlined in Proposition 4, which shows that, under three scenarios, the economic sustainability of GASCs meets certain outcomes.

Proposition 4: Under three scenarios, the economic sustainability of GASCs is:

$$S_{ec}{}^{NC*} = \frac{\theta(\alpha - \beta c)^2[2\beta\theta - (\beta k + \delta)^2]}{2[2\beta\theta - (\beta k + \delta)^2]^2}, S_{ec}{}^{ND*} = \frac{\theta(\alpha - \beta c)^2[6\beta\theta - (\beta k + \delta)^2]}{2[4\beta\theta - (\beta k + \delta)^2]^2},$$

$$S_{ec}{}^{AD*} = \frac{\theta(\alpha - \beta c)^2[2\beta\theta(3 - \eta_m) - (\beta k + \delta)^2]}{2[\beta\theta(4 - \eta_m) - (\beta k + \delta)^2]^2}$$

From Proposition 4, Theorem 1 is achieved.

Impact of Government Subsidies

According to Theorem 1, government subsidies consistently bolster the economic sustainability of GASC systems by augmenting the total profits of manufacturers and retailers within the system. A higher rate of government subsidy correlates with the increased economic sustainability of the GASC. This phenomenon can be attributed to the incentivizing effect of government subsidies, which prompt manufacturers to invest in environmentally friendly technologies, thereby enhancing the green level of agricultural products. Consequently, manufacturers are able to attract more consumers with green preferences, leading to an expansion in market demand, as outlined in Corollary 2. From the perspective of the supply chain system, a higher government subsidy rate translates to heightened economic sustainability and increased profits for the GASC system as a whole.

Theorem 1: Under three scenarios, the economic sustainability of GASC has a certain relationship with government subsidies: $\frac{\partial S_{ec}^{NC*}}{\partial k} > 0$, $\frac{\partial S_{ec}^{ND*}}{\partial k} > 0$, and $\frac{\partial S_{ec}^{AD*}}{\partial k} > 0$.

Impact of Consumer Green Preferences

According to Theorem 2, consumer green preferences consistently contribute to the economic sustainability of GASC systems by bolstering the total profits of manufacturers and retailers within the supply chain. The stronger the consumer green preferences, the greater the economic sustainability of the GASC. This phenomenon can be attributed to the motivating effect of consumer green preferences, which incentivize manufacturers to invest in emissions reduction for their own self-interest. Consequently, this investment enhances the green level of agricultural products, aligning with consumer demands for green preferences and expanding market demand, as elucidated in Corollaries 1 and 5. From the perspective of the supply chain system, heightened consumer green preferences correlate with increased economic sustainability and higher profits for the GASC system as a whole.

Theorem 2: Under three scenarios, the economic sustainability of GASC has certain relationships with consumer green preferences: $\frac{\partial S_{ec}^{NC*}}{\partial \delta} > 0$, $\frac{\partial S_{ec}^{ND*}}{\partial \delta} > 0$, and $\frac{\partial S_{ec}^{AD*}}{\partial \delta} > 0$.

Impact of Outward Altruism

According to Theorem 3, the manufacturer's outward altruism positively influences economic sustainability, leading to increased total profits for manufacturers and retailers within the GASC system. The stronger the degree of outward altruism, the more robust the economic sustainability of the GASC. While a higher level of outward altruism may result in lower profits for the manufacturer, it fosters greater utility, as discussed in Corollary 8. From the perspective of the GASC, heightened manufacturer outward altruism correlates with enhanced economic sustainability and increased profits for the entire system.

Theorem 3: If the manufacturer exhibits outward altruistic preferences, the economic sustainability of the GASC has a positive relationship with outward altruistic preferences: $\frac{\partial S_{ec}^{AD*}}{\partial \eta_m} > 0$.

Environmental Sustainability of GASC

The environmental pillar of sustainability within the agricultural supply chain has these indicators: carbon footprint (Cao et al., 2023), energy consumption (Liao et al., 2023), agricultural waste utilization (Perdana et al., 2023), and greenhouse gas emissions (Jonkman et al., 2019; De et al., 2022; Manteghi et al., 2021). In the GASC, the manufacturer is dedicated to implementing environmentally sustainable production practices by reducing the use of pesticides, chemical fertilizers, and similar substances, while increasing the utilization of biodegradable, compostable materials. This approach aims to decrease the emission of pollutants such as carbon dioxide and wastewater, thereby promoting environmental sustainability. Following Qu et al. (2021), Jian et al. (2019), and so on, the total reduction in pollutant emissions serves as a proxy for the environmental pillar of sustainability in the agricultural supply chain, as expressed by Equation 7.

$$S_{en} = \xi_{gq} = \xi_{g}\left(\alpha - \beta_{p} + \delta_{g}\right) \tag{7}$$

where ξ denotes the degree of environmental damage per unit of pollutant, and g represents the degree of pollutant emission reduction per unit.

By substituting p^* and g^* under three scenarios into the model in Equation 7, we obtain the results of the environmental sustainability of the GASC, as outlined in Proposition 5.

Proposition 5: Under three models, the environmental sustainability of the GASC is:

$$S_{en}{}^{NC*} = \frac{\beta\theta\xi(\alpha - \beta c)^2(\beta k + \delta)}{[2\beta\theta - (\beta k + \delta)^2]^2},$$

$$S_{en}{}^{ND*} = \frac{\beta\theta\xi(\alpha - \beta c)^2(\beta k + \delta)}{[4\beta\theta - (\beta k + \delta)^2]^2}, \text{ and} S_{en}{}^{AD*} = \frac{\beta\theta\xi(\alpha - \beta c)^2(\beta k + \delta)}{[\beta\theta(4 - \eta_m) - (\beta k + \delta)^2]^2}$$

Impact of Government Subsidies

According to Theorem 4, government subsidies consistently enhance the environmental sustainability of the GASC by incentivizing manufacturers to invest in emission reduction. This leads to a total reduction in pollutant emissions within the GASC system and an improvement in the green level, as elucidated in Corollary 2. Specifically, higher government subsidy rates enhance environmental sustainability, resulting in increased emissions reductions in the GASC system.

Theorem 4: Under three models, the environmental sustainability of the GASC has a certain relationship with government subsidies: $\frac{\partial S_{en}{}^{NC*}}{\partial k} > 0, \frac{\partial S_{en}{}^{ND*}}{\partial k} > 0$, and $\frac{\partial S_{en}{}^{AD*}}{\partial k} > 0.$

Impact of Consumer Green Preferences

According to Theorem 5, consumer green preferences consistently bolster the environmental sustainability of the GASC by fostering a greater total reduction in pollutant emissions within the supply chain system. This occurs as consumer green preferences motivate manufacturers to invest in emissions reduction for self-interest, thereby elevating the green level to meet consumer demands and expanding market demand, as detailed in Corollaries 1 and 5. Consequently, heightened consumer green preferences correspond to stronger environmental sustainability and increased total pollutant emissions reduction within the GASC system.

Theorem 5: Under three scenarios, the environmental sustainability of the GASC a certain relationship with consumer green preferences: $\frac{\partial S_{en}{}^{NC*}}{\partial \delta} > 0, \frac{\partial S_{en}{}^{ND*}}{\partial \delta} > 0$, and $\frac{\partial S_{en}{}^{AD*}}{\partial \delta} > 0.$

Impact of Outward Altruism

According to Theorem 6, the manufacturer's outward altruism enhances the environmental sustainability in the GASC by reducing the total pollutant emissions in the supply chain system. One possible reason is that consumer green preferences incentivize the manufacturer to invest in emissions reduction, thereby raising the green level of agricultural products. Moreover, this investment addresses the demand of consumers with green preferences, leading to an expansion in market demand, as described in Corollary 8. From the perspective of the GASC, greater outward altruism corresponds to stronger environmental sustainability and a higher total reduction in pollutant emissions reduction within the GASC system.

Theorem 6: Under the model where the manufacturer exhibits outward altruism, the environmental sustainability of the GASC relies on the level of outward altruism: $\frac{\partial S_{en}^{AD*}}{\partial \eta_m} > 0$.

Social Sustainability of GASC

The social sustainability within the supply chain is assessed through various indicators such as food quality (Zhao et al., 2021) and social welfare (Sunar et al., 2016; Hong et al., 2023). Drawing from the methodology proposed by Sinayi et al. (2018), a proxy for social welfare is derived from consumer surplus. Consumers with environmental awareness are often willing to pay higher prices for greener products when manufacturers invest in environmentally friendly technologies. Despite the potential increase in costs, the transition towards greener products ultimately enhances consumer satisfaction and overall utility. This ultimately leads to a higher consumer surplus, reflecting the social sustainability of the GASC. Accordingly, Equation 8 utilizes consumer surplus as a measure of the social sustainability of the GASC.

$$S_{so} = \lambda c_s = \frac{\lambda(\alpha - \beta p + \delta g)^2}{2\beta} \tag{8}$$

where λ represents the extent of consumer surplus expenditure under sustainable development.

By substituting p^* and g^* under three scenarios into the model in Equation 8, we obtain the results of the social sustainability of the GASC outlined in Proposition 6.

Proposition 6: Under three scenarios, the social sustainability of the GASC is:

$$S_{so}^{NC*} = \frac{\beta\lambda\theta^2(\alpha - \beta c)^2}{2[2\beta\theta - (\beta k + \delta)^2]^2}, S_{so}^{ND*} = \frac{\beta\lambda\theta^2(\alpha - \beta c)^2}{2[4\beta\theta - (\beta k + \delta)^2]^2}, \text{ and } S_{so}^{AD*} = \frac{\beta\lambda\theta^2(\alpha - \beta c)^2}{2[\beta\theta(4 - \eta_m) - (\beta k + \delta)^2]^2}$$

From Proposition 6, Theorem 7 is achieved.

Impact of Government Subsidies

According to Theorem 7, government subsidies consistently enhance social sustainability within the GASC system. This is attributed to the capacity of government subsidies to incentivize manufacturers to invest in emissions reduction, thereby elevating the green level of agricultural products. This investment attracts more consumers with green preferences, thereby expanding market demand, as described in Corollary 2. Consequently, a higher rate of government subsidy correlates with stronger social sustainability, resulting in a greater total consumer surplus within the GASC system.

Theorem 7: Under three models, the social sustainability of the GASC has certain relationships with government subsidies: $\frac{\partial S_{so}^{NC*}}{\partial k} > 0$, $\frac{\partial S_{so}^{ND*}}{\partial k} > 0$, and $\frac{\partial S_{so}^{AD*}}{\partial k} > 0$.

Impact of Consumer Green Preferences

According to Theorem 8, consumer green preferences consistently improve social sustainability within the GASC system. This enhancement implies an increase in the total consumer surplus of the GASC system. This enhancement arises from the ability of consumer green preferences to prompt manufacturers to invest in emissions reduction for their own benefit, thereby promoting the green level of agricultural products and meeting the demands of consumers with green preferences. Consequently, market demand expands, as outlined in Corollaries 1 and 5. For the GASC, heightened consumer green preferences correspond to stronger social sustainability, resulting in a greater total consumer surplus within the GASC system.

Theorem 8: Under three scenarios, the social sustainability of the GASC has certain relationships with consumer green preferences: $\frac{\partial S_{so}{}^{NC*}}{\partial \delta} > 0$, $\frac{\partial S_{so}{}^{ND*}}{\partial \delta} > 0$, and $\frac{\partial S_{so}{}^{AD*}}{\partial \delta} > 0$.

Impact of Outward Altruism

According to Theorem 9, the manufacturer's outward altruistic preference improves social sustainability within the GASC system, leading to an increase in the total consumer surplus. From a corporate perspective, the higher level of outward altruism implies higher green level and more market demand, as outlined in Corollary 8. From the standpoint of supply chain system, greater outward altruism leads to stronger social sustainability and a higher total consumer welfare within the GASC system.

Theorem 9: Under the model in which the manufacturer has outward altruistic preferences, the social sustainability of the GASC exhibits a specific relationship with outward altruism: $\frac{\partial S_{so}{}^{AD*}}{\partial \eta_m} > 0$.

Comparative Analysis of the Sustainability of the GASC under Three Scenarios

As per Remark 1, the manufacturer's outward altruism contributes to the improvement of economic, environmental, and social sustainability within the GASC simultaneously. This effect stems from the manufacturer's outward altruistic behaviors, which drive enhancements in the green level, market demand, retailer's profits, and cooperation within a stable supply chain, as demonstrated in Corollary 8. Nonetheless, despite these advancements, the economic, environmental, and social sustainability of the GASC remains stronger under centralized decision-making compared to decentralized decision-making. This comparison highlights that while the manufacturer may exhibit outward altruistic behaviors towards consumers, the total profits, total reduction in pollutant emissions, and total consumer surplus in the GASC system under decentralized decision-making are still lower compared to those under centralized decision-making. To further improve the overall profits and enhance the green level and the level of social welfare of the GASC, manufacturers need to enhance cooperation and collaboration within the GASC system. Remark 2 shows that under three different decision models, certain rules hold true.

Remark 2: $S_{ec}{}^{ND*} < S_{ec}{}^{AD*} < S_{ec}{}^{NC*}$, $S_{en}{}^{ND*} < S_{en}{}^{AD*} < S_{en}{}^{NC*}$, $S_{so}{}^{ND*} < S_{so}{}^{AD*} < S_{so}{}^{NC*}$.

CASE STUDY

Green Production of QFDY

QFDY, Qiao Fu Da Yuan Agricultural Co., Ltd. located in the Heilongjiang Province of China, was established in 1998. It specializes in the agricultural activities, including the cultivation, production and processing, of high-quality rice. Since 2005, the company has been dedicated to cultivating green, high-quality rice under the trademark Qiao Fu Da Yuan. This commitment has earned QFDY several prestigious awards, including China Green Food Expo Gold Award and the 105th Panama International Expo Grand Gold Prize Award. Aligned with China's governmental policies, such as the Rural Revitalization Strategy (*China's Rural Vitalization*, 2024) and China's No.1 Central Document (*China's 11 No.1 Central Documents on Agriculture*, 2014), aimed at promoting green agricultural practices, QFDY has received substantial support for its rapid development.

Since 2010, QFDY has embarked on altruistic initiatives by embracing green production practices to cater to the growing demand for environmentally friendly products among consumers. Collaborating with the Institute of Genetics and Developmental Biology of the Chinese Academy of

Sciences, QFDY has engaged in technology breeding, purifying, and revitalizing the Rice Fragrance 2 variety, and developing the new variety of Zhongke 613 rice. Additionally, the company has established 266,670-Hectares of standardized planting bases in the core production area of Wuchang rice, employing methods such as land circulation, cooperative societies, and farmer-shareholding companies. QFDY has introduced innovative techniques like "Duck-Rice Co-Cultivation" and established four planting technology standards, namely Ecological, EU Organic, Chinese Organic, and Green Rice. By refraining from pesticide spraying, avoiding chemical fertilizers, and implementing eco-planting and eco-breeding practices, QFDY has achieved a comprehensive balance in the ecological cycle, fostering sustainable coexistence with the land.

The green high-quality production and outward altruism initiatives have led to the recognition of QFDY rice among consumers willing to pay more for environmentally friendly products. For instance, the price of QFDY organic rice is priced at CNY178/kg (China JD Mall, 2024), significantly higher than the average price of regular rice at CNY7/kg. Major retailers like Yonghui and JD actively distribute QFDY organic rice in key cities such as Beijing, Shanghai, and Guangzhou. QFDY emphasizes outward altruism throughout the production process, brand leadership, and technical services, thereby promoting the development of a green, high-quality rice supply chain.

Based on the theoretical assumptions and real data collected for QFDY, standardized similar to the approach taken by Wei et al. (2022), key factors, such as market scale α=20, price sensitivity $\beta = 0.2$, marginal cost of green investment $\theta = 100$, unit production cost $c = 5$, environmental damage per unit of pollutant $\xi = 25$, and consumer surplus expenditure $\lambda = 2.5$, are considered for analysis due to their economic significance and the comparability across different backgrounds.

Combined Impact of Altruism, Subsidy, and Green Preference on Market Price

In the GASC system, the retail price is intricately tied to several factors, including the manufacturer's outward altruism coefficient, consumer green preferences, and government subsidy. When consumers have a weak green preference ($\delta = 0.5$), an increase in the manufacturer's outward altruism coefficient tends to result in a decrease in the retail price. Conversely, when consumers have a moderate green preference but low government subsidies ($\delta = 4$, $k = 4$), there exists a negative correlation between the retail price and the manufacturer's outward altruism coefficient. However, this correlation becomes positive when consumer green preferences are moderate but with high government subsidies ($\delta = 4$, $k = 10$). On the other hand, in the case of strong consumer green preferences, the retail price escalates with an increase in the manufacturer's outward altruism coefficient. This pattern emerges because manufacturers face lower green costs in markets with weaker consumer green preference, leading to adjustments in wholesale and, consequently, retail prices to stimulate demand.

In scenarios where consumer green preferences and government subsidies are at moderate levels, manufacturers balance the demonstration of their altruistic behavior with pricing strategies. With high subsidies, investments in emissions reduction reach optimal green levels, prompting retailers to raise price levels. In markets characterized by strong green preferences, retailers prioritize their self-interest, resulting in higher retail prices. The retailer's pricing decisions are directly influenced by consumer green preferences, assuming a constant level of manufacturer altruism and government subsidies. Consequently, prices rise in tandem with increased green preferences. Similarly, retail prices escalate with the rise in government subsidies under fixed altruism levels and consumer preference intensities. Table 2 represents the changes in the retail price of green agricultural products under different outward altruism.

Impact of Integrating Altruism and Subsidy on Sustainability of the GASC

We assume the manufacturer's outward altruism $\eta_m \in (0, 0.9]$, green preference $\delta = 4$, and three scenarios of government subsidies $k = 4$, $k = 5$, and $k = 6$, ceteris paribus. The parameters should satisfy the condition for the existence of an equilibrium solution in the model. For example, when η_m=0.9, $k = 6$, there are $\beta\theta(4 - \eta_m) - (\beta k + \delta)^2 = 34.96 > 0$, and $2\beta\theta - (\beta k + \delta)^2$=12.96>0.

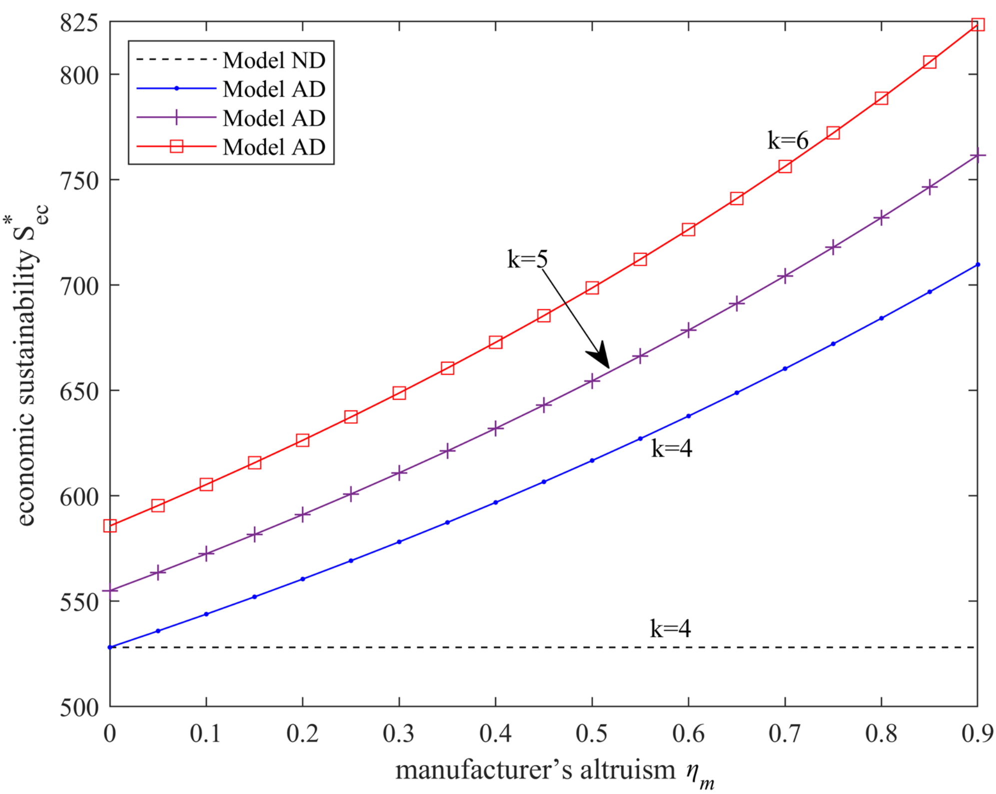
Table 2. Changes in the Retail Price of Green Agricultural Products Under Different Outward Altruism Coefficients

Green preference δ	Subsidy k	Outward altruism η_m								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.5	10	75.17	74.46	73.71	72.91	72.06	71.15	70.19	69.16	68.05
4	4	98.62	98.56	98.51	98.45	98.38	98.31	98.23	98.14	98.05
4	10	109.05	109.50	110	110.56	111.18	111.88	112.67	113.57	114.62
4.5	10	124.58	126.04	127.68	129.54	131.67	134.13	137	140.40	144.49

Economic Sustainability

Figure 3 illustrates the impact of integrating altruism and subsidy on the economic sustainability within the GASC. As depicted in Figure 3, outward altruism positively enhances the economic sustainability within the GASC, corroborating the assertions made in Theorem 3. Furthermore, government subsidies contribute to the improvement of economic sustainability in the GASC, aligning with the insights provided in Theorem 1. Additionally, in scenarios characterized by decentralized decision-making, the economic sustainability of the GASC is notably stronger when outward altruism is present compared to scenarios where it is absent, a trend consistent with Remark 2.

Figure 3. Impact of Integrating Altruism and Subsidy on the Economic Sustainability of the GASC



Environmental Sustainability

Figure 4 illustrates the effects of integrating altruism and subsidy on the environmental sustainability within the GASC. As depicted in Figure 4, outward altruism positively impacts environmental sustainability within the GASC, consistent with the economic observation and confirming the findings outlined in Theorem 6. Moreover, government subsidies play a significant role in increasing environmental sustainability within the GASC, supporting the assertions made in the economic dimension and affirming Theorem 4. Furthermore, under decentralized decision-making scenarios, the environmental sustainability of the GASC exhibits greater strength in the presence of outward altruism compared to scenarios where it is absent, aligning with Remark 2.

Social Sustainability

Figure 5 depicts the effect of integrating altruism and subsidy on the social sustainability of the GASC. According to Figure 5, outward altruism contributes positively to the social sustainability of the GASC, echoing the observations made in the economic and environmental dimensions and confirming the insights provided in Theorem 9. Additionally, government subsidies are instrumental in enhancing social sustainability within the GASC, validating the findings in the economic and environmental dimensions of sustainability as well as Theorem 7. Moreover, under decentralized decision-making scenarios, the social sustainability of the GASC demonstrates greater resilience in the presence of outward altruism compared to scenarios where it is absent, consistent with Remark 2.

Figure 4. Impact of Integrating Altruism and Subsidy on the Environmental Sustainability of the GASC

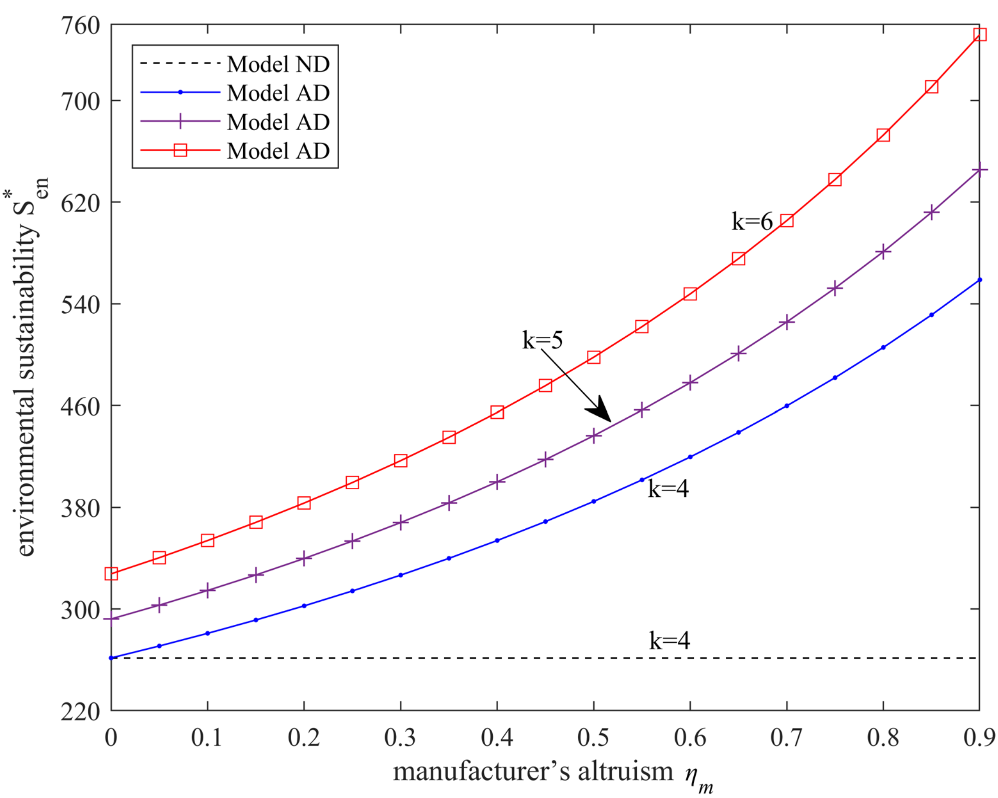
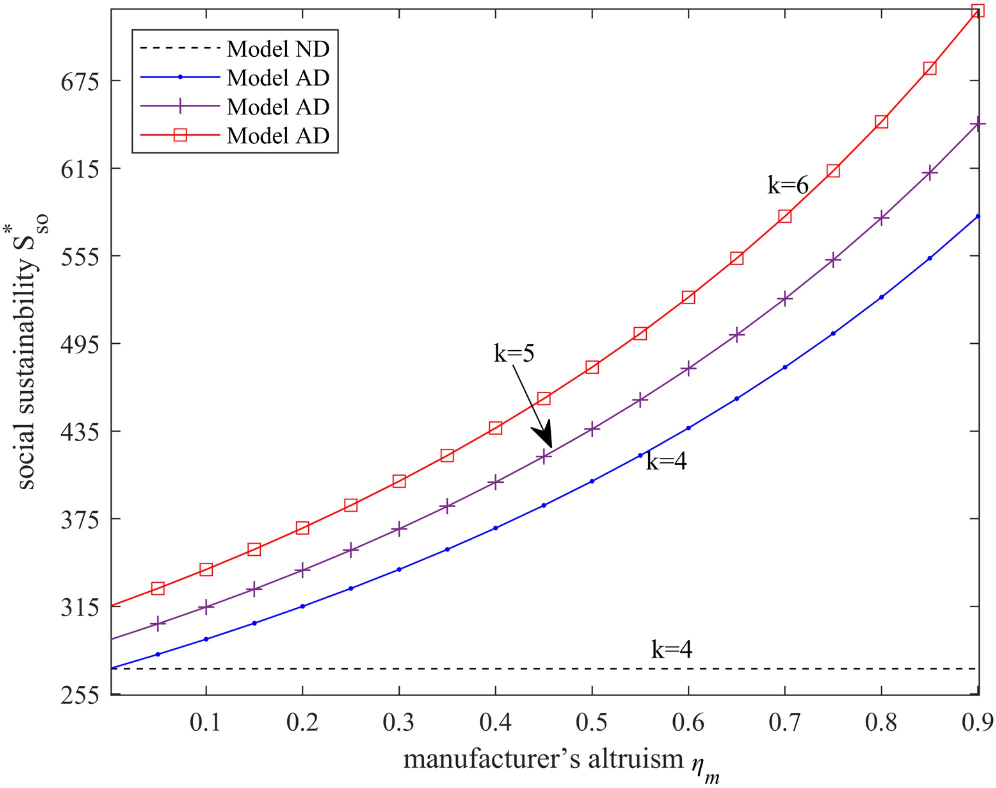


Figure 5. Impact of Integrating Altruism and Subsidy on the Social Sustainability of the GASC



Impact of Green Preference on the Sustainability of the GASC

We assume consumer green preferences $\delta \in (0,4]$, manufacturer's altruism $\eta_m = 0.5$, government subsidy $k = 4$, ceteris paribus. The parameters should satisfy the condition for the existence of an equilibrium solution in the model. For example, when δ=4, there are $\beta\theta(4 - \eta_m) - (\beta k + \delta)^2 = 41.91 > 0$, and $2\beta\theta - (\beta k + \delta)^2$=11.91>0.

Economic Sustainability

Figure 6 shows the effects of green preference on the economic sustainability in the GASC. Based on Figure 6, consumer green preferences positively contribute to developing the economic sustainability in the GASC, confirming the findings in Theorem 2 and outward altruism. Moreover, under decentralized decision-making, the economic sustainability of the GASC with outward altruism is stronger than without outward altruism, while the economic sustainability of the GASC is highest under centralized decision-making, consistent with Remark 2.

Environmental Sustainability

Figure 7 displays the influence of green preference on the environmental sustainability in the GASC. Regarding Figure 7, consumer green preferences enhance the environmental sustainability in the GASC, confirming the findings stated in Theorem 5 and outward altruism. In addition, under decentralized decision-making, the environmental sustainability of the GASC with outward altruism is stronger than without outward altruism, while the environmental sustainability of the GASC is the strongest under centralized decision-making, aligned with Remark 2.

Figure 6. Impact of Green Preference on the Economic Sustainability of the GASC

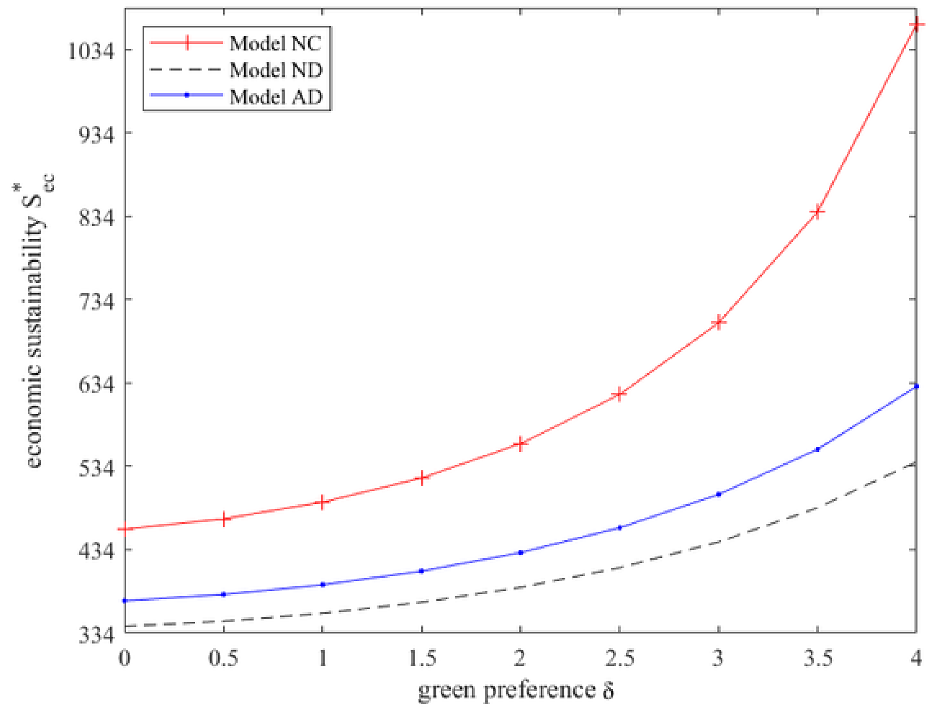
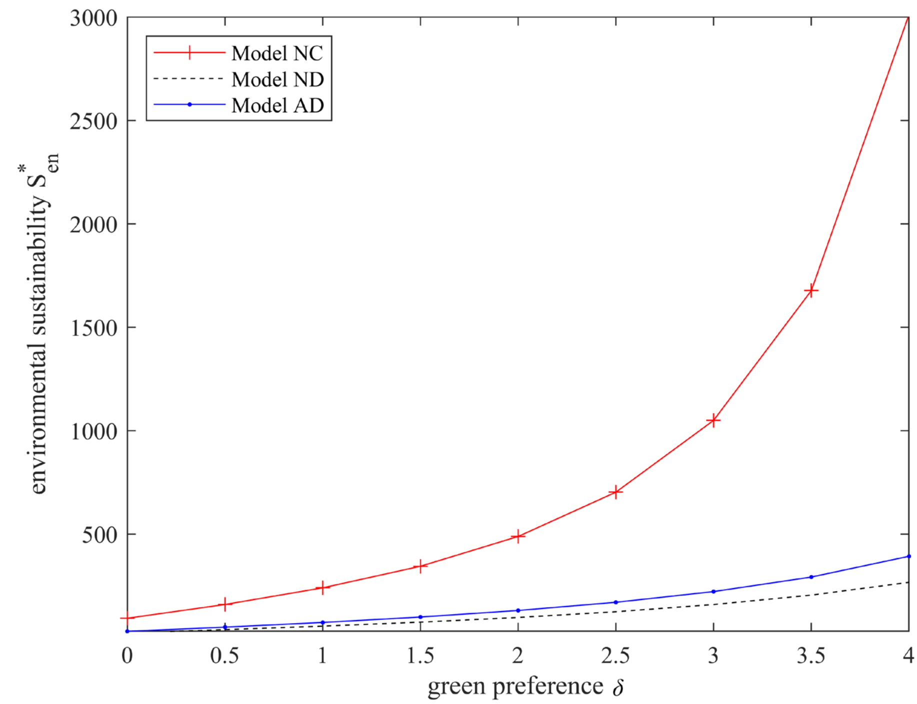


Figure 7. Impact of Green Preference on the Environmental Sustainability of the GASC



Social Sustainability

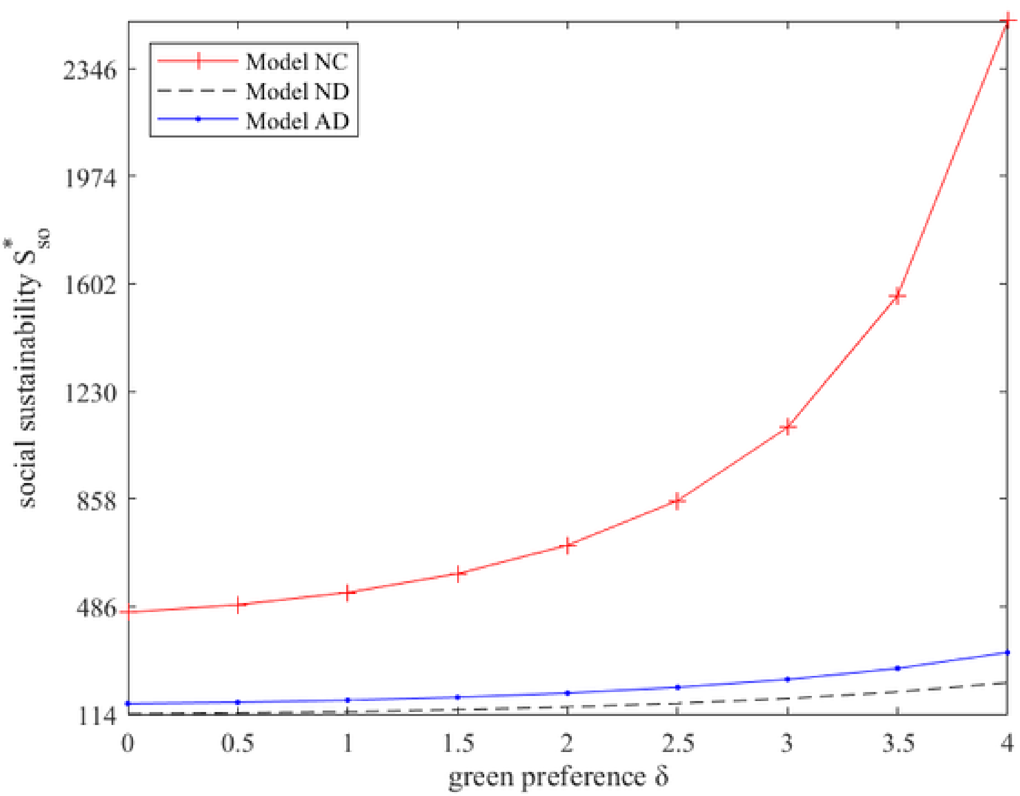
Figure 8 illustrates the effect of green preference on the social sustainability in the GASC. Based on Figure 8, consumer green preferences enhance the social sustainability in the GASC, confirming the findings in Theorem 8 and outward altruism. Furthermore, under decentralized decision-making, the social sustainability of the GASC with outward altruism is stronger than without outward altruism, while the social sustainability of the GASC is the highest under centralized decision-making, consistent with Remark 2.

CONCLUSIONS

This study delves into the operational decision and sustainability of the GASC, a supply chain comprising manufacturers and retailers. It constructs decision-making models for manufacturers, considering both scenarios with and without outward altruism, and examines the impacts of government subsidies, manufacturer outward altruism, and consumer green preferences on GASC operations and sustainability. The study offers several significant insights.

Firstly, while outward altruism may lead to reduced pricing and profits for manufacturers, it concurrently elevates the green level of agricultural products and boosts market demand. Moreover, it enhances the manufacturer's utility and fosters cooperation among supply chain enterprises. Secondly, consumer green preferences contribute to heightened green levels within the agricultural supply chain, increased market demand, higher retail prices of agricultural products, and enhanced retailer profits. Notably, in scenarios of high outward altruism, consumer green preferences may bolster manufacturer

Figure 8. Impact of Green Preference on the Social Sustainability of the GASC



profits; however, in case of lower altruism, they may harm manufacturer interests. Thirdly, the retail prices of agricultural products are influenced by the government subsidy coefficient under both centralized and decentralized decision-making scenarios. When the government subsidy coefficient surpasses (falls below) a certain threshold, the retail price of agricultural products is highest (lowest) within the centralized decision-making scenario. Fourthly, the retail price of agricultural products hinges not solely on outward altruistic behavior but also on government subsidies and consumer green preferences. Higher government subsidies correlate with increased retail prices, as they reflect the costs of emissions reduction investments borne by manufacturers. Fifthly, in the case of GASC sustainability, manufacturer outward altruism, consumer green preferences, and government subsidies synergistically enhance economic, environmental, and social sustainability. Centralized decision-making demonstrates the highest sustainability across these dimensions, followed by decentralized decision-making with outward altruism, and decentralized decision-making without outward altruism yielding the weakest sustainability. This highlights a synergistic mechanism wherein these elements interact to enhance overall sustainability outcomes.

However, previous literature has scarcely addressed outward altruism, thus neglecting to explore its combined impact with government subsidies and consumer green preferences on operational decisions and the three dimensions of sustainability. Additionally, previous studies have not compared the retail price and sustainability dimensions of the GASC under three distinct scenarios. Consequently, this paper contributes novel insights by uncovering previously unexplored relationships among government subsidies, consumer green preferences, and outward altruism. These findings provide decision-makers with a deeper understanding of the intricate dynamics at play, a perspective that has been lacking in prior literature.

Managerial Implications

The findings of this study provide valuable insights for management stakeholders. For governmental bodies, there are several strategic actions to consider. Firstly, governments should prioritize the integration of multidimensional objectives encompassing economic, environmental, and social sustainability in agricultural policies. Additionally, advocating for green consumption concepts and behaviors among consumers is essential. Moreover, providing financial incentives, such as subsidies tailored to the greenness of each agricultural product unit, can encourage manufacturers to adopt green production practices. However, caution is warranted to ensure that government subsidies do not lead to excessive retail price hikes for agricultural products. Furthermore, governments can incentivize altruistic preferences among manufacturers by implementing policies aimed at fostering coordinated and sustainable development within the GASC. For the supply chain, it is necessary to facilitate cooperation between upstream and downstream enterprises to leverage the positive impacts of outward altruism. This coordination can enhance the economic, environmental, and social sustainability of the supply chain while bolstering operational stability. For the enterprise, enterprises should incorporate outward altruism with green production strategies into their corporate development plans. Active implementation of outward altruism can enhance market competitiveness and yield increased benefits, particularly as consumers increasingly prioritize green agricultural products.

Future Research

Two areas merit exploration in future research endeavors. Firstly, while this paper solely examines scenarios with deterministic market demand, it's crucial to acknowledge that market demand in practical settings is frequently stochastic and uncertain. Exploring how stochasticity impacts the outcomes of the model would provide valuable insights. Secondly, this study exclusively investigates cases where manufacturers exhibit outward altruism. However, it would be beneficial to explore and compare scenarios where retailers demonstrate outward altruism, as well as scenarios where both manufacturers and retailers simultaneously exhibit outward altruism. Such investigations would offer a comprehensive understanding of how different agents' altruistic behaviors influence supply chain dynamics and outcomes.

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CONFLICTS OF INTEREST

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